MSc Program
Renewable Energy Systems

ACADEMY FOR CONTINUING EDUCATION

Implementation, diversification and coupling of different renewable energy sources and renewable energy systems in local and district heating networks

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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51822568

Vienna, 06.08.2024

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Affidavit

I, **DIPL.-ING. DOMINIC WÖSS, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "IMPLEMENTATION, DIVERSIFICATION AND COUPLING OF DIFFERENT RENEWABLE ENERGY SOURCES AND RENEWABLE ENERGY SYSTEMS IN LOCAL AND DISTRICT HEATING NETWORKS", 186 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 06.08.2024

Signature

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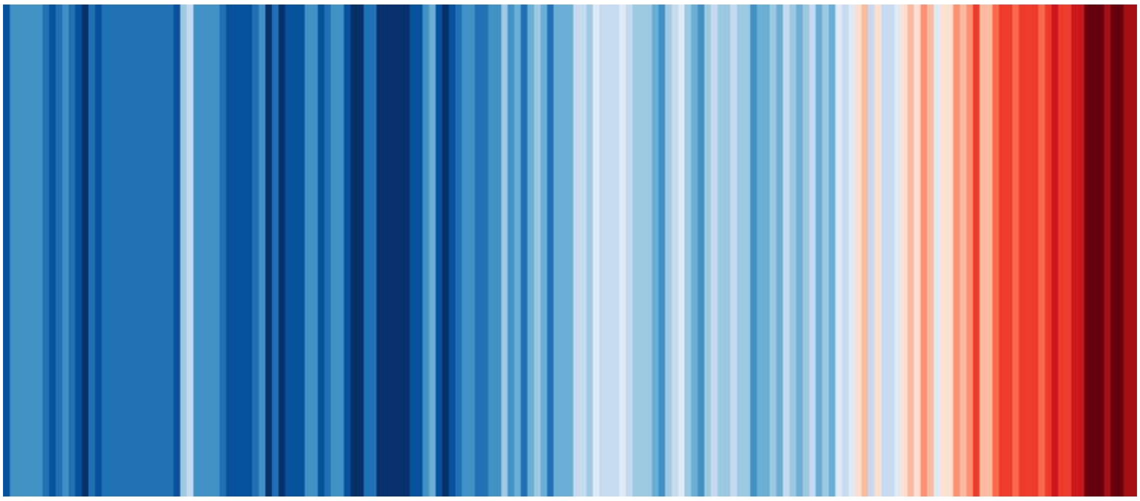
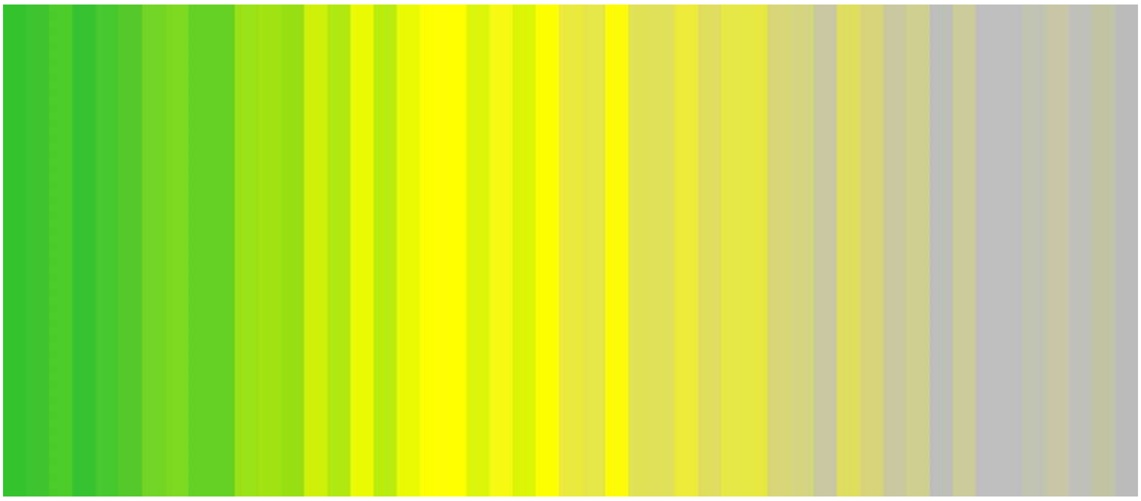


"Agglomeration of powerful blues and reds" [1]



"Collection of bright colours" [2]

Something like this could be the names of these pictures. Furthermore, an uninformed person could assume that these pictures are abstract art. In reality, these images represent alarming facts – the rise in average temperature and the decline in biodiversity. For this reason, it is important to increase the awareness of the population and to adapt our lifestyle to slow down and reverse these destructive and hostile processes.

[1] (Hawkins, 2022)
[2] (ZSL/WWF, 2022)

“A transition to clean energy is about making an investment in our future.”

Quote from Gloria Reuben

“Der Umstieg auf saubere Energie bedeutet eine Investition in unsere Zukunft.“

Zitat von Gloria Reuben

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Preface and acknowledgements

About 10 years ago, I had first thoughts about continuing my education at university. Today I am very happy with the decision I made in the past to continue my education at university, and I am glad that I chose this path, even if it wasn't always a simple one.

After completing my education in mechanical engineering at the Higher Technical College in Linz and completing my community service at the Red Cross Upper Austria, I started my career at Wacker Neuson Linz GmbH. At Wacker Neuson Linz GmbH, I had the opportunity to apply the knowledge I had acquired during my education at the Higher Technical College in the R&D department for earthmoving machinery. After working in various divisions in the R&D department, I became more and more interested in continuing my education at the university.

From 2015 to 2018, I completed my bachelor's degree in mechanical engineering at the University of Applied Sciences Upper Austria at Campus Wels. After my bachelor's degree, I continued my academic education at the University of Applied Sciences Upper Austria at Campus Wels with a master's degree in plant engineering. During my university education, I was always supported by Wacker Neuson Linz GmbH. I would like to thank the company for their support.

My master's thesis was about a topic in the energy sector. Due to the intensive focus on the energy sector and the associated interest, I decided to continue my professional career in the energy sector. In 2020, I started working in the heating and cooling department as a project planner and project manager for decentralized heat supplies at LINZ STROM GAS WÄRME GmbH, a subsidiary of LINZ AG, the municipal utility of the city of Linz. At the same time, I started working as a part-time lecturer in the Higher Technical College in Linz in the field of mechanical engineering. After a year's break from further education, I started a bachelor's degree in "Relevant Studies, Supplementary Studies" at the University of Education Upper Austria, which was required for the part-time work at the Higher Technical College.

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Another year later, in 2022, I continued my university education with the master's degree "Renewable Energy Systems" at the TU Wien. This master's thesis is the final thesis of this master program.

I would like to take the opportunity to thank my superiors and colleagues at LINZ AG and the Higher Technical College, as well as my colleagues in the master's program and everyone else who has supported me during this master's degree program. Without their support and understanding, it would not have been possible to combine the job, the part-time employment and the two studies.

Furthermore, I would like to express my sincere thanks to Mr. Alexander Fischer, MSc for his supervision and support of this master's thesis. Mr. Alexander Fischer, MSc supported me in the preparation of my master's thesis at a high professional level, which contributed significantly to the success of my master's thesis. For the high level of commitment, I would like to express many thanks.

Finally, I would like to express my warmest thanks to my family. Without my family, who supported me in all matters and situations all the time, the successful completion of my university education would not have been possible. Due to the multiple responsibilities of my job, the part-time employment and the two studies, the time was sometimes very limited, which is why many compromises had to be made. For this reason, I would like to thank my family for always understanding me in my endeavors in the past.

I would also like to thank all the suppliers who supported me with information. At this point, I would like to highlight that the aim of my master's thesis was not to give preference to a particular technology. Each technology has its strengths and weaknesses. The detailed description of these strengths and weaknesses would have exceeded the scope of this master's thesis. Furthermore, some assumptions and simplifications were made in the master's thesis, making it almost impossible to identify a preference for one of the technologies.

Finally, I would like to express my thanks also to all the people I have not explicitly mentioned for their support during my master's degree program.

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Abstract

In local heating networks and district heating networks, where heat is supplied to heat consumers, it is known that different energy sources can be used to generate heat. In addition to fossil fuels (such as coal, oil, gas), also renewable energy sources (such as biomass, solar energy, geothermal energy, electricity, etc.) can be used. Climate protection targets of countries and associations of countries such as the European Union will regulate among other things the generation of heat in local and district heating networks in the future. The goal of the European Union is the defossilisation and decarbonisation of all energy sectors by 2050. Some countries, such as Austria, have committed to achieve climate neutrality already in 2040, which means that only renewable energy sources can be used for energy generation from then on. For local and district heating networks, this will result in challenges that have to be solved on several levels.

On the one hand, there will be a strong conversion boom in the space heating sector to replace existing heating systems that are based on fossil fuels by renewable heating systems. In future, existing heating systems based on coal, oil and gas will be replaced by heat pump heating systems, biomass heating systems or local and district heating systems. In places where a local or a district heating network already exists, additional households will be connected to the local or the district heating system. The strong expansion of the existing local and district heating network infrastructure and the construction of new local and district heating network infrastructures will increase the demand for heat to operate these local and district heating networks. In addition to an increasing demand for heat, the heat generation in local and district heating networks must also be transformed to renewable energy sources. Nowadays, renewable local and district heat is generated from biomass (e.g. wood), solar energy, geothermal energy, heat pumps, renewable waste, residual heat, or electricity.

In most local and district heating networks, wood is used to provide renewable heat, because the utilization of the other mentioned renewable energy sources is technically and / or economically difficult or even impossible.

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But also, wood as a renewable energy source is limited if the forest is cultivated in a sustainable way so that it can be assumed that the generation of renewable local and district heat cannot only be based on wood as a biomass source in the future. Instead, it can be expected that renewable local and district heat generation will be based on various sources in the future.

In the course of this master's thesis, various technologies will be presented that can be used to generate renewable local and district heat in existing and growing local and district heating networks as well as in local and district heating networks that will be erected in the future. A major focus in the master's thesis will be put on the coupling of all energy sectors. The sector coupling will be an essential factor in the energy system of the future to ensure a reliable and efficient utilization of all renewable energy sources despite their volatility. In addition to the presentation of the generation technologies, measures to increase the efficiency will be presented. The applicability of the generation technologies and the efficiency improvement measures will be analyzed and demonstrated based on a technological analysis as well as on a technical and an economic calculation.

Finally, the master's thesis should enable the derivation of an optimal system constellation (best practice) for local and district heating networks which need to be expanded as well as for new local and district heating networks taking into account technical and ecological framework conditions. The conclusion will reflect the experience and knowledge that has been gained as well as problems that must be solved in future. A future perspective will provide a rough forecast on the local and district heating networks of the future.

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Kurzfassung

Bei Nahwärmenetzen sowie bei Fernwärmenetzen, welche die Wärmeversorgung für Wärmeabnehmer bereitstellen ist bekannt, dass die Wärmeerzeugung mit unterschiedlichen Energieträgern erfolgen kann. Neben fossilen Energieträgern (wie zum Beispiel Kohle, Öl, Gas) können auch erneuerbare Energieträger (wie zum Beispiel Biomasse, Sonnenenergie, Geothermie, Elektrizität, etc.) verwendet werden. Klimaschutzziele von Ländern und Staatenverbunden wie zum Beispiel der europäischen Union werden zukünftig unter anderem die Wärmeerzeugung in Nah- und Fernwärmenetzen reglementieren. Das Ziel der europäischen Union ist die Defossilisierung bzw. die Dekarbonisierung aller Energiesektoren bis zum Jahr 2050. Einige Länder, wie zum Beispiel Österreich haben sich zum Ziel gesetzt, bereits im Jahr 2040 Klimaneutralität zu erreichen, was bedeutet, dass ab diesem Zeitpunkt nur mehr erneuerbare Energieträger zur Energieerzeugung verwendet werden dürfen. Für Nah- und Fernwärmenetze ergeben sich dadurch auf mehreren Ebenen zu lösende Herausforderungen.

Einerseits wird es im Raumwärmesektor zu einem starken Umstellungsboom kommen, um bestehende fossile Heizsysteme durch erneuerbare Heizsysteme zu ersetzen. Bestehende Kohle-, Öl- und Gasheizungen werden zukünftig durch Wärmepumpenheizungen, Biomasseheizungen oder Nah- und Fernwärmesysteme ersetzt werden. In Orten, in denen bereits ein Nah- oder Fernwärmenetz vorhanden ist, werden zusätzliche Haushalte an das Nah- oder Fernwärmesystem angeschlossen. Durch den starken Ausbau der bestehenden Nah- und Fernwärmenetzinfrastruktur und die Errichtung neuer Nah- und Fernwärmenetzinfrastrukturen wird der Wärmebedarf für den Betrieb ebendieser Nah- und Fernwärmenetze steigen. Neben einem steigenden Wärmebedarf muss auch die Wärmeerzeugung bei Nah- und Fernwärmenetzen auf erneuerbare Energieträger umgestellt werden. Gegenwärtig wird erneuerbare Nah- und Fernwärme unter anderem mit Biomasse (z.B. Holz), Solarenergie, Geothermie, Wärmepumpen, erneuerbaren Abfall, Abwärme oder Strom erzeugt.

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Kurzfassung

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Bei einem Großteil von Nah- und Fernwärmenetzen wird Holz zur erneuerbaren Wärmebereitstellung verwendet, da die Erschließung der anderen genannten erneuerbaren Energieträger technisch und / oder wirtschaftlich schwierig bis unmöglich ist.

Aber auch Holz als erneuerbare Energiequelle ist bei nachhaltiger Bewirtschaftung des Waldes begrenzt, sodass davon auszugehen ist, dass die Erzeugung von erneuerbarer Nah- und Fernwärme nicht nur auf Holz als Biomasse basieren kann. Vielmehr ist zu erwarten, dass die erneuerbare Nah- und Fernwärmeerzeugung in Zukunft auf verschiedenen Quellen basieren wird.

Im Zuge dieser Masterarbeit werden verschiedene Technologien vorgestellt, mit denen in bestehenden und wachsenden Nah- und Fernwärmenetzen sowie in zukünftig zu errichtenden Nah- und Fernwärmenetzen erneuerbare Nah- und Fernwärme bereitgestellt werden kann. Ein wesentliches Augenmerk soll dabei auf die Kopplung aller Energiesektoren gelegt werden. Die Sektorenkopplung wird im Energiesystem der Zukunft eine wesentliche Rolle spielen, um eine zuverlässige und effiziente Nutzung aller erneuerbaren Energieträger trotz ihrer Volatilität gewährleisten zu können. Neben der Vorstellung von Erzeugungstechnologien sollen auch Maßnahmen zur Steigerung der Effizienz vorgestellt werden. Die Anwendbarkeit der Technologien bzw. der Effizienzsteigerungsmaßnahmen soll auf Basis einer technologischen Betrachtung sowie einer technischen und wirtschaftlichen Berechnung analysiert und dargelegt werden.

Abschließend soll die Masterarbeit eine Ableitung einer optimalen Anlagenkonstellation (best practice) für zu erweiternde Nah- und Fernwärmenetze als auch für neue Nah- und Fernwärmenetze unter Berücksichtigung der technischen und wirtschaftlichen Rahmenbedingungen ermöglichen. Die Schlussfolgerung wird die erworbenen Erfahrungen und Erkenntnisse als auch die offenen noch zu lösenden Probleme widerspiegeln. Ein Zukunftsausblick soll einen groben Ausblick auf die Nah- und Fernwärmenetze der Zukunft eröffnen.

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1 Motivation for the energy transition

At the beginning of the master's thesis, a short section will be dedicated to the necessity of the energy transition and a sustainable lifestyle.

The last few years have highlighted and underlined the importance of the energy transition and a sustainable lifestyle on several levels. On the one hand, weather catastrophes associated with extreme weather conditions have caused enormous damage and costs. The accumulation of these weather disasters is without any doubt linked to the climate change. A key parameter that helps to make climate change more visible is the change in average temperature. Figure 1 shows the change in the average annual temperature for the years 1850 to 2022 in relation to the average temperature from 1971 to 2000. Each bar represents the difference between the global average temperature of a year and the reference temperature. This figure shows that the average temperature has sharply risen in the last 20 years.

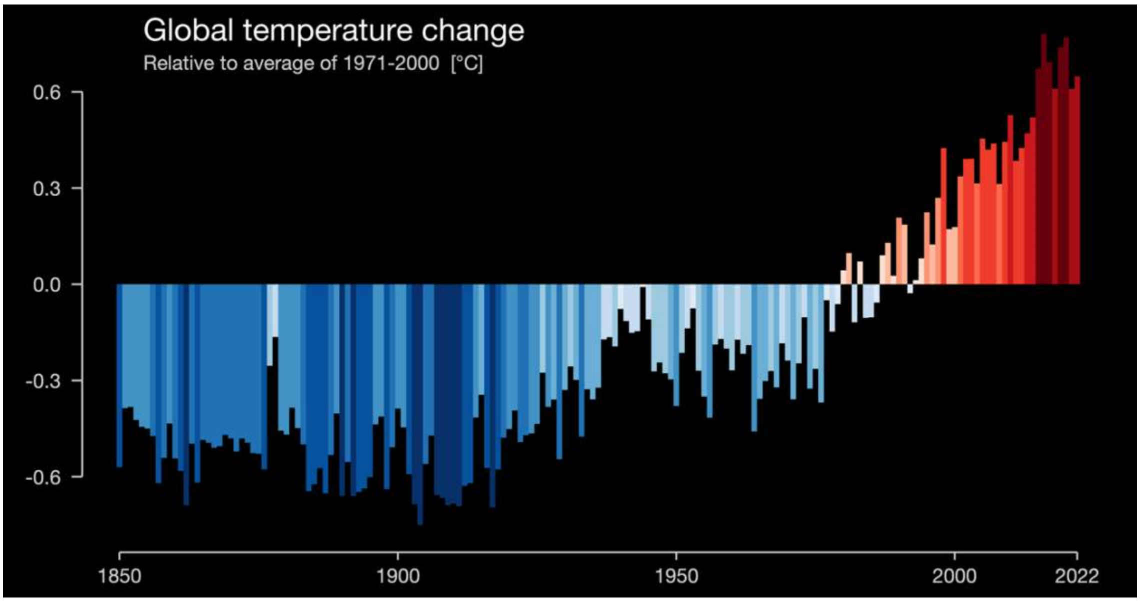

Figure 1: Global temperature change from 1850 to 2022 [3]

Now somebody could argue that the increase in the global average temperature only results from an increase in temperature in some countries, while the temperature in other countries has remained the same or has even fallen.

[3] (Hawkins, 2022)

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This assertion can be refuted with Figure 2. Figure 2 shows the temperature changes in all countries from 1901 to 2018. Also in this figure, a dramatic increase of the temperature can be noticed.

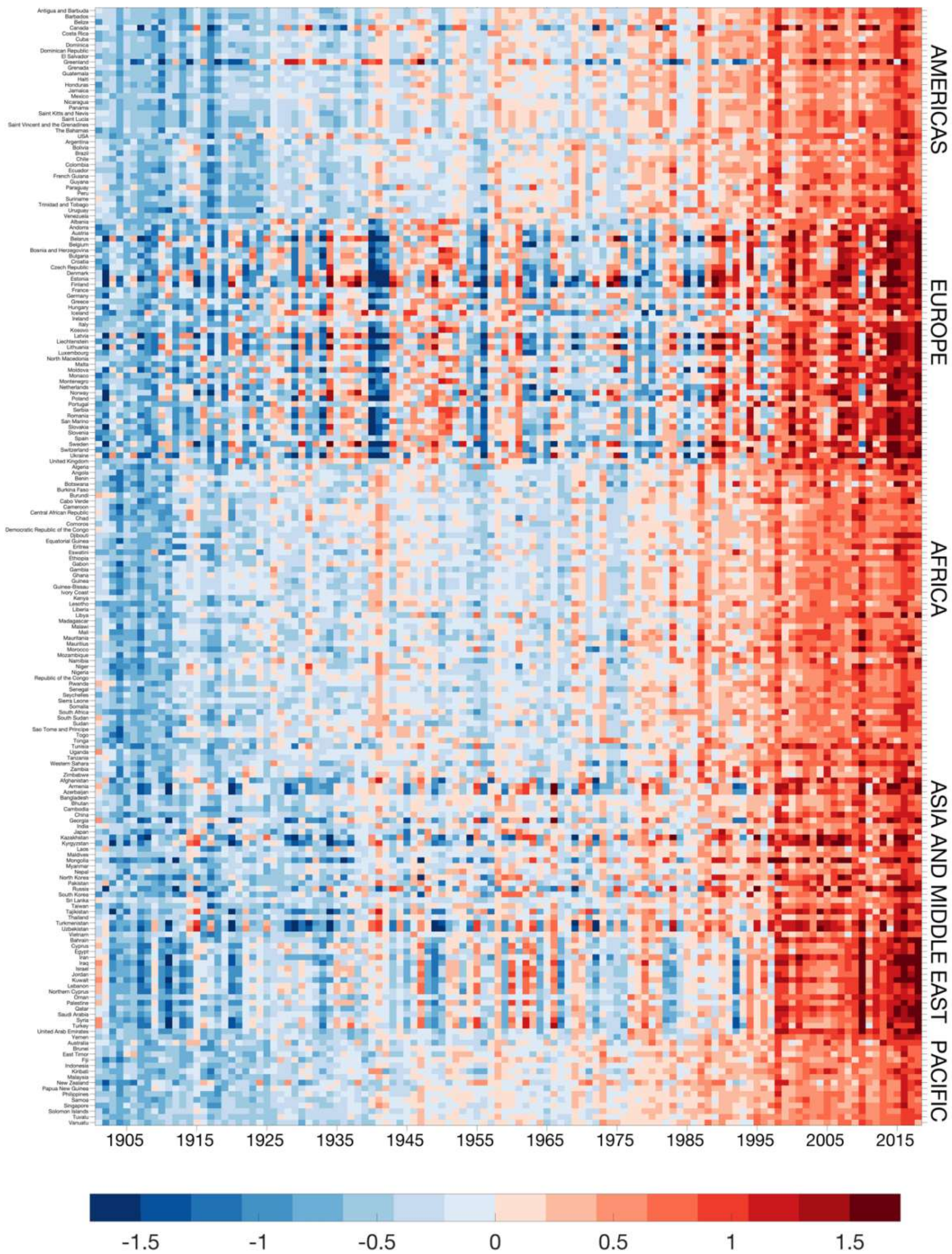

Figure 2: Temperature changes around the world (1901 – 2018) [4]

[4] (Hawkins, 2019)

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This climate change and the increase in the average temperature can be directly linked to the greenhouse gas emissions caused by humans, which include CO_2 emissions, CH_4 emissions and N_2O emissions.

These greenhouse gases act in a similar way to the glass in a greenhouse. They absorb the heat radiated from the earth's surface, trap it in the atmosphere and prevent it from being released into the space. The greenhouse effect ensures that it is warmer on earth than it would be without it and generally makes life on earth possible at all. Many greenhouse gases occur naturally in the atmosphere, and they are also needed to keep this greenhouse effect alive to make life possible. However, humans are responsible for the accumulation of greenhouse gases in the atmosphere. As a result, the greenhouse effect in the atmosphere is intensified and changes the climate of our planet, which can be recognized by shifts in snow and rainfall behavior, an increase in average temperatures and extreme climate events such as heat waves and floods. [5]

Figure 3 shows the global carbon dioxide budget for the year 2023, including all anthropogenic emissions and sinks and neglecting all natural emissions and sinks.

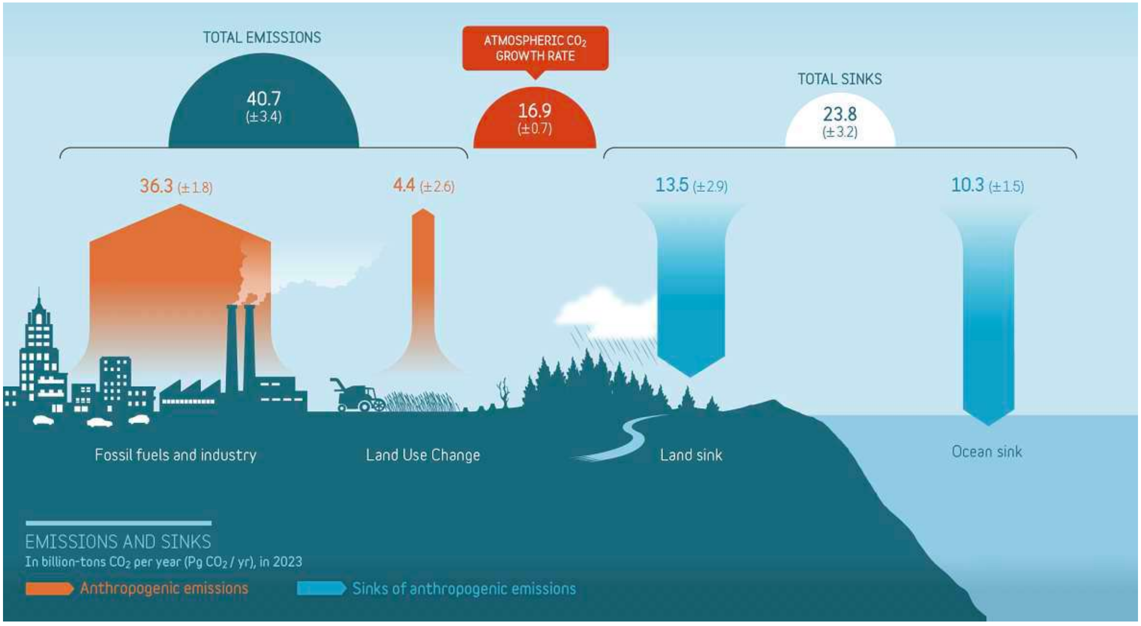

Figure 3: Global carbon dioxide budget 2023 [6]

[5] Cf. (Europäisches Parlament, 2023) (own translation)
[6] (Friedlingstein, et al., 2023)

This figure illustrates that the majority of carbon dioxide emissions result from fossil fuels and industry. The carbon dioxide emissions from fossil fuels, industry and land use are mostly balanced by sinks. Here it can be recognized that the sinks in the form of land and water cannot absorb all carbon dioxide emissions, which results in an accumulation of carbon dioxide in the atmosphere. This increasing concentration of carbon dioxide in the atmosphere further accelerates the climate change, especially as carbon dioxide is a greenhouse gas.

To identify a potential link between climate change – the increase of the average temperature – and anthropogenic carbon dioxide emissions, a longer-term perspective on the carbon dioxide balance is required. Figure 4 shows the annual and cumulative carbon dioxide emissions and carbon dioxide sinks from 1850 to 2023. This figure shows an increase in fossil carbon dioxide emissions from the beginning of industrialization and a strong, continuous increase in fossil carbon dioxide emissions from around 1950.

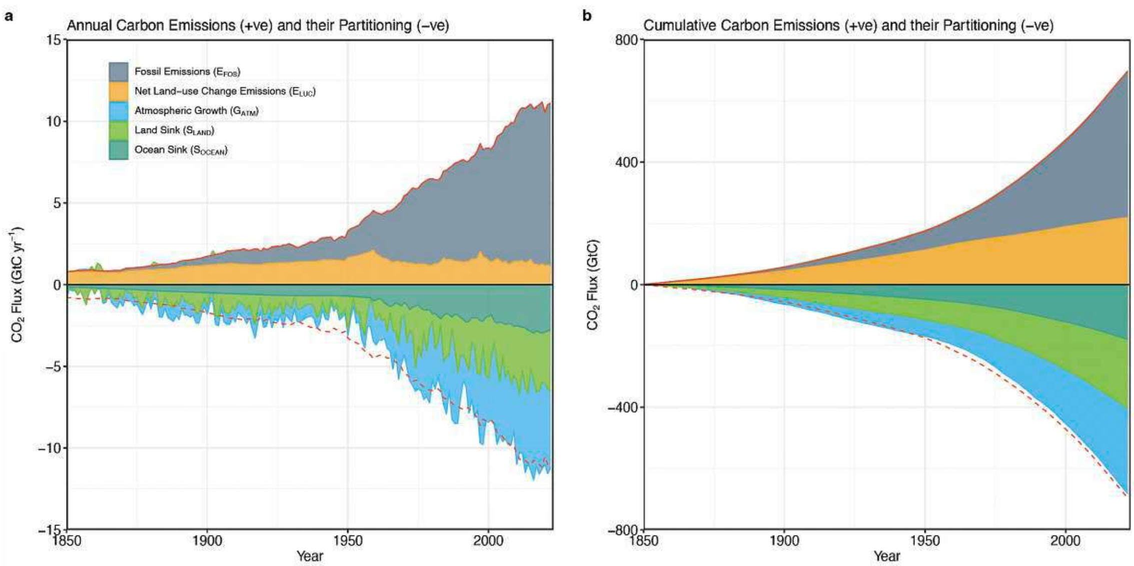

Figure 4: Annual and cumulative carbon dioxide emissions and sinks 1850 – 2023 [7]

Figure 2 and Figure 4 show that the anthropogenic carbon dioxide emissions and the climate change – the increase of the average temperature – show a similar trend. As already mentioned, there are also other emissions in addition to carbon dioxide emissions that are responsible for climate change, such as methane and nitrous oxide.

[7] (Friedlingstein, et al., 2023 p. 5320)

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Figure 5 shows the global methane budget for one year, based on the average from 2008 to 2017, including all anthropogenic and natural emissions and sinks. From this figure it can be derived that the largest methane emissions result from the production and use of fossil fuels, as well as from agriculture and waste. The different types of modelling such as "Bottom-up view (BU)" and “Top-down view (TD)" lead to different results. The interested reader is referred to the relevant literature for the explanation.

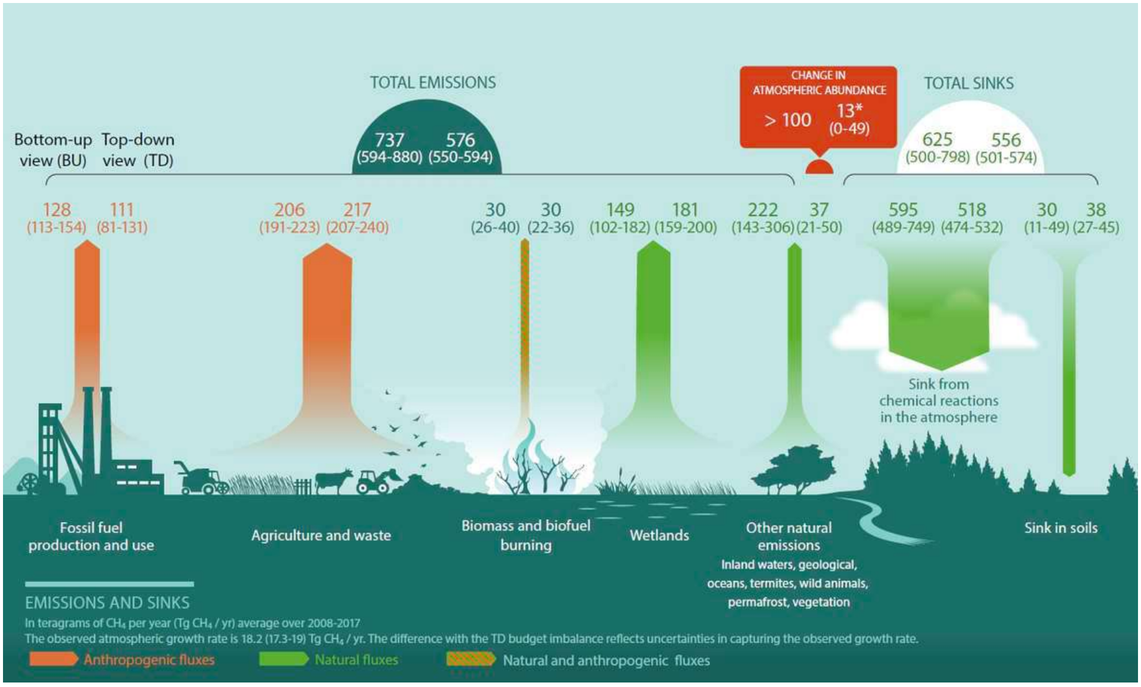

Figure 5: Global methane budget 2008 – 2017 [8]

In addition to anthropogenic carbon dioxide emissions and anthropogenic methane emissions, greenhouse gas emissions from humans also include nitrous oxide emissions and other emissions (fluorinated greenhouse gases).

Figure 6 shows the global nitrous oxide budget for one year, based on the average from 2007 to 2016, including all anthropogenic and natural emissions. This figure shows that the largest nitrous oxide emissions are caused by agriculture, but also the sector of fossil fuels and the industry are responsible for a large amount of nitrous oxide emissions. To be able to compare the various emissions, it is necessary to evaluate the greenhouse effect of the different gases. This can be carried out with the global warming potential (GWP).

[8] (Saunois, et al., 2020), (Jackson, et al., 2020)

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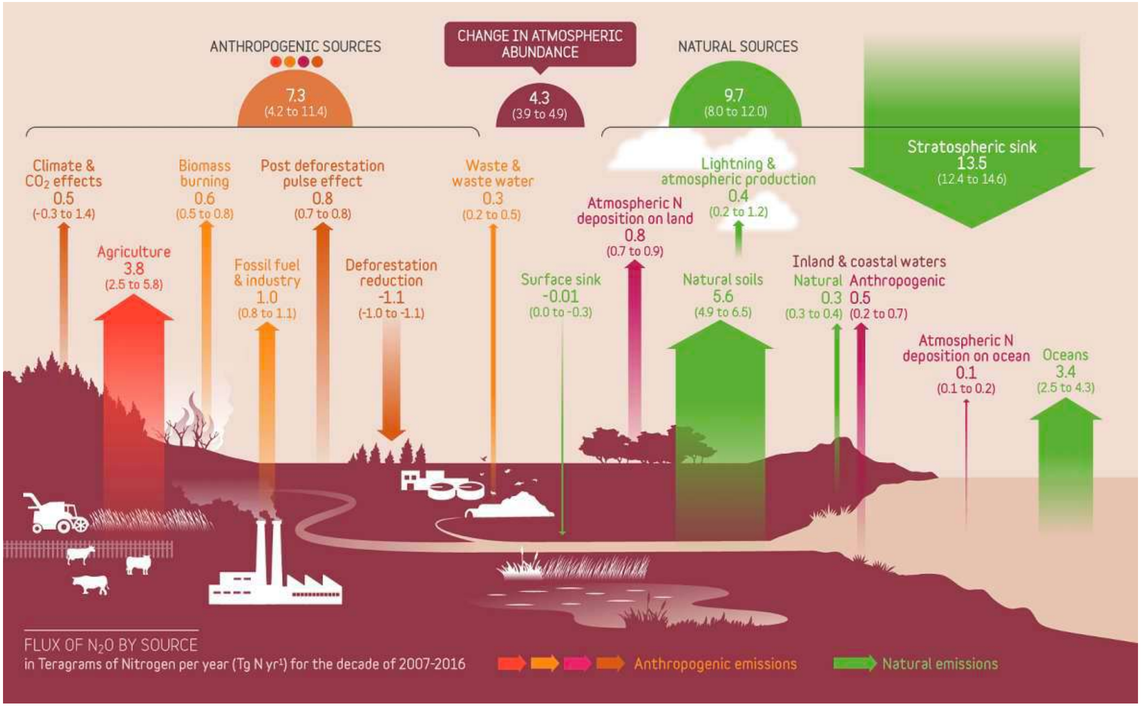

Figure 6: Global nitrous oxide budget 2007 – 2016 [9]

The GWP factor (Greenhouse Warming Potential / Global Warming Potential) represents the global warming potential of a substance compared to CO_2. It indicates the extent of contribution to the direct greenhouse effect compared to CO_2 over an agreed time horizon for 20 (GWP-20), 100 (GWP-100) or 500 years (GWP-500). [10] Table 1 shows the global warming potential (GWP) for selected species for different time horizons.

Table 1: Global warming potential (GWP) for selected species [11]

Species	**GWP-20**	**GWP-100**	**GWP-500**
CO_2	1,0	1,0	1,0
CH_4-fossil	82,5 ± 25,8	10,0 ± 3,8	13,2 ± 6,1
CH_4-non fossil	79,7 ± 25,8	27,0 ± 11	7,2 ± 3,8
N_2O	273 ± 118	273 ± 130	130 ± 64

In Table 1, no fluorinated gases were listed that could have GWP values of over 2.000. [12]

[9] (Tian, et al., 2020)
[10] Cf. (Keller, et al., 2021 pp. 68-70) (own translation)
[11] Cf. (Forster, et al., 2021 p. 1017), Cf. (Ritchie, et al., 2023)
[12] (Keller, et al., 2021 p. 74)

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The combination of the annual carbon dioxide emissions, the annual methane emissions, and the annual nitrous oxide emissions with their global warming potential results in the greenhouse gas emissions in carbon dioxide equivalents. Figure 7 shows the greenhouse gas emissions in carbon dioxide equivalents for the years 1850 to 2021.

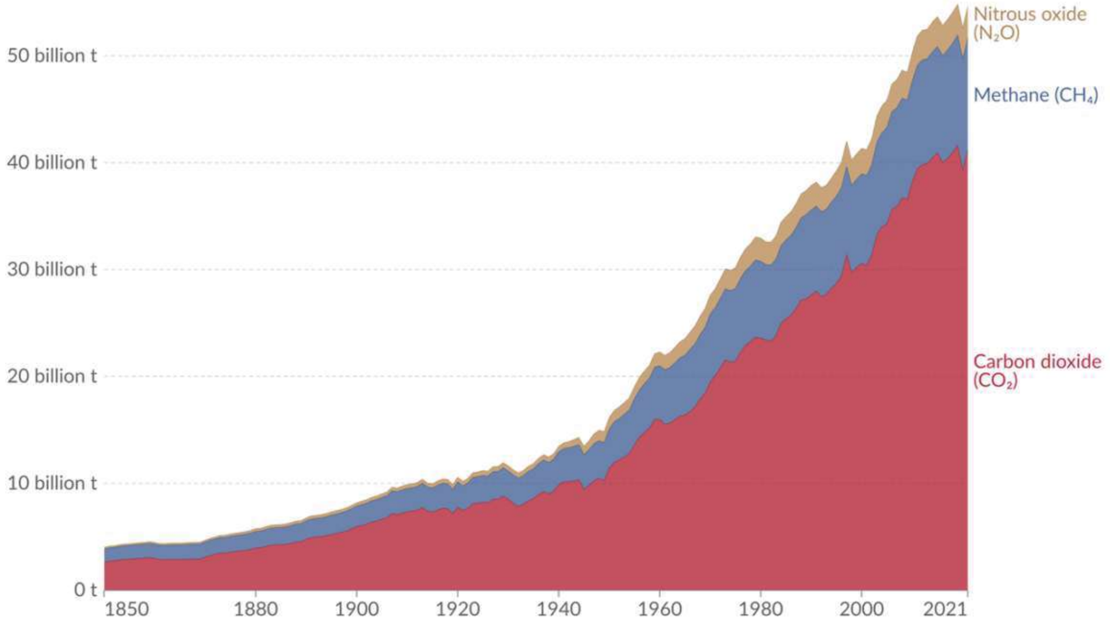

Figure 7: Greenhouse gas emissions from all sources in carbon dioxide equivalents [13]

This figure shows that the carbon dioxide emissions have the strongest influence on the greenhouse effect, although the different impacts of the greenhouse gases have been considered. The reduction of carbon dioxide emissions is without any doubt the most important objective for climate protection, but also the reduction of methane emissions and the reduction of nitrous oxide emissions make an important contribution to climate protection. These facts and figures can be used to derive the following effective approaches for climate protection:

- Reduction of carbon dioxide emissions by avoiding fossil fuels
- Reduction of methane emissions by avoiding fossil fuels and adapting agriculture (e.g. reducing livestock farming and adapting crops)
- Reduction of nitrous oxide by avoiding fossil fuels and adapting agriculture (e.g. reducing fertilization)

[13] (Ritchie, et al., 2020), (Jones, et al., 2023)

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From these points it is obvious that avoiding fossil fuels supports the reduction of carbon dioxide emissions, the reduction of methane emissions and the reduction of nitrous oxide emissions. Nevertheless, the other mentioned measures are also important points for climate protection.

In addition to the aspect of climate protection, there is another point that represents an incentive to change the energy system. Without discussing the reasons in detail, it can be mentioned that the COVID pandemic and the conflict between Russia and Ukraine resulted in a sharp increase in energy prices. As a result of these invasive events, the majority of the population realized for the first time that our society is highly dependent on fossil fuels from abroad. Figure 8 visualizes the price indices for various energy sources used in Austria for the years 2010 to 2023. In this figure, all price indices are related to the index from 1 January 2010. For this reason, this figure does not show the energy prices over time, but rather the development of the energy prices over this period. It can be seen that energy prices have risen sharply due to the COVID pandemic and the conflict between Russia and Ukraine, especially for fossil natural gas and electricity due to the merit order principle.

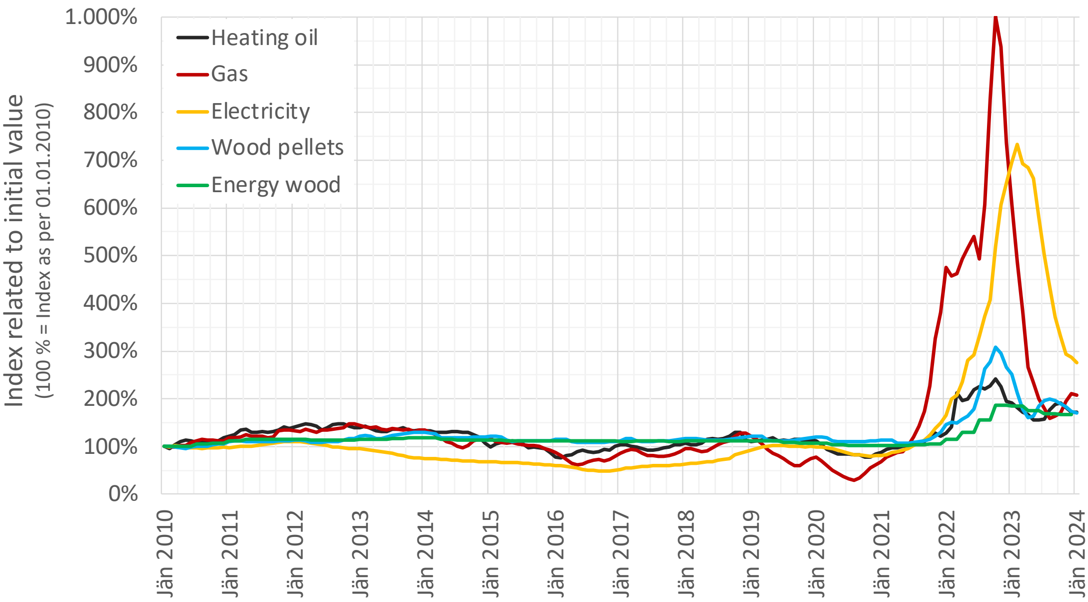

Figure 8: Price indices of various energy sources from 2010 to 2023 [14]

[14] (Köck, 2023), (Österreichische Energieagentur, 2024a), (Österreichische Energieagentur, 2024b), (proPellets Austria, 2024), (Statistik Austria, 2024)

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2 Introduction

The target of the European Union is the defossilization and decarbonization of all energy sectors by 2050, while Austria has set the target to achieve climate neutrality by 2040, so that only renewable energy sources can be used for energy generation from then on. In addition to the legal requirements that are designed to achieve climate neutrality, the energy transition is necessary to achieve independence from fossil fuels from abroad and to ensure a resilient and secure energy supply in the future. The majority of the energy consumed in Austria, the so-called gross domestic consumption, can be attributed to fossil fuels. For Austria, the transformation of the energy system is a mammoth task due to the current strong dependence on fossil fuels from abroad. [15]

Figure 9 shows the gross domestic consumption in petajoules for Austria for the period from 2005 to 2022. Furthermore, the figure shows the structure of the gross domestic consumption of around 1.355 petajoules for the year 2022, according to the shares of energy sources. The gross domestic consumption is defined as the sum of the domestic primary energy production, the imports, and the reductions in stock minus the sum of the exports and the increases in stock. This figure highlights the fact that more than half of the gross domestic consumption was and is still based on fossil fuels. It is also worth mentioning that the gross domestic consumption has mostly stabilized in recent years. [16]

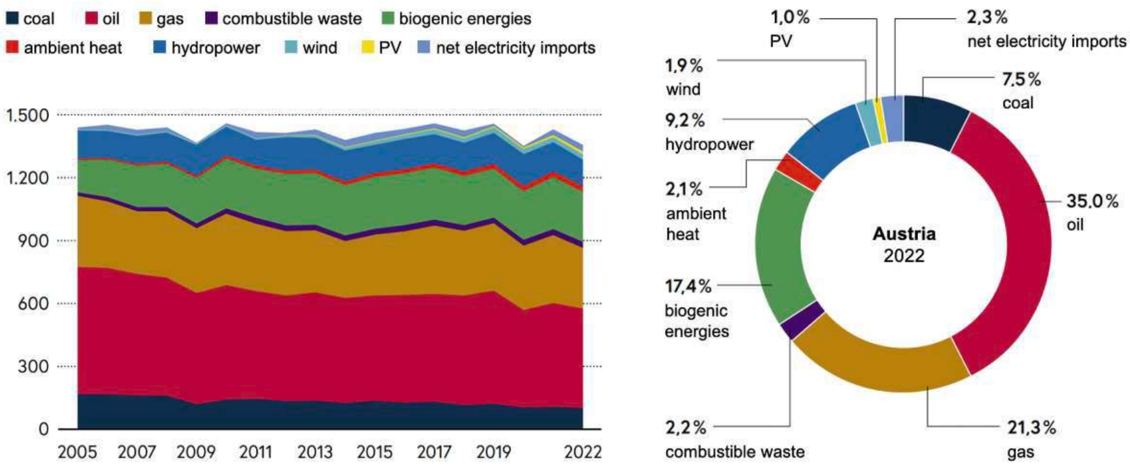

Figure 9: Gross domestic consumption by energy source in petajoules and percent [17]

[15] Cf. (BMK, 2023a), Cf. (BMK, 2023b)
[16] Cf. (BMK, 2023b pp. 10-12), Cf. (BMK, 2023c p. 2)
[17] (BMK, 2023b p. 12) (own translation)

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Although not shown in Figure 9, it is remarkable that the share of renewable energies in Austria is almost twice as high as the average across the European Union. [18]

In Figure 10 the composition of the energy imported from foreign countries is shown by energy source for the period from 2005 to 2022 as well as the percentage shares of the energy sources in the imported energy for 2022. The imported energy of approximately 1.184 petajoules consisted of about 98 percent fossil fuels, assuming that the imported electrical energy is generated from fossil fuels. Even if the imported electrical energy was generated from renewable energy sources, still 89 percent of the imported energy consisted of fossil fuels. [19]

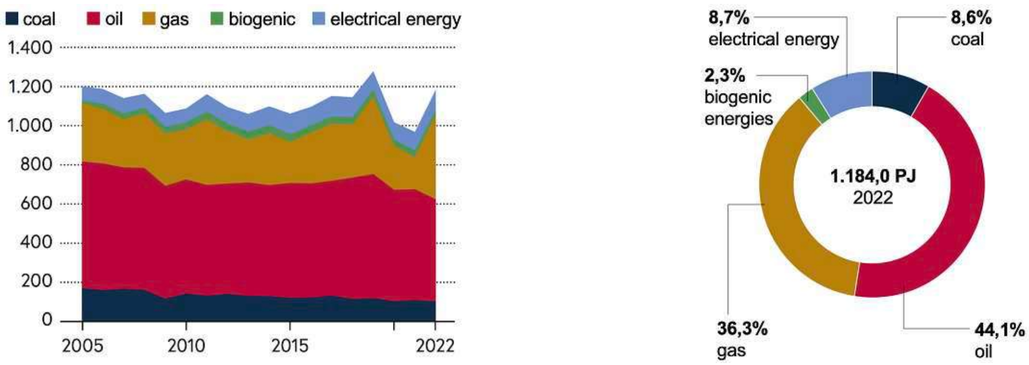

Figure 10: Energy imports by energy source in petajoules and percent [20]

For the primary energy that could be harvested and produced directly in Austria, the picture is completely different compared to the imported energy. In Figure 11 the domestic primary energy production by energy source for the period from 2005 to 2022 and the percentage shares of the energy sources in the domestic primary energy production for 2022 are shown. This domestically harvested and generated energy, which was approximately 508 petajoules in 2022, consisted of 86 percent renewable energy sources (such as biogenic energies, hydropower, wind power, photovoltaics and ambient heat) and 14 percent fossil energy sources. [21] In this case, the combustible waste was counted as a fossil energy source. However, it will not be discussed any further at this point whether combustible waste is a fossil or a renewable energy source.

[18] Cf. (BMK, 2023b p. 12)
[19] Cf. (BMK, 2023b pp. 10-11), Cf. (BMK, 2023b p. 13), Cf. (BMK, 2023c p. 2)
[20] (BMK, 2023b p. 13) (own translation)
[21] Cf. (BMK, 2023b pp. 10-11), Cf. (BMK, 2023b p. 14), Cf. (BMK, 2023c p. 2)

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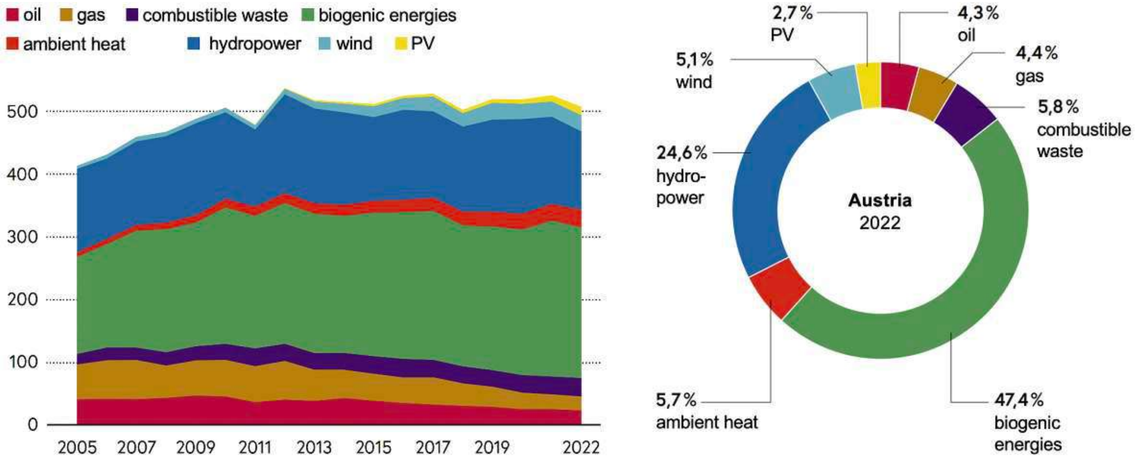

Figure 11: Domestic primary energy production by energy source in petajoules/percent [22]

The gross domestic consumption reduced by the non-energy consumption (e.g. for the chemical industry) as well as the conversion losses (corresponds to the conversion input minus the conversion output) and the consumption of the energy sector (including transportation losses and measurement differences) results in the final energy consumption. The final energy consumption is the amount of energy that is available to the end consumer for the various useful energy applications. In Figure 12, the composition of the final energy consumption by energy source in Austria for the period from 2005 to 2022 and the structure of the final energy consumption from Austria, which amounts to approximately 1.059,5 petajoules, is shown by economic sector for 2022. [23]

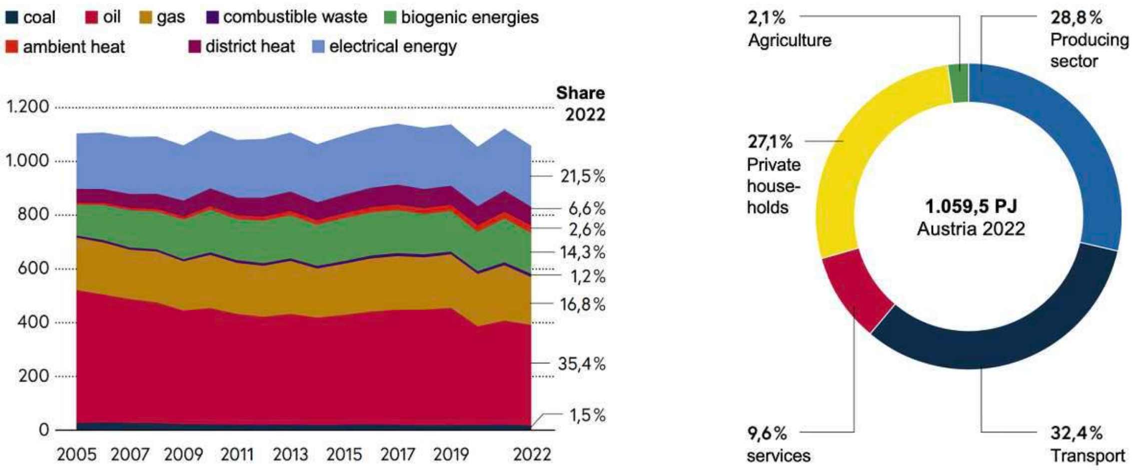

Figure 12: Final energy consumption by energy source in petajoules and percent [24]

[22] (BMK, 2023b p. 14) (own translation)
[23] Cf. (BMK, 2023b pp. 10-11), Cf. (BMK, 2023b p. 15), Cf. (BMK, 2023b p. 17), Cf. (BMK, 2023c p. 2)
[24] (BMK, 2023b p. 17) (own translation)

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Figure 12 shows that private households were responsible for around 27 percent of the final energy consumption. As a result, the total energy demand of households in 2022 was around 286 petajoules. According to Figure 12, the energy demand of private households is roughly equivalent to the energy demand of the manufacturing sector and the transportation sector. [25]

A different view of this final energy demand is shown in Figure 13, in which the final energy consumption is broken down by the useful energy categories. From this figure, it can be seen that around one third of the final energy consumption is used in the sector of space and water heating. Another third of the final energy consumption can be attributed to the mobility sector. The remaining third of the final energy consumption occurs in the sectors of process heat, stationary engines, lighting and computing and electrochemical purposes.

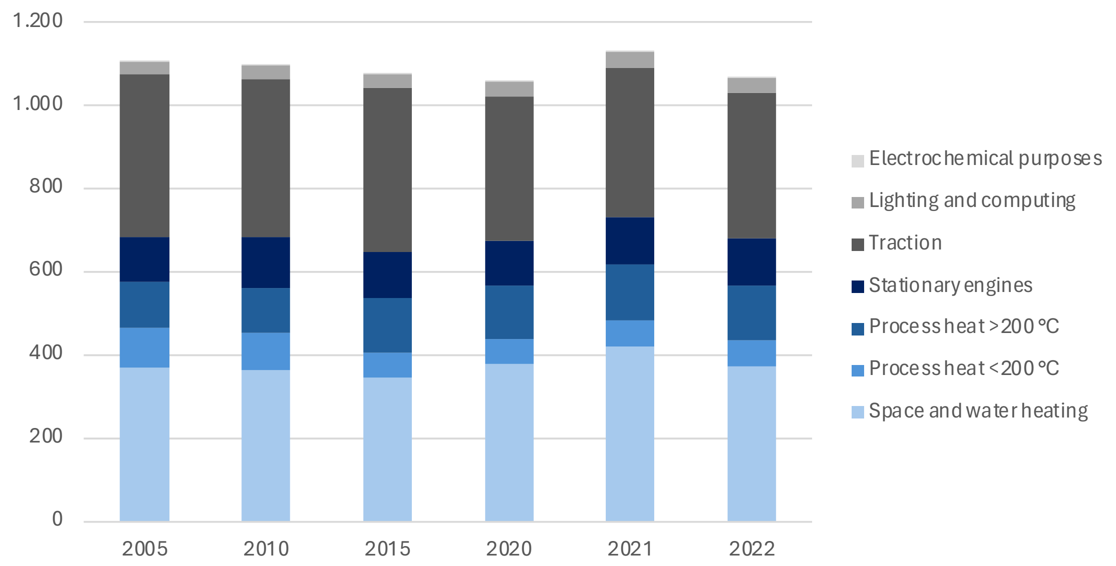

Figure 13: Final energy consumption by useful energy categories in PJ [26]

Furthermore, it makes sense to analyze the sector of space and water heating in more detail and to divide the energy demand for this sector according to the energy source. Figure 14 shows the final energy demand for the space and water heating sector classified by the used energy source.

[25] Cf. (BMK, 2023b pp. 10-11), Cf. (BMK, 2023b p. 15), Cf. (BMK, 2023b p. 17), Cf. (BMK, 2023c p. 2)
[26] (Statistik Austria, 2023c)

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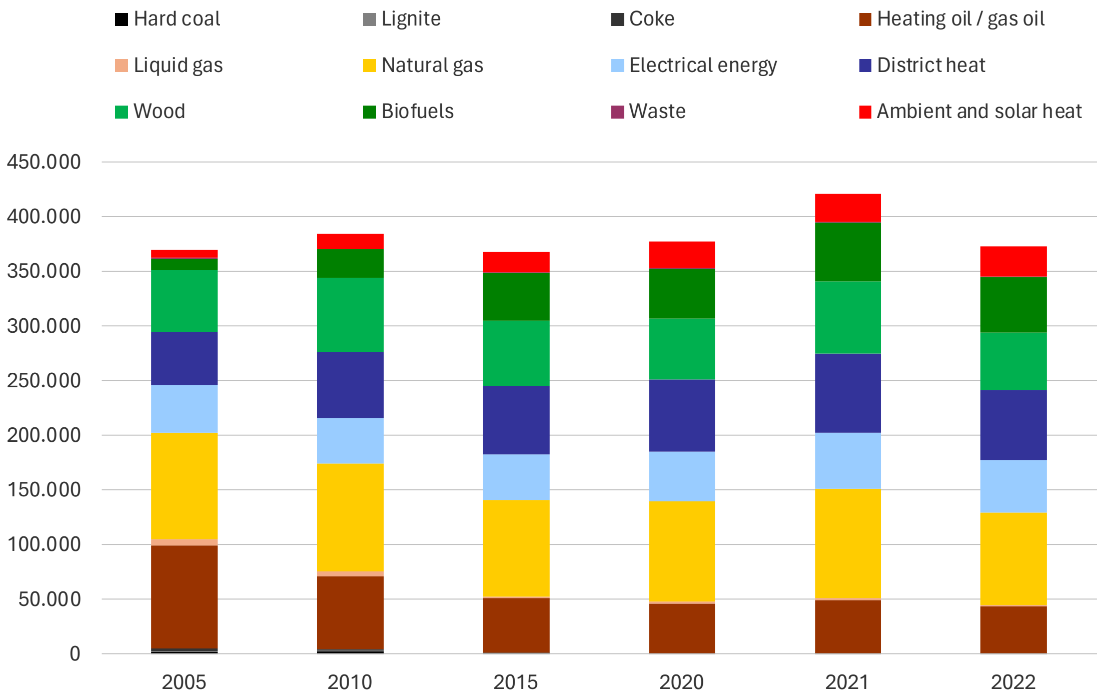

Figure 14: Final energy demand for space and water heating by energy source in PJ [27]

The energy demand for the space and water heating sector remained at an almost constant level between the years 2005 and 2022. Nevertheless, the share of fossil fuels (such as hard coal, lignite, coke, heating oil, gas oil, liquid gas, natural gas) has decreased from around 55 percent in the year 2005 to a still high level of about 25 percent in the year 2022, not considering the generation structure of district heat and electricity. In this context, it should also be mentioned that between the years 2005 and 2022, around 90 percent of the generated district heat was used for the sector of space and water heating. Only 10 percent of the generated district heat was used for the sector of process heat. [28]

The generation of district heat in Austria has continuously increased in recent years, with an annual growth rate of around 1,9 percent per year between the years 2005 and 2022. Figure 15 shows the continuous increase in district heat generation as well as the structure of the generation and the strong growth in renewable energy sources. In the year 2022, around 92 petajoules of district heat were generated from roughly equal shares of fossil and renewable energy sources. [29]

[27] Cf. (Statistik Austria, 2023c)
[28] Cf. (Statistik Austria, 2023c)
[29] Cf. (BMK, 2023b p. 16)

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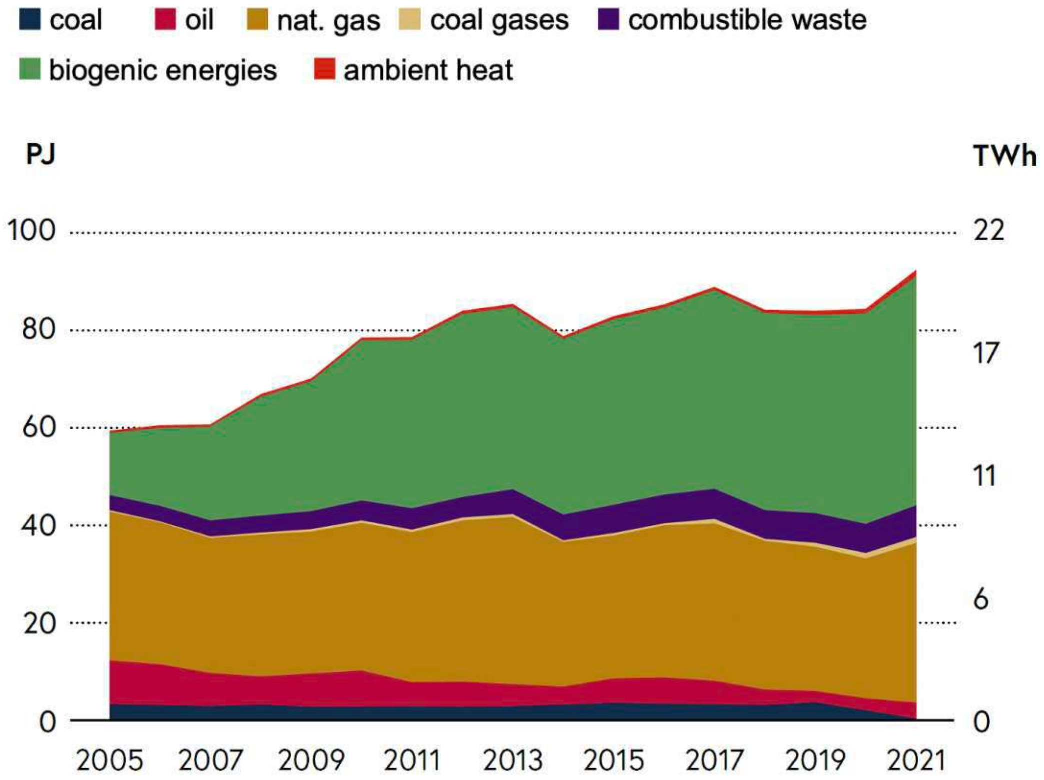

Figure 15: Generation of district heat by energy source [30]

If combustible waste is considered as a renewable energy source together with biogenic energies and ambient heat, the renewable share in district heat generation was approximately 59,5 percent in the year 2022. The share of combustible waste in district heat generation was around 7 percent in the year 2022, which means that the share of renewables in district heat decreases to around 52,5 percent in the year 2022 if combustible waste is classified as a fossil energy source (such as coal, oil, natural gas, coal gases). [31]

Based on the data from Figure 14 and Figure 15, the amount of energy that needs to be decarbonized until the year 2040 for the sector of space and water heating can be estimated assuming that the quantity of the final energy for this sector remains the same. The amount of energy required for the space and water heating sector was approximately 372,9 petajoules in the year 2022, of which approximately 35 percent were directly generated from fossil fuels. [32]

[30] (BMK, 2023b p. 16) (own translation)
[31] Cf. (BMK, 2023b p. 16)
[32] Cf. (BMK, 2023b p. 16), Cf. (Statistik Austria, 2023c)

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Furthermore, about 17 percent of the final energy of the space and water heating sector were provided by district heat, of which about 40,5 to 47,5 percent were based on fossil energy sources. This results in around 156 to 161 petajoules that need to be decarbonized, assuming that the quantity of the final energy for the space and water heating sector remains at the same level as in the year 2022. This corresponds to around 15 percent of the total final energy consumption, or around 26 percent of the fossil final energy consumption if the electricity generation structure is neglected. Based on this, it can be seen that the decarbonization of the space and water heating sector can replace roughly a quarter of the amount of fossil fuels. By contrast, the mobility sector is responsible for 53 percent, the process heating sector for 19 percent and the stationary engines sector for 2 percent of the fossil final energy consumption, ignoring the generation structure of electricity. A very small proportion is caused by the sectors lighting and computing as well as electrochemical purposes. [33] The heat currently generated from fossil fuels for space and water heating must be decarbonized by 2040. To achieve this goal, all heating systems based on fossil fuels must be converted to heating systems that use renewable energy sources. Figure 16 provides an overview of the number of primary heating systems by predominant energy source for the years 2003 to 2022 for private households.

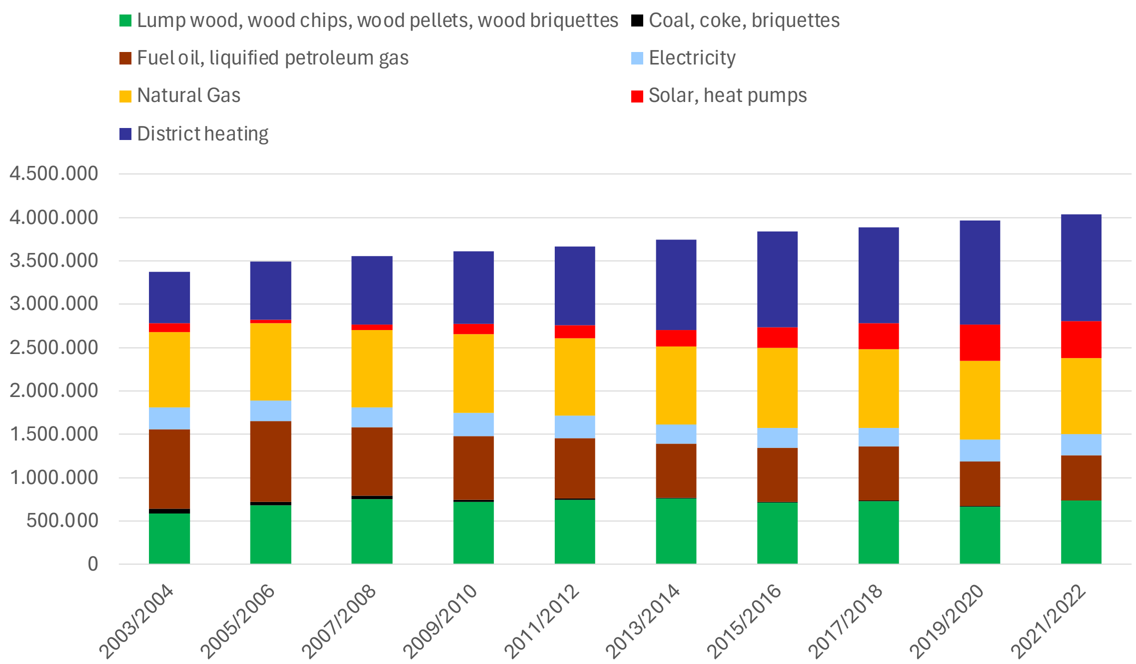

Figure 16: Number of primary heating systems by predominant energy source [34]

[33] Cf. (BMK, 2023b p. 16), Cf. (BMK, 2023b p. 17), Cf. (Statistik Austria, 2023c)
[34] Cf. (Statistik Austria, 2023b)

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This figure shows a decrease in fossil heating systems and an increase in renewable heating systems as well as an increase in district heating systems. By 2040, all fossil heating systems must be converted to renewable heating systems based on wood (such as lump wood, wood chips, wood pellets and wood briquettes), solar, heat pumps or renewable district heating. In the years 2021 / 2022, around 1,4 million heating systems based on fossil fuels were still in operation in private households in Austria, including around 3.500 coal heating systems, around 521.000 oil heating systems and around 878.000 gas heating systems. To achieve the target of a renewable heat supply, a conversion rate of around 78.000 heating systems per year is required in private households. [35]

In the next few years, the generation of district heat will increase due to the conversion of heating systems. In addition to the increasing demand for district heat, the generation of district heat must be decarbonized. Figure 17 shows a decarbonization pathway for district heat in Austria by 2040, based on a study published by the Austrian Energy Agency. In addition to the increasing demand for district heat, the figure also shows the diversification of renewable energy sources in the generation of district heat.

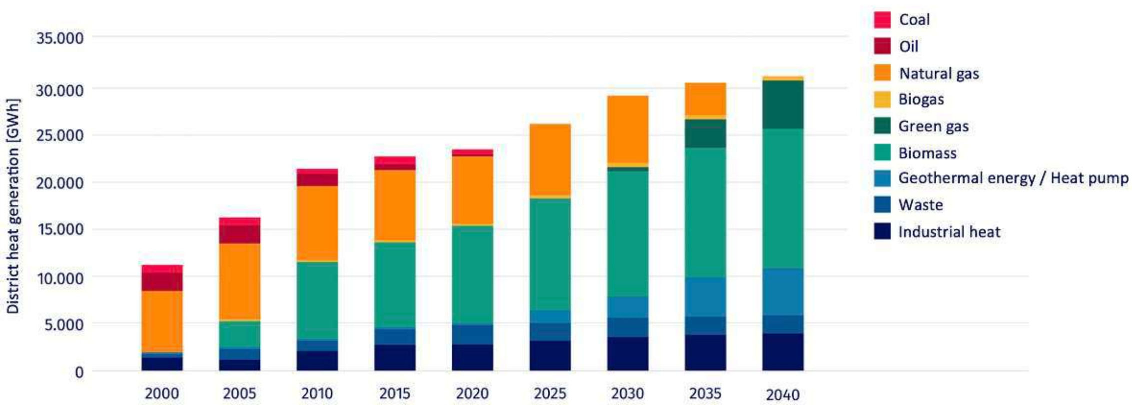

Figure 17: Decarbonization pathway for the district heat generation in Austria [36]

From this figure it can be seen that biomass has the largest share on decarbonized district heat at present and will also have the largest share in the future. Furthermore, it should be mentioned that biomass cannot cover the entire demand for renewable district heat.

[35] Cf. (Statistik Austria, 2023b)

[36] (Wien Energie, 2022b) (own translation), Cf. (FGW, 2022 p. 6), Cf. (Österreichische Energieagentur, 2020)

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In any case, a diversification of the energy sources for the generation of renewable district heat will be necessary. For this reason, it can be assumed that a diversification of renewable energy sources will be necessary for the generation of renewable district heat in existing as well as in new district heating networks that have not been erected yet. For existing district heating networks, it can be expected that this diversification will take place without taking into account the current type of district heat generation. This diversification, which will take place in the future, will also partially affect the biomass heating plants and biomass cogeneration plants existing in Austria in 2023, as shown in Figure 18. Figure 18 also shows the installed capacity as well as the generated quantities of heat and electricity.

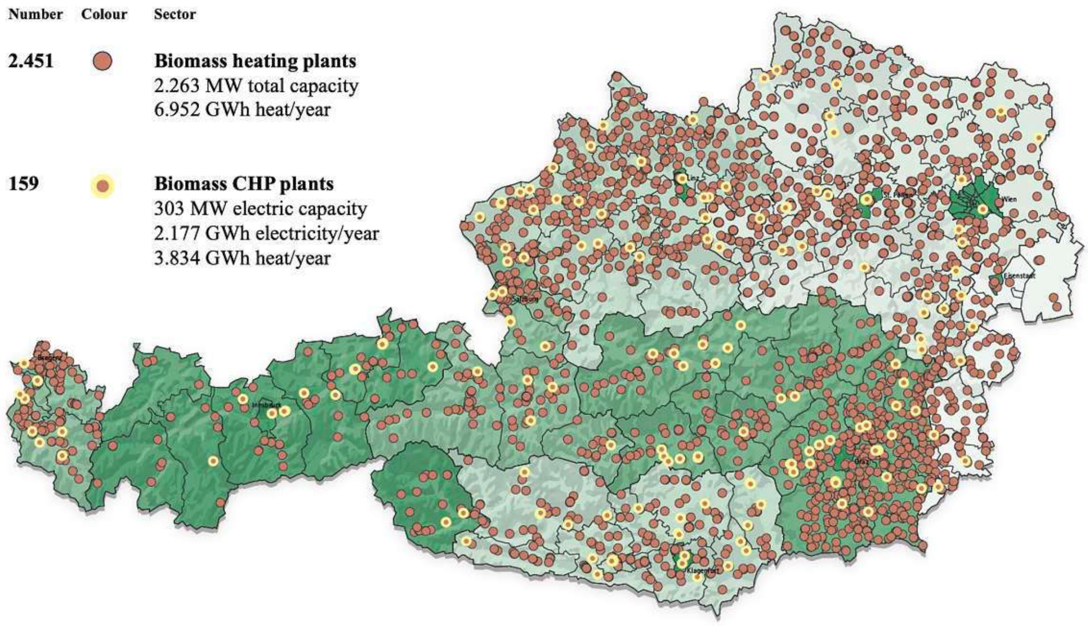

Figure 18: Biomass heating plants and Biomass CHP plants in Austria in 2023 [37]

To achieve a renewable district heat generation in the future, the following research question will be addressed within the scope of this master's thesis:

- Which renewable energy sources and - systems can be implemented in existing and continuously growing district heating systems as well as in new district heating systems, taking into account technical and economic framework conditions? (Research question 1)

[37] Cf. (Pfemeter, et al., 2023 p. 44) (own translation)

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3 Status quo – The principle of local and district heating networks

The basic principle of local and district heating systems consists in general of a central heat generation system and a heat distribution system to the various heat consumers using a network of pipes. In the past, many different district heating systems have been established. The main differences between these district heating systems are as follows:

- Type of network structure (primary -, secondary -, tertiary network)
- Type of network design (star network, line network, mesh network, ring network)
- Number of pipes (two-wire, three-wire, four-wire)
- Type of connection (direct connection, indirect connection)
- Type of system (opened system, closed system)
- Type of installation of the pipes (above ground, below ground)
- Temperature level of the district heating network (warm water, hot water, steam)
- Pressure level of the district heating network

The most common district heating system, as shown in Figure 19, generally consists of generation, distribution and demand and includes the following main components:

- Generation of heat
- Two-pipe district heating network consisting of forward and return line
- House connection and house substation
- House distribution

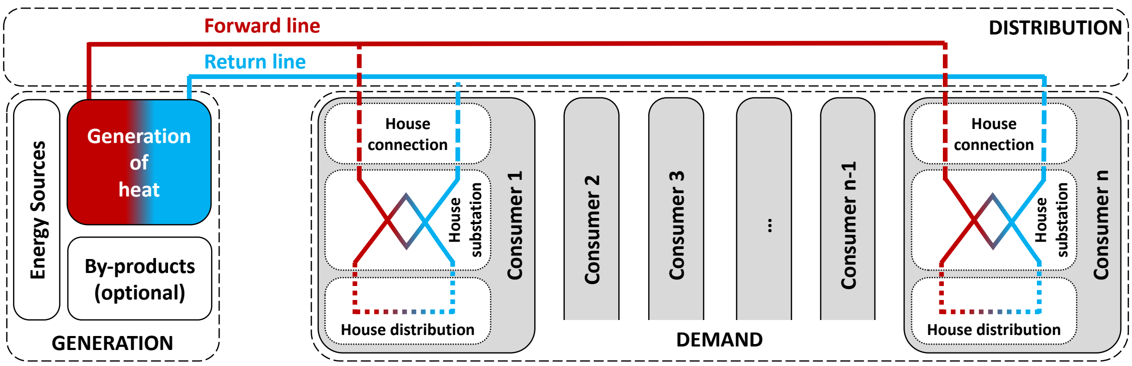

Figure 19: Layout of the most common district heating system

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3.1 Generation

The generation of district heat can be carried out in various ways from different energy sources. On the one hand, the simple conversion of energy sources into heat is known. The pure generation of heat is also known as the heat-only boiler process (abbreviated to HOB process). In addition to the pure generation of heat, a combined generation of heat and power in the form of electricity is known. This combined generation is also known as the combined heat and power process (abbreviated to CHP process). Figure 20 shows the total generation of district heat in Austria from 1970 to 2022. Furthermore, this figure shows that district heat in Austria has been generated and is still generated in HOB plants as well as in CHP plants.

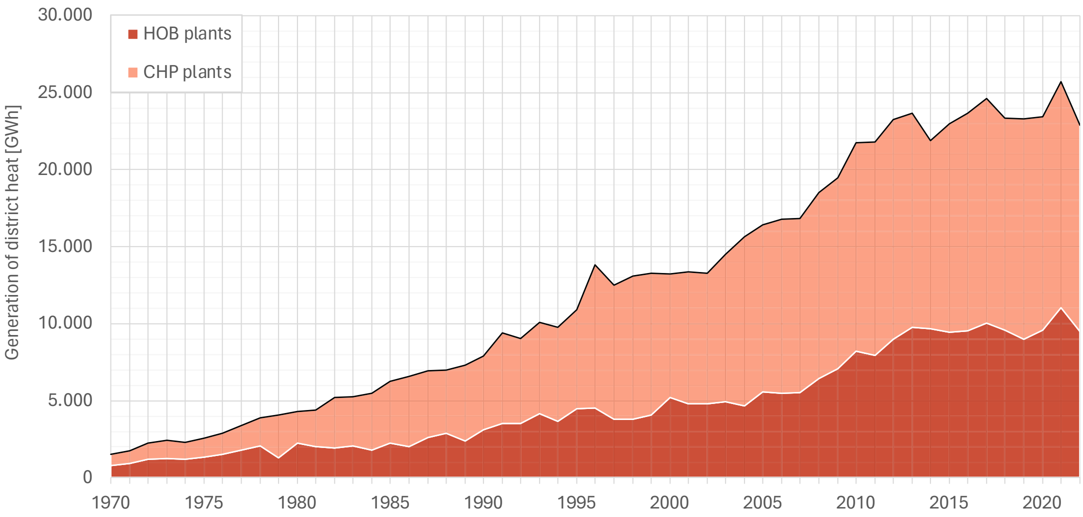

Figure 20: Total generation of district heat in Austria from 1970 to 2022 in GWh [38]

3.1.1 Generation of heat

The generation of district heat in a heat only boiler is based on the thermal utilization of an energy source without generating an additional product. For the case that the energy is stored in the energy source as chemical energy, the energy source is burned in a furnace. The chemical energy is converted into thermal energy by the combustion process. [39]

[38] (Statistik Austria, 2023a)
[39] Cf. (Rab, 2019 p. 18)

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This thermal energy contained in the resulting flue gas is transferred to water, which is used as an energy carrier in the district heating network. In addition to the combustion of energy sources, the direct use of thermal energy such as solar thermal energy, geothermal energy and waste heat is possible if the temperature level of the thermal energy and the district heating network are approximately the same. Furthermore, it is possible to use any kind of thermal energy in heating plants that has been raised to a higher temperature level using a heat pump process if the temperature level of the energy source is below the temperature level of the district heating network. [40]

In Figure 21, the generation of district heat from heat-only boilers is shown for Austria for the period from the year 1970 to the year 2022. This figure also shows the energy sources used to generate the district heat from heat-only boilers. From the figure it can be seen that until the year 1986, the generation of district heat from heat-only boilers was only based on fossil fuels. In addition to the continuous growth of district heat from heat-only boilers, the share of the energy source biomass in district heat from heat-only boilers has increased significantly. In the year 2022, biomass was the most dominant energy source in district heat from heat-only boilers. But also, the fossil energy source natural gas made a significant contribution to district heat generation from heat-only boilers in the year 2022.

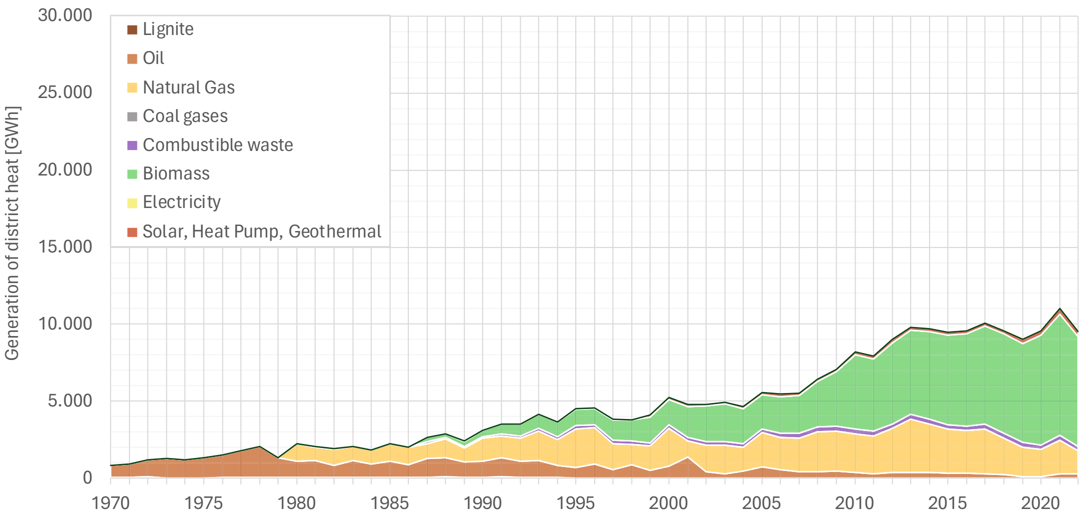

Figure 21: Generation of district heat from heat-only boilers in Austria [41]

[40] Cf. (Rab, 2019 p. 18)
[41] (Statistik Austria, 2023a), Cf. (Rab, 2019 p. 17)

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3.1.2 Generation of heat and power

In addition to the pure generation of district heat from a heat-only boiler, the combined generation of heat and electricity is possible. In most cases, an energy source is burned, in the same way as in a heat only boiler. The chemical energy contained in the fuel is converted into thermal energy. This thermal energy, which is contained in the flue gas, is either used directly to generate electricity and heat or is transferred to a working medium, which is then used to generate electricity and heat. In the case of energy sources (e.g. geothermal energy) where the temperature level is high enough, the generation of electricity and heat can be carried out directly with this energy source or with a separate working medium.

Figure 22 shows the generation of district heat from CHP plants for Austria for the period from 1970 to 2022. This figure also shows the energy sources used to generate heat and electricity in CHP plants. The energy source biomass has been used for the combined generation of heat and electricity since the year 1970. From the figure, it can be seen that the generation of district heat from CHP plants has increased significantly from the year 1970 to the year 2022. Also, the share of biomass in district heat generated in CHP plants has grown considerably. But overall, it can be recognized that the district heat generated in CHP plants is still predominantly based on fossil fuels.

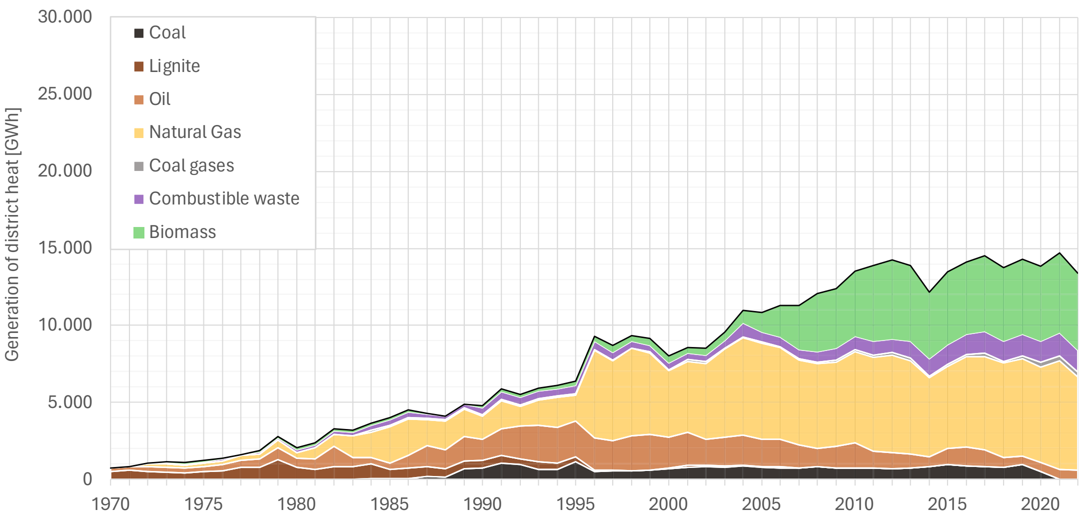

Figure 22: Generation of district heat from CHP plants in Austria [42]

[42] (Statistik Austria, 2023a), Cf. (Rab, 2019 p. 17)

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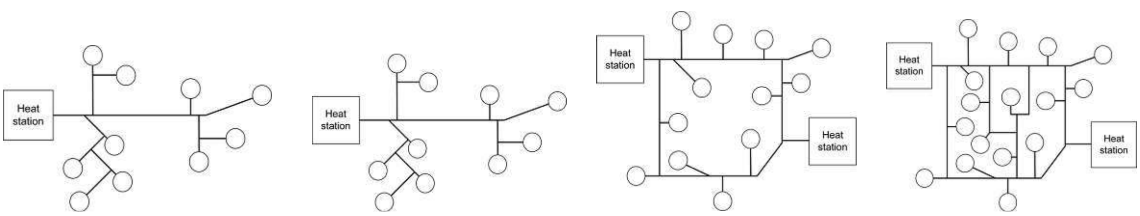
3.2 Distribution

The generated district heat is distributed via a network of district heating pipes. This district heating pipe network usually consists of a supply pipe and a return pipe, which are structured in different ways depending on their complexity. Figure 23 shows the different structures of district heating pipe networks. In addition to line networks (a), there are star networks (b), ring networks (c) and meshed networks (d). With an increasing level of complexity, the structure of a district heating pipe network changes from a line network to star network, then to a ring network and finally to a meshed network. [43]



(a) (b) (c) (d)

Figure 23: Types of district heating network structures [44]

Besides the structure of the district heating network, also the method of installation of the district heating network is relevant as shown in Figure 24. In general, a district heating network can be installed underground or above ground. For underground installation, the network can be ducted (Figure 24, a) or ductless (Figure 24, b). In the case of an above-ground installation, the network is always installed as an overhead line (Figure 24, c). [45]

(a) (b) (c)

Figure 24: Installation types of district heating networks [46]

[43] Cf. (Nussbaumer, et al., 2020 p. 72)
[44] (Nussbaumer, et al., 2020 p. 72)
[45] Cf. (Konstantin, et al., 2022 p. 77)
[46] (Aelker, et al., 2020 pp. 624, 626, 640)

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A further differentiation of district heating networks is possible according to the type of pipes used, whereby the majority of pipes that are installed underground without ducts are pre-insulated pipes, as shown in Figure 25. The most popular district heating pipe has a medium pipe made of steel, which is tightly insulated with a rigid polyurethane foam and a polyethylene casing pipe (Figure 25, a). For higher operating temperatures and operating pressures, as well as for difficult installation conditions, a district heating pipe is used which consists of a medium pipe made of steel, an insulation, a ring space, and a concentric steel casing pipe (Figure 25, b). In addition, there are also flexible district heating pipes in use, which usually have a medium pipe made of plastic (sometimes also steel, stainless steel, or copper) as well as an insulation made of polyurethane foam and a polyethylene casing pipe (Figure 25, c). In general, pre-insulated district heating pipes only have one integrated pipe. Nevertheless, it is also possible that pre-insulated district heating pipes have several integrated pipes. [47]

(a) (b) (c)

Figure 25: Types of district heating pipes [48]

Figure 20 shows that the generation of district heat in Austria has increased significantly between the years 1970 and 2022. A similar development could also be observed in the length of the district heating networks. In Figure 26, the development of the district heating network length in Austria from 2002 to 2022 is shown. The length of the district heating networks increased from approximately 3.300 km in the year 2002 to around 6.000 km in the year 2022, which corresponds to an annual growth rate of about 135 km per year. The forecast for the year 2032 shows a district heating network length of around 7.200 km, which corresponds to an average growth rate of 120 km per year for the period from 2022 to 2032. [49]

[47] Cf. (Aelker, et al., 2020 pp. 625-642)
[48] (Nussbaumer, et al., 2020 p. 60), (Konstantin, et al., 2022 pp. 81-82)
[49] Cf. (FGW, 2023 p. 23)

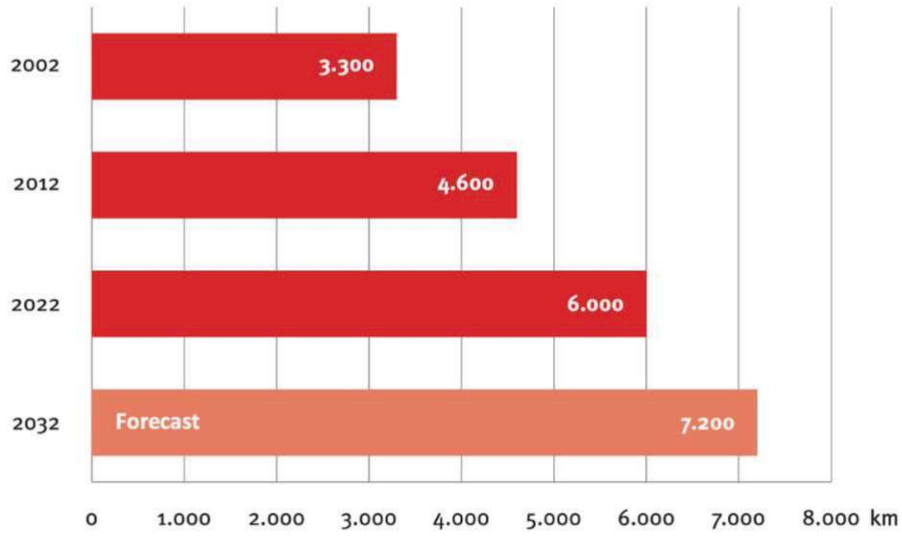

Figure 26: Development of the district heating network length in Austria [50]

3.3 Demand

The district heating network transports the district heat from the generation site to the individual heat consumers, who can use the district heat for different purposes. In addition to space heating, the district heat can be used for domestic hot water preparation as well as for process heat. To ensure that the individual heat consumers can use the district heat from the district heating network, several components are required, such as a house connection, a house substation and a house distribution as shown in Figure 27.

(a) (b) (c)

Figure 27: Components on the demand side [51]

[50] (FGW, 2023 p. 23)
[51] (LINZ AG, 2023 p. 12), (Aqotec, 2020a), (Aqotec, 2020b)

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The house connection (Figure 27, a) connects the supply and return pipe of the main pipe of the district heating network with the house substation of the individual heat consumer. Usually, a house connection only supplies a single heat consumer. Under special circumstances, it is also possible that a house connection supplies several heat consumers. Moreover, it is common that the house connection is realized with the same type of pipe as the main pipe of the district heating network. For special installation requirements, the house connection can be realized with a different but technically suitable piping system.[52]

The house substation (Figure 27, b) can be defined as the link between the house connection and the house distribution. In the case of an indirect house substation, the house substation separates the heat transfer medium of the district heating network from the heat transfer medium of the house distribution by means of a heat exchanger. For the direct house substation, no heat exchanger is required, which means that the heat transfer medium of the district heating network is the same as the heat transfer medium of the house distribution. Both systems have advantages and disadvantages, which will not be discussed in detail. The house substation consists of at least the following parts, regardless of whether it is a direct or an indirect house substation: connections and shut-off valves to the district heating network and to the house distribution, draining and venting options, a heat meter, a differential pressure - and volumetric flow rate control (pressure independent control valve), safety devices and other auxiliary equipment and fittings. [53]

The house distribution (Figure 27, c) is not part of the district heating system. Only in the case of a direct house substation the heat transfer medium of the district heating network flows through the house distribution. In general, the house distribution is the overall system that transports the heat within the building to the specific heat consumer. The heat consumers within a building are either the heat distribution systems for space heating (e.g. radiators, surface heating or ventilation systems), the systems for domestic hot water preparation or other heat-consuming facilities (machines, devices, etc.). [54]

[52] Cf. (Nussbaumer, et al., 2020 p. 85), Cf. (Konstantin, et al., 2022 pp. 84-85), Cf. (Aelker, et al., 2020 pp. 694-695)

[53] Cf. (Nussbaumer, et al., 2020 pp. 85-86, 134), Cf. (Konstantin, et al., 2022 pp. 85-87), Cf. (Nussbaumer, et al., 2021 pp. 22-30)

[54] Cf. (Nussbaumer, et al., 2020 pp. 85-86, 134), Cf. (Konstantin, et al., 2022 pp. 157-158) Cf. (Nussbaumer, et al., 2021 pp. 8-16)

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4 Methodical approach

As already discussed in the previous chapters, a large share of the district heat that is currently generated is based on fossil fuels. Furthermore, the district heat generation will increase in the future due to the decarbonization of the space heating sector. To achieve these goals, this master's thesis will develop approaches which renewable energy sources and renewable energy systems can be implemented in existing and new district heating systems and which technical and economic conditions are required for the implementation. The associated research question, which will be addressed in this master's thesis and which has already been mentioned in Chapter 2 (p. 17) is as follows:

- Which renewable energy sources and - systems can be implemented in existing and continuously growing district heating systems as well as in new district heating systems, taking into account technical and economic framework conditions?

To be able to process and answer this research question, several methodological approaches are required, which will be explained in this chapter.

4.1 Evaluation of data from local and district heating networks

The master's thesis will be based on existing district heating networks, whereby the district heat in these district heating networks is generated by using heat-only boilers. The majority of the generated district heat is based on biomass in form of wood chips. Only a small proportion of the generated district heat is generated from fossil fuels (natural gas or heating oil) in heat-only boilers, which are mainly used to cover peak loads and to provide a backup supply. Table 2 provides an overview of selected data from the biomass heating plants of LINZ AG for the financial year 2023. In addition to the installed capacity and the type of boilers, the annual heat generation, the total subscribed connection load on the customer side and the length of the district heating network are shown for the reporting date 30.09.2023. [55]

[55] (LINZ AG, 2022), Financial year 2023: 01.10.2022 – 30.09.2023

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Table 2: Data from the biomass heating plants of LINZ AG for the financial year 2023 [56]

Location	Capacity and type of the boilers	Generation of heat per year [57]	Total subscribed connection load	Length of the district heating network
Haid [58]	2.000 kW (biomass) 4.000 kW (biomass) 8.000 kW (gas) [59]	24.100 MWh	15.720 kW	7.783 m
Asten [58]	2.000 kW (biomass) 4.000 kW (biomass) 8.000 kW (gas) [59]	14.120 MWh [60]	9.040 kW	6.627 m
Marchtrenk [58]	500 kW (biomass) 3.500 kW (biomass) 4.000 kW (gas) [59]	10.380 MWh	7.730 kW	3.714 m
Grein	3.500 kW (biomass) 4.500 kW (oil) [59]	9.987 MWh	5.530 kW	11.203 m
Puchenau [58]	2.000 kW (biomass) 3.500 kW (gas) [59]	9.670 MWh	6.440 kW	3.364 m
Steyregg [58]	1.500 kW (biomass) 3.500 kW (gas) [59] 850 kW (biomass) [61]	7.790 MWh	7.120 kW	5.194 m
Tragwein [58]	820 kW (biomass) 1.500 kW (oil) [59]	4.538 MWh	2.880 kW	4.806 m

For all biomass heating plants listed in Table 2, a continuous recording of operating parameters is carried out. These operating parameters are available as 15-minute values and 1-hour values in a processable data table for all heating plants except the site in Grein.

[56] (LINZ AG, 2024 pp. 15-21), (LINZ AG, 2022), Financial year 2023: 01.10.2022 – 30.09.2023
[57] measured at the heating plant at the district heating network feed-in
[58] 15-minute values and 1-hour values available
[59] for peak load coverage and as a backup supply
[60] thereof approx. 50 percent waste heat from electricity generation from biogas (sewage treatment plant)
[61] on a separate site

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An extract from these operating parameters, mainly operating parameters of the district heating network, are used to assess which renewable energy sources and renewable energy systems can be used in district heating systems, taking into account the technical and economic framework conditions. In addition to the output of the district heating network, also the supply flow temperature and the return flow temperature are analyzed. These data are used to create annual duration curves and temperature profiles so that the various technologies can be dimensioned.

4.2 Literature and market research

The investigation of the master's thesis will include a literature research and a market research. As part of the literature research, the status quo of the energy sector will be discussed with a specific focus on the generation of district heat. Furthermore, the literature research will provide a rough overview of the functionality and structure of a district heating system. For the elaboration of this section, the relevant literature, peer-reviewed articles, gray literature such as national statistics and strategies for the energy sector as well as websites and news articles will be used. To identify appropriate renewable energy sources and renewable energy systems for the generation of renewable district heat, a literature research will be carried out, taking into account relevant literature and peer-reviewed articles. Furthermore, it can be assumed that the relevant literature cannot answer all relevant details, which results in a market research by contacting the manufacturers of the different technologies.

4.3 Technical and economic analysis

On the basis of the analyzed measurement data according to chapter 4.1 and the collected information according to chapter 4.2, a technical analysis of these systems will be carried out. In this context, it should be mentioned that the technical analyses will only be based on the operating parameters for the year 2023, even if the operating parameters would be available over a longer period of time. Furthermore, it is important to underline that the calculations will not contain any programmed simulations of the respective technology or combinations of several technologies. The technical analyses will be based on physical equations that are relevant for the respective technology using the calculation software Microsoft Excel. After the technical analysis, a profitability calculation will be carried out using well-known and established methods.

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5 Research task

In this chapter, all necessary technical and economic fundamentals are determined so that the implementation of different technologies for the heating plants listed in Table 2 can be examined in the following chapter.

5.1 Characteristic parameters of local and district heating networks

The district heating network is responsible for the transportation of heat from the generation site to the individual heat consumers. To ensure that all consumers are supplied, it is necessary to transport a certain heat flow via the district heating network. This heat flow that needs to be transported does in general not correspond to the sum of the outputs of all individual consumers, as not all individual consumers require the maximum output at the same time. This effect is also known as concurrency and describes the relationship between the maximum simultaneous heat demand of all customers and the total subscribed connected load and can be calculated using equation (5.1). [62]

$$g = \frac{\sum_{i=1}^{n} \dot{Q}_i(t_{max})}{\sum_{i=1}^{n} \dot{Q}_{N\_i}(t)} \quad ^{63} \tag{5.1}$$

With the following meanings:

g	Concurrency factor (unitless)
$\dot{Q}_i(t_{max})$	Heat consumer output i at the time of the maximum total output requirement in kW
$\dot{Q}_{N\_i}(t)$	Subscribed rated output of the heat consumer i in kW
n	Number of heat consumers

In the case of a district heating network with only one heat consumer, the concurrency factor must be set to 1. Even if this heat consumer does not constantly require the maximum heat output, it can be assumed that the maximum heat output is required from time to time.

[62] Cf. (Nussbaumer, et al., 2020 pp. 96-97)
[63] (Nussbaumer, et al., 2020 p. 97)

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With an increasing number of heat consumers, the concurrency factor decreases because the time at which the individual heat consumers require the maximum heat output diversifies. In a study from the year 2001, an approximation equation for the concurrency factor was developed as shown in equation (5.2) based on two district heating networks.

$$g = a + \frac{b}{1 + \left(\frac{n}{c}\right)^{d}} \qquad (5.2)$$ [64]

With the following meanings:

a	Parameter for the approximation equation suggested to be 0,449677646267461 for 1< n < 200 (unitless)
b	Parameter for the approximation equation suggested to be 0,551234688 for 1< n < 200 (unitless)
c	Parameter for the approximation equation suggested to be 53,84382392 for 1< n < 200 (unitless)
d	Parameter for the approximation equation suggested to be 1,762743268 for 1< n < 200 (unitless)
n	Number of heat consumers

Figure 28 shows the approximation function (blue) and the scattering range (black) for the concurrency factor as a function of the number of heat consumers.

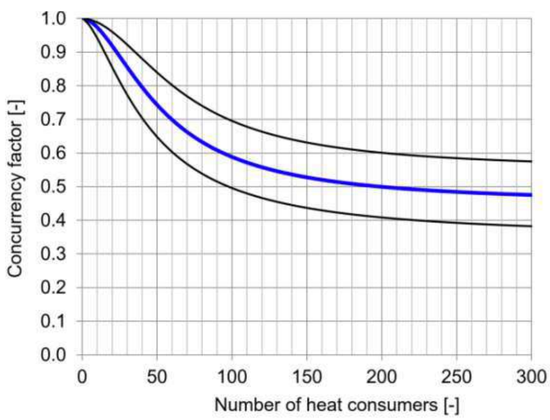

Figure 28: Approximation function and scattering range for the concurrency factor [65]

[64] (Winter, et al., 2001 p. 12)
[65] (Nussbaumer, et al., 2020 p. 97), (Winter, et al., 2001 p. 12)

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The concurrency factor converges towards the value 0.47 for a large number of heat consumers, as shown in Figure 28. [66] The maximum heat flow that needs to be transported through the district heating pipe can be calculated from the subscribed rated output of the heat consumers and the concurrency factor. For this maximum heat flow that must be transported through the district heating pipe, there is an additional correlation of physical variables according to equation (5.3).

$$\dot{Q} = \dot{m} \cdot c \cdot \Delta T = \dot{V} \cdot \rho \cdot c \cdot \Delta T \quad (5.3)$$ [67]

With the following meanings:

$\dot{Q}$	Transport capacity of the pipe in kW
$\dot{m}$	Mass flow in kg/s
c	Specific heat capacity in kJ/kg·K
ΔT	Temperature difference between supply line and return line in K
$\dot{V}$	Volume flow in m^3/s
ρ	Density in kg/m^3

From this equation it can be seen that the transport capacity of a pipe increases with an increasing mass flow and an increasing temperature difference between supply line and return line.

Besides the transportation of the heat flow, the district heating network is affected by an unavoidable but controllable heat loss and pressure loss during the operation. This heat loss is equal to the difference between the amount of heat supplied into the district heating network from the heat generation and the amount of heat consumed from all heat consumers. In the opposite direction, it can be derived that the heat flow supplied into the district heating network is the sum of the heat flow consumed by all heat consumers and the heat flow due to heat losses. [68]

[66] Cf. (Winter, et al., 2001 p. 12)
[67] (Konstantin, et al., 2022 p. 64), (Nussbaumer, et al., 2020 p. 12)
[68] Cf. (Nussbaumer, et al., 2020 p. 200), Cf. (Good, et al., 2022 p. 243)

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This heat flow that occurs in a district heating network due to heat losses can be calculated by using equation (5.4). One of the objectives when planning a district heating network should be the minimization of these heat losses.

$$\dot{Q}_L = U_P \cdot A_{S/R} \cdot \Delta T_{ELP} \quad (5.4)$$
[69]

$$A_{S/R} = 2 \cdot D_a \cdot \pi \cdot L \quad (5.5)$$
[70]

$$\Delta T_{ELP} = \frac{T_{SPLY} + T_{RTN}}{2} - T_{gr} \quad (5.6)$$
[71]

With the following meanings:

$\dot{Q}_L$	Heat loss flow in the supply and return pipe in W
U_P	Overall heat transfer coefficient in W/m²·K
$A_{S/R}$	Outer surface of the supply and return pipe in m²
ΔT_{ELP}	Temperature difference for earth-laid pipes in K
D_a	Outer diameter in m
L	Route length in m
T_{SPLY}	Supply temperature in °C or K
T_{RTN}	Return temperature in °C or K
T_{gr}	Mean soil temperature in °C or K

The movement of the heat transfer medium in the district heating pipes results as already mentioned in a pressure loss. To ensure that the medium is conveyed within the district heating network, pumps are required which must compensate the pressure loss of the pipe system, the pressure difference from a geographical height difference and the pressure difference over the house connection. The volume flow that must be delivered from the pump on the coldest day can be calculated from equation (5.3). [72]

[69] (Nussbaumer, et al., 2020 p. 114)
[70] (Nussbaumer, et al., 2020 p. 114)
[71] (Nussbaumer, et al., 2020 p. 114)
[72] Cf. (Nussbaumer, et al., 2020 p. 122)

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This volume flow results in a specific pressure loss in the pipe according to equation (5.7).

$$\Delta p = \frac{8 \cdot \rho \cdot \dot{V}^2 \cdot \lambda}{{D_i}^5 \cdot \pi^2} \quad (5.7)$$ [73]

With the following meanings:

Δp	Specific pressure loss in Pa/m
ρ	Density in kg/m^3
$\dot{V}$	Volume flow in m^3/s
λ	Friction coefficient of the pipe (unitless)
D_i	Inner diameter in m

During the design process of a district heating network, an optimum balance between heat loss and pressure loss must be found. In general, it can be said that reducing the pipe diameter reduces the investment costs and the heat loss but increases on the other hand the pressure loss. An increase in diameter results in higher investment costs and a higher heat loss but decreases the pressure loss. Figure 29 shows the investment costs and the costs for the heat loss as well as the costs for the electricity of the pumps, which are directly proportional to the pressure loss in the pipes. The diagram shows that there is an optimum pipe dimension at which the total costs are at a minimum. [74]

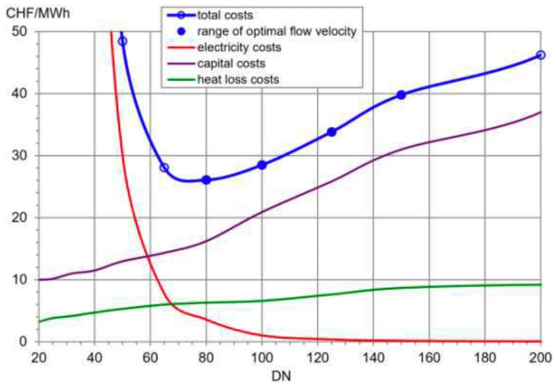

Figure 29: Heat distribution costs as a function of the nominal diameter [75]

[73] (Konstantin, et al., 2022 p. 64)
[74] Cf. (Nussbaumer, et al., 2020 p. 13)
[75] (Nussbaumer, et al., 2020 p. 13)

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5.1.1 Temperature level

Besides the subscribed rated output, also the provided temperature is an important factor for the heat consumer. Table 3 shows the required supply temperatures depending on the type of heat consumer.

Table 3: Supply and return temperatures depending on generation and consumer [76]

Heat Consumer	Supply-Temperature
Process Heat	
Hospital with sterile steam generation 3 bar	≥ 160 °C
Drying process from the food technology	≥ 130 °C
Industrial plant with secondary domestic hot water network 80/60	≥ 85 °C
Spa and wellness resort (Hygiene Circuit)	≥ 70 °C
Greenhouse with air heating	≥ 60 °C
Greenhouses with floor heating	≥ 40 °C
Space Heating and Domestic Hot Water (DHW)	
Building with radiator (with or without DHW)	≥ 65 °C
Building with low temperature heating (without DHW)	≥ 40 °C

Heat Network		Return-Temperature
Waste incineration plant > 10 MW	Practice-oriented Value	55-65 °C
Wood-fired furnace with flue gas condensation	Practice-oriented Value Target Value	> 45 °C ≤ 45 °C
Housing estate	Practice-oriented Value Target Value	> 38 °C ≤ 35 °C

In general, it can be said that the district heating network must always be operated with the highest temperature requirement, although it is possible to operate the district heating network in different operating modes in terms of temperature, as shown in Figure 30. The operation can be realized in such a way that the network temperature is either independent or dependent on the outside temperature.

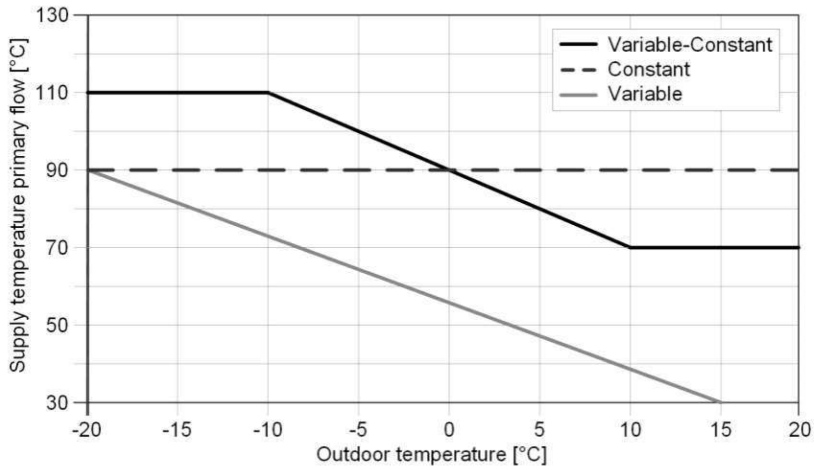

Figure 30: Supply temperature curve for the three different operation modes [77]

[76] (Nussbaumer, et al., 2020 pp. 44-45)
[77] (Nussbaumer, et al., 2020 p. 45)

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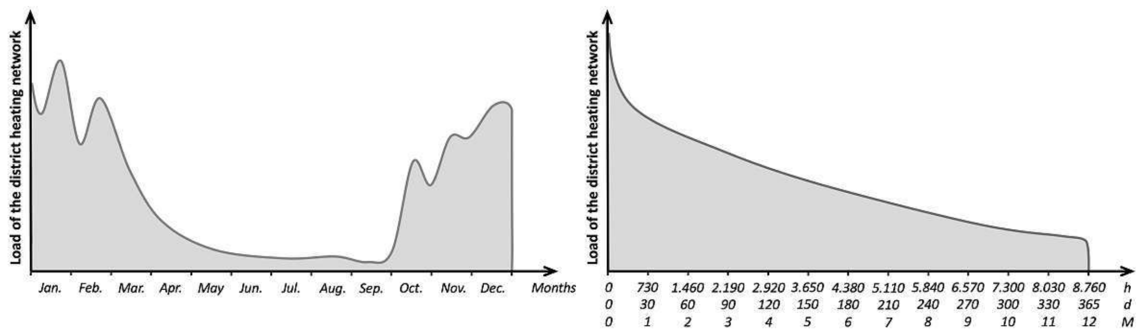
5.1.2 Annual duration curve

A district heating supply is imaginable for a wide variety of heat consumers according to Table 3. As already mentioned, the heat can be used for space heating (e.g. radiators, surface heating or ventilation systems), for domestic hot water preparation or other heat-consuming facilities (machines, devices, etc.). [78] The subscribed rated output of the heat consumers as well as the calculated maximum output requirement according to equation (5.1) are maximum occurring outputs. In the case of space heating, it is known that the required output for space heating is in a linear relationship to the outside temperature. At present, around 90 percent of the generated district heat in Austria is used for the space heating sector. From this it can be derived that the output requirement in a district heating network is linked to the outside temperature and therefore fluctuates with the seasons. This dependency on the outside temperature mainly results from the heat demand for heating the buildings and not from the heat demand for domestic hot water preparation, as this is almost independent of the outside temperature. [79]

Figure 31 shows a schematic load profile and the associated annual duration curve of a district heating network. The load profile (Figure 31, a) shows the required output in a district heating network over an entire year. By sorting the required outputs that occur during a year according to their size, the annual duration curve is obtained (Figure 31, b). In both cases, the area under the curve is equal to the heat fed into the network.



(a) (b)

Figure 31: Load profile and annual duration curve of a district heating network

[78] Cf. (Nussbaumer, et al., 2020 pp. 85-86, 134), Cf. (Konstantin, et al., 2022 pp. 157-158) Cf. (Nussbaumer, et al., 2021 pp. 8-16)

[79] Cf. (Recknagel, et al., 2020 pp. 1320-1321), Cf. (Seifert, et al., 2015 pp. 198, 199, 204) Cf. (Statistik Austria, 2023c), Cf. (Wolf, 1959 pp. 483-492)

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For the annual duration curves, different approaches are proposed by (Wolf, 1959). By adding the purpose of the heat demand to the annual duration curve, it becomes obvious for a typical district heating network as shown in Figure 32 that the heat supplied into the network is attributable to a year-round network loss, a year-round heat demand for domestic hot water preparation and a heat demand for space heating in the heating period. In terms of heat losses, it should be noted that the amount of heat that is lost from the network should not exceed 10 to 15 percent of the amount of heat fed into the network, especially to be able to receive subsidies. [80]

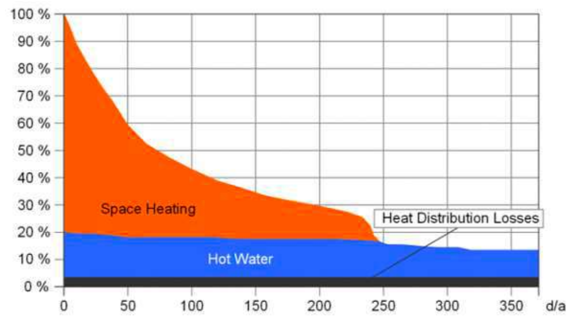
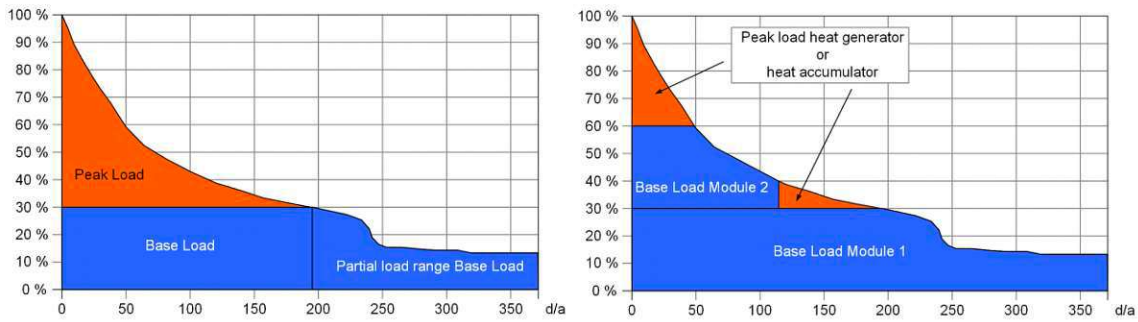


Figure 32: Annual duration curve of the heat demand for a district heating network [81]

The heat fed into the district heating network must be provided by heat generation systems. For the generation of this heat, different generation strategies can be used, as shown in Figure 33. In principle, there is always a division into base load and peak load generation, but also two base load generation units and a heat storage unit are possible.



(a) (b)

Figure 33: Annual duration curve of heat generation for a district heating network [82]

[80] Cf. (Nussbaumer, et al., 2020 p. 98), Cf. (KPC, 2024 p. 1)
[81] (Nussbaumer, et al., 2020 p. 16)
[82] (Nussbaumer, et al., 2020 p. 19)

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5.2 Renewable energy sources and - systems for the generation of heat

Based on the previous fundamental survey, especially with regard to the generation strategy for covering the heat demand within the annual duration curve according to Figure 33 and the temperature profile of the district heating network according to Figure 30, renewable energy sources and renewable energy systems for covering the heat demand should be identified and described. Figure 34 shows the development of the district heating systems and district heat generation systems until now and provides an outlook on the district heating systems and district heat generation systems in the future, based on a publication released in the year 2018.

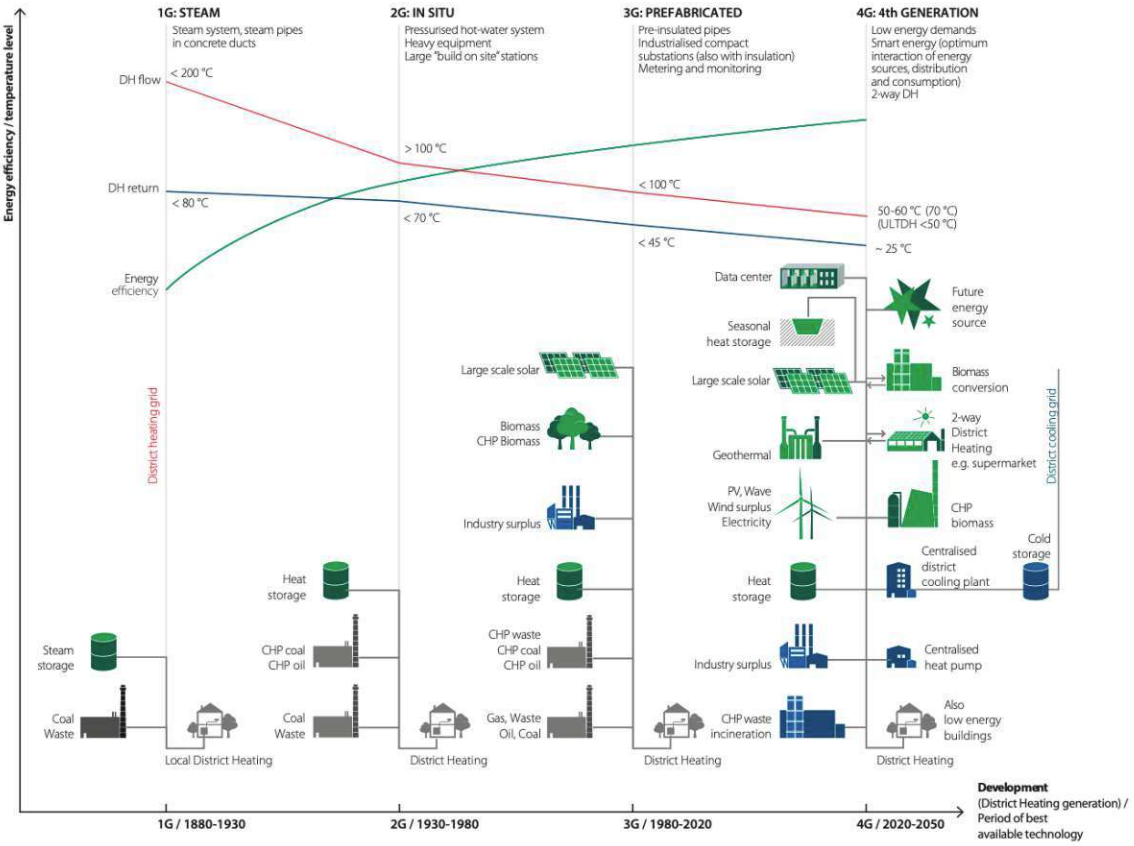

Figure 34: Progression of district heating – 1st to 4th generation [83]

The figure above shows that a strong diversification of energy sources and energy systems and the implementation of storage systems can be expected. Additionally, it will be necessary to reduce the temperatures of the district heating systems.

[83] (Thorsen, et al., 2018)

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5.3 Biomass HOB systems

The current state of the art for the generation of renewable district heat is represented, among other systems, by a biomass heat-only boiler system as shown in Figure 35. In such boiler systems, biomass (usually wood chips) is burned in furnaces, whereby the energy contained in the flue gas is transferred to the heat transfer medium which is then fed into the district heating network. As the state of the art, it can be assumed that a biomass heat-only boiler system as shown in Figure 35 consists of the following components: (1) fuel store with discharge, (2) boiler, (3) fine dust separators (in the figure designed as electrostatic precipitator), (4) exhaust gas ventilator and (5) chimney. [84]

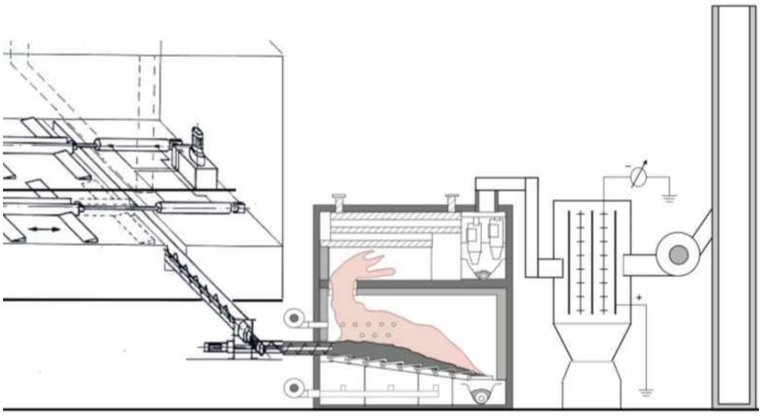
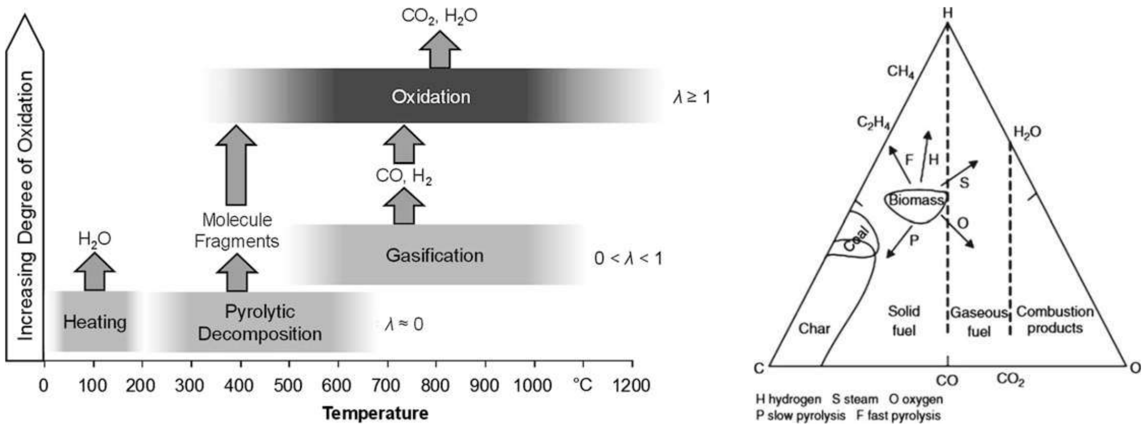


Figure 35: Biomass heat-only boiler system [85]

5.4 Alternative conversion routes besides the combustion of biomass

Besides the combustion of biomass that is typically used in biomass heat-only boiler system as shown in Figure 35, there are also other conceivable routes for converting biomass. A fundamental factor to differentiate these conversion routes is the excess air ratio, as shown in Figure 36 (a), when the biomass is heated. The excess air ratio is defined as the ratio between the amount of oxidizing agent supplied to the conversion process to the amount of oxidizing agent required to oxidize all reaction products completely. In addition to the heating of biomass, which is not a conversion process, the processes of pyrolysis, gasification, and oxidation (combustion) are known. [86]

[84] Cf. (Nussbaumer, et al., 2020 p. 26), Cf. (Nussbaumer, 2013 pp. 389-397)
[85] (Nussbaumer, et al., 2020 p. 26), (Nussbaumer, 2013 pp. 389-397)
[86] (Meyers, et al., 2019 pp. 362-364)



(a) [87] (b) [88]

Figure 36: Possible conversion routes for biomass

5.4.1 Pyrolysis

After the heating process of the biomass, in which the biomass is only dried and no reaction takes place, the process of pyrolysis begins. During the pyrolysis process, no oxidizing agent is added to the biomass, only the temperature is further increased. This means that the excess air ratio is 0. By heating, the long molecular structure of the biomass is broken down into shorter molecular fragments. These short molecular fragments (also known as volatile elements) are driven out of the biomass in gaseous form. At the end of the complete pyrolysis process, the following elements are present: volatile compounds (such as hydrogen, carbon monoxide, methane, carbon dioxide, nitrogen and steam), char and low molecular weight organic compounds as well as high molecular weight compounds. [89] From Figure 36 (b) it can be seen that the process of pyrolysis and therefore the resulting products can be influenced. The residence time, the heating rate and the final temperature significantly influence the composition of the products. In general, it can be said that slow pyrolysis (long residence time, low heating rate, low final temperature) results in a higher yield of solid products (coal), while fast pyrolysis (short residence time, high heating rate, high final temperature) results in a higher yield of liquids (bio crude oil). [90] For the technologies which will be described in the following section, only the pyrolysis process with a high yield of solid products (coal) is of interest.

[87] (Meyers, et al., 2019 p. 362), Cf. (Kaltschmitt, et al., 2016)
[88] (De, et al., 2018 p. 49)
[89] Cf. (Meyers, et al., 2019 pp. 362-364)
[90] Cf. (De, et al., 2018 pp. 49-50), Cf. (Bunbury, et al., 1925 pp. 85-88), Cf. (Meyers, et al., 2019 pp. 402-405), Cf. (Bruckman, et al., 2016 p. 256)

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5.4.1.1 The main product of slow pyrolysis

The main product of slow pyrolysis is coal. In the case of biomass that has been pyrolyzed, the resulting coal is also known as biochar or charcoal (for cases in which wood is pyrolysed). The possible applications of this biochar are very manifold due to its properties. In addition to energy applications (heating plants, combined heat and power plants, industrial furnaces, small furnaces, gasification plants, barbecue charcoal) also industrial applications (metallurgy, adsorbents, cement and lime plants, silicon production, chemical production) as well as soil-related and agricultural applications (soil incorporation, compost additives, animal farming, animal feed) are possible. One of the most important positive effects is attributed to the incorporation into soils. In this context, the anthropogenic (i.e. human-made), nutritious so-called Amazonian black soils, which are commonly referred in Brazil as "Terra Preta de Indio", are worth to be mentioned. These soils are characterized by their ability to regenerate on their own, their high absorption capacity of nutrients and water and their higher yields compared to other soils. In addition to fragments of clay and organic waste to provide nutrients and build up humus, biochar is the most important ingredient for Terra Preta. In addition to the effect of improving the quality of the soil, the incorporation into the soil has an additional advantage, which is the capture and long-term storage of carbon. The carbon produced by pyrolysis was removed from the atmosphere as carbon dioxide and is stored in a stable form in the soil in form of biochar. This type of application is based on the principle of carbon capture and storage. For the production, the use and the certification of biochar, clear rules have been defined by the Ithaka Institute in form of the European Biochar Certificate (EBC-Certificate) and the World Biochar Certificate (WBC-Certificate). [91]

In general, it can be said that from a physical point of view, one kilogram of carbon corresponds to approximately 3,66 kg of carbon dioxide, based on an atomic mass of 12,011 g/mol for carbon (C) and 15,999 g/mol for oxygen (O). In the case of pyrolyzed straw, the carbon content is usually between 40 and 50 percent while the carbon content of pyrolyzed wood and nutshells is between 70 and 90 percent. [92]

[91] Cf. (De, et al., 2018 p. 49), Cf. (Quicker, et al., 2016 pp. 3-4, 202, 214, 277, 282, 284-285, 299, 302) Cf. (Dunst, 2022 pp. 210-211), Cf. (Dunst, 2019 pp. 238-247), Cf. (Bier, et al., 2020 p. 20), Cf. (WBC, 2023), Cf. (EBC, 2020), Cf. (EBC, 2012-2023)

[92] (Vinke, et al., 2013 p. 31), Cf. (EBC, 2012-2023 p. 21)

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In the year 2017, the prices for biochar were around 200 to 2.000 euros per ton depending on the quality, the type of production and the market situation. [93]

For cases where the biochar is long-term stored in a stable form and is not used for the generation of energy, it is possible to trade the captured carbon as a carbon sink. Also in this case, there are regulations that replicate the value chain of the biochar to ensure that all carbon dioxide equivalent expenditures (production of biomass, storage and processing of biomass, production of biochar, processing and transportation of biochar) are deducted from the carbon storage capacity of the biochar. In the relevant regulation for the certification of carbon sinks from biochar, an example is given in which 100 kg of biochar represents a carbon sink of 69,7 kg of carbon, which corresponds to a carbon dioxide equivalent of 255,6 kg, taking into account the carbon content of the biochar and the value chain of the biochar. [94]

From this it can be deduced that the value of the biochar that is not used for the generation of energy must be at least equal to the price that must be paid on the market for the same amount of carbon dioxide that is stored in the biochar. Figure 37 shows the price trend for the EU carbon permits for the period of 01.01.2014 to 25.03.2024.

Figure 37: Price development of EU carbon permits (EU-ETS) [95]

[93] (BMLFUW, 2017 p. 19)
[94] Cf. (EBC, 2012-2023)
[95] (Trading Economics, 2024) (adapted)

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If we assume that the price of the EU carbon permits is 80 euros per ton and 100 kg of biochar represents a carbon sink of 69,7 kg of carbon, the price of biochar would be around 205 euros per ton, assuming that only the amount of carbon dioxide is compensated with the value of the EU carbon permits.

5.4.2 Gasification

If an oxidizing agent (air, oxygen, water) is added after the process of pyrolysis, which has taken place without adding an oxidizing agent (air, oxygen, water), the products from the pyrolysis process (coal, carbon monoxide, methane) are mainly converted into the following products: hydrogen, carbon monoxide and methane. A strict distinction between pyrolysis and gasification is not possible, as biomass itself contains a certain amount of oxygen. In any case, the excess air ratio during gasification is between 0 and 1. [96]

5.4.3 Combustion

In the last step, the combustion, such an amount of oxidizing agent (air, oxygen, water) is added to ensure that the products of gasification (hydrogen, carbon monoxide and methane) are completely oxidized to the products carbon dioxide and water. To achieve a complete oxidation of all oxidizable elements, an excess air number of at least 1 is required. [97]

5.5 Biomass pyrolysis systems

Biomass pyrolysis systems use the pyrolysis process described in chapter 5.4.1. Depending on the process management (slow pyrolysis vs. fast pyrolysis), it is possible to produce either solid substances (biochar) or liquids (bio crude oil) from any type of biomass. Various processes have been developed for the slow pyrolysis as well as for the fast pyrolysis, but only processes for the slow pyrolysis are described in the following chapter. [98]

[96] Cf. (Meyers, et al., 2019 pp. 362-364)
[97] Cf. (Meyers, et al., 2019 pp. 362-364)
[98] Cf. (Meyers, et al., 2019 pp. 402-405)

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5.5.1 Biomass pyrolysis plant – PYREG

The pyrolysis process that was developed from the company PYREG uses an indirectly heated screw reactor as shown in Figure 38. To heat the screw reactor, the process gas released during the process of pyrolysis is used. This process gas is burned in a separate furnace. The produced flue gas is then used to heat the screw reactor. The entry of ambient air which contains oxygen is prevented by a rotary valve on the biomass inlet and the biochar discharge. In addition to the production of biochar from the biomass, renewable energy in form of heat is generated. [99]

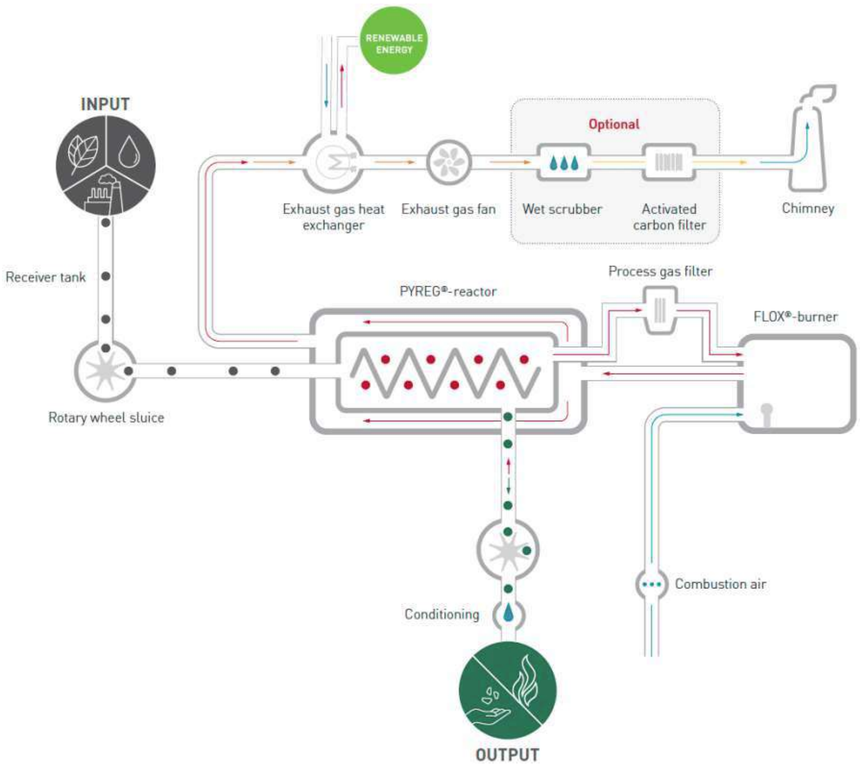

Figure 38: Operating principle of the PYREG plant [100]

In addition to biomass, this process can also pyrolyze composite materials, sewage sludge, food waste, industrial waste and mixed waste to produce coal and heat. The input material only must fulfill the following requirements: average particle size between 3 and 30 millimeters, minimum dry substance of 80 percent, minimum calorific value of 10 MJ/kg. [101]

[99] Cf. (Bruckman, et al., 2016 p. 207), Cf. (Pyreg, 2022 p. 14)
[100] (Pyreg, 2022 p. 15)
[101] Cf. (Pyreg, 2022 pp. 16-17)

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Table 4 shows all relevant data for the different available plant sizes for the reference fuel residual forest wood. Based on these data, the implementation of a pyrolysis plant in a district heating network will be examined. The generated heat from the pyrolysis plant will cover a part of the heat demand of the district heating network. The main product of the pyrolysis plant, the produced biochar, will be marketed as a high qualitative product.

Table 4: Data of the different PYREG pyrolysis plants for residual forest wood [102]

Type	Unit	PX500	PX1500	PX6000
Biomass input	[kW] [kg/h] [103]	550 109	1.571 311	6.285 1.244
Biochar output	[kW] [kg/h] [103] [kg/h] [104]	200 26 33	571 75 94	2.285 299 374
CO_2 withdrawal potential	[t/a] [105]	627	1.792	7.182
Heat output	[kW]	217	627	2.395
Electricity consumption	[kW]	12	40	120
Personnel expenses	[h/d]	4	4	4
Costs for maintenance and service in relation to the investment costs	[% / a]	2,5	2,5	2,5
Minimal partial load in relation to the rated output	[%]	70	70	70
Investment costs	[EUR]	1.000.000	2.200.000	5.500.000

There are also other pyrolysis systems available on the market, which are compared in a study of (Klauser, et al., 2024).

[102] Cf. (Pyreg, 2023a p. 2), Cf. (Reichardt, 2023), Cf. (Pyreg, 2023b pp. 2-4)
[103] absolutely dry / water-free
[104] with 20 % water
[105] for 8.000 operating hours

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5.6 Biomass CHP systems

In addition to the generation of heat from biomass based on either combustion (in biomass heat-only boiler systems) or pyrolysis (in biomass pyrolysis systems), it is also possible to generate heat and electricity simultaneously in biomass combined heat and power systems. For combined generation of heat and power, many different technologies are available such as:

- CHP systems with combustion engines [106]
- CHP plants with gas turbines [106]
- CHP plants with steam turbines [106]
- CHP plants with steam engines [106]
- CHP plants with Stirling engines [106]
- CHP plants with ORC processes [106]
- CHP plants with fuel cells [106]

For a combined heat and power generation system, the conversion rate of the energy source into heat and electricity is of interest. The conversion rate, which is equal to the efficiency, from fuel to heat and from fuel to electricity can be calculated using equations (5.8) and (5.9). The overall efficiency of the CHP system is the sum of the two efficiencies. In addition to the efficiencies, the quantity ratio of the two different types of energy that are generated is of interest. This ratio, also known as the power-to-heat ratio, can be calculated with equation (5.10). [106]

$$\eta_{th} = \frac{\dot{Q}_{th}}{\dot{Q}_{f}} \quad [107] \tag{5.8}$$

$$\eta_{el} = \frac{P_{el}}{\dot{Q}_{f}} \quad [108] \tag{5.9}$$

$$\sigma = \frac{P_{el}}{\dot{Q}_{th}} = \frac{\eta_{el}}{\eta_{th}} \quad [109] \tag{5.10}$$

[106] Cf. (Schmitz, et al., 2004 p. VIII), Cf. (Suttor, 2014 p. 40), Cf. (Kirchner, et al., 2018 pp. 8-9)
[107] Cf. (Kirchner, et al., 2018 p. 8)
[108] Cf. (Kirchner, et al., 2018 p. 8)
[109] Cf. (Kirchner, et al., 2018 p. 9)

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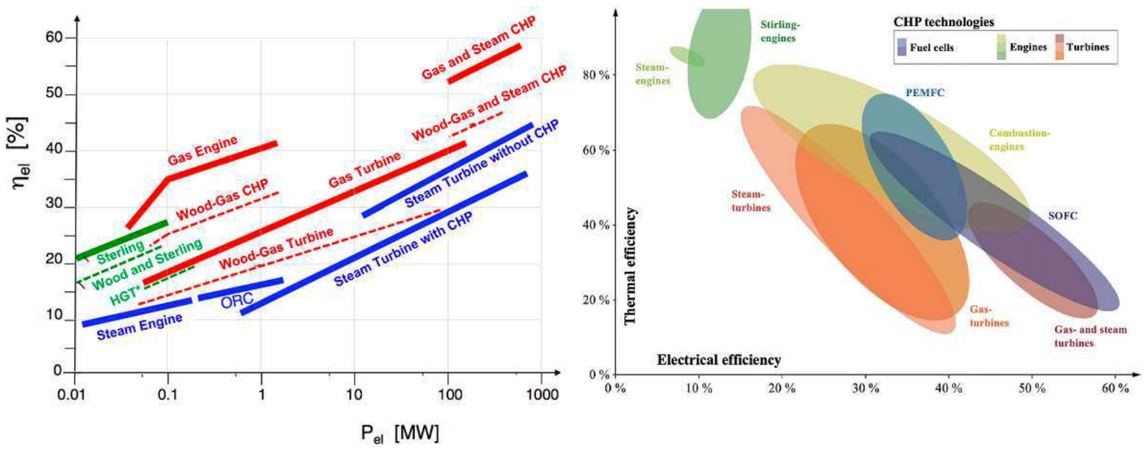
With the following meanings:

η_{th}	Thermal efficiency of the CHP plant in %
$\dot{Q}_{th}$	Thermal output of the CHP plant in kW
$\dot{Q}_{f}$	Rated fuel output of the CHP plant related to the calorific value in kW
η_{el}	Electrical efficiency of the CHP plant in %
P_{el}	Electrical output of the CHP plant in kW
σ	Power-to-heat ratio (unitless)

The thermal efficiency, the electrical efficiency and the power-to-heat ratio are mainly influenced by the type of CHP plant used as shown in Figure 39 (a) and Figure 39 (b).

Figure 39 (a) shows furthermore on the one hand, that the system output has an influence on the electrical efficiency and on the other hand that the different types of CHP systems are used for different system outputs. Another aspect shown in Figure 39 (b) is that the ratio of thermal efficiency to electrical efficiency, the so-called power-to-heat ratio, can be influenced more or less depending on the type of the CHP plant.



(a) [110] (b) [111]

Figure 39: Thermal and electrical efficiencies of different CHP systems

[110] (Nussbaumer, et al., 2020 p. 35)
[111] (Kirchner, et al., 2018 p. 9)

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5.6.1 Biomass CHP plant – PYREG

This combined heat and power plant is not a conventional combined heat and power plant as described in 5.6. In addition to heat and electricity, this plant also produces biochar. This system can generally be seen as an extension of the system described under 5.5.1. The heat generated during the process of pyrolysis, which is recovered in the exhaust gas heat exchanger in Figure 38, is used in an ORC process, as shown in Figure 40.

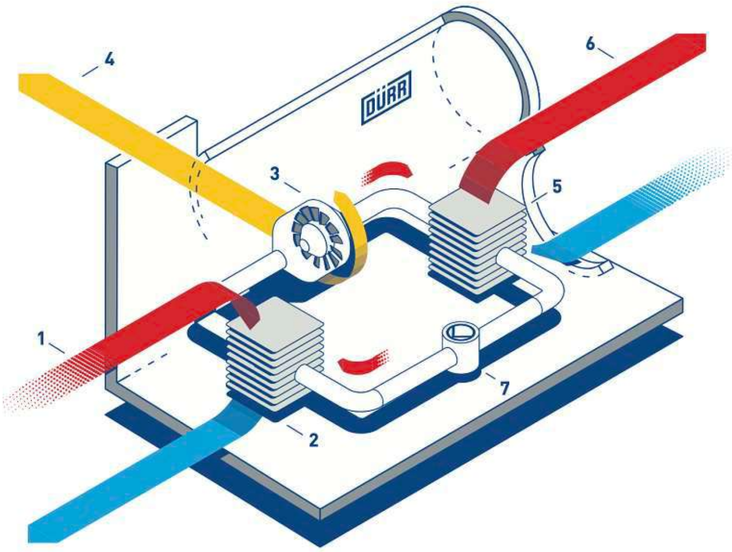

Figure 40: Simplified process diagram of the ORC process [112]

The operating principle of the ORC process (Organic Rankine Cycle process) as shown in Figure 40 is mainly the same as the operating principle of the Clausius Rankine process. In contrast to the Clausius Rankine process, which uses water as working fluid, the ORC process uses an organic working fluid. The process consists of a steam generator, also known as evaporator (2), which absorbs heat (1) – in this case from the flue gas of the pyrolysis plant – and uses this heat to evaporate the pressurized working fluid. In the turbine (3), part of the energy is extracted from the working medium, which is then used in a generator (4) to generate electricity. The working medium is then liquified in the condenser (5), whereby the released heat (6) can be used for further processes, like in this case to operate a district heating network. The expanded and liquefied working medium is then pressurized by a pump (7) so that the process starts again from the beginning. [113]

[112] (Dürr, 2020 p. 4)
[113] Cf. (Dürr, 2020 p. 4), Cf. (Nussbaumer, et al., 2020 p. 34), Cf. (Baehr, et al., 2016 pp. 544-550)

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Table 5 shows the data for the pyrolysis plants available on the market designed as a CHP plant for the production of biochar with heat extraction and an ORC plant for the generation of electricity. As already mentioned, this plant is not a conventional CHP plant. As shown in Table 5, slightly more than a third of the fuel heat output is discharged from the plant with the product biochar. The main focus of this plant is therefore on the production of biochar and not on the generation of heat and electricity. But in general, it can be highlighted that the combination of a pyrolysis plant with heat and power generation makes sense from an energetic, ecological and economic point of view. There are also other pyrolysis systems available, which are compared in (Klauser, et al., 2024).

Table 5: Data of the different PYREG CHP plants for residual forest wood [114]

Type	Unit	PX500	PX1500	PX6000
Biomass input	[kW] [kg/h] [115]	not available	1.571 311	6.285 1.244
Biochar output	[kW] [kg/h] [115] [kg/h] [116]		571 75 94	2.285 299 374
CO_2 withdrawal potential	[t/a] [117]		1.792	7.182
Heat output	[kW]		533	2.036
Electricity output	[kW]		94	359
Electricity consumption	[kW]		40	120
Personnel expenses	[h/d]		4	4
Costs for maintenance and service in relation to the investment costs	[% / a]		2,5	2,5
Minimal partial load in relation to the rated output	[%]		70	70
Investment costs	[EUR]		2.800.000	6.500.000

[114] Cf. (Pyreg, 2023a p. 2), Cf. (Reichardt, 2023), Cf. (Pyreg, 2023b pp. 2-4), Cf. (Reichardt, 2024)
[115] absolutely dry / water-free
[116] with 20 % water
[117] for 8.000 operating hours

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5.6.2 Biomass CHP plant – SYNCRAFT

The combined heat and power generation system from SYNCRAFT is primarily a system for generating fuel gas from solid biomass such as wood chips. This fuel gas – in case of wood chips, the gas is wood gas – can then be used in a gas engine to generate heat and electricity. The process for the production of the product gas is a multi-stage gasification process in which the individual process steps of pyrolysis, oxidation and reduction are separated in terms of space and control technology, as shown in Figure 41. [118]

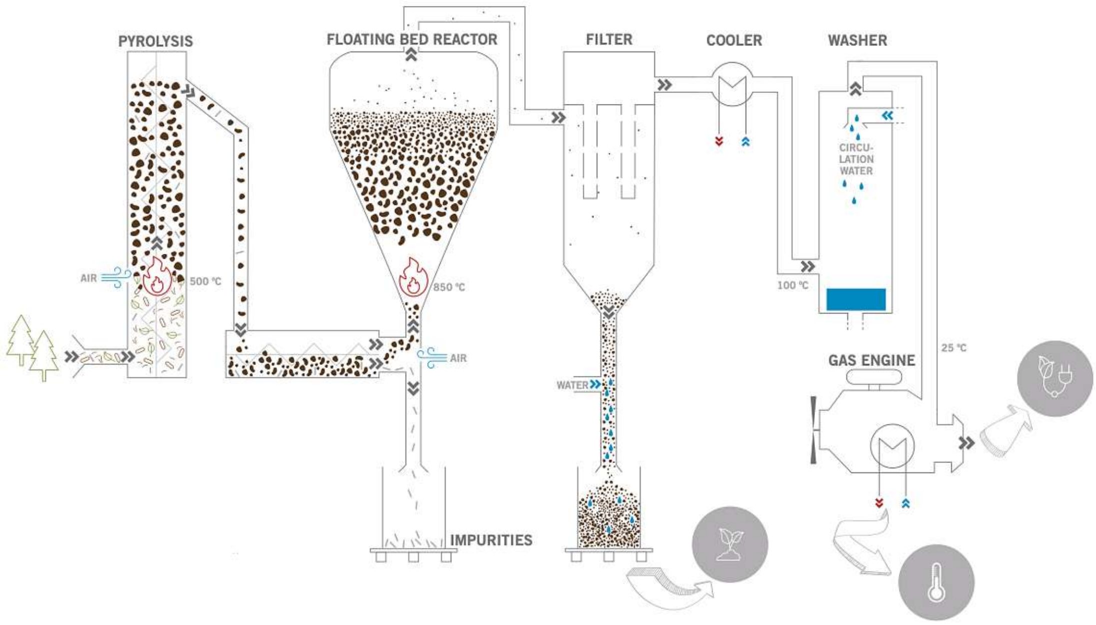

Figure 41: Operating principle of the SYNCRAFT CHP plant [119]

The fuel for the CHP plant must be uncontaminated wood chips with a grain size of at least 40 mass percent larger than 25 mm, maximum 20 mass percent smaller than 8 mm and generally a maximum grain size of 150 mm. The calorific value of the wood chips must be more than 720 kWh/m^3 or 4 kWh/kg. [120] The wood chips are first dried to a water content of 10 percent using a drying process that is decoupled from the gasification process. After drying, a part of the biomass is burned in the pyrolysis reactor, while the remaining part is broken down into its solid, liquid and gaseous components, whereby the gas still contains a very high proportion of tars. [121]

[118] Cf. (Syncraft, 2023b p. 1)
[119] (Huber, et al., 2019 p. 2)
[120] Cf. (Syncraft, 2023b), Cf. (Syncraft, 2023a)
[121] Cf. (Syncraft, 2023b pp. 1-3)

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In the oxidation process, which is located between the pyrolysis process and the reduction process in the reduction reactor (in Figure 41 named as floating bed reactor), some of the pyrolysis products are burned by adding air. Due to the high temperatures that occur, almost all of the tar is broken down. The solid carbon from the pyrolysis process forms a stable, floating fixed bed in the reduction reactor, through which the gas flows. The effective gasification of the biomass takes place in this reduction reactor. In the filter, the product gas is cleaned of dust (mainly biochar), which is discharged into a storage container. The product gas is cooled in the cooler, whereby the thermal energy is transferred to a heat consumer (e.g. district heating network). The product gas is further cooled down in a washer where also condensate is removed. The cleaned and cooled product gas is fed to a gas engine. The product gas is converted into electricity and heat in the gas engine. The generated electricity is fed into the electricity grid and the generated heat is supplied to a heat consumer (e.g. district heating network). [122] Table 6 shows the data for the different SYNCRAFT CHP plants available on the market. In addition to the main products heat and electricity, the product biochar is produced.

Table 6: Data of the different SYNCRAFT CHP plants [123]

Type	Unit	CW1200-400	CW1800-500	2 x CW1800-500
Biomass input	[kW] [kg/h] [124]	1.429 286	1.808 362	3.527 705
Gas output	[kW] [125]	1.000	1.266	2.469
Biochar output	[kW] [126] [m^3/d] [127]	258 3,5	325 4,5	634 9,0

[122] Cf. (Syncraft, 2023b pp. 1-3)
[123] Cf. (Syncraft, 2022a), Cf. (Syncraft, 2022b), Cf. (Syncraft, 2022c), Cf. (Besendörfer, 2024a), Cf. (Besendörfer, 2024b)
[124] absolutely dry / water-free
[125] for the use in the gas engine
[126] calculated with the following assumption:
Biochar output [kW] = Biomass input [kW] – Gas output [kW] – Heat output of gas generation [kW]
[127] moistened

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Heat output (90 – 95°C) … thereof gas generation … thereof gas engine Heat output (50°C)	[kW] [kW] [kW] [kW]	572 171 401 227	740 217 523 250	1.404 424 980 500
Electricity output	[kW]	400	500	1.000
Electricity consumption	[kW]	40	40	80
Personnel expenses	[h/d] [128]	4	4	4
Costs for maintenance and service in relation to the investment costs	[% / a]	8,0	8,0	8,0
Minimal partial load in relation to the rated output	[%]	75 – 80	75 – 80	75 – 80
Investment costs	[EUR]	3.400.000	3.700.000	6.300.000

5.6.3 Biomass CHP plant – STEAMERGY

Another combined heat and power generation system that will be analyzed in the course of this master's thesis is the system from the company STEAMERGY. This system is a cascadable steam power process. Figure 42 shows a CHP system with one steam engine.

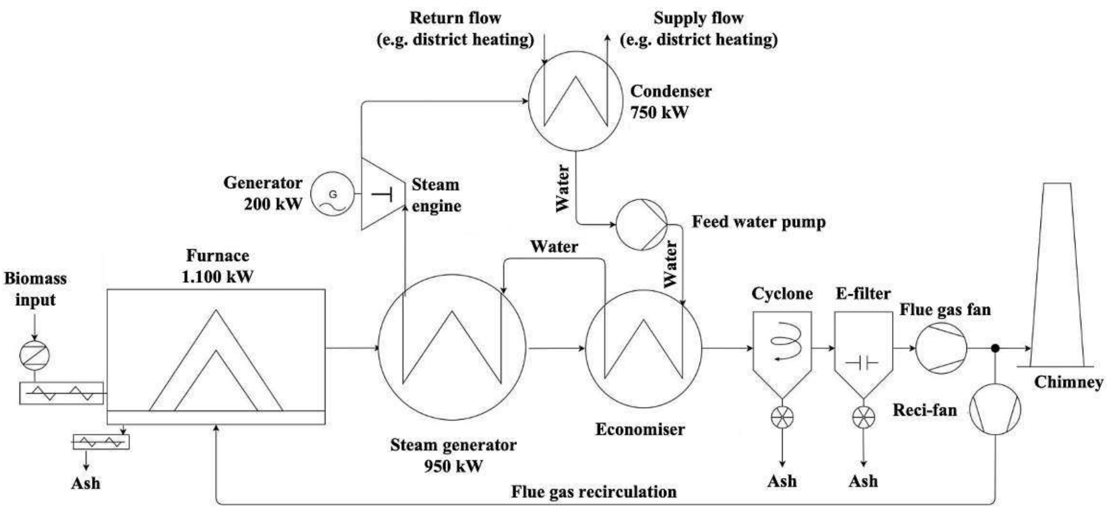

Figure 42: Operating principle of the STEAMERGY CHP plant [129]

[128] own assumption
[129] (Flemming, 2023b p. 14) (own translation), (Brauwelt, 2024 pp. 165-170) (own translation)

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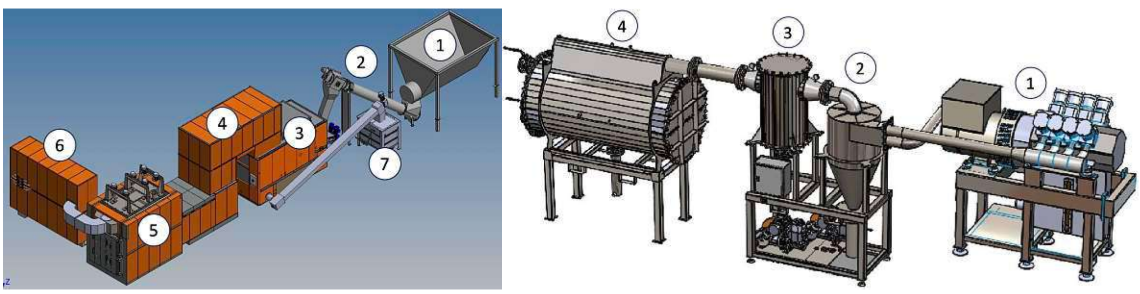
The operating principle of the STEAMERGY system corresponds to the Clausius Rankine process. In a furnace, the energy source biomass (wood chips) is burned. The produced flue gas transfers the heat to a steam generator, which is designed as a liquid salt storage tank and is operated at a temperature of approximately 450 to 550 degrees Celsius. In a downstream economizer, the flue gas releases a further amount of heat to the pressurized feed water. The flue gas is then cleaned by means of a cyclone separator and an electrostatic filter before the flue gas enters the chimney using the flue gas fan. The heat transferred to the liquid salt storage tank is transferred from the liquid salt to the water via a heat exchanger tube. The water in the heat exchanger tube is vaporized and superheated in the liquid salt storage tank. The superheated steam is utilized in a piston steam engine, which generates electricity with a generator. The steam from the steam engine is liquefied in a condenser, whereby the heat extracted from the steam is supplied to a heat consumer (e.g. district heating network). After condensation of the steam, the pressure is increased in a feed water pump so that the feed water can be preheated in the economizer using the residual heat extracted from the flue gas. A significant advantage of this system is the unpressurized liquid salt storage tank and the relatively small steam volume, which avoids the traditional and costly steam boiler operation. The system can be divided into the producer side and the consumer side as shown in Figure 43. The producer side, shown in Figure 43 (a), consists of a silo discharge (1), fuel transport system (2), furnace (3), hot gas duct (4), liquid salt steam generator (5), economizer (6) and an ash removal system (7). The consumer side, shown in Figure 43 (b), consists of a steam engine (1), cyclone oil separator (2), fine flow separator (3) and a condenser (4).[130]



(a) (b)

Figure 43: Components of the STEAMERGY CHP plant [131]

[130] Cf. (Flemming, 2023b pp. 4-11), Cf. (Nussbaumer, et al., 2020 p. 34), Cf. (Baehr, et al., 2016 pp. 544-550), Cf. (Brauwelt, 2024 pp. 165-170)

[131] Cf. (Flemming, 2023b pp. 10-11), Cf. (Brauwelt, 2024 pp. 165-170)

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Table 7 shows the data for the various STEAMERGY CHP plants available on the market. This system is a conventional CHP system in which heat and electricity are generated without any by-products.

Table 7: Data of the different STEAMERGY CHP plants [132]

Type	Unit	System with 1 engine	System with 5 engines	System with 12 engines
Biomass input	[kW]	1.100	5.500	13.200
Heat output	[kW]	750	3.750	9.000
Electricity output	[kW]	200	1.000	2.400
Electricity consumption	[kW] [133]	20	100	240
Personnel expenses	[h/wk] [134]	1	2	4
Costs for maintenance and service in relation to the investment costs	[% / a] [135]	1,5	1,5	1,5
Minimal partial load in relation to the rated output	[%]	20	20	20
Investment costs	[EUR]	1.700.000	6.400.000	14.200.000

In addition to the investment costs for the output sizes listed in Table 7, the investment costs also for other sizes are known. The investment costs for a system with 2 engines amount to 3.000.000 euros, a system with 3 engines to 4.100.000 euros, a system with 8 engines to 9.800.000 euros and a system with 10 engines to 11.800.000 euros. [136]

[132] Cf. (Flemming, 2023b pp. 13-14), Cf. (Flemming, 2023a), Cf. (Flemming, 2023c), Cf. (Brauwelt, 2024 pp. 165-170)
[133] own assumption (10 percent of the generated electricity)
[134] according to the web meeting of 18 July 2024 (Mr. DI Duschl, Mr. DI Flemming, Mr. DI Wöss)
[135] according to the web meeting of 18 July 2024 (Mr. DI Duschl, Mr. DI Flemming, Mr. DI Wöss)
[136] Cf. (Flemming, 2023a), Cf. (Flemming, 2023c)

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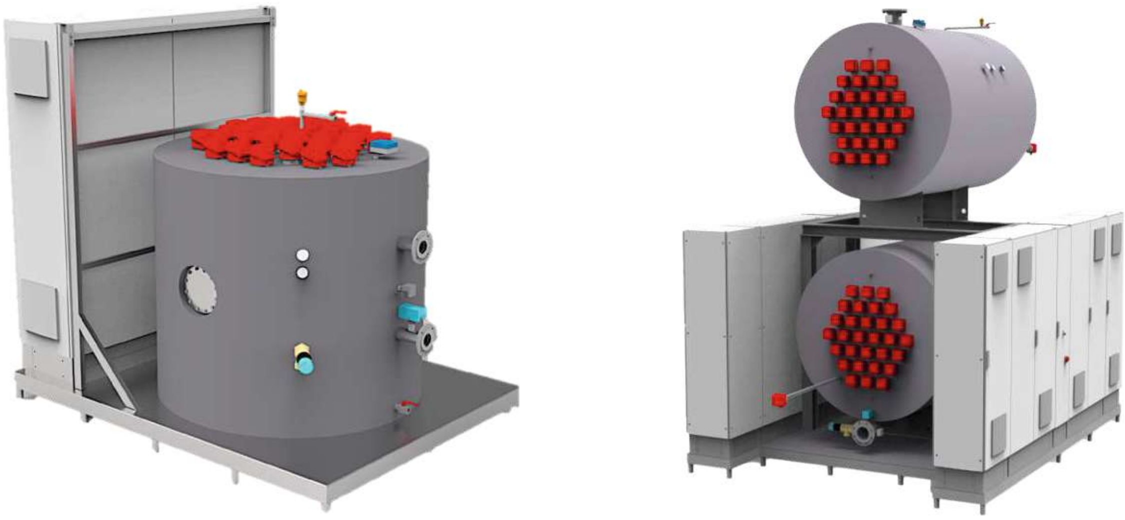
5.7 Electric boiler systems

In electric boiler systems, electrical energy is converted into heat. The integration of an electric boiler system into a district heating system can pursue different objectives. On the one hand, electric boiler systems as shown in Figure 44 can be used to cover the peak loads of a district heating network. On the other hand, it is also possible to operate the electric boiler system during periods with negative electricity prices or to offer the network operator a control reserve. The peak load coverage would be associated with high costs and is therefore not considered in this master's thesis.



(a) (b)

Figure 44: Types of electric boiler systems [137]

In addition to electric boiler systems, it is also possible to use electric flow heaters or heat pump systems in district heating networks to cover peak loads and to use negative electricity prices for the generation of heat as well as to provide a control reserve for the network operator. In general, it can be said that electric flow heaters have slightly lower investment costs than electric boiler systems. In contrast, the investment costs for heat pump systems are considerably higher. [138] This master's thesis focuses only on electric boiler systems that are used when the electricity price is negative and to provide a control reserve for the network operator.

[137] (Ecotherm, 2023 p. 1)
[138] Cf. (Eller, 2015 pp. 13, 109-111), Cf. (Gold, 2017 pp. 8-14), Cf. (Pieper, et al., 2015 pp. 391-393)

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Table 8 shows rounded prices for electric boiler systems with different heat outputs from the manufacturer ECOTHERM.

Table 8: Investment costs for different electric boiler systems [139]

Type	Heat output [kW]	Investment costs [EUR]
EEII-TS-1000-HA	1.008	113.000
EEII-TS-1200-HA	1.188	121.000
EEII-TS-1500-HA	1.512	137.000
EEII-TS-1750-HA	1.764	161.000
EEII-TS-2000-HA	2.016	173.000
EEII-TS-3000-HA	3.024	180.000
EEII-TS-4000-HA	3.618	346.000
EEII-TS-5250-HA	4.536	484.000
EEII-TS-6000-HA	6.048	519.000

To ensure that the electric boiler system can be operated with negative electricity prices in general, it is necessary to participate in the day-ahead market. The day-ahead market and the intraday market are part of the spot market. The spot market is the short-term trading market for physical energy trading transactions to optimize the procurement and the sale of electricity volumes for a short period of time. On the day-ahead market, prices for hourly products are determined daily in an auction for each hour of the following day. The intraday market, on the other hand, is used for short-term trading during the day. [140] Figure 45 shows the unsorted energy prices on the day-ahead market in Austria for the years 2020 to 2023 in chronological order. This figure shows that the prices on the day-ahead market are very volatile and highlights the tense situation on the energy market in the years 2021 and 2022. Furthermore, the figure shows that the number of hours in which there were negative electricity prices on the day-ahead market was very low in the last 4 years. Figure 46 shows the energy prices from Figure 45 sorted by their size.

[139] Cf. (Ecotherm, 2023 p. 2)
[140] Cf. (Doleski, et al., 2023 p. 321)

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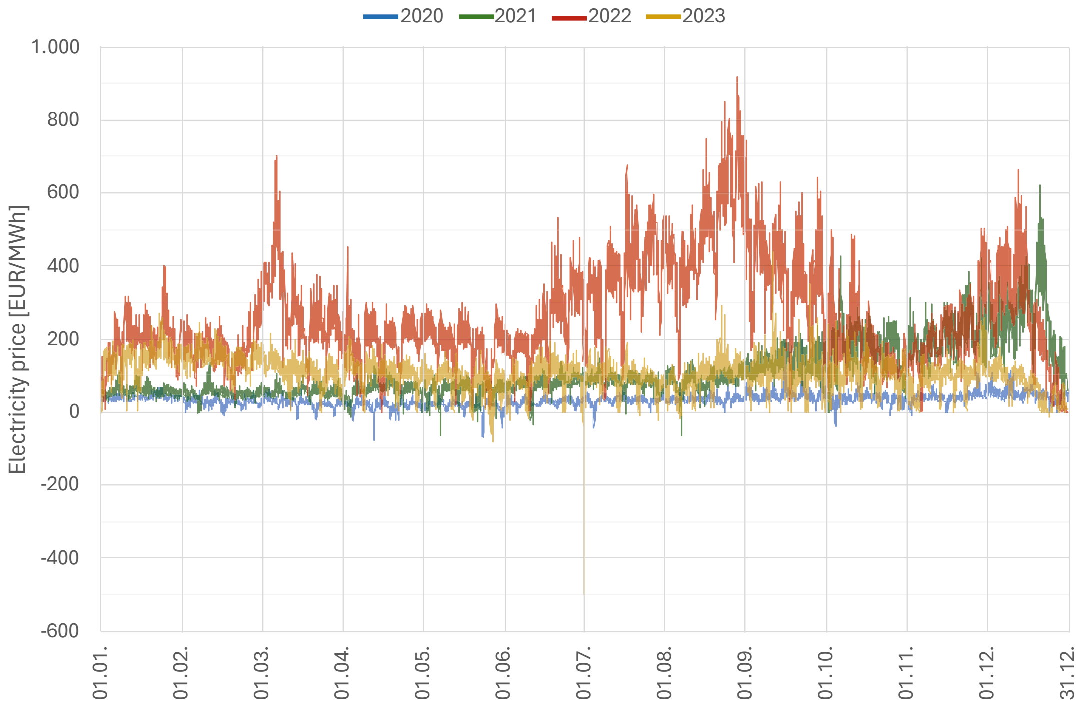

Figure 45: Unsorted energy prices on the day-ahead market for 2020 to 2023 [141]

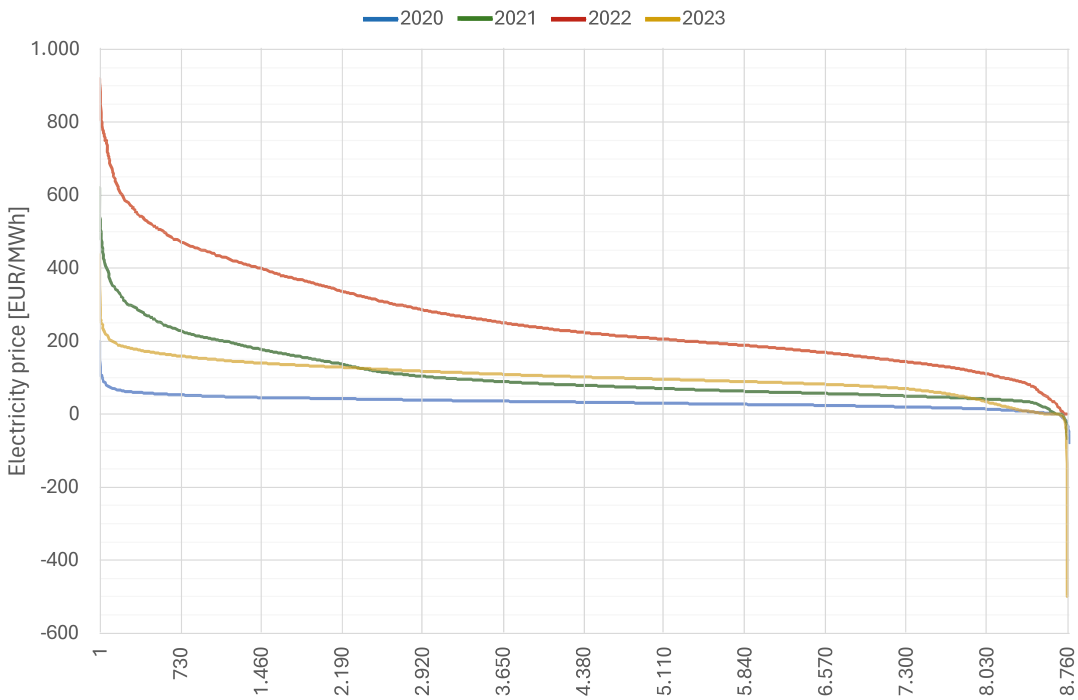

Figure 46: Sorted energy prices on the day-ahead market for 2020 to 2023 [142]

[141] Cf. (APG, 2024a)
[142] Cf. (APG, 2024a)

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Table 9 shows characteristic values of the energy prices on the day-ahead market. In addition to the minimum energy price and the maximum energy price, the number of hours with negative energy prices and the average negative energy price for the years 2020 to 2023 are listed.

Table 9: Characteristic values of the energy prices on the day-ahead market [143]

Year	Minimum energy price [EUR / MWh]	Maximal energy price [EUR / MWh]	Hours with neg. energy prices [h]	Average neg. energy price [EUR / MWh]
2020	-77,68	200,04	120	-15,43
2021	-66,18	620	67	-11,14
2022	0	919,64	2	0
2023	-500	437,47	137	-12,56

Another application of the electric boiler system that should be considered is the provision of control reserve for the network operator. For this reason, the different control reserves will be described in the following section.

In general, it can be said that the frequency in the electricity grid must always be kept at 50 ± 0,2 Hertz. To ensure that this frequency can be kept within this range, it is necessary that the generation corresponds to the consumption and vice versa. In case of a deviation between the generation and the consumption, first of all the inertia of the interconnected electricity grid (operating reserve, OR) minimizes a frequency deviation. If the frequency deviation exceeds a certain level, a cascaded activation of the primary control reserve (frequency containment reserves, FCR), the secondary control reserve (automatic frequency restoration reserves, aFRR) and the tertiary control reserve (manual frequency restoration reserves, mFRR) takes place. In cases where the generation is lower than the consumption, the frequency decreases and an additional generation is necessary (positive reserve). On the other hand, when the generation is bigger than the consumption, the frequency increases and an additional consumption is necessary (negative reserve). [144]

[143] Cf. (APG, 2024a)
[144] Cf. (Doleski, et al., 2023 pp. 77-78), Cf. (A1, 2024), Cf. (APG, 2024d)

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The primary control reserve must be fully available within a period of 30 seconds for at least 30 minutes and is only remunerated per capacity provided (MW). If the frequency deviation still exists, the secondary control reserve is automatically activated as a second product. It must be fully available after 5 minutes. The secondary control reserve is differentiated into positive and negative secondary control reserve. The remuneration is granted both for the capacity provided (MW) and for the energy supplied (MWh). If there is still a frequency deviation, the tertiary control reserve is activated manually as the third product. It must be fully available after 15 minutes. The tertiary control reserve is divided into positive and negative tertiary control reserve, like the secondary control reserve. The compensation is carried out in the same way as for the secondary control reserve and is based on the capacity provided (MW) and the energy supplied (MWh). The cascaded activation of the different control reserves and the characteristics of the different control reserves can be seen in Figure 47 and Table 10. [145]

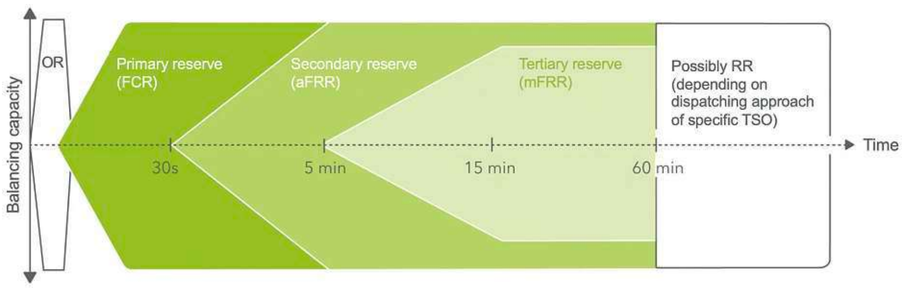

Figure 47: Cascaded activation of the different control reserves [146]

Table 10: Characteristics of the different control reserves [147]

Product	FCR	aFRR	mFRR
Activation type	Automatic, local	Automatic, signal	Manual, message
Activation time	< 30 s	< 5 min	< 15 min
Minimum volume	± 1 MW	1 MW	1 MW
Direction of delivery	Both direction	One direction	One direction
Compensation	Capacity	Capacity, energy	Capacity, energy

145 Cf. (APG, 2024d), Cf. (APG, 2024e), Cf. (APG, 2024f), Cf. (APG, 2024g), Cf. (A1, 2024)
146 (Next Kraftwerke, 2023) (own translation), Cf. (Next Kraftwerke, 2024a) (own translation)
147 Cf. (Gicevskis, et al., 2023), Cf. (APG, 2024d), Cf. (APG, 2024e), Cf. (APG, 2024f), Cf. (APG, 2024g), Cf. (Doleski, et al., 2023 p. 77), Cf. (A1, 2024), Cf. (E-Control, 2024)

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Table 10 shows that the primary control reserve only allows symmetrical deliveries, which means that an electric boiler cannot be used to offer a primary control reserve. According to Table 10, an electric boiler can only be used to offer secondary control reserve and tertiary control reserve. In contrast to the tertiary control reserve, the primary control reserve is activated very frequently. A frequent activation of the primary control reserve means that in addition to the capacity price, the energy price – in the event of a negative energy price – can be obtained, resulting in several advantages for a supplier of district heat, because

1. the provision of negative reserve capacity results in a capacity price that can be obtained, [148]
2. the heat generation costs are covered by the energy price if energy is supplied as a result of a capacity request, [149]
3. the heat generated is sold to the heat customers under the conditions specified in the heat supply contracts, [150]
4. other energy resources can be saved and the residual heat demand can be covered by cheaper energy sources in accordance with the internal merit order principle, which reduces the supplier's heat generation costs while the remuneration paid by the end consumers remains the same. [151]

But also, a moderate positive energy price can be beneficial for the supplier of district heat if the heat generation costs are lower than the heat generation costs of the other energy sources used. Figure 48 shows the unsorted capacity prices and the unsorted energy prices for primary control reserve in Austria for the year 2023 in chronological order. The unsorted capacity prices correspond to the weighted average capacity prices of the awarded capacities on a daily basis, whereby the unsorted energy prices correspond to the weighted average energy prices of the requested energy on a daily basis. Figure 49 shows the capacity prices from Figure 48 sorted by their size as well as the associated energy prices and the cumulative average energy price. In this context, it should also be mentioned that all control reserves are awarded on the basis of tenders.

[148] Cf. (Pieper, et al., 2015 p. 397)
[149] Cf. (Pieper, et al., 2015 p. 397)
[150] Cf. (Pieper, et al., 2015 p. 397)
[151] Cf. (Pieper, et al., 2015 p. 397)

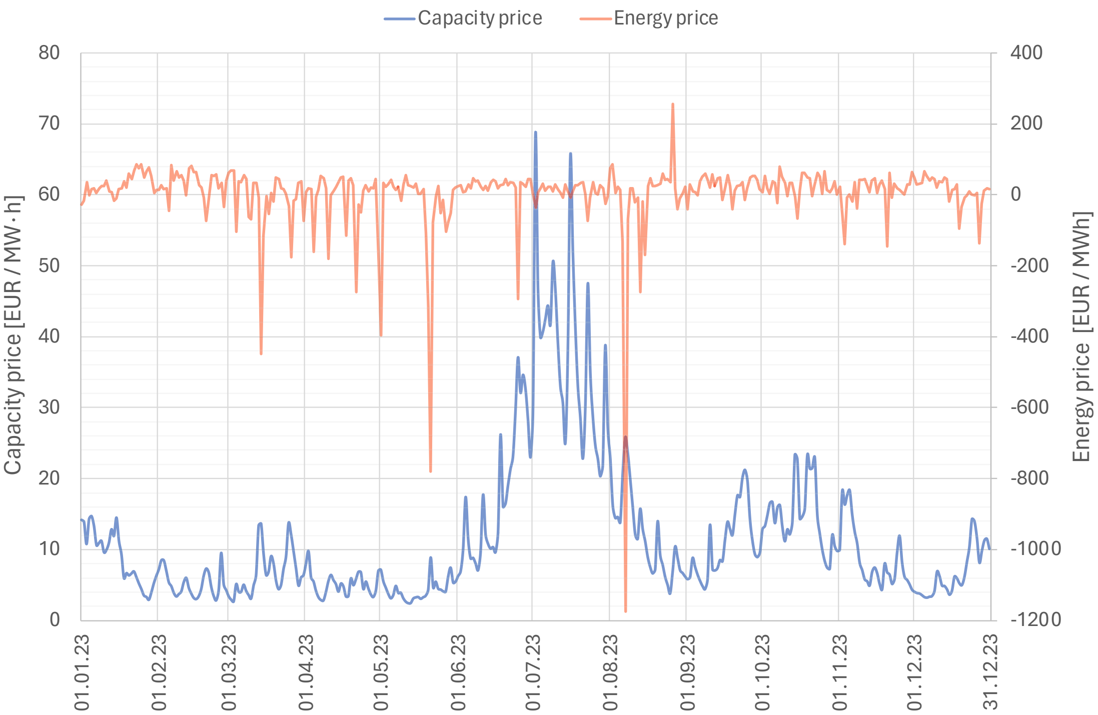

Figure 48: Unsorted performance and energy prices for aFRR for 2023 [152]

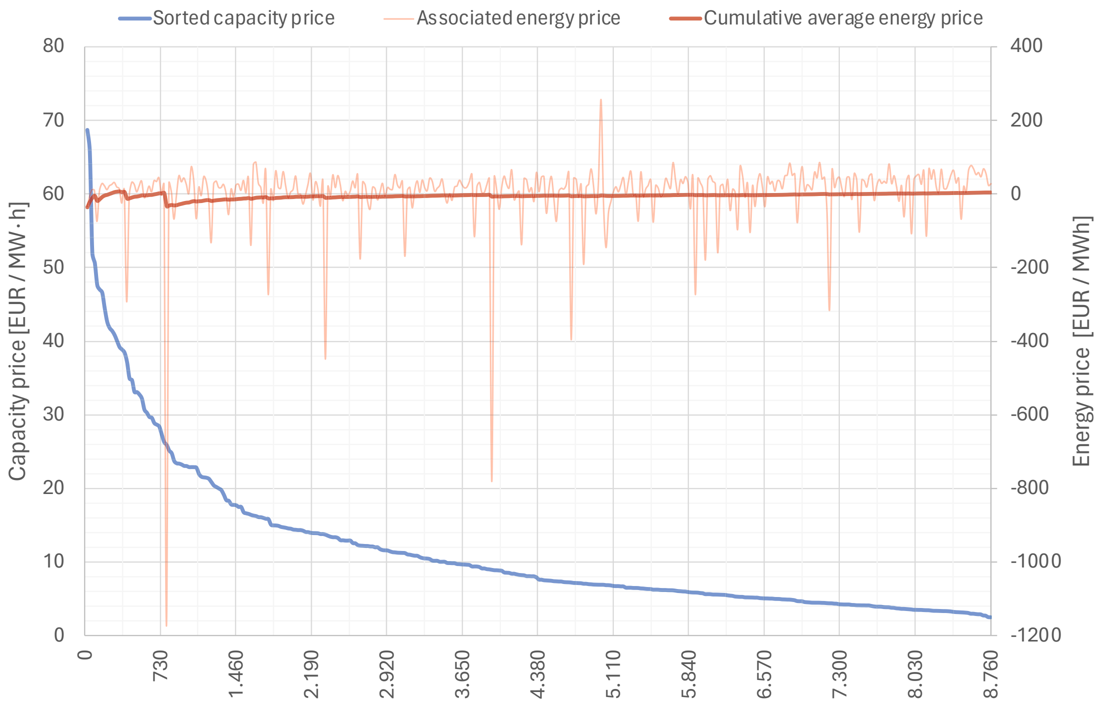

Figure 49: Sorted performance price and associated energy prices for aFRR for 2023 [153]

[152] Cf. (APG, 2024b), Cf. (APG, 2024c)
[153] Cf. (APG, 2024b), Cf. (APG, 2024c)

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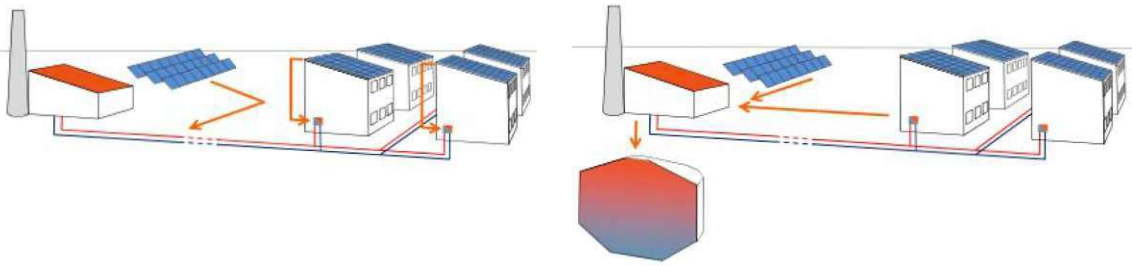
5.8 Solar thermal systems

The generation and use of solar thermal heat for a district heating network can be realized in different ways according to Figure 50. A first distinction is whether the heat is generated by a central collector field or by several decentralized collector fields. Another differentiation is the way in which the generated heat from the solar collectors is used or stored. In addition to the direct use without a large storage, there are also systems in which the generated heat from the collectors is stored for a longer period of time. [154]



(a) (b)

Figure 50: Generation and usage of solar thermal energy in a district heating network [155]

In Figure 51, a simplified layout of a heat source in combination with a solar thermal system can be seen. A system that uses solar thermal heat consists in general of a heat source, a solar thermal system and a thermal storage. In this figure, the generated heat is used directly for space heating and domestic hot water preparation using a thermal storage. Furthermore, it is also possible that the heat generated by a boiler and a solar thermal system is fed into a district heating network that supplies heat to heat consumers. The dimensioning of the boiler, the solar thermal field and the thermal storage are dependent on the amount of heat that should be generated by the boiler system and the amount of heat that should be generated by the solar thermal system. In this context, it should be mentioned that the use of solar thermal energy is not limited to space heating and domestic hot water preparation. In addition to the provision of space heat and domestic hot water, a solar thermal system can also be used to provide heat at high temperatures for industry or heat at low temperatures for swimming pools. [156]

[154] Cf. (SDH, 2017 p. 6), Cf. (Bollin, et al., 2013 pp. 85-89), Cf. (Hauer, et al., 2013 pp. 71-84)
[155] (SDH, 2017 p. 6)
[156] Cf. (Schabbach, et al., 2021 p. 3), Cf. (Quaschning, 2022 p. 109), Cf. (Sterner, et al., 2017 pp. 736-744)

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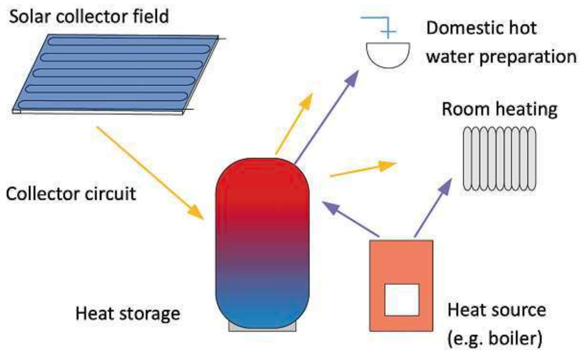
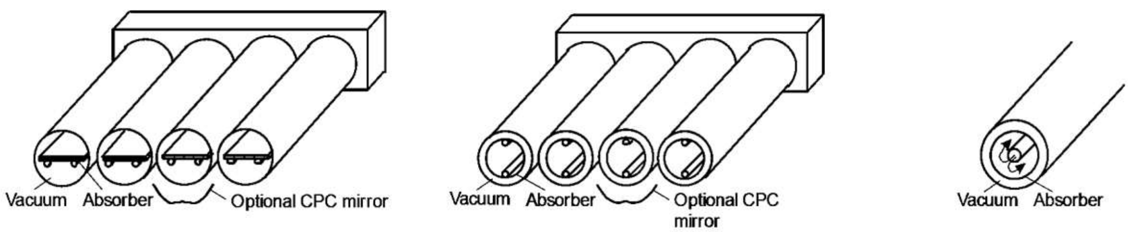


Figure 51: Layout of a solar thermal system [157]

As already mentioned, a solar thermal system can provide thermal energy at low temperatures for swimming pools as well as thermal energy at high temperatures for the industry. The main difference between solar thermal systems for the different temperature levels is the collector that is used to convert the solar irradiation into heat energy. Figure 52 and Figure 53 show the different available collector types.

(a) (b)

Figure 52: Types of solar thermal collectors [158]



(a) (b) (c)

Figure 53: Types of solar thermal collectors [159]

[157] (Schabbach, et al., 2021 p. 3) (own translation)
[158] (a) Swimming-pool collector, (b) Flat-plate collector, (Stryi-Hipp, et al., 2015 p. 19)
[159] (a) Vacuum-tube collector, (b) Sidney vacuum tube collector,
(c) Sidney vacuum tube collector with flow in concentric tubes, (Stryi-Hipp, et al., 2015 p. 20)

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The reason why the collectors shown are used for different temperature levels is the conversion efficiency that can be achieved. The efficiency of a collector is generally defined according to equation (5.11).

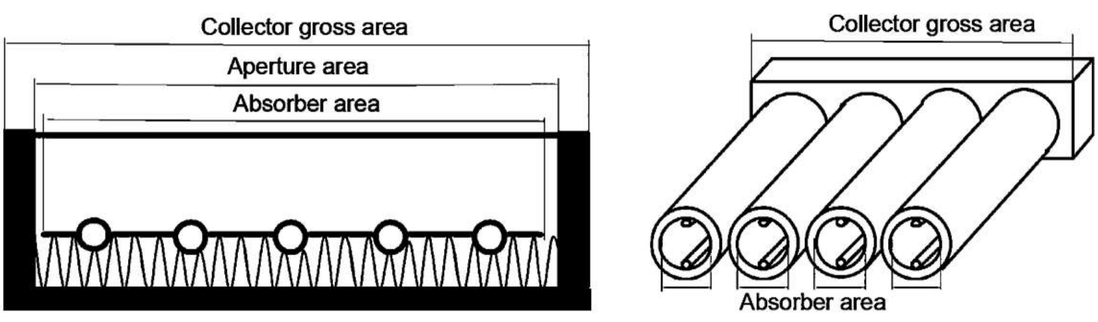
$$\eta_{col} = \frac{q_N}{E} \quad (5.11)$$

[160]

With the following meanings:

η_{col}	Efficiency of the solar collector in %
q_N	Specific performance in W/m²
E	Irradiance in W/m²

To be able to define the efficiency of a collector precisely, it is always necessary to specify the area to which the efficiency is related. In addition to the collector gross area and the aperture area, the absorber area can be used to define the efficiency. Figure 54 shows the difference between the areas of a flat-plate collector (a) and a vacuum-tube collector (b).



(a) (b)

Figure 54: Definition of the different collector areas [161]

The efficiency of a collector depends mainly on the construction and the operating mode and can be calculated according to equation (5.12) and equation (5.13), considering the different areas. In equation (5.12), only the collector gross area and the absorber area are mentioned for the efficiency.

[160] (Weyres-Borchert, et al., 2015 p. 31)
[161] (Stryi-Hipp, et al., 2015 p. 18)

Nevertheless, it is also possible to refer the efficiency to the aperture area.

$$\eta_{col,gr/abs} = \eta_{0,gr/abs} - \frac{\alpha_{1,gr/abs} \cdot \Delta\vartheta}{E} - \frac{\alpha_{2,gr/abs} \cdot \Delta\vartheta^2}{E} \quad (5.12)$$

[162]

$$\Delta\vartheta = \vartheta_m - \vartheta_a \quad (5.13)$$

With the following meanings:

$\eta_{col,gr/abs}$	Efficiency of the solar collector related to the collector gross area or the absorber area in %
$\eta_{0,gr/abs}$	Optical efficiency related to the collector gross area or the absorber area in %
$\alpha_{1,gr/abs}$	Linear heat loss coefficient related to the collector gross area or the absorber area in W/m²·K
$\alpha_{2,gr/abs}$	Squared heat loss coefficient related to the collector gross area or the absorber area in $W/m^2 \cdot K^2$
E	Irradiance in W/m^2
$\Delta\vartheta$	Temperature difference in K
ϑ_m	Mean absorber temperature in °C
ϑ_a	Ambient temperature in °C

The specific performance and the efficiency of a collector can be demonstrated graphically as a function of the temperature difference between the absorber and the ambient according to equation (5.13) and the irradiation. In Figure 55 the specific performance of a flat-plate collector as a function of the irradiation and the temperature difference is shown.

[162] (Weyres-Borchert, et al., 2015 p. 32), (Weiss, 2023 pp. 64-65)

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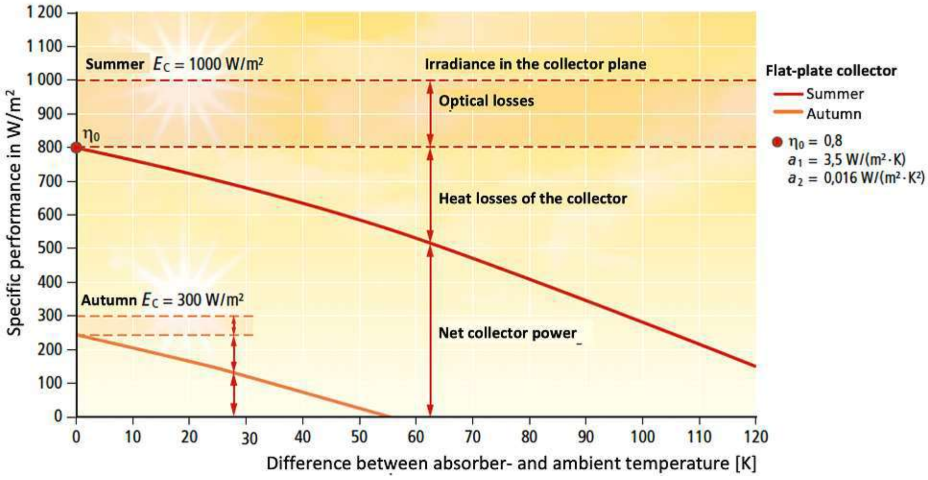

Figure 55: Specific performance of a flat-plate collector [163]

The efficiency of a collector depends on the temperature difference between the absorber and the ambient, the irradiance, as well as on other coefficients like the optical efficiency, the linear and squared heat loss coefficient. The optical efficiency as well as the linear and squared heat loss coefficient depend only on the collector design. Table 11 shows the various factors, the production effort and the application of the different collector designs.

Table 11: Properties of the different collector types [164]

	Optical efficiency η_0	Thermal loss factor a_1 in W/(m² K)	Typical temperature range[a] in °C	Required production input	Typical application
Swimming-pool absorber[b]	0.92	12–17	0–30	Small	OASW
Flat-plate collector 1[c]	0.80–0.85	5–7	20–80	Medium	DHW
Flat-plate collector 2[d]	0.65–0.70	4–6	20–80	Medium	DHW
Flat-plate collector 3[e]	0.75–0.81	3.0–4.0	20–80	Medium	DHW, SH
Vacuum-pipe collector	0.45–0.80	0.6–1.2	50–120	Medium	DHW, SH, PH
Sidney collector	0.35–0.6	0.8–1.5	50–120	Medium	DHW, SH, PH
CPC tube collector	0.6–0.7	0.8–1.2	50–120	Large	DHW, SH, PH

Note: OASW, open-air swimming pool; DHW, domestic hot water; SH, space heating; PH, process heat.
[a]Medium work temperatures.
[b]Black, nonselective, not covered.
[c]Nonselective absorber, single cover.
[d]Nonselective absorber, double glass or supporting foil.
[e]Selective absorber, single cover.
Source: Streicher (2015) and SPF (2015).

163 (Weyres-Borchert, et al., 2015 p. 36) (own translation)
164 (Stryi-Hipp, et al., 2015 p. 21)

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The global irradiation of the sun, the area of the solar thermal system, the efficiency of the solar thermal system and the system efficiency results in the solar energy yield according to equation (5.14).

$$Q_{solar,m/a} = G_{m/a} \cdot A_{gr/abs} \cdot \eta_{col,gr/abs} \cdot \eta_{sys} \text{ [165]} \tag{5.14}$$

With the following meanings:

$Q_{solar,m/a}$	Solar energy yield in kWh/month or kWh/year
$G_{m/a}$	Global irradiation in kWh/m^2·month or kWh/m^2·year
$A_{gr/abs}$	Total collector gross area or total absorber area in m^2
$\eta_{col,gr/abs}$	Efficiency of the solar collector related to the collector gross area or the absorber area in %
η_{sys}	Efficiency of the system in %

In this master's thesis, only the direct use of the generated solar thermal heat in the district heating network is analyzed. The direct use of the generated heat has several advantages. On the one hand, there is no need to install a large-volume heat storage system, which means that there are no investment costs for a seasonal storage. On the other hand, the direct use of the solar thermal energy in the summer enables a relatively simple autonomous operation without any other heat sources, as the largest amount of heat can be harvested with the solar thermal collectors in summer, as shown in Figure 56.

The data in Figure 56 correspond to the monthly average global irradiation for the years 2005 to 2020 for the location at a latitude of 48,300° and a longitude of 14,300° at an inclination angle of 33° using the PVGIS-SARAH2 model. From this figure it can be seen that the global irradiation and therefore the solar yield is highest in the summer months. In Figure 57, Figure 58 and Figure 59, the monthly global irradiation is allocated to groups. These figures also show that the proportion of the annual global irradiation is higher for the groups that are closer to the summer months.

[165] (Weyres-Borchert & Kasper, 2015, p. 31), (Weiss, 2023, pp. 64-65)

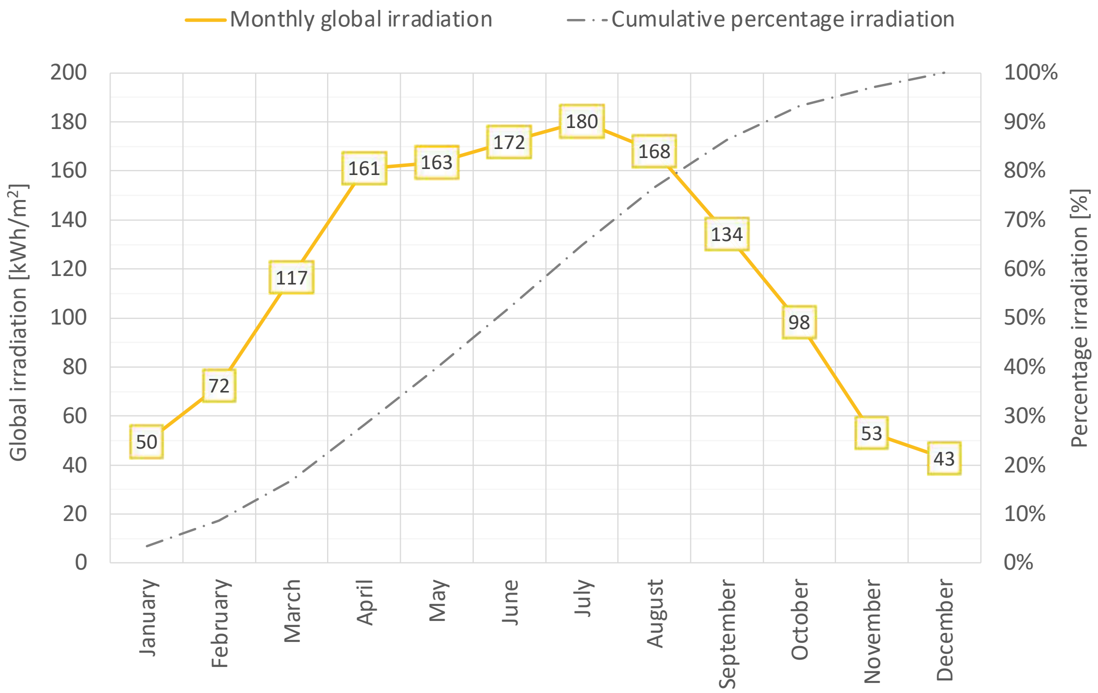

Figure 56: Monthly average of the global irradiation [166]

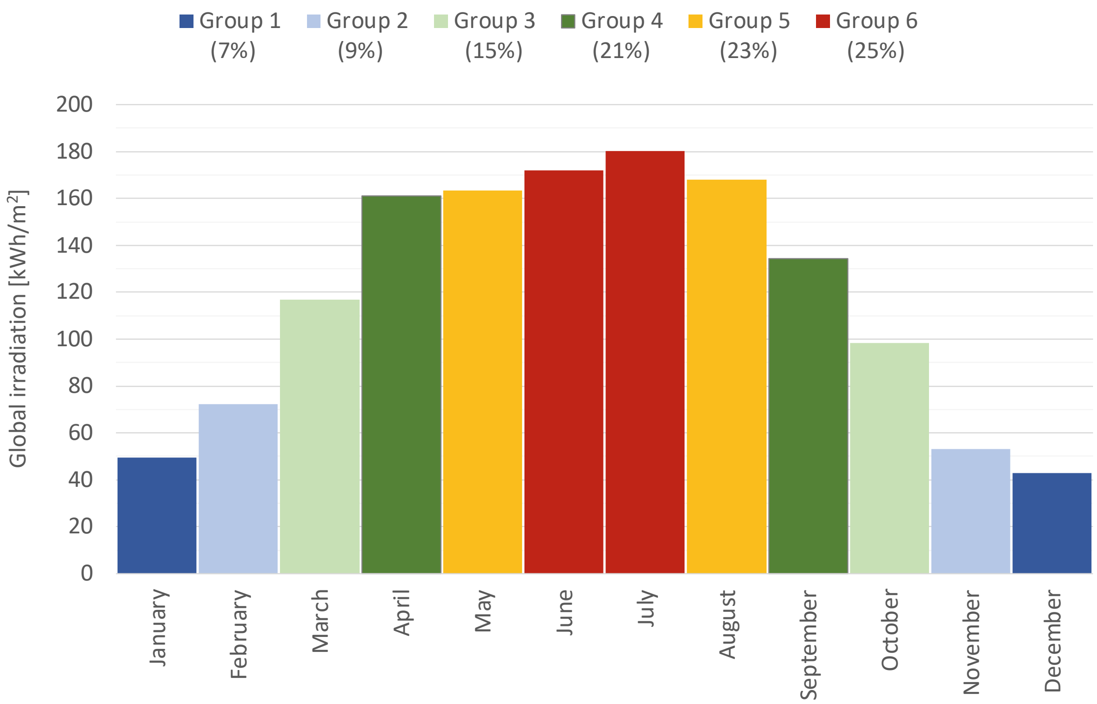

Figure 57: Monthly average of the global irradiation in a six-group allocation [167]

[166] Cf. (GSA, 2024)
[167] Cf. (GSA, 2024)

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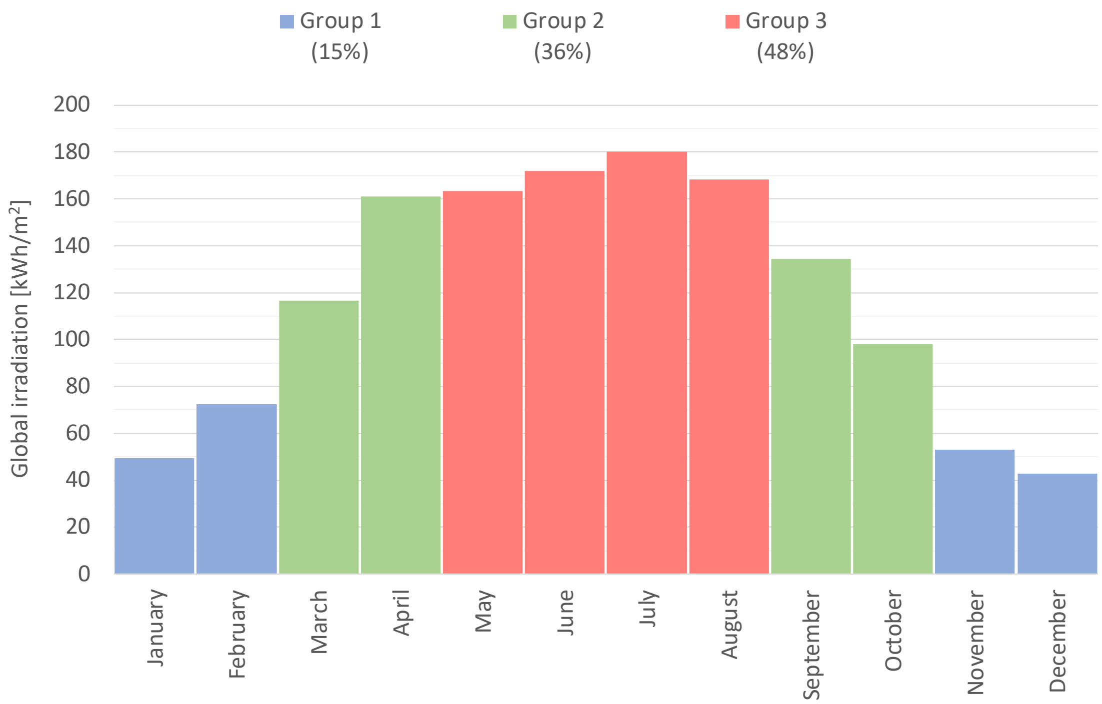

Figure 58: Monthly average of the global irradiation in a triple-group allocation [168]

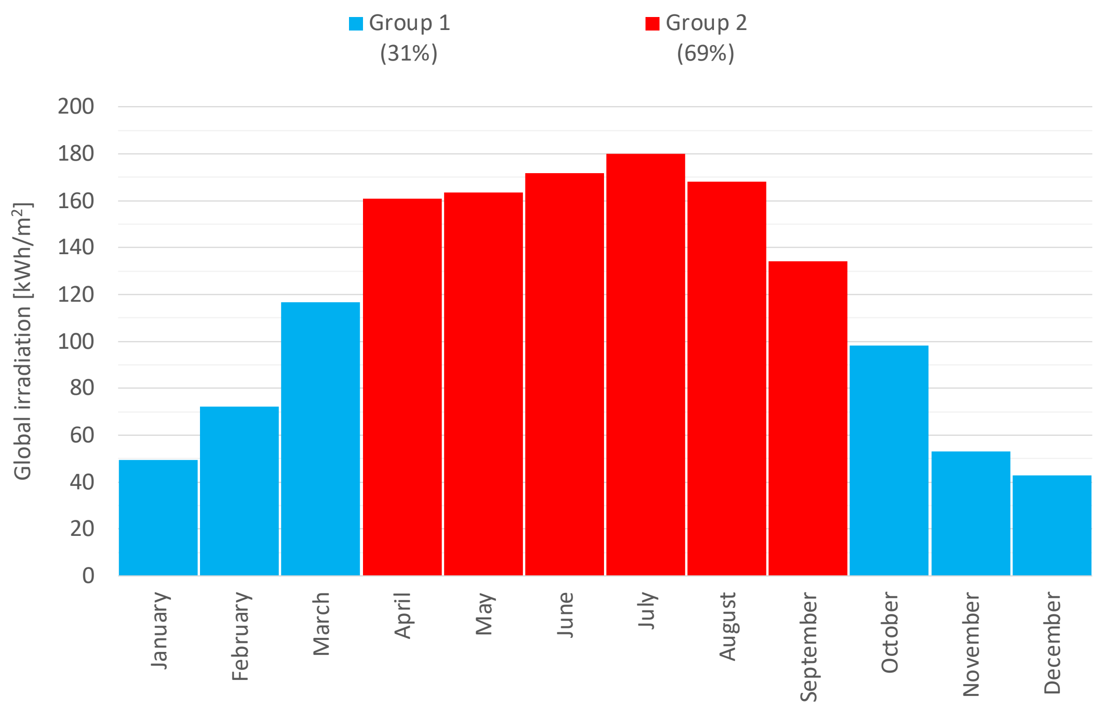

Figure 59: Monthly average of the global irradiation in a dual-group allocation [169]

[168] Cf. (GSA, 2024)
[169] Cf. (GSA, 2024)

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The investment costs for ground-mounted solar thermal collector systems can be assumed to be around 350 – 550 euros per m^2 of collector area (for 10.300 m^2 resp. 1.300 m^2 of collector area), whereby around 2 – 2,5 m^2 of land is required per m^2 of collector area. To ensure a reliable operation of the solar thermal system, a buffer volume of approximately 100 – 200 liters per m^2 of collector area is required, with investment costs for the buffer tank of approximately 380 – 750 euros per m^3 of storage volume (for 2.000 m^3 resp. 400 m^3 storage volume). The operating costs for the solar thermal systems can be assumed to be around 5 euros per megawatt hour generated. Depending on the operating parameters of the solar thermal system, a yield of around 390 – 490 kWh per m^2 of collector area can be expected. [170] Based on the above-mentioned framework conditions and on previous enquiries, Table 12 shows initial designs for solar thermal systems to cover the summer load of heating plants of different sizes.

Table 12: Initial designs of solar thermal systems to cover the summer load [171]

Location	Solar thermal heat generation per year	Share on total heat generation	Collector area	Buffer tank	Investment costs for solar thermal system and for buffer tank
Haid	4.550 MWh	20 %	10.270 m^2	2.000 m^3	EUR 4.355.000
Asten	4.000 MWh	30 %	10.270 m^2	2.000 m^3	EUR 4.355.000
Marchtrenk	2.120 MWh	22 %	5.270 m^2	800 m^3	EUR 2.420.000
Puchenau	1.410 MWh	15 %	3.030 m^2	400 m^3	EUR 1.540.000
Steyregg	1.530 MWh	22 %	3.560 m^2	500 m^3	EUR 1.760.000
Tragwein	1.180 MWh	28 %	2.770 m^2	400 m^3	EUR 1.430.000

In addition to the direct use of the generated heat from the solar thermal collectors in the district heating network, it is also possible to store this heat in a seasonal storage. For the long-term storage of heat, it is possible to use different types of seasonal storages.

[170] Cf. (Temper, 2024b), Cf. (Schramm, 2024)
[171] Cf. (Temper, 2024b), Cf. (Temper, 2024a)

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The seasonal storage can optionally be equipped with a heat pump, as shown in Figure 60. If the storage temperature is too low to use the heat directly in the district heating network the heat pump can raise the temperature of the heat from the storage tank to a higher temperature so that it can be used in the district heating network.

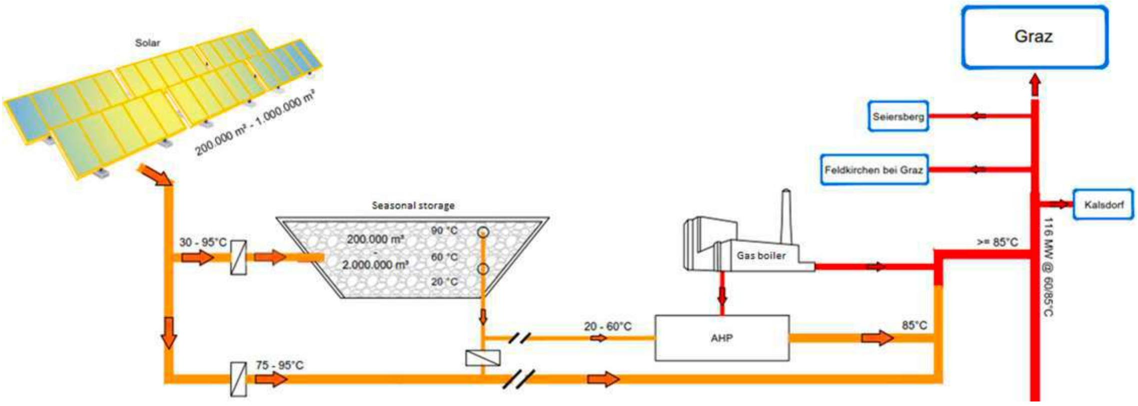

Figure 60: Concept of BIG Solar Graz [172]

5.9 Flue gas condensation systems

Another technology that will be roughly mentioned in this master's thesis due to its potential, but will not be discussed in detail, is the flue gas condensation. In principle, the flue gas condensation is not an independent energy system, especially as the flue gas condensation can only be operated with a furnace. Nevertheless, there is a high potential for this technology, as it can be used to increase the efficiency of existing furnaces that are not currently equipped with a flue gas condensation system. By increasing the efficiency, the heat output of a furnace can be increased when the fuel input remains the same, or the fuel input can be reduced when the heat output of the furnace remains the same. To achieve the goal of a renewable district heat generation in the future, it will be necessary to increase the efficiency of existing systems in addition to implementing renewable energy sources and renewable energy systems. Figure 61 shows the furnace efficiency of a biomass boiler (related to the lower calorific value) as a function of the flue gas temperature when using wood with different water contents (w) for combustion at different excess air ratios (λ). The figure shows that the reduction of the flue gas temperature and the excess air ratio results in an increase in the furnace efficiency. [173]

[172] (Reiter, et al., 2016)
[173] Cf. (Averfalk, et al., 2021 pp. 36-37)

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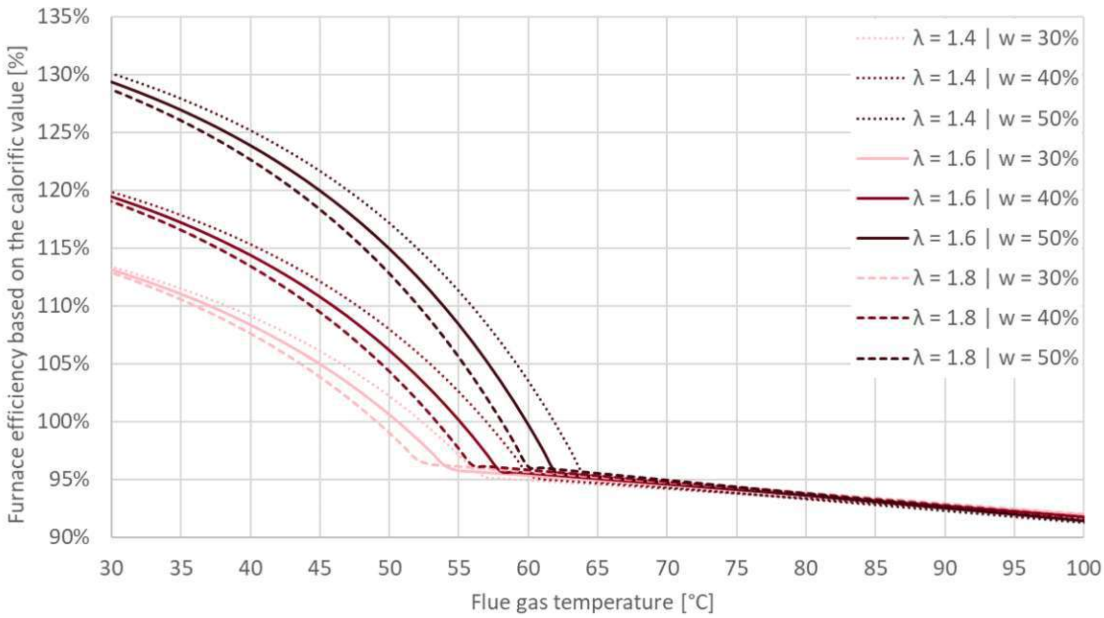

Figure 61: Furnace efficiency of a biomass boiler [174]

With a continuous reduction of the flue gas temperature at a specific water content and a specific excess air ratio, a certain flue gas temperature will be reached, the so-called dew point temperature of the flue gas, from which on the efficiency of the furnace increases over-proportionally to the temperature reduction of the flue gas. At this point, the moisture contained in the flue gas begins to condense. As the temperature reaches and falls below the dew point temperature, it is possible to extract the latent heat in addition to the sensible heat. The fact that the latent heat is considerably higher than the sensible heat results in an over-proportional increase in the efficiency. The figure could lead to the conclusion that a higher furnace efficiency can be reached by using a fuel with a higher water content. In this context, it should be mentioned that this diagram is related to the lower calorific value. The definition of the lower calorific value assumes that there is no condensation of the flue gas. In contrast, the upper calorific value is defined assuming that the flue gas is condensed. Therefore, it can be deduced that the lower calorific value of a wet fuel is lower than the upper calorific value of a wet fuel, that the lower calorific value of a wet fuel is always lower than the lower calorific value of a dry fuel and that the upper calorific value of a fuel is independent of the water content of the fuel. If the diagram would be related to the upper calorific value, the efficiency would appear independent of the moisture content. [175]

[174] (Averfalk, et al., 2021 p. 36)
[175] Cf. (Averfalk, et al., 2021 pp. 36-37), Cf. (Good, et al., 2022 pp. 32-33, 59-60, 157-164)

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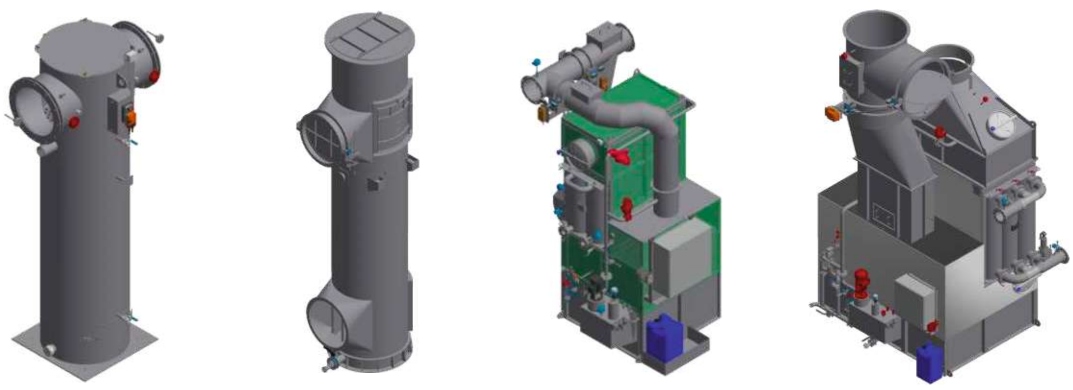
5.9.1 Passive flue gas condensation systems

One way to use the latent condensation heat is to install a passive flue gas condensation system. The passive flue gas condensation system is a heat exchanger in which the condensation can take place and which is also suitable for a condensing operation. This option is also the simplest possibility from a technical point of view. [176]

To ensure that this condensation heat can be used, the return flow of the district heating network must be around 5 to 10 degrees Celsius according to (Averfalk, et al., 2021) or around 2 to 4 degrees Celsius according to (Good, et al., 2022) below the dew point temperature of the flue gas. According to Figure 61, the dew point temperature of the flue gas can be between 52 and 64 degrees Celsius, depending on the water content of the fuel and the excess air ratio used for the combustion process. [177]

For an initial estimation, the rough rule of thumb is that the heat recovery rate is increased by one percent if the flue gas is cooled down by one Kelvin within the condensation range. The way in which the flue gas condensation system is integrated hydraulically has a significant influence on the benefits of the flue gas condensation system. [178] Figure 62 shows passive flue gas condensation system of different sizes.



(a) (b) (c) (d)

Figure 62: Different systems for passive flue gas condensation [179]

[176] Cf. (Averfalk, et al., 2021 pp. 36-37), Cf. (Good, et al., 2022 pp. 59-60)
[177] Cf. (Averfalk, et al., 2021 pp. 36-37), Cf. (Good, et al., 2022 pp. 59-60)
[178] Cf. (Good, et al., 2022 pp. 158-160)
[179] (Pretzl, 2023 pp. 7-8)

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5.9.2 Active flue gas condensation systems

For cases where the return temperature of the district heating network cannot be reduced to a level at which flue gas condensation occurs or occurs only in insufficient quantities, the use of a heat pump in the flue gas path should be considered. The heat pump extracts sensible and latent heat or only latent heat from the flue gas at a low temperature level and raises the heat to a higher temperature level. In addition to compression heat pumps, which are driven by mechanical energy (e.g. by an electric engine), it is also possible to use absorption heat pumps, which are driven by thermal energy. In addition to the type of the heat pump, it is necessary to consider other parameters for the implementation of a heat pump in the flue gas path, such as the number of heat pumps and the hydraulic integration. [180] Figure 63 shows a possible integration of a heat pump system into the flue gas path to ensure condensation of the moisture contained in the flue gas.

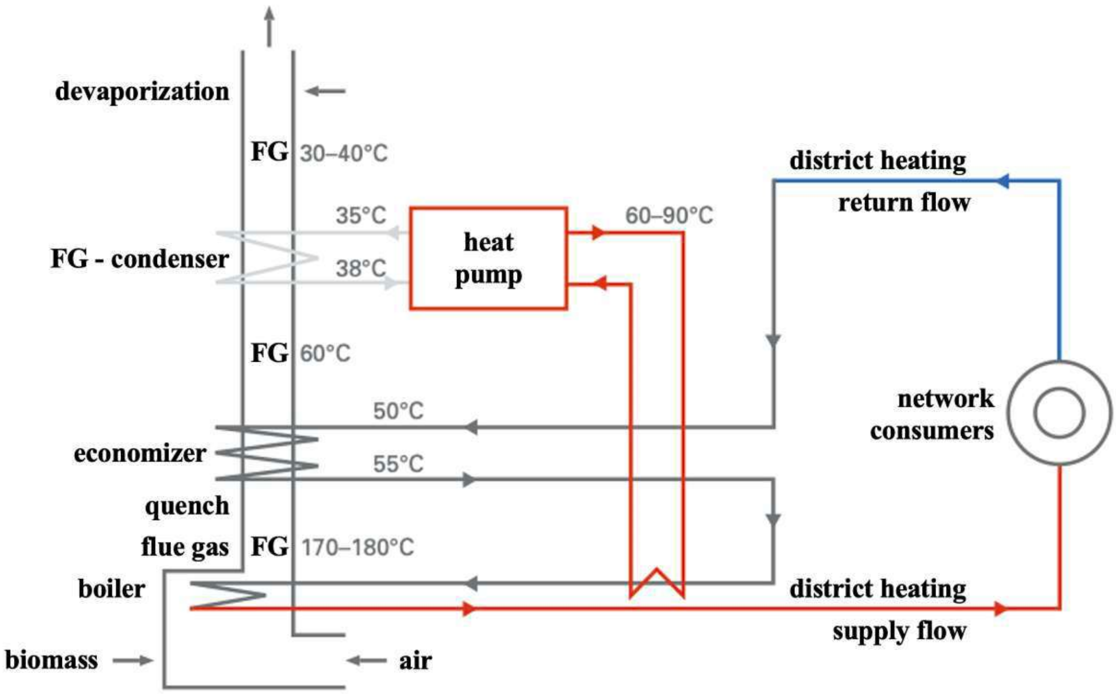

Figure 63: System for active flue gas condensation [181]

The energy efficiency of heat pumps is one of the most important factors for the selection as well as the operation and can be calculated for compression heat pumps according to equation (5.15) and for absorption heat pumps according to equation (5.16).

[180] Cf. (Good, et al., 2022 pp. 160-164)
[181] (Ochsner, 2024 pp. 20-21) (own translation)

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$$\mathrm{COP} = \frac{\dot{Q}_{th}}{P} \quad (5.15)$$

[182]

$$\zeta = \frac{\dot{Q}_{C} + \dot{Q}_{A}}{\dot{Q}_{D}} \quad (5.16)$$

[183]

With the following meanings:

COP	Coefficient of performance (unitless)
$\dot{Q}_{th}$	Heat output at the condenser in kW
P	Power input of the compressor in kW
ζ	Heat ratio (unitless)
$\dot{Q}_{C}$	Heat output at the condenser in kW
$\dot{Q}_{A}$	Heat output at the absorber in kW
$\dot{Q}_{D}$	Heat input at the desorber in kW

The theoretical achievable efficiency (Coefficient of performance and Heat ratio) of a heat pump is physically limited by the Carnot-process and can be calculated according to equation (5.17). It can be seen from the equation that the maximum efficiency depends only on the temperature levels of the source and sink. To ensure a high efficiency of the heat pump, a low temperature difference between the sink and source is necessary. [184]

$$\mathrm{COP}_{Carnot} = \zeta_{Carnot} = \frac{T_{Sink}}{T_{Sink} - T_{Source}} \quad (5.17)$$

[185]

With the following meanings:

COP_{Carnot}	Coefficient of performance for the Carnot-process (unitless)
ζ_{Carnot}	Heat ratio for the Carnot-process (unitless)

[182] Cf. (Maurer, 2016 p. 61), Cf. (Sobotta, 2022 p. 78), Cf. (Bonin, 2023 pp. 52-53), Cf. (Keller, et al., 2021 pp. 79-80), Cf. (Bongs, et al., 2013 pp. 20-21)
[183] Cf. (Maurer, 2016 pp. 121, 125)
[184] (Averfalk, et al., 2021 p. 33), (Good, et al., 2022 p. 160)
[185] (Averfalk, et al., 2021 p. 32), Cf. (Maurer, 2016 p. 43)

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T_{Sink}	Temperature of the heat sink in K
T_{Source}	Temperature of the heat source in K

The equation (5.17) can be represented as a function of the temperature of the heat sink and the temperature of the heat source in a diagram as shown in Figure 64.

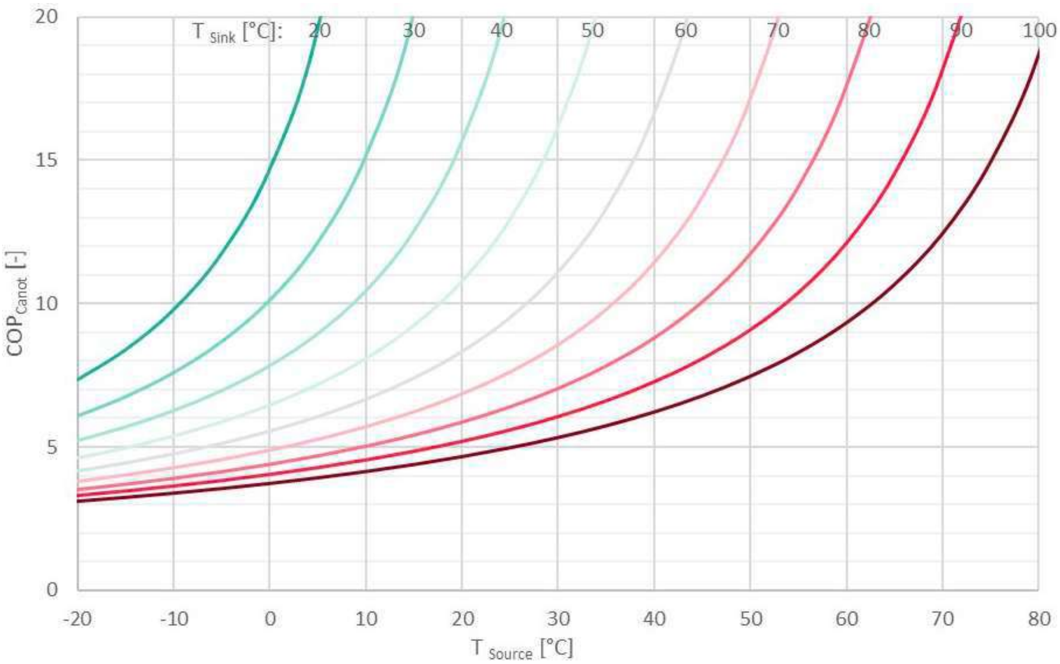

Figure 64: COP for the Carnot-process as a function of sink and source temperature [186]

Based on practical surveys of heat pumps, the relationship between the theoretical and real coefficient of performance can be defined according to equation (5.18).

$$COP_{Real} = K \cdot COP_{Carnot} \quad (5.18)$$

[187]

With the following meanings:

COP_{Real}	Coefficient of performance for the real process (unitless)
K	Quality grade from 0,4 to 0,6 (unitless)
COP_{Carnot}	Coefficient of performance for the Carnot-process (unitless)

186 (Averfalk, et al., 2021 p. 33)
187 Cf. (Keller, et al., 2021 p. 80), Cf. (Good, et al., 2022 p. 161)

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5.10 Systems for heat utilization from other heat sources

In addition to the systems for heat generation and heat utilization that have already been mentioned, there are also other systems such as the use of geothermal energy and the use of waste heat, which will only be briefly mentioned here.

5.10.1 Systems for heat utilization from geothermal heat sources

Another possible heat source is geothermal energy, as shown in Figure 65.

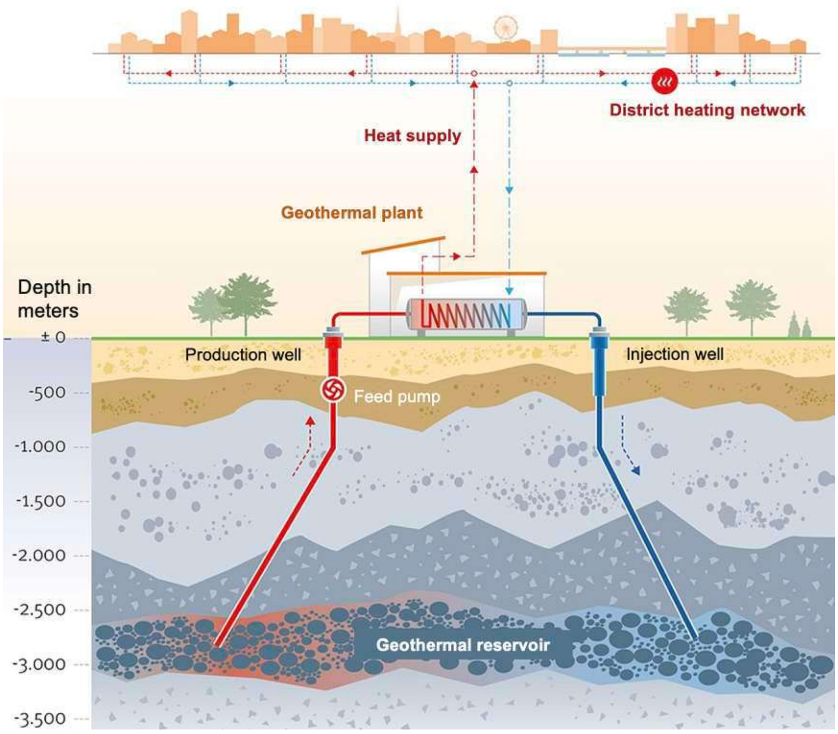

Figure 65: Principle of geothermal heat utilization in district heating systems [188]

As shown in Figure 65, the geothermal energy can be used to generate heat directly for a district heating network when the temperature of the geothermal reservoir is high enough. For cases where the temperature of the geothermal reservoir is too low, the geothermal energy can be used as a heat source for a heat pump. The heat pump raises the heat to a higher temperature level that is suitable for the district heating system. Another possibility is the use of the geothermal well for a combined generation of heat and electricity. [189]

[188] (Wien Energie, 2024) (own translation)
[189] Cf. (Good, et al., 2022 pp. 166-168), Cf. (Nussbaumer, et al., 2020 pp. 27-29), Cf. (Schmitz, et al., 2004 pp. 210-215)

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5.10.2 Systems for heat utilization from wastewater

The use of waste heat from wastewater is another possible heat source, as shown in Figure 66. The temperature of the wastewater is in general too low for the direct use in a district heating network, so that the available heat must be raised to a higher temperature by using a heat pump. [190]

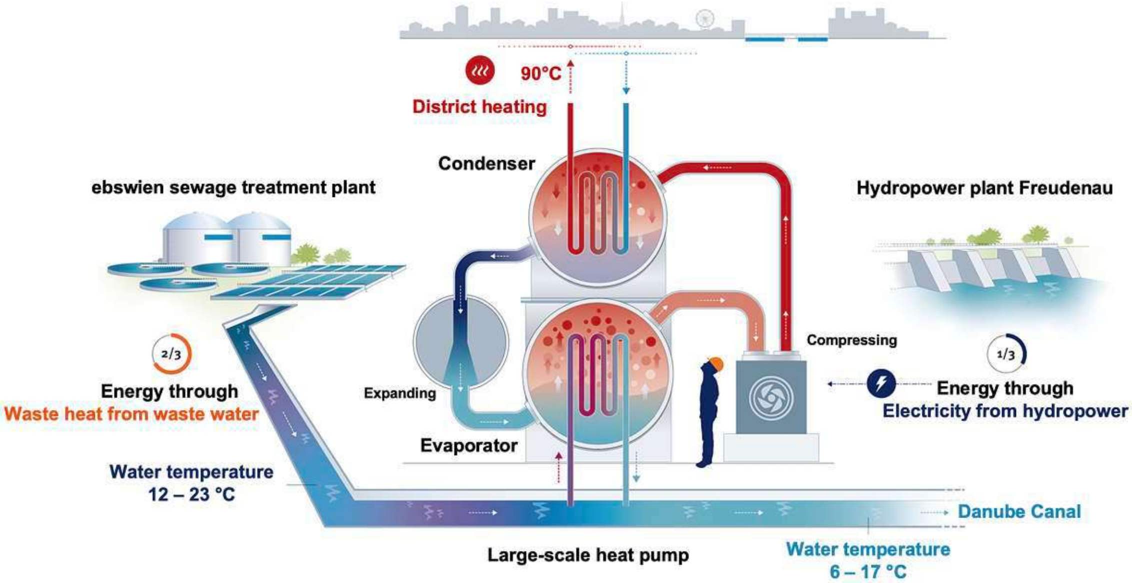

Figure 66: Principle of wastewater heat utilization in district heating systems [191]

5.10.3 Systems for heat utilization from other (waste) heat sources

There are also heat sources such as industrial waste heat, waste heat from refrigeration systems and heat from bodies of water (e.g. groundwater, seawater or river water), which can be used either directly or via heat pumps in district heating networks, depending on the temperature level of the individual heat source and the temperature level of the individual district heating network. [192]

[190] Cf. (Good, et al., 2022 pp. 166-168), Cf. (Nussbaumer, et al., 2020 pp. 27-29)
[191] (Wien Energie, 2022a) (own translation)
[192] Cf. (Good, et al., 2022 pp. 166-168), Cf. (Nussbaumer, et al., 2020 pp. 27-29)

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5.11 Fundamentals of investment calculation

The aim of the investment calculation is to determine the heat generation costs of the different renewable energy systems. For this reason, the following chapter will explain all the principles that have been used to carry out the investment calculations.

To understand the principle of investment calculation, it is also necessary to be familiar with the term "investment". For the term "investment", there are various definitions, whereas the following definitions demonstrate the principle of an investment clearly:

> *"The investment is characterized by the fact that a disbursement at time t = 0 (that would be the investment) causes various related subsequent payments of any size in the period t = 1 ... T."* [193]

> *"An investment is a cash flow that begins with a disbursement and is expected to result in inflows or a reduction in outflows in the future. "* [194]

The principle of an investment, which consists of a disbursement A_0 at the time t = 0 and the associated subsequent payments Z_1 to Z_T (that can be revenues or disbursements) of any amount, is shown in Figure 67.

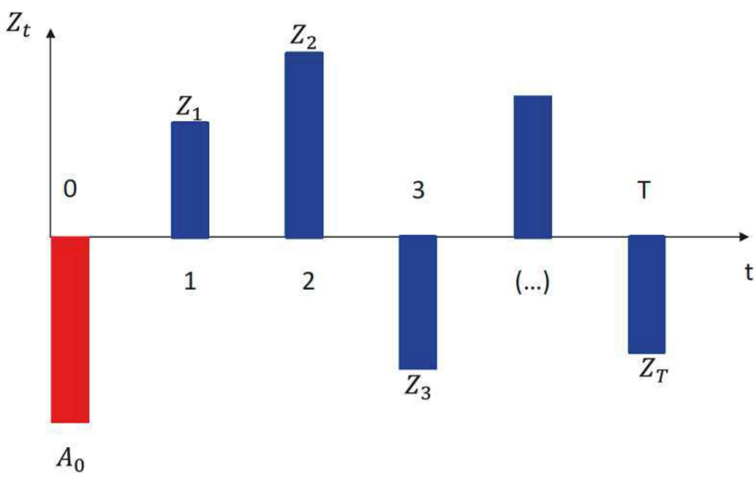

Figure 67: Principle of an investment [195]

[193] (Krimmling, 2018 p. 3) (own translation)
[194] (Müller, 2013 p. 403) (own translation)
[195] (Krimmling, 2018 p. 4)

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To assess investments in monetary terms, there are static and dynamic investment calculation methods. In static investment calculation methods, the time at which the payments occur is not or only insufficiently considered. In dynamic investment calculation methods, on the other hand, the time at which the payments occur is considered. The interest effect and therefore the actual value of the payments is taken into account by compounding and discounting the payments. For more complex investments that extend over a longer period, dynamic investment calculation methods should be used. [196]

The dynamic investment calculation methods include the net present value method, the dynamic amortization method, the internal interest flow method, the annuity method and the method of complete financial plans. [197] In this master's thesis, the net present value method in combination with the annuity method is used.

In the net present value method as well as in the annuity method, all payments (that can be revenues or disbursements) within the observation period are discounted to the time t_0, as shown in Figure 68.

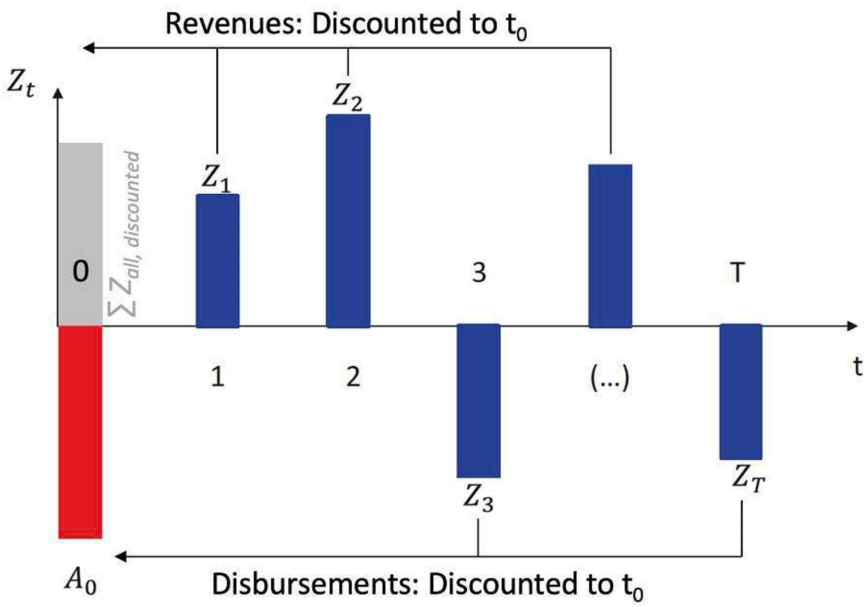

Figure 68: Principle of discounting of revenues and disbursements [198]

[196] Cf. (Notger, et al., 2017 p. 128), Cf. (Krimmling, 2018 p. 9), Cf. (Müller, 2013 p. 421)
[197] Cf. (Notger, et al., 2017 p. 129), Cf. (Krimmling, 2018 p. 10), Cf. (Müller, 2013 p. 408) Cf. (Hering, 2014 p. 2)
[198] (Krimmling, 2018 pp. 4, 12) (own adaptation), Cf. (Notger, et al., 2017 p. 133)

The discounting to time t_0 of a payment that occurred at time t can be carried out by using equation (5.19).

$$Z_{t,\mathrm{discounted}} = Z_t \cdot \frac{1}{(1+i)^t} \quad (5.19)$$ [199]

With the following meanings:

$Z_{t,\mathrm{discounted}}$	Net present value of the payment Z_t at time t_0 (currency unit)
Z_t	Payment Z_t at time t (currency unit)
i	Discount rate in %
t	Time t from t = 1 to T

The sum of all net present values of all payments according to equation (5.19) and the disbursement at time t_0 results in the net present value according to equation (5.20).

$$NPV = \sum Z_{\mathrm{all,discounted}} = -A_0 + \sum_{t=1}^{T} Z_t \cdot \frac{1}{(1+i)^t} \quad (5.20)$$ [200]

With the following meanings:

$NPV = \sum Z_{\mathrm{all,discounted}}$	Net present value of all payments at time t_0 (currency unit)
A_0	Disbursement at time t_0 (currency unit)
T	Observation period
Z_t	Payment Z_t at time t (currency unit)
i	Discount rate in %
t	Time t from t = 1 to T

[199] Cf. (Krimmling, 2018 p. 12), Cf. (Notger, et al., 2017 p. 133)
[200] Cf. (Krimmling, 2018 p. 12), Cf. (Notger, et al., 2017 p. 133)

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By distributing the net present value calculated according to equation (5.20) over the entire observation period, considering the discount rate, the annuity is obtained as shown in Figure 69. [201]

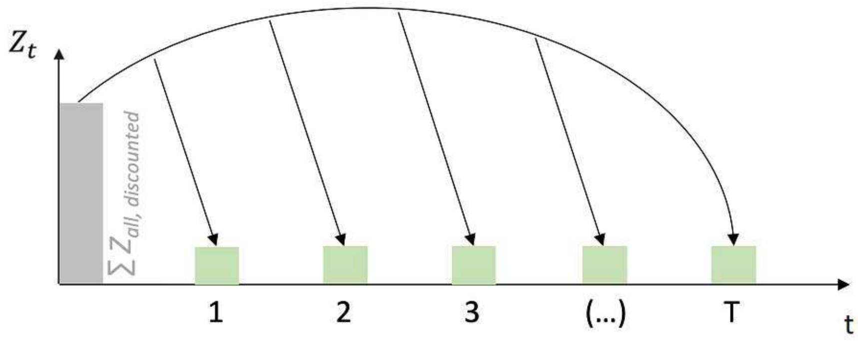

Figure 69: Principle of an annuity [202]

The annuity is calculated according to the equations (5.21), (5.22) and (5.23).

$$q = 1 + i \quad [203] \tag{5.21}$$

$$a = \frac{i}{1-(1+i)^{-T}} = \frac{q^T \cdot (q-1)}{q^T - 1} \quad [204] \tag{5.22}$$

$$A = a \cdot NPV \quad [205] \tag{5.23}$$

With the following meanings:

q	Discount rate factor in %
i	Discount rate in %
a	Annuity factor (unitless)
T	Observation period
A	Annuity (currency unit)
NPV	Net present value of all payments at time t_0 (currency unit)

[201] Cf. (Müller, 2013 p. 430), Cf. (Krimmling, 2018 pp. 13-14)
[202] (Krimmling, 2018 pp. 4, 14) (own adaptation)
[203] Cf. (Müller, 2013 p. 422)
[204] Cf. (Müller, 2013 pp. 423-424), Cf. (Krimmling, 2018 p. 14)
[205] Cf. (Müller, 2013 pp. 423-424), Cf. (Krimmling, 2018 p. 14)

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5.11.1 Division of the total heat provision costs

The costs that occur with the provision of heat to an end customer can be roughly divided into heat generation costs, heat storage costs and heat distribution costs. [206]

5.11.1.1 Heat generation costs

The heat generation costs (also called long-run generation costs in Chapter 5.11.2) are the costs that are associated with the generation of the heat. In addition to the investment costs, also the costs for the operation of the heat generation systems must be considered in the calculation. In the master's thesis, only these costs will be calculated, assuming that the balance limit between the heat generation costs and the other costs is the outlet of the heat generation system. The calculation of the heat storage costs and the heat distribution costs can also be carried out on the basis of the presented dynamic investment calculation methods. In some systems (such as the pyrolysis plants and the combined heat and power plants), also other products (e.g. electricity and biochar) are generated in addition to heat. The heat generation costs are calculated on the basis of the residual value method. All revenues from the products generated in addition to heat (e.g. electricity and biochar) are deducted from the costs. The remaining costs must be covered by the sale of heat. [207]

5.11.1.2 Heat storage costs

The heat storage costs are the costs that are associated with the long-term storage of heat (e.g. seasonal storage of heat). In addition to the costs for the investment and the operation of the heat storage system, also the costs associated with storage losses must be considered in the calculation.

5.11.1.3 Heat distribution costs

The heat distribution costs are the costs that are associated with the investment costs for the erection and the operation of the district heating network as well as the house substations. Due to the balance limit that was chosen in the master's thesis, all heat losses of the district heating network must be considered in the heat distribution costs. [208]

[206] Cf. (Konstantin, et al., 2022 pp. 136-143)
[207] Cf. (Konstantin, et al., 2022 pp. 150-156)
[208] Cf. (Konstantin, et al., 2022 pp. 142-143)

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5.11.2 Fundamentals of long-run generation costs

Based on the approaches that have already been presented, the following section will describe the calculation of the long-run generation costs. According to (VDI, 2012), costs can be divided into four categories. [209] Table 13 shows the cost categories and cost types according to (VDI, 2012).

Table 13: Cost groups and cost types [210]

Capital-related costs	Demand-related costs	Operation-related costs	Other costs
Technical installations, e.g.: • heat generator • radiators • ventilators • drive motors etc. Structural installations, e.g.: • equipment rooms • smokestacks • noise protection • thermal insulation • connection costs	Energy costs • basic price • working price Costs for auxiliary energy Costs for operating material • lubricants • additives • chemicals etc.	Operating Cleaning Maintaining Inspecting Repairing	Planning costs Insurance Taxes General levies Administration costs Profit and loss Dismantling and disposal costs

The net present value and the annuity of the capital-related costs can be calculated with the equations (5.24) and equation (5.25).

$$NPV_{N,K} = \left(A_0 + \sum_{m=1}^{n} A_m - R_W \right) \tag{5.24}$$

$$A_{N,K} = \left(A_0 + \sum_{m=1}^{n} A_m - R_W \right) \cdot a \tag{5.25}$$

[211]

With the following meanings:

$NPV_{N,K}$ Net present value of the capital-related costs (currency unit)

[209] Cf. (VDI, 2012 pp. 21, 29)
[210] (VDI, 2012 p. 29)
[211] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

A_0	Initial investment (currency unit)
A_m	Net present value of the replacement m (currency unit)
n	Total number of replacements in the observation period (unitless)
R_W	Net present value of the residual value (currency unit)
$A_{N,K}$	Annuity of the capital-related costs (currency unit)
a	Annuity factor (unitless)

The net present value of the replacements is calculated using equation (5.26), equation (5.27) and equation (5.28).

$$q = 1 + i \quad (5.26)$$

[212]

$$r = 1 + j \quad (5.27)$$

[213]

$$A_m = A_0 \cdot \frac{r^{m \cdot T_N}}{q^{m \cdot TN}} \quad (5.28)$$

[214]

With the following meanings:

q	Discount rate factor in %
i	Discount rate in %
r	Price change factor in %
j	Price change in %
A_m	Net present value of the replacement m (currency unit)
A_0	Initial investment (currency unit)
m	Number of replacement in the observation period (unitless)
T_N	Service life of the component being replaced

[212] Cf. (Müller, 2013 p. 422)
[213] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[214] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

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The net present value of the residual value is calculated using the following equation (5.29).

$$R_W = A_0 \cdot r^{n \cdot T_N} \cdot \frac{(n+1) \cdot T_N - T}{T_N} \cdot \frac{1}{q^T} \quad (5.29)$$ [215]

With the following meanings:

R_W	Net present value of the residual value (currency unit)
A_0	Initial investment (currency unit)
r	Price change factor in %
n	Total number of replacements in the observation period (unitless)
T_N	Service life of the component being replaced
T	Observation period
q	Discount rate factor in %

The annuity factor is calculated according to equation (5.30).

$$a = \frac{i}{1-(1+i)^{-T}} = \frac{q^T \cdot (q-1)}{q^T - 1} = \frac{q-1}{1-q^T} \quad (5.30)$$ [216]

With the following meanings:

a	Annuity factor (unitless)
i	Discount rate in %
T	Observation period
q	Discount rate factor in %

The price-dynamic net present value factor is calculated according to equation (5.31) and equation (5.32).

[215] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[216] Cf. (Müller, 2013 pp. 423-424), Cf. (Krimmling, 2018 p. 14), (VDI, 2012 pp. 16-20)

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$$b = \frac{1 - \left(\frac{r}{q}\right)^T}{q - r} \quad \text{for } r \neq q \quad {}^{217} \tag{5.31}$$

$$b = \frac{T}{q} \quad \text{for } r = q \quad {}^{218} \tag{5.32}$$

With the following meanings:

b	Price-dynamic net present value factor (unitless)
r	Price change factor in %
q	Discount rate factor in %
T	Observation period

The net present value and the annuity of the demand-related costs can be calculated with the equations (5.33) and (5.34).

$$NPV_{N,V} = A_{V1} \cdot b \tag{5.33}$$

$$A_{N,V} = A_{V1} \cdot a \cdot b \quad {}^{219} \tag{5.34}$$

With the following meanings:

$NPV_{N,V}$	Net present value of the demand-related costs (currency unit)
A_{V1}	Demand-related costs in the first year (currency unit)
b	Price-dynamic net present value factor (unitless)
$A_{N,V}$	Annuity of the demand-related costs (currency unit)
a	Annuity factor (unitless)

The demand-related costs in the first year can be calculated using equation (5.35), whereby adjustments must be made depending on the application.

[217] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[218] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[219] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

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$$\begin{aligned} A_{V1} = {} & Q_{3,Heat} \cdot Price_{Heat} \\ & + Q_{3,Fuel} \cdot Price_{Fuel} \\ & + Q_{3,Cold} \cdot Price_{Cold} \\ & + Q_{3,Electricity} \cdot Price_{Electricity} \\ & + Q_{3,Water} \cdot Price_{Water} \end{aligned} \quad [220] \tag{5.35}$$

With the following meanings:

A_{V1}	Demand-related costs in the first year (currency unit)
$Q_{3,Heat}$	Energy effort for heating (quantity unit)
$Price_{Heat}$	Price for heating (currency unit per quantity unit)
$Q_{3,Fuel}$	Fuel input (quantity unit)
$Price_{Fuel}$	Price for fuel (currency unit per quantity unit)
$Q_{3,Cold}$	Energy effort for cooling (quantity unit)
$Price_{Cold}$	Price for cooling (currency unit per quantity unit)
$Q_{3,Electricity}$	Electricity input (quantity unit)
$Price_{Electricity}$	Price for electricity (currency unit per quantity unit)
$Q_{3,Water}$	Water input (quantity unit)
$Price_{Water}$	Price for water (currency unit per quantity unit)

The net present value and the annuity of the operation-related costs can be calculated with the equations (5.36), (5.37) and (5.38).

$$NPV_{N,B} = A_{B1} \cdot b_B + A_{IN} \cdot b_{IN} \tag{5.36}$$

$$A_{N,B} = A_{B1} \cdot a \cdot b_B + A_{IN} \cdot a \cdot b_{IN} \quad [221] \tag{5.37}$$

$$A_{IN} = A_0 \cdot \left(f_{Inst} + f_{W+Insp}\right) \quad [222] \tag{5.38}$$

[220] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[221] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[222] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

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With the following meanings:

$NPV_{N,B}$	Net present value of the operation-related costs (currency unit)
A_{B1}	Operation-related costs in the first year for actual operation (currency unit)
b_B	Price-dynamic net present value factor for operation-related costs (unitless)
A_{IN}	Operation-related costs in the first year for maintenance (currency unit)
b_{IN}	Price-dynamic net present value factor for maintenance (unitless)
$A_{N,B}$	Annuity of the operation-related costs (currency unit)
a	Annuity factor (unitless)
A_0	Initial investment (currency unit)
f_{Inst}	Factor for repair effort (unitless)
f_{W+Insp}	Factor for servicing and inspection effort (unitless)

The net present value and the annuity of the other costs can be calculated with the equations (5.39) and (5.40).

$$NPV_{N,S} = A_{S1} \cdot b_S \tag{5.39}$$

$$A_{N,S} = A_{S1} \cdot a \cdot b_S \quad [223] \tag{5.40}$$

With the following meanings:

$NPV_{N,S}$	Net present value of the other costs (currency unit)
A_{S1}	Other costs in the first year (currency unit)
b_S	Price-dynamic net present value factor for other costs (unitless)
$A_{N,S}$	Annuity of the other costs (currency unit)
a	Annuity factor (unitless)

[223] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

The net present value and the annuity of the revenues can be calculated with the equations (5.41) and (5.42).

$$NPV_{N,E} = E_1 \cdot b_E \tag{5.41}$$

$$A_{N,E} = E_1 \cdot a \cdot b_E \quad ^{224} \tag{5.42}$$

With the following meanings:

$NPV_{N,E}$	Net present value of the revenues (currency unit)
E_1	Revenues in the first year (currency unit)
b_S	Price-dynamic net present value factor for the revenues (unitless)
$A_{N,E}$	Annuity of the revenues (currency unit)
a	Annuity factor (unitless)

The net present value and the annuity of the investment can be calculated with the equations (5.43) and (5.44).

$$NPV_N = NPV_{N,E} - \left(NPV_{N,K} + NPV_{N,V} + NPV_{N,B} + NPV_{N,S}\right) \tag{5.43}$$

$$A_N = A_{N,E} - \left(A_{N,K} + A_{N,V} + A_{N,B} + A_{N,S}\right) \quad ^{225} \tag{5.44}$$

With the following meanings:

NPV_N	Net present value of the investment (currency unit)
$NPV_{N,E}$	Net present value of the revenues (currency unit)
$NPV_{N,K}$	Net present value of the capital-related costs (currency unit)
$NPV_{N,V}$	Net present value of the demand-related costs (currency unit)
$NPV_{N,B}$	Net present value of the operation-related costs (currency unit)
$NPV_{N,S}$	Net present value of the other costs (currency unit)

[224] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)
[225] (Krimmling, 2018 pp. 13-16), (VDI, 2012 pp. 16-20)

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A_N	Annuity of the investment (currency unit)
$A_{N,E}$	Annuity of the revenues (currency unit)
$A_{N,K}$	Annuity of the capital-related costs (currency unit)
$A_{N,V}$	Annuity of the demand-related costs (currency unit)
$A_{N,B}$	Annuity of the operation-related costs (currency unit)
$A_{N,S}$	Annuity of the other costs (currency unit)

The annuity of the total annual payments results from the difference between the annuity of the revenues and the sum of the capital-related, demand-related, operation-related and other annuities and can finally be used for the evaluation of the investment. In the case of heating systems, the investment does not generate any revenues. The annuity for heating systems is therefore a negative value. The most favorable system and therefore the economically preferable system is the system with the lowest annuity, as this system causes the least costs. [226] As heating systems only generate expenditures, the absolute amounts of all negative annuities were used to simplify the comparison.

The long-run generation costs can be calculated with equation (5.45).

$$\mathrm{LRGC} = \frac{A_N}{Q_{total}} \tag{5.45}$$

With the following meanings:

LRGC	Long-run generation costs (currency unit per quantity unit)
A_N	Annuity of the investment (currency unit)
Q_{total}	Total annual energy generation of the system (quantity unit)

[226] (VDI, 2012 p. 20)

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5.11.3 Sensitivity Analysis

The investment calculation is influenced by numerous input parameters. Although the input parameters are carefully defined, there is still an uncertainty in terms of whether and how the input parameters will change over time. For this reason, it is recommended to vary individual input parameters systematically to determine their influence (sensitivity) on the result. The selection of the input parameters that should be varied and the variation of these input parameters is called sensitivity analysis. [227]

During the sensitivity analysis, only one of the input parameters that should be varied is changed, while the other input parameters that should be varied remain the same. The result for each input parameter that should be varied is a graph whose gradient is a measure of the sensitivity: The steeper the gradient, the more the result of the calculation changes by varying this input parameter. [228]

Figure 70 shows an example of a sensitivity analysis with two input parameters that should be varied.

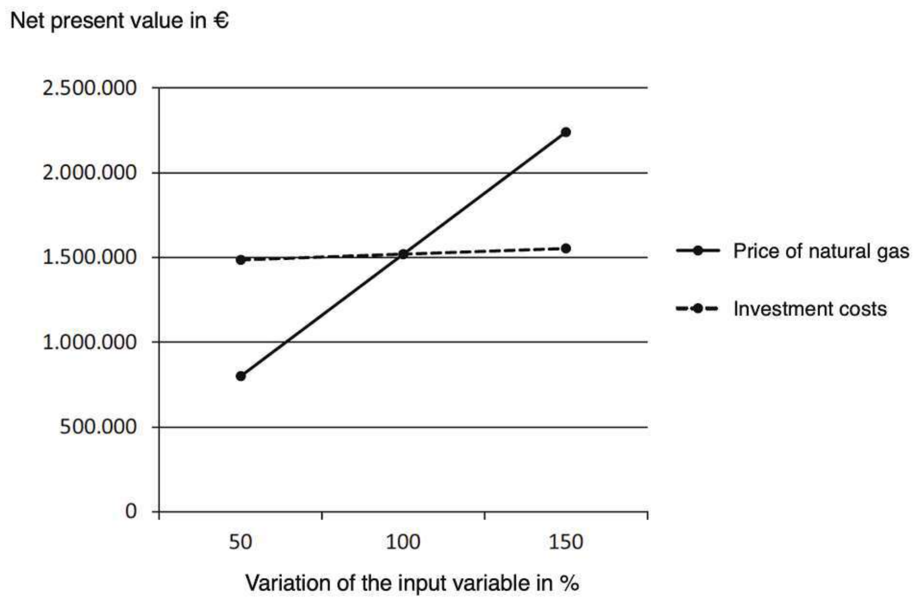

Figure 70: Example of a sensitivity analysis [229]

[227] Cf. (Geilhausen, et al., 2015 pp. 275-276), Cf. (Konstantin, et al., 2022 p. 48), Cf. (Daum, et al., 2010 p. 265)
[228] Cf. (Geilhausen, et al., 2015 pp. 275-276), Cf. (Konstantin, et al., 2022 p. 48), Cf. (Daum, et al., 2010 p. 265)
[229] (Geilhausen, et al., 2015 p. 276)

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5.11.4 Input parameters applicable to multiple systems

To be able to compare all systems in the master's thesis with each other, in the following section the parameters that are valid for all investment calculations are explained.

5.11.4.1 Investment costs

The investment costs for the respective system can be found in the chapter on the respective system. Furthermore, the investment costs for the erection of the building and the required infrastructure were estimated based on personal experience.

5.11.4.2 Costs for energy carriers

Figure 71 shows the costs for the energy carriers heating oil, natural gas, pellets, log wood and wood chips from January 2008 to January 2024 in relation to the lower calorific value. For the investment calculation, the energy carrier costs from January 2024 were used. For all systems that use biomass in form of wood chips as an energy source, an energy price of 40 euros per megawatt hour was assumed. The electricity price (energy including fees and charges) for the auxiliary devices was defined to be 200 euros per megawatt hour.

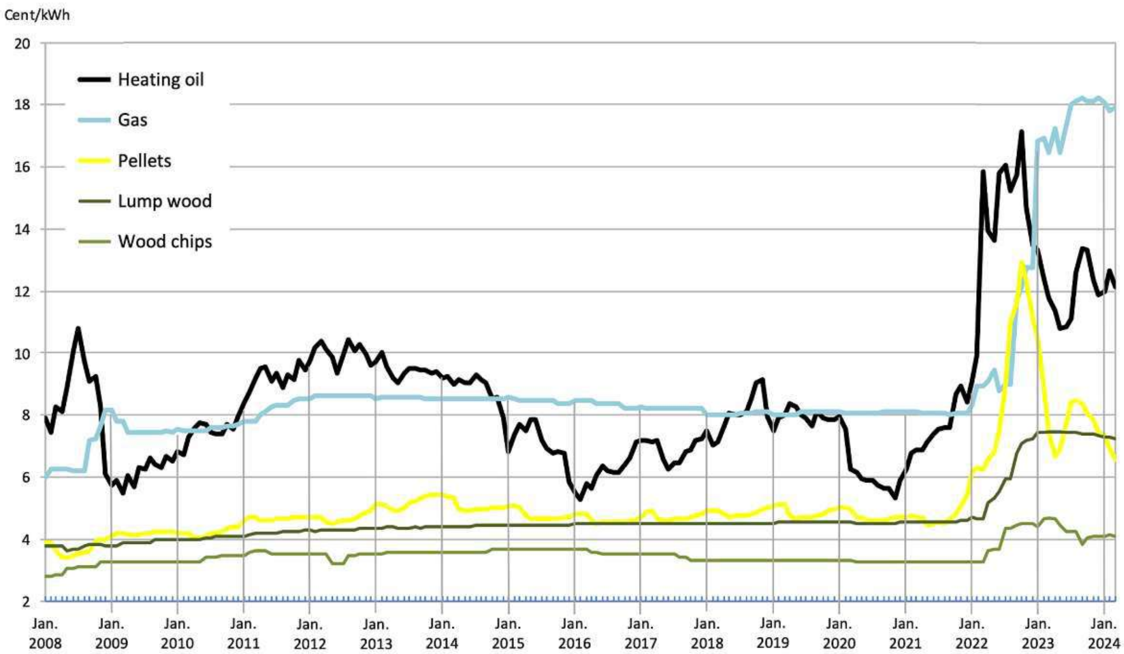

Figure 71: Prices of energy sources in relation to lower calorific value [230]

[230] Cf. (ÖBV, 2024)

5.11.4.3 Costs for electricity connection and electricity grid

For the operation of the CHP systems and the electric boiler systems, an electricity connection is required. The network level is defined by the ownership boundary and the required capacity. The ownership boundaries are defined according to § 4 (7) to § 4 (11) of the System Usage Fee Regulation (Systemnutzungsentgelte-Verordnung 2018 – SNE-V 2018 [231]). The capacities are defined according to § 55 (7) of the Electricity Industry and Organization Law (Elektrizitätswirtschafts- und -organisationsgesetz 2010 – ElWOG 2010 [232]). Table 14 shows the different grid levels with their characteristic values.

Table 14: Different network levels, the boundaries of ownership and capacities [231] [232]

Network level	Boundary of ownership is …	Min. capacity [kW]	Max. capacity [kW]
7	… in the low-voltage grid of the grid operator (transformer owned by grid operator)	0	100
6	… on the customer-side clamps of the transformer substation (transformer owned by grid operator)	100	400
5	… in the medium-voltage grid of the grid operator (transformer owned by grid user)	400	5.000
4	… on the customer-side clamps of the transformer substation (transformer owned by grid operator)	5.000	200.000
3	… in the high-voltage grid of the grid operator (transformer owned by grid user)	5.000	200.000
2	-	200.000	∞
1	-	200.000	∞

[231] Verordnung der Regulierungskommission der E-Control, mit der die Entgelte für die Systemnutzung bestimmt werden (Systemnutzungsentgelte-Verordnung 2018 – SNE-V 2018) BGBl. II Nr. 398/2017 idF. BGBl. II Nr. 395/2023

[232] Bundesgesetz, mit dem die Organisation auf dem Gebiet der Elektrizitätswirtschaft neu geregelt wird (Elektrizitätswirtschafts- und -organisationsgesetz 2010 – ElWOG 2010) BGBl. I Nr. 110/2010 idF. BGBl. I Nr. 145/2023

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The network access fees for consumption systems must be charged on a time and material basis according to § 54 (1) and § 54 (2) of the Electricity Industry and Organization Law (Elektrizitätswirtschafts- und -organisationsgesetz 2010 – ElWOG 2010 [232]), whereby the network operator has the option of charging a flat rate for comparable network users of a network level. As a result, the network access fees charged by the grid operators can vary according to § 7 (1) of the System Usage Fee Regulation (Systemnutzungsentgelte-Verordnung 2018 – SNE-V 2018 [231]). Table 15 shows the network access fees for Linz, the rest of Upper Austria and an average of the network access fees of Austria.

Table 15: Network access fees for consumption systems for different regions [231]

Network level	Network access fee for Linz [EUR / kW]	Network access fee for Upper Austria [EUR / kW]	Network access fee (Austrian average) [EUR / kW]
7	226,63	208,00	219,55
6	171,01	150,00	151,26
5	113,32	97,50	100,32
4	49,45	45,67	55,03
3	-	11,80	16,95

For the connection of generation systems based on renewable energy sources, flat-rate network access fees have to be charged for the network levels 3 to 7 according to § 54 (3) and § 54 (4) of the Electricity Industry and Organization Law (Elektrizitätswirtschafts- und -organisationsgesetz 2010 – ElWOG 2010 [232]) as shown in Table 16:

Table 16: Network access fees for generation systems [232]

Capacity [kW]	0 – 20	21 – 250	251 – 1.000	1.001 – 20.000	20.001 –
Network access fee [EUR / kW]	10	15	35	50	70

The network usage fees and the network loss fees are defined by region in accordance with § 5 (1) 1 to § 5 (1) 7 and § 6 of the System Usage Fee Regulation (Systemnutzungsentgelte-Verordnung 2018 – SNE-V 2018 [231]), which can result in different prices for the different network providers.

For reasons of simplicity, the network usage fees and the network loss fees are not shown in detail. Table 17 shows the average amount of fees and charges that must be paid in addition to the energy price.

Table 17: Average amount of fees and charges besides the energy price [231]

Network level	Flat rate [EUR / a]	Capacity price [EUR / kW]	Working price [Cent / kWh]
7 [233]	-	-	4,8276
7 [234]	36,00	-	7,3826
7 [235]	-	64,87	4,7838
6	-	60,24	3,2272
5	-	52,53	2,0169
4	-	41,02	1,1565
3	-	32,81	0,7665

For systems that offer reserve capacity, a capacity price of 1,00 EUR / kW and a working price of 0,085 Cent / kWh can be assumed as the network usage fee for all grid levels in accordance with § 5 (1) 9 of the System Usage Fee Regulation (Systemnutzungsentgelte-Verordnung 2018 – SNE-V 2018 [231]).

[233] interruptible
[234] unmeasured capacity
[235] measured capacity

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5.11.4.4 Revenue for the electricity fed into the grid

For the investment calculations, it was assumed that the electricity generated by the CHP plants is remunerated according to a market premium model as shown in Figure 72. The advantage for a plant operator is that the generated electricity can be sold at the applicable value for a long-term period. The applicable value consists of the reference market price and the market premium.

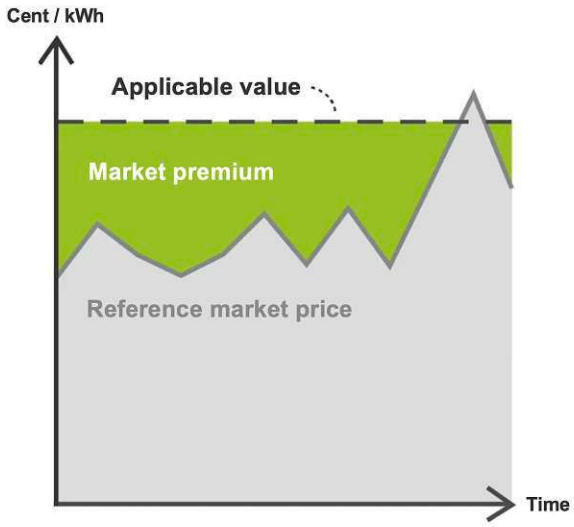

Figure 72: Market premium model [236]

This market premium model is defined according to of the Renewables Expansion Law (Erneuerbaren-Ausbau-Gesetz – EAG [237]) and the Market Premium Regulation to the Renewables Expansion Law (EAG-Marktprämienverordnung – EAG-MPV [238]).

For biomass plants, there are two different market premium models. The administrative market premium model is applicable for biomass plants with an electrical capacity of less than 500 kW. In the case of the administrative market premium model, the applicable value is defined in a regulation. [239]

[236] (Next Kraftwerke, 2024b) (own translation)
[237] Bundesgesetz über den Ausbau von Energie aus erneuerbaren Quellen (Erneuerbaren-Ausbau-Gesetz – EAG) BGBl. I Nr. 150/2021 idF. BGBl. I Nr. 27/2024
[238] Verordnung der Bundesministerin für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie zur Gewährung von Marktprämien nach dem Erneuerbaren-Ausbau-Gesetz (EAG-Marktprämienverordnung – EAG-MPV) BGBl. II Nr. 369/2022 idF. BGBl. II Nr. 77/2024
[239] Cf. (Next Kraftwerke, 2024b), Cf. (IG Holzkraft, 2024)

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For biomass plants with an electrical capacity of more than 500 kW, the market premium model by tender is applicable. In the case of the market premium model by tender, the applicable value is determined through a tender process. [240]

According to § 10 (1) 1 lit. f of the Market Premium Regulation to the Renewables Expansion Law (EAG-Marktprämienverordnung – EAG-MPV [238]) the applicable values for new plants that exclusively use biomass and fulfil the requirements of the administrative market premium model (< 500 kW) are shown Table 18.

Table 18: Applicable values for new plants that exclusively use biomass [231]

Electrical capacity [kW]	Applicable value [Cent / kWh]
< 50	25,75
> 50	24,71

For plants that fulfil the requirements of the market premium model by tender (> 500 kW), a maximum price of 19,32 Cents / kWh applies for newly constructed plants in accordance with § 4 (1) 2 of the Market Premium Regulation to the Renewables Expansion Law (EAG-Marktprämienverordnung – EAG-MPV [238]), up to which bids will be considered.

5.11.4.5 Interest rates, price escalation rates and consumer price index

The interest rates, the price escalation rates, and the consumer price index are generally defined on the basis of economic analyses. In this master's thesis, the interest rates were assumed to be 7 percent per annum. To simplify the investment calculations, the price escalation rates, and the consumer price index are set to 2 percent per year.

[240] Cf. (Next Kraftwerke, 2024b), Cf. (IG Holzkraft, 2024)

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5.11.4.6 Investment horizon

All investment calculations are carried out with an observation period of 20 years. The lifetime of the systems is defined to be 20 years and the lifetime of the buildings is defined to be 50 years.

5.11.4.7 Subsidies

For all investment calculations, no subsidies were taken into account in connection with the investment costs.

5.11.4.8 Biochar production and biochar sales

For investment calculations of systems in which biochar is produced, a biochar sales price of 400 euros per ton and a biochar conversion factor of 7,7 megawatt hours per ton were assumed. The above-mentioned conversion factor is equal to the calorific value of the biochar. [241]

5.11.4.9 Operation of the systems

The operation of each system is carried out by operating personnel. The expenses for the operation of a respective system can be found in the chapter on the respective system. The salary of the operating personnel is assumed to be 100 euros per hour.

[241] Cf. (Käppler, 2017 pp. 45-46), Cf. (Pyreg, 2023a p. 2), Cf. (Reichardt, 2023), Cf. (Pyreg, 2023b pp. 2-4)

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6 Results

In this chapter, the results of the technologies mentioned in chapter 5 are discussed. To ensure that the scope of the chapter remains manageable, only the results for one plant size are presented. Further results for the other plant sizes can be found in the appendix.

6.1 Analysis of the characteristic parameters of existing networks

The aim of this chapter is to analyze selected operating parameters from the district heating networks of the biomass heating plants listed in Table 2, whereby only district heating networks were analyzed for which 15-minute values and 1-hour values were available. Besides the output of the district heating network, the supply flow temperature and the return flow temperature were analyzed using the recorded 1-hour values. Figure 73 shows the operating parameters (output, supply flow temperature, return flow temperature) of the district heating network in Asten for the year 2023 in chronological order. In addition to the operating parameters, the degree of data integrity is mentioned, as the operating parameters are not fully available.

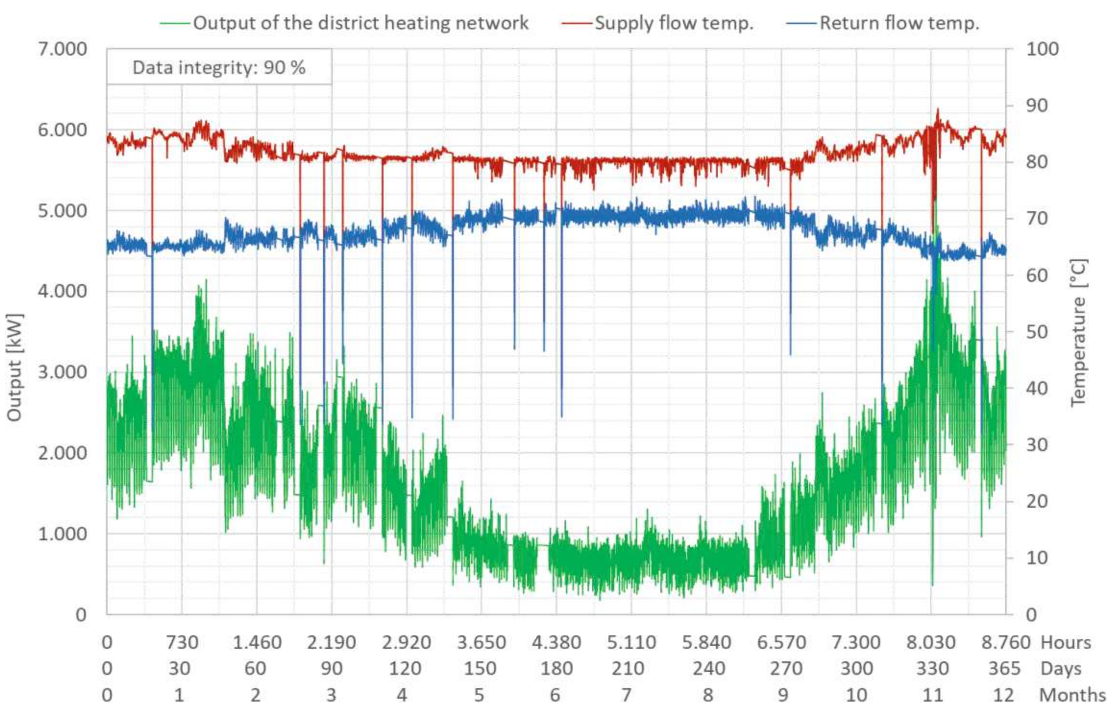

Figure 73: Unsorted output and temperatures of the DHN in Asten [242]

[242] For the year 2023

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If the chronological outputs of the district heating network as shown in Figure 73 are sorted by their size, the annual duration curve is obtained, as shown in Figure 74. Figure 74 shows the annual duration curve of the district heating network in Asten. In addition to the output that is required in the district heating network at a certain point in time, the supply flow temperature and the return flow temperature that occur at that time are also shown.

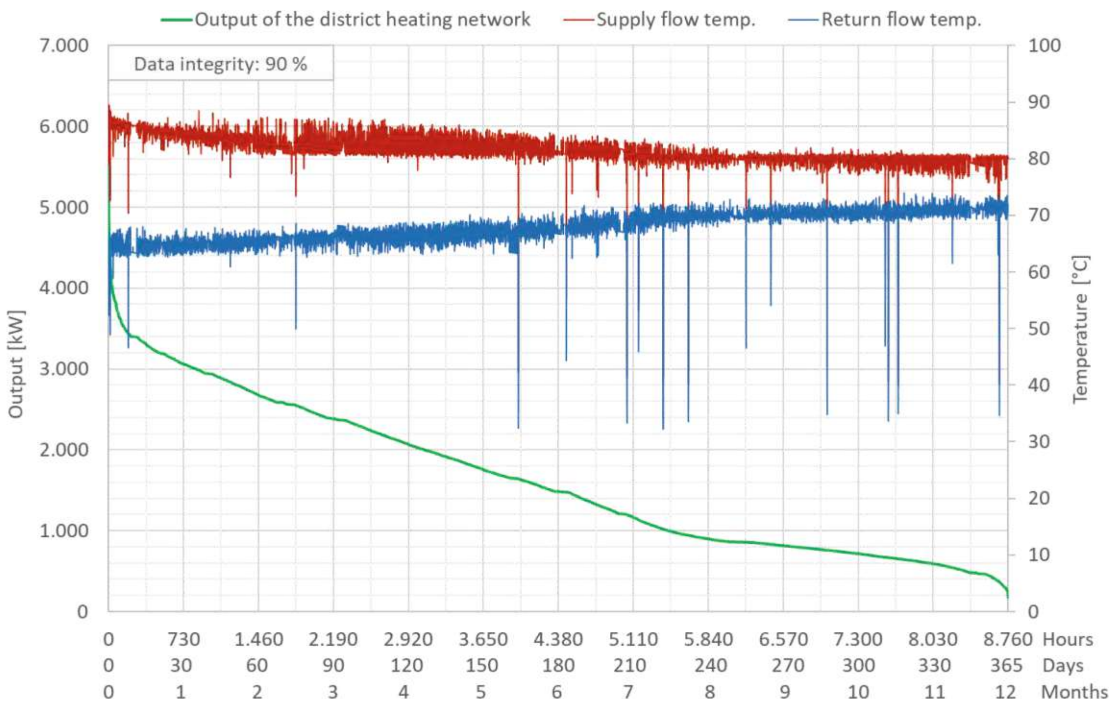

Figure 74: Sorted output and temperatures of the DHN in Asten [243]

The area below the annual duration curve represents the amount of heat supplied into the district heating network. This area can be subdivided horizontally as shown in Figure 75 or vertically as shown in Figure 76. The size of the partial areas that are limited by a dashed line in the case of a partial area at the edge and otherwise by two dashed lines is equal to 10 percent of the total area and is therefore also equal to 10 percent of the heat supplied into the district heating network. If a partial area is limited by one dashed and one dotted line or in the case of a partial area at the edge only by one dotted line, the partial area is equal to 5 percent of the total area and is therefore also equal to 5 percent of the heat supplied into the district heating network.

[243] For the year 2023

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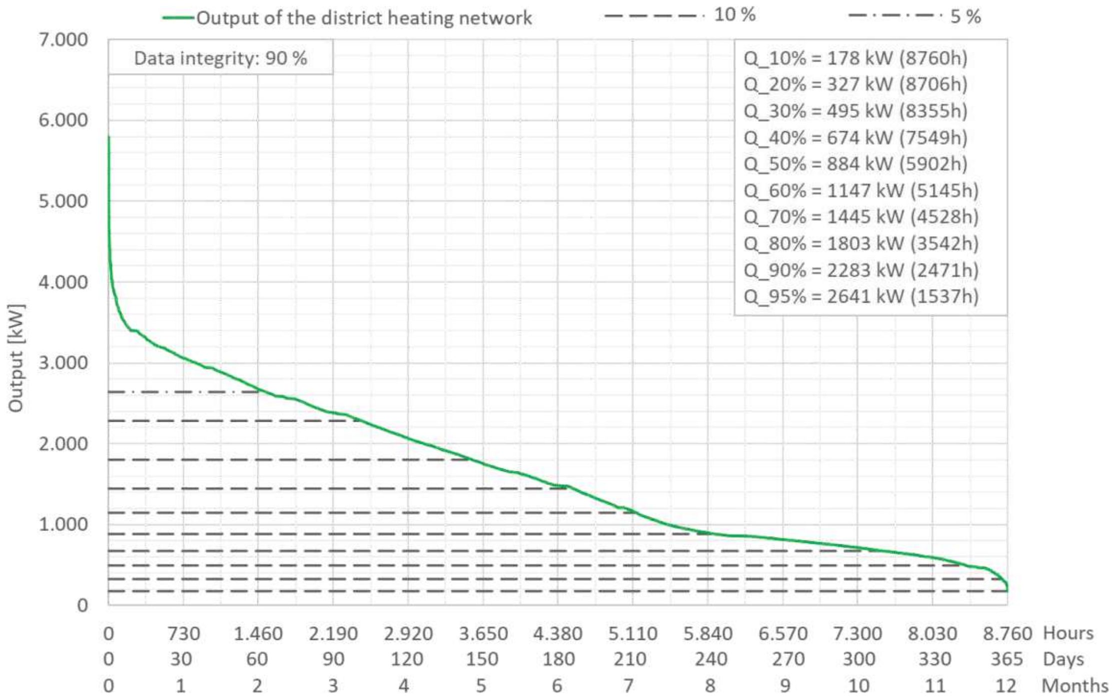

Figure 75: Duration curve with horizontal subdivisions of the DHN in Asten [244]

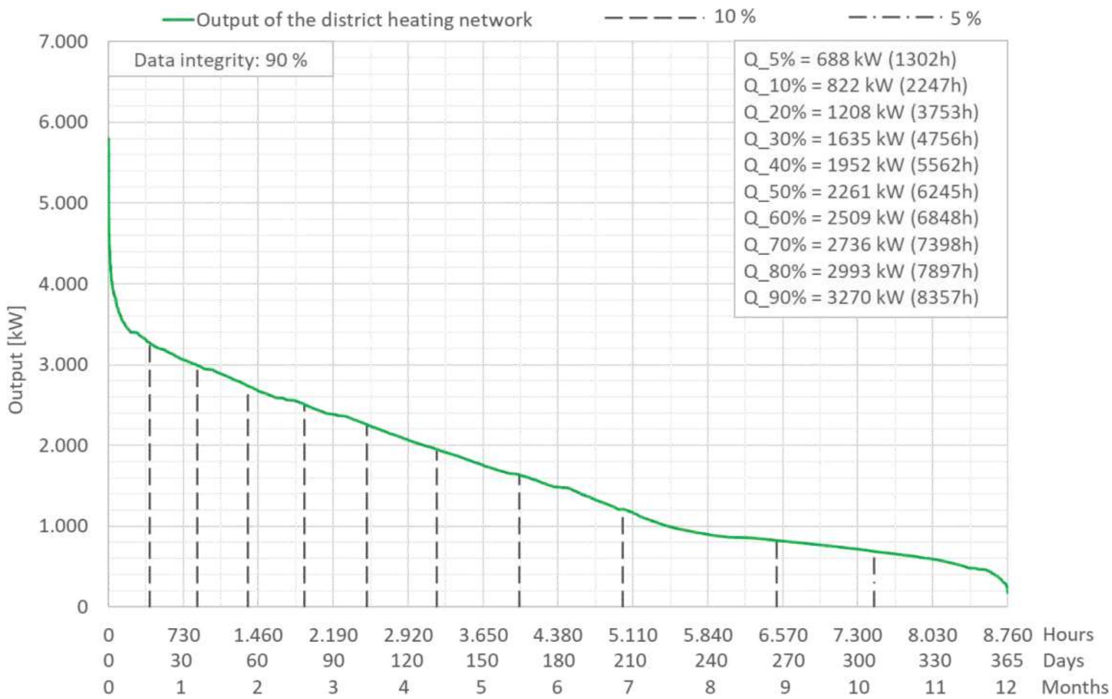

Figure 76: Duration curve with vertical subdivisions of the DHN in Asten [245]

[244] For the year 2023
[245] For the year 2023

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This horizontal and vertical subdivision, as shown in Figure 75 and Figure 76 , provides information on the correlation between output, heat quantity and duration and can be used to design and analyze systems. Figure 75 and Figure 76 shows the horizontal and vertical subdivision of the district heating network in Asten.

Besides the horizontal and vertical subdivision, also a seasonal group allocation is possible, which is based on Figure 58 and Figure 59. A seasonal group allocation makes it clear in which period the outputs of the annual duration curve occur and which heat quantities must be fed into the district heating network in which period. Figure 77 shows a dual-group allocation in accordance with Figure 59. Group 1 includes the months of January, February, March, October, November and December. On the other hand, group 2 consists of the months of April, May, June, July, August and September. Figure 78 shows a triple-group allocation in accordance with Figure 58. Group 1 includes the months of January, February, November and December. Group 2 is made up of the months of March, April, September and October. Group 3, on the other hand, comprises the months of May, June, July and August.

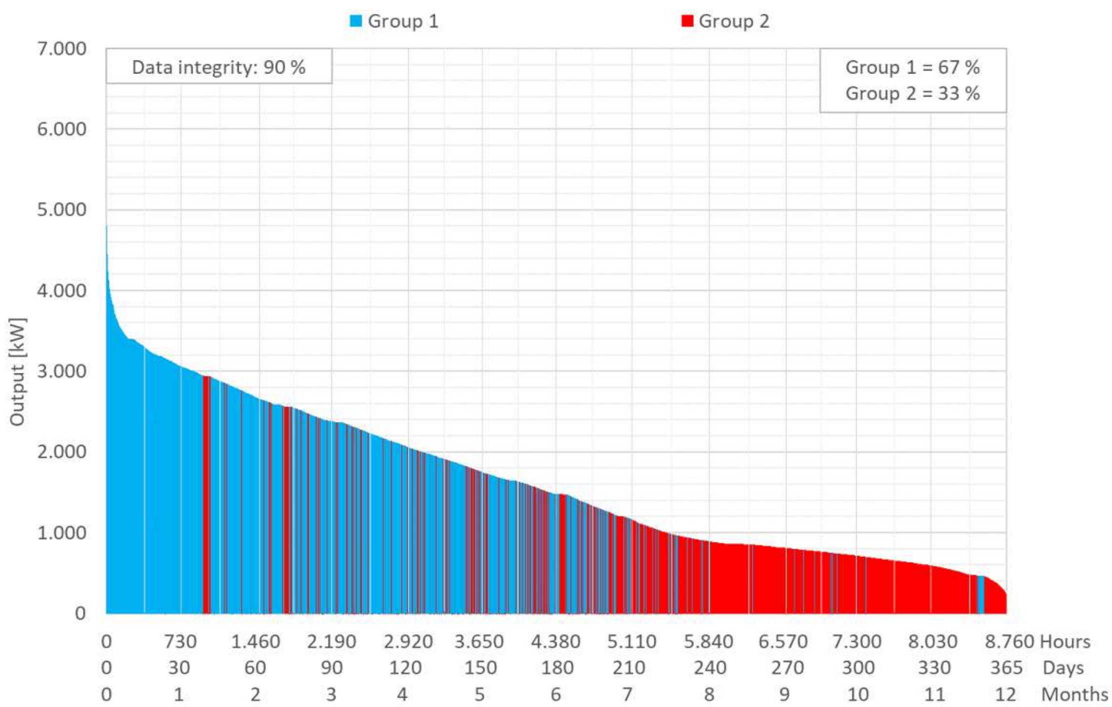

Figure 77: Duration curve with dual-group allocation of the DHN in Asten [246]

[246] For the year 2023

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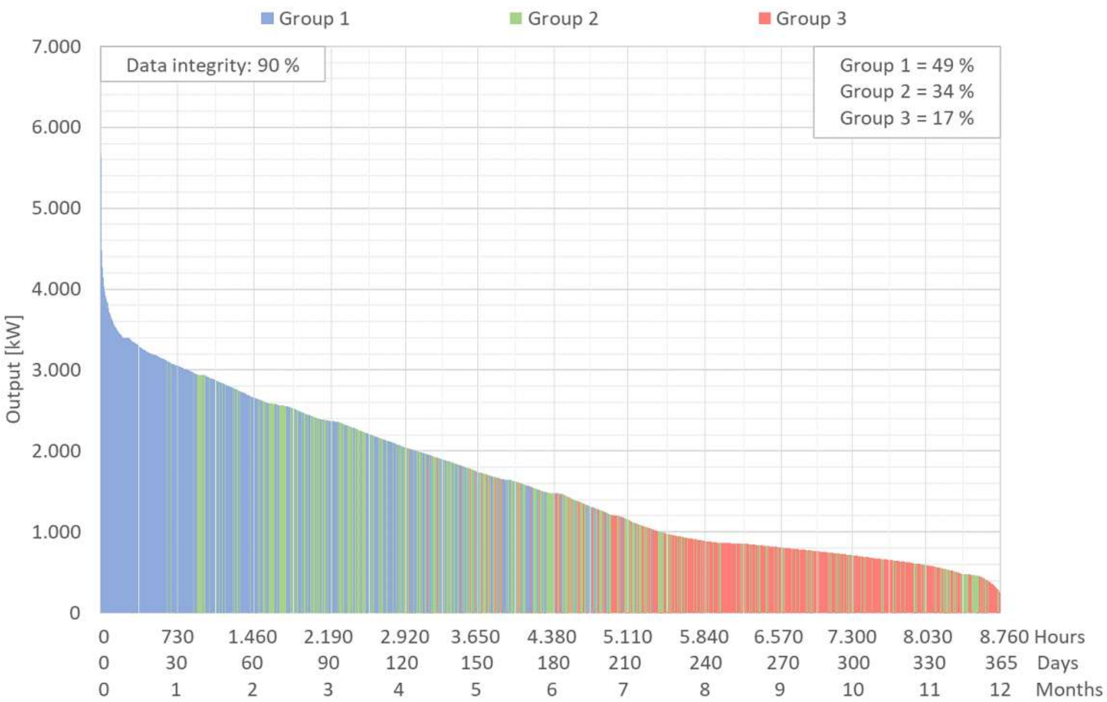

Figure 78: Duration curve with triple-group allocation of the DHN in Asten [247]

Figure 77 and Figure 78 shows a dual-group allocation and triple-group allocation of the district heating network in Asten. The diagrams for the other district heating networks can be found in the appendix.

6.2 Biomass pyrolysis systems

In this chapter, the application of a biomass pyrolysis system in the district heating network in Asten will be examined from an economic point of view.

6.2.1 Biomass pyrolysis plant – PYREG

The plant under consideration converts biomass into heat and biochar. Figure 79 shows a possible operation of the biomass pyrolysis plant PX1500 from the manufacturer PYREG, under consideration of the nominal heat output and the partial load capability of the plant listed in Table 4. In this context, it should be mentioned that the heat storage capacity of the buffer storage tank was neglected in this exemplary operation scenario.

[247] For the year 2023

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Furthermore, it should be pointed out that it was assumed that the biomass pyrolysis plant is used to cover the base load of the heat demand, resulting in 8.480 full load hours for the plant.

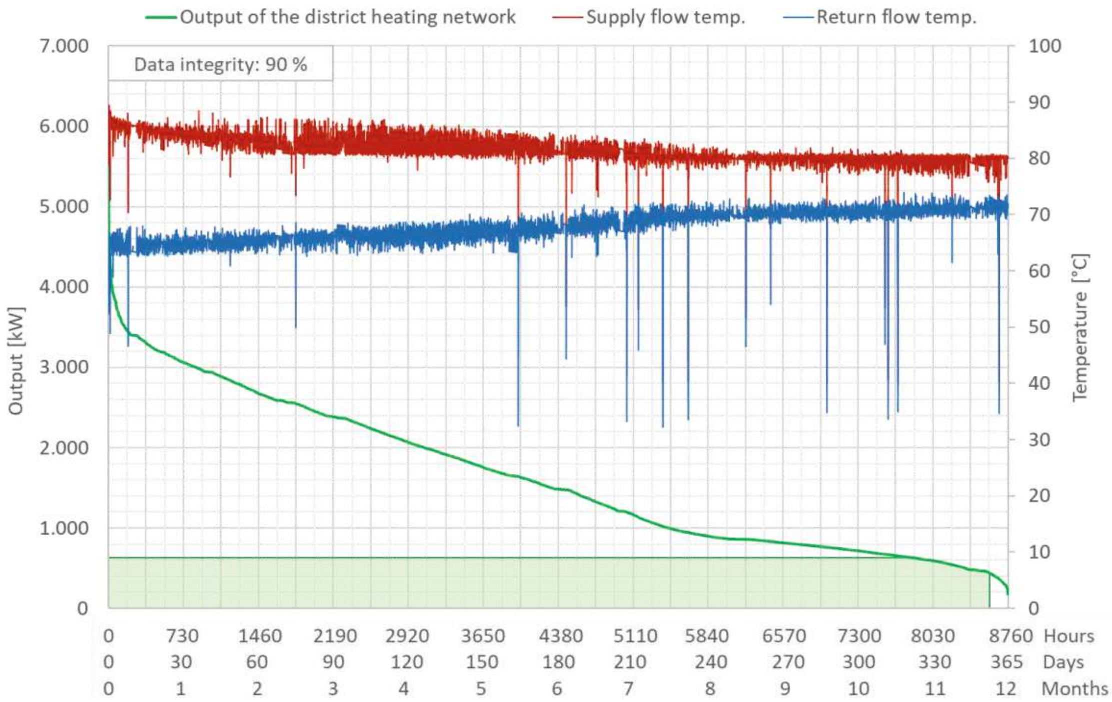

Figure 79: Exemplary operation of the biomass pyrolysis plant – PYREG [248]

The economic calculation of the biomass pyrolysis plant is based on the values listed in Table 4. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 19 shows moreover a list of values that were also used for the calculation.

Table 19: Additional parameters for the biomass pyrolysis plant – PYREG

Full load hours [h]	8.480
Investment costs [249] [EUR]	1.000.000

The investment calculation results in long-run generation costs of 176,80 euros per megawatt hour for the generation of heat. For a biomass heat-only boiler the long-run generation costs for the generation of heat are around 81 euros per megawatt hour. [250]

[248] Annual duration curve of the year 2023
[249] For construction and infrastructure
[250] Heat output = 850 kW, η = 85 %, FLH = 8.200 h, Total investment = 470.000 euros + 500.000 euros

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These long-run generation costs result for a biomass heat-only boiler applying the same framework conditions without going into a detailed calculation. To achieve these long-run generation costs for the biomass pyrolysis plant, a biochar sales price of around 1.100 euros per ton would be required if all other framework conditions remain the same. In Figure 80, a sensitivity analysis for selected parameters is shown for the investment calculation of the biomass pyrolysis plant.

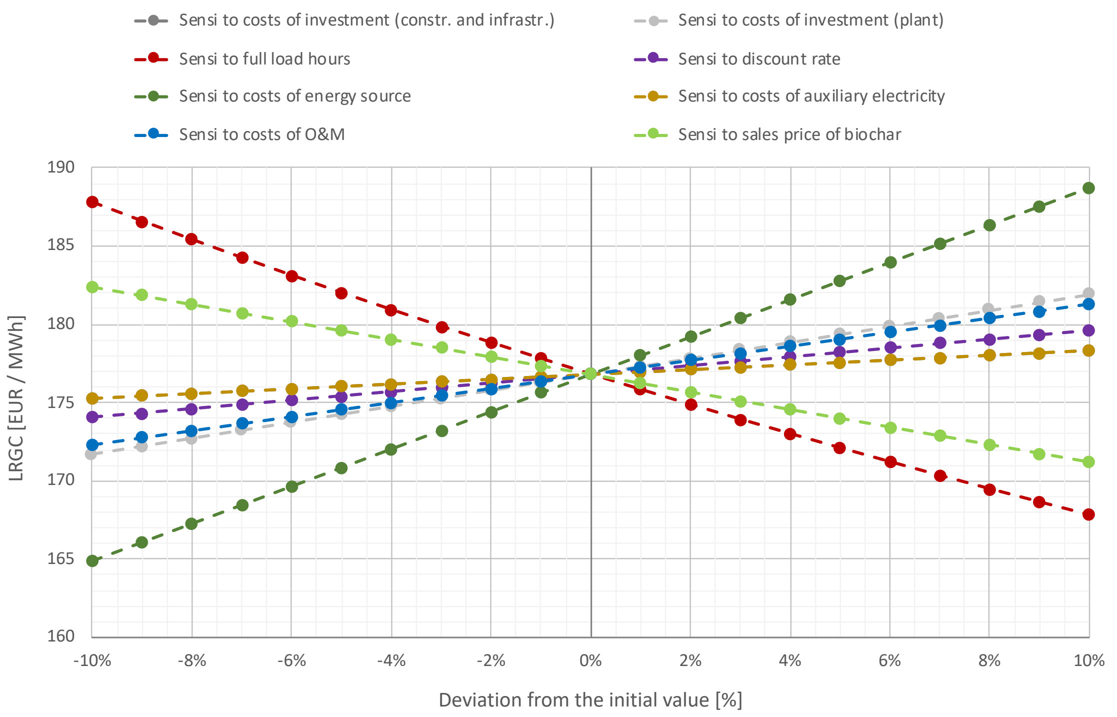

Figure 80: Sensitivity analysis for biomass pyrolysis plant – PYREG

The sensitivity analysis in Figure 80 shows that the number of full load hours and the price of the energy source have the most significant influence on the long-run generation costs for the generation of heat. The biochar sales price and the investment costs of the plant also have a significant influence on the long-run generation costs. The investment costs for construction and infrastructure are almost as sensitive as the costs of auxiliary electricity. The figure clearly shows that the main product of this plant is biochar. With the applied parameters, it is not possible to realize a heat supply in an economical way. To achieve competitive long-run generation costs for the generation of heat, the biochar must be sold at a higher price and a more affordable biomass must be used.

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6.3 Biomass CHP systems

In this chapter, the application of different biomass CHP systems in the district heating network in Asten will be examined from an economic point of view.

6.3.1 Biomass CHP plant – PYREG

The plant under consideration converts biomass into heat, electricity and biochar. Figure 81 shows a possible operation of the biomass CHP plant PX1500 from the manufacturer PYREG, under consideration of the nominal heat output and the partial load capability of the plant listed in Table 5. In this context, it should be mentioned that the heat storage capacity of the buffer storage tank was neglected in this exemplary operation scenario. Furthermore, it should be pointed out that it was assumed that the biomass CHP plant is used to cover the base load of the heat demand, resulting in 8.620 full load hours for the plant.

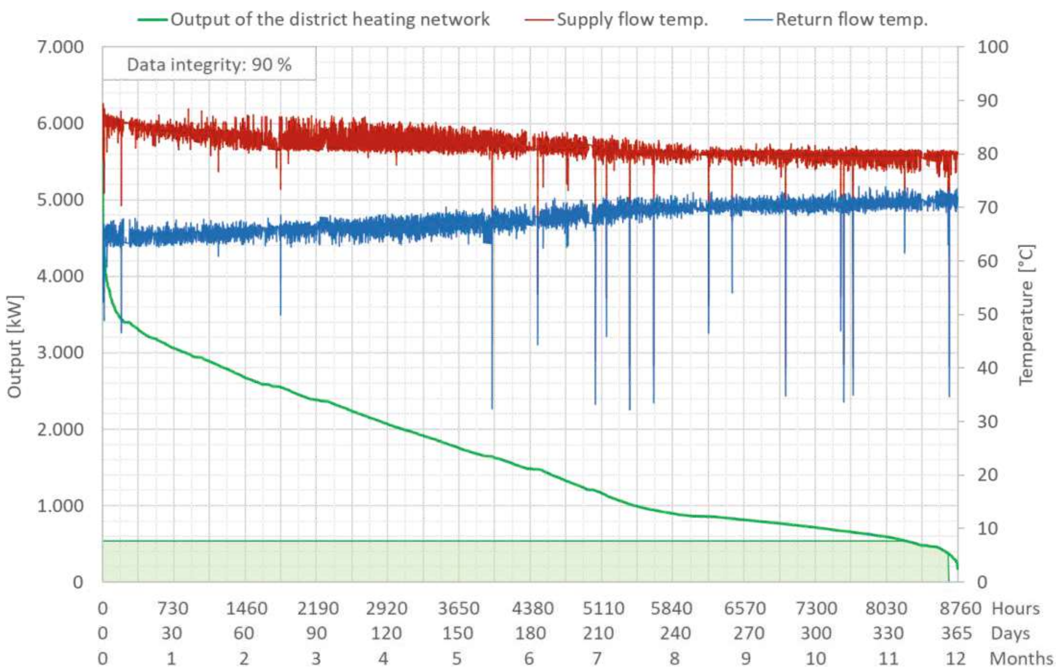

Figure 81: Exemplary operation of the biomass CHP plant – PYREG [251]

The economic calculation of the biomass CHP plant is based on the values listed in Table 5. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 20 shows moreover a list of the values that were also used for the calculation.

[251] Annual duration curve of the year 2023

Table 20: Additional parameters for the biomass CHP plant – PYREG

Full load hours [h]	8.620
Investment costs [252] [EUR]	1.500.000

The investment calculation results in long-run generation costs of 179,28 euros per megawatt hour for the generation of heat. These long-run generation costs, like the long-run generation costs of the biomass pyrolysis plant, are at a much higher level than those of the biomass heat-only boiler. In Figure 82, a sensitivity analysis for selected parameters is shown for the investment calculation of the biomass CHP plant.

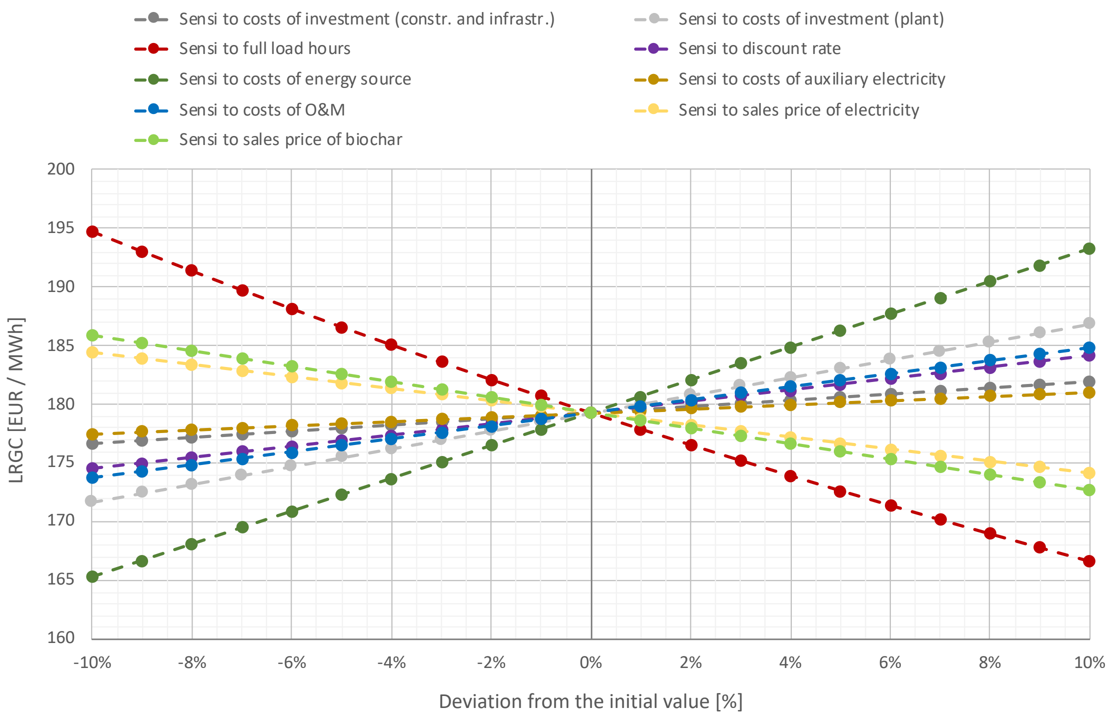

Figure 82: Sensitivity analysis for biomass CHP plant – PYREG

The sensitivity analysis in Figure 82 shows that the number of full load hours and the price of the energy source have the most significant influence on the long-run generation costs for the generation of heat. The biochar sales price, the electricity sales price and the investment costs of the plant also have a significant influence on the long-run generation costs. The figure clearly shows that the main product of this plant is also biochar.

[252] For construction and infrastructure

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With the applied parameters, it is also not possible to realize a heat supply in an economical way. To achieve competitive long-run generation costs for the generation of heat, the biochar must be sold at a higher price and a more affordable biomass must be used. The sales price of the electricity also has a significant influence on the long-run generation costs. Nevertheless, it should be noted that a higher sales price for the electricity generated will hardly be possible.

6.3.2 Biomass CHP plant – SYNCRAFT

The plant under consideration converts biomass into heat, electricity and biochar. Figure 83 shows a possible operation of the biomass CHP plant CW1800-500 from the manufacturer SYNCRAFT, under consideration of the nominal heat output and the partial load capability of the plant listed in Table 6. In this context, it should be mentioned that the heat storage capacity of the buffer storage tank was neglected in this exemplary operation scenario. Furthermore, it should be pointed out that it was assumed that the biomass CHP plant is used to cover the base load of the heat demand, resulting in 8.060 full load hours for the plant.

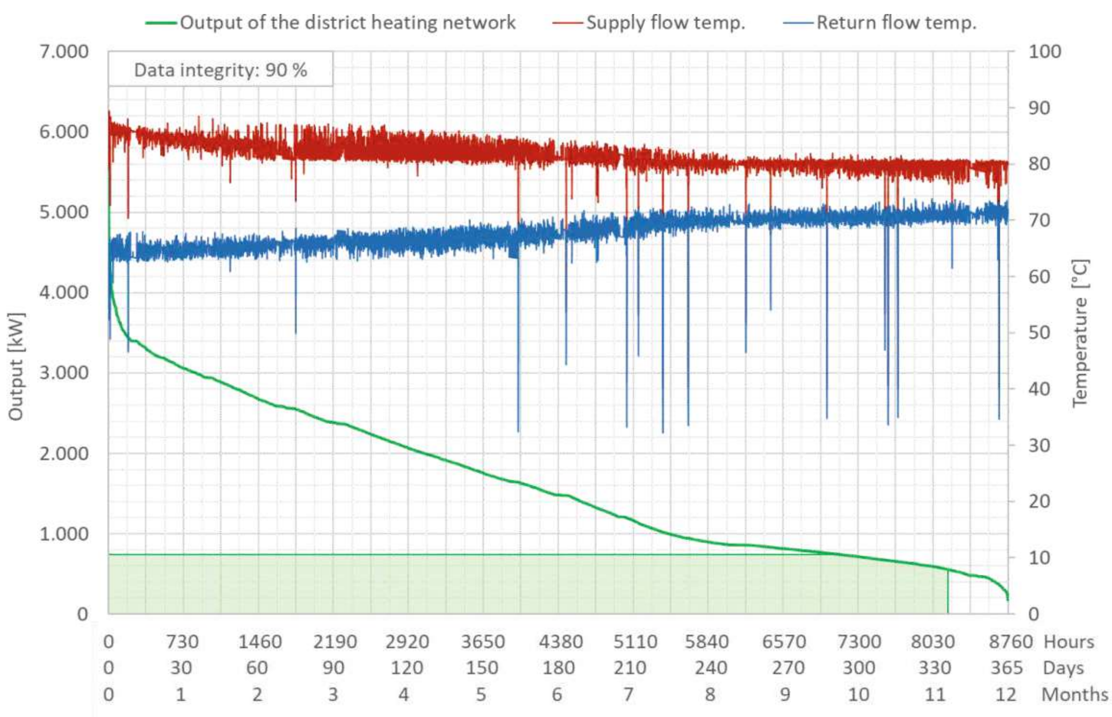

Figure 83: Exemplary operation of the biomass CHP plant – SYNCRAFT [253]

[253] Annual duration curve of the year 2023

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The economic calculation of the biomass CHP plant is based on the values listed in Table 6. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 21 shows moreover a list of the values that were also used for the calculation.

Table 21: Additional parameters for the biomass CHP plant – SYNCRAFT

Full load hours [h]	8.060
Investment costs [254] [EUR]	1.500.000

The investment calculation results in long-run generation costs of 70,16 euros per megawatt hour for the generation of heat. These long-run generation costs are at a lower level compared to the long-run generation costs of a biomass heat-only boiler, which are around 81 euros per megawatt hour. Under consideration of the chosen framework conditions, it becomes obvious that the combined generation of heat and electricity is beneficial. In Figure 84, a sensitivity analysis for selected parameters is shown for the investment calculation of the biomass CHP plant.

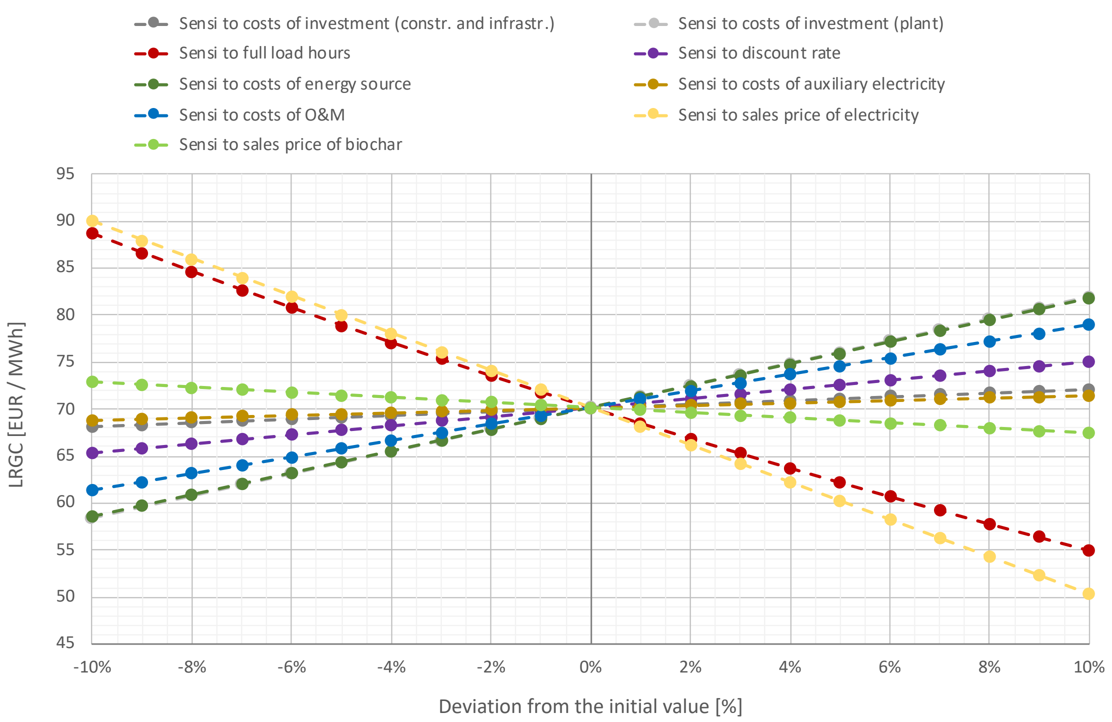

Figure 84: Sensitivity analysis for biomass CHP plant – SYNCRAFT

[254] For construction and infrastructure

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The sensitivity analysis in Figure 84 shows that the sales price of the electricity and the number of full load hours have the most significant influence on the long-run generation costs for the generation of heat. The price of the energy source and the investment costs of the plant also have a significant influence on the long-run generation costs. The price of the energy source is almost as sensitive as the investment costs of the plant.

The biochar sales price influences the long-run generation costs only slightly, as this plant converts most of the energy source in the form of biomass into heat and electricity. Compared to the two previous plants, which were biomass pyrolysis plants, a much smaller proportion of biochar is discharged from this plant.

To ensure that the long-run generation costs remain at a low level, it is important to aim for a high number of full load hours and to use biomass with a low price. The sales price of the electricity also has a significant influence on the long-run generation costs. Nevertheless, it should be noted that a higher sales price for the electricity generated will hardly be possible.

6.3.3 Biomass CHP plant – STEAMERGY

The plant under consideration converts biomass into heat and electricity. Figure 85 shows a possible operation of the biomass CHP plant with one engine from the manufacturer STEAMERGY, under consideration of the nominal heat output and the partial load capability of the plant listed in Table 7. In this context, it should be mentioned that the heat storage capacity of the buffer storage tank was neglected in this exemplary operation scenario. Furthermore, it should be pointed out that it was assumed that the biomass CHP plant is used to cover the base load of the heat demand, resulting in 8.400 full load hours for the plant.

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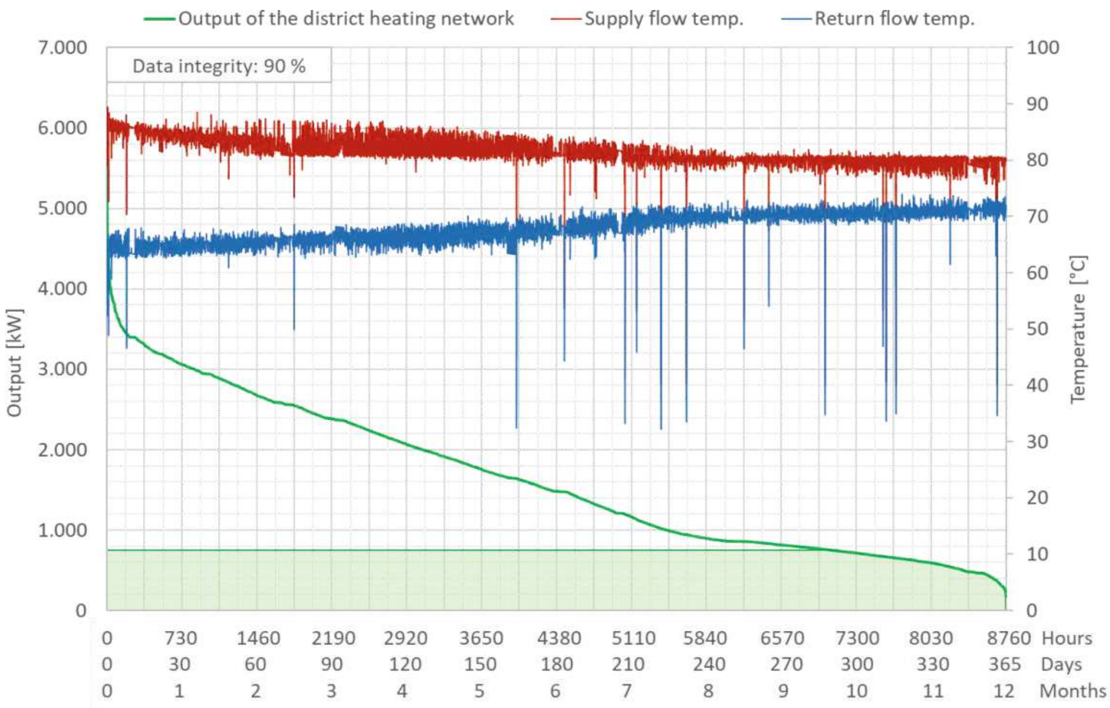

Figure 85: Exemplary operation of the biomass CHP plant – STEAMERGY [255]

The economic calculation of the biomass CHP plant is based on the values listed in Table 7. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 22 shows moreover a list of the values that were also used for the calculation.

Table 22: Additional parameters for the biomass CHP plant – STEAMERGY

Full load hours [h]	8.400
Investment costs [256] [EUR]	1.500.000

The investment calculation results in long-run generation costs of 48,53 euros per megawatt hour for the generation of heat when the price of biomass is assumed to be 40,00 euros per megawatt hour according to chapter 5.11.4.

The plant from the manufacturer STEAMERGY also enables the use of biomass with a significantly lower quality, which costs around 20,00 euros per megawatt hour. [257]

[255] Annual duration curve of the year 2023
[256] For construction and infrastructure
[257] according to the web meeting of 18 July 2024 (Mr. DI Duschl, Mr. DI Flemming, Mr. DI Wöss)

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The adapted investment calculation results in long-run generation costs of 13,74 euros per megawatt hour for the generation of heat when the price of biomass is assumed to be 20,00 euros per megawatt hour. In Figure 86, a sensitivity analysis for selected parameters is shown for the adapted investment calculation of the biomass CHP plant.

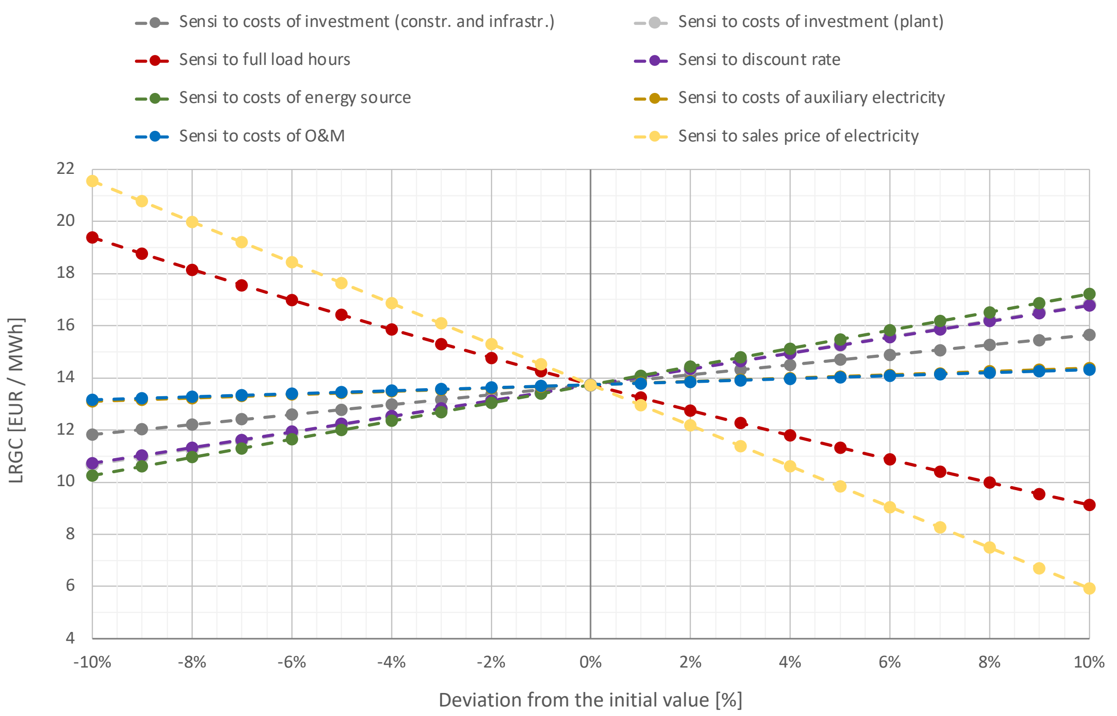

Figure 86: Sensitivity analysis for biomass CHP plant – STEAMERGY

The sensitivity analysis in Figure 86 shows that the sales price of the electricity and the number of full load hours have the most significant influence on the long-run generation costs for the generation of heat. The price of the energy source also has a significant influence on the long-run generation costs. The sensitivity of the investment costs of the plant is almost equal to the sensitivity of the discount rate, whereby these two mentioned sensitivities are slightly lower than the sensitivity of the energy source for this biomass CHP plant. The costs for operation and maintenance are almost as sensitive as the costs for the auxiliary electricity. Also, for this biomass CHP plant it is important to aim for a high number of full load hours and to use biomass with a low price to ensure that the long-run generation costs remain at a low level. The sales price of the electricity also has a significant influence on the long-run generation costs. Nevertheless, it should be noted that a higher sales price for the electricity generated will hardly be possible.

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6.4 Electric boilers systems

In this chapter, the application of an electric boiler system with different backgrounds in the district heating network in Asten will be examined from an economic point of view.

6.4.1 Electric boiler systems to use negative energy prices

A detailed description of the investment calculation of the electric boiler that is used with negative electricity prices is not given. The low number of hours in which negative electricity prices occur, as well as the fees and charges in addition to the energy price, lead to high long-run generation costs for the generation of heat. In the year 2023, there were only 137 hours with negative electricity prices with an average negative electricity price of -12,56 euros per megawatt hour. In addition to the negative energy price, fees and charges of around 20,169 euros per megawatt hour and 52,53 euros per kilowatt still have to be paid. These framework conditions and the framework conditions mentioned in Table 8 and Table 23 (except the full load hours, the energy source price and the capacity price) result in long-run generation costs of more than 1.000 euros per megawatt hour.

For this reason, it is not possible to operate such a system economically under any circumstances.

6.4.2 Electric boiler systems to provide control reserve

The system under consideration converts electricity into heat. Figure 87 shows a possible operation of the electric boiler system EEII-TS-1000-HA, under consideration of the nominal heat output of the system listed in Table 8. In this context, it should be mentioned that the heat storage capacity of the buffer storage tank was neglected in this exemplary operation scenario. Furthermore, it should be pointed out that it was assumed that the electric boiler system is only used to provide control reserve when there is enough heat demand in the district heating network, resulting in 5.450 full load hours for the system.

The economic calculation of the electric boiler system is based on the values listed in Table 8. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 23 shows moreover a list of the values that were also used for the calculation.

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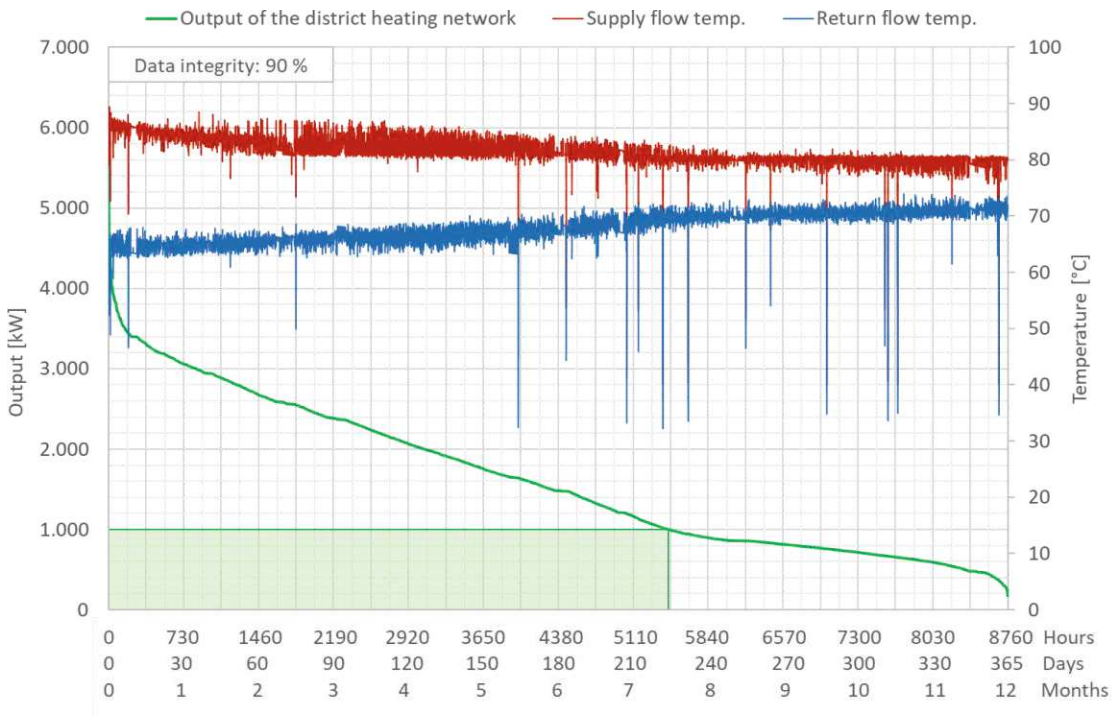

Figure 87: Exemplary operation of the electric boiler system – control reserve [258]

Table 23: Additional parameters for the electric boiler system – control reserve

Full load hours [h]	5.450
Energy source price [259] [EUR / MWh]	0,85
Capacity price [260] [EUR / MW·h]	-5,82
Auxiliary electricity [%] [261]	1,50
Investment costs [262] [EUR]	500.000
Maintenance and service [%] [263]	2,00
Operation [h / d]	1,00

[258] Annual duration curve of the year 2023
[259] Price for the energy (control reserve) = EUR 0,00 / MWh
Price for the grid (control reserve) = EUR 0,85 / MWh
[260] Price for capacity (control reserve) = EUR – 5,82 / MW·h
[261] Related to energy source input
[262] For construction and infrastructure
[263] Related to the investment costs of the plant

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The investment calculation results in long-run generation costs of 15,38 euros per megawatt hour for the generation of heat. The selected framework conditions result in heat generation costs for this system that are significantly lower than for all other systems presented. In Figure 88, a sensitivity analysis for selected parameters is shown for the investment calculation of the electric boiler system.

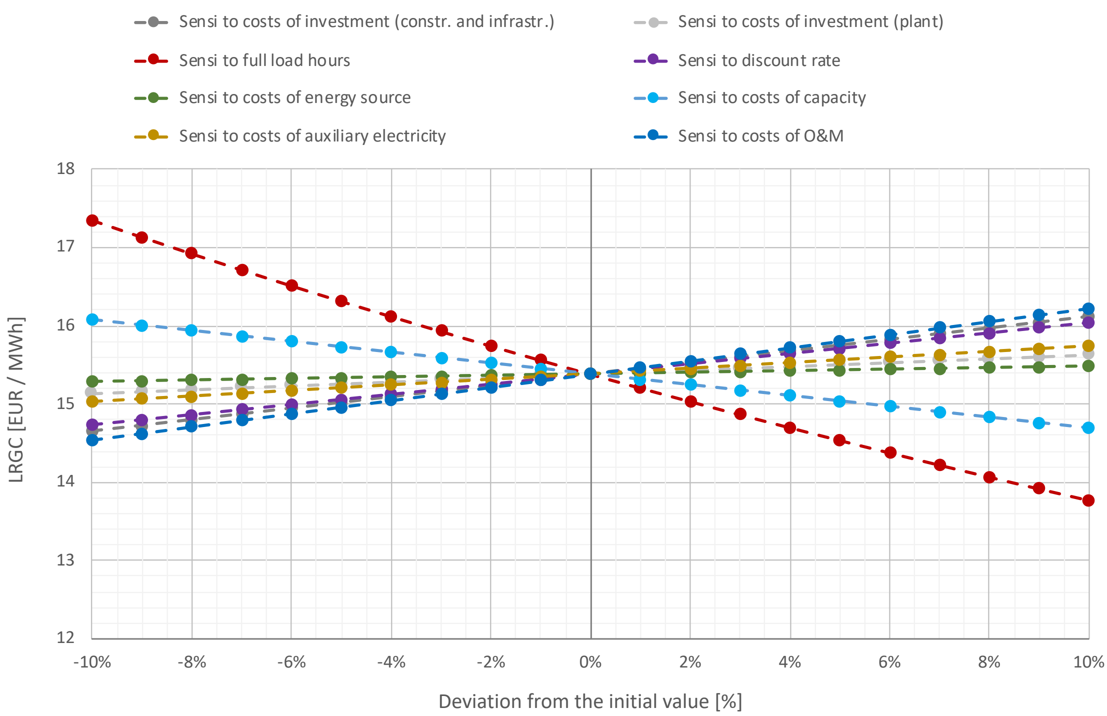

Figure 88: Sensitivity analysis for electric boiler system – control reserve

The sensitivity analysis in Figure 88 shows that the number of full load hours as well as the costs of the capacity and the costs of operation and maintenance have the most significant influence on the long-run generation costs for the generation of heat.

In cases where heat can be generated indefinitely, which means that the base load is high or a heat storage system is available, some derivations can be made. The costs of capacity – which are revenues in the case of control reserve – are directly related to the maximum possible full load hours according to Figure 49. The optimum of the long-run generation costs can be determined using an algorithm for optimization problems, taking into account the heat demand of the district heating network. Furthermore, it should be mentioned that the control reserve is traded on a highly dynamic market which must also be considered.

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6.5 Solar thermal systems

In this chapter, the application of a solar thermal system in the district heating network in Asten will be examined from an economic point of view.

The system under consideration converts solar irradiation into heat. Figure 89 shows a possible operation of a solar thermal system, taking into account the system data listed in Table 12. In this context, it should be mentioned that Figure 89 only shows the principle of a solar thermal heat generation and that the representation of the heat storage capacity of the buffer storage tank in the annual duration curve was neglected. In the calculation, however, the buffer storage tank and its heat storage capacity were taken into account.

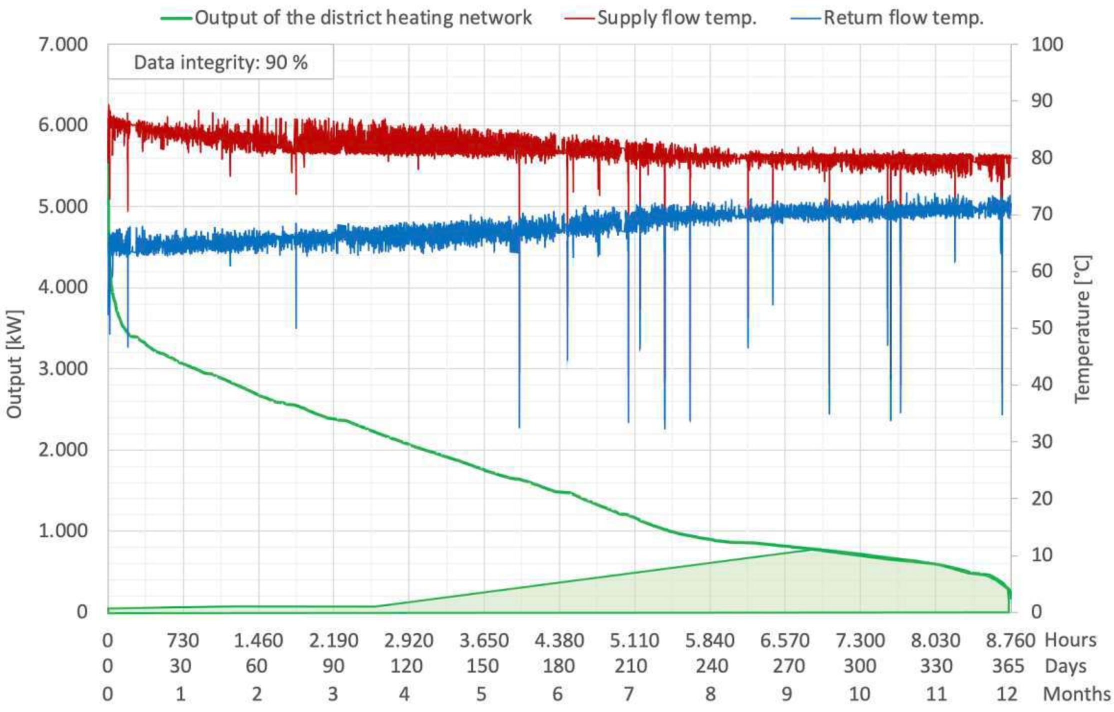

Figure 89: Exemplary operation of the solar thermal system [264]

The economic calculation of the solar thermal system is based on the values listed in Table 12. Furthermore, the calculation is based on the values mentioned in chapter 5.11.4. Table 24 shows moreover a list of the values that were also used for the calculation.

[264] Annual duration curve of the year 2023

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Table 24: Additional parameters for the solar thermal system

Full load hours [h] [265]	1.000
Auxiliary electricity [%] [266]	1,50
Investment costs [267] **[EUR]**	100.000
Maintenance and service [%] [268]	1,50

The investment calculation results in long-run generation costs of 127,69 euros per megawatt hour for the generation of heat. In Figure 90, a sensitivity analysis for selected parameters is shown for the investment calculation of the solar thermal system.

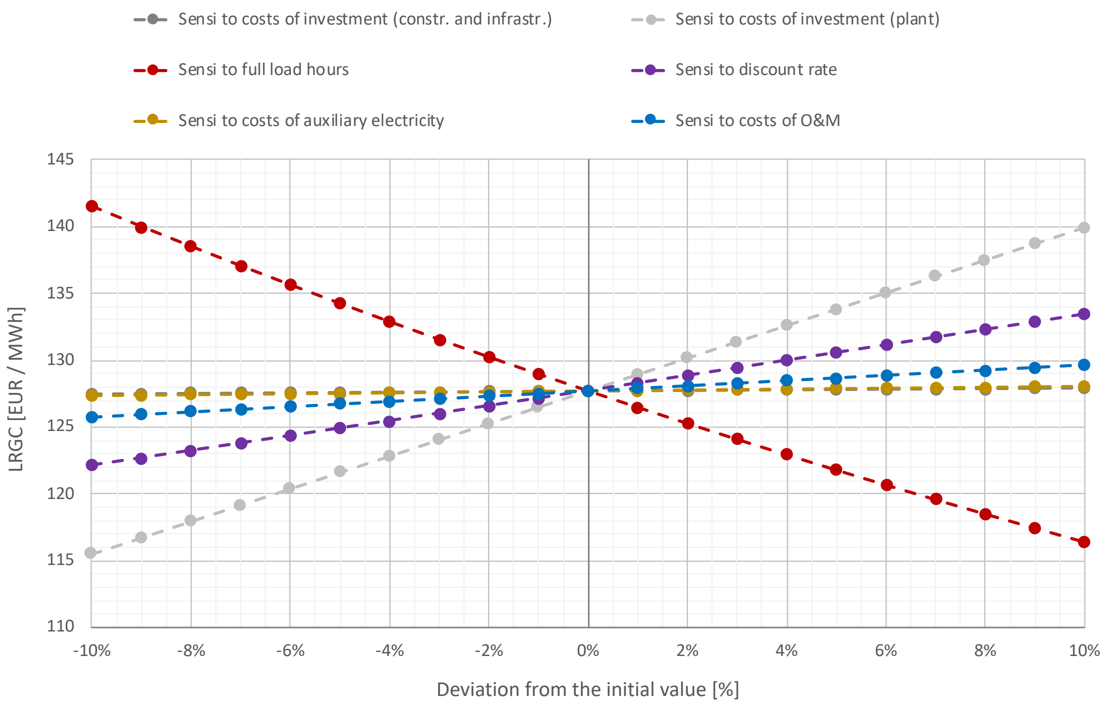

Figure 90: Sensitivity analysis for solar thermal system

The sensitivity analysis in Figure 90 shows that the number of full load hours and the investment costs of the plant have the most significant influence on the long-run generation costs for the generation of heat.

265 The calculation assumes a collector area of 10.270 m^2, a rated capacity of 4.000 kW and 1.000 full load hours.
266 Related to solar thermal heat generation
267 For construction and infrastructure
268 Related to the investment costs of the plant

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To ensure that the generation costs of the solar thermal system can be kept at a low level, it is important to maximize the yield, which is directly related to the full load hours. Besides an optimal location, a proper operation and monitoring of the operating parameters is therefore essential.

6.6 Combination of the individual systems

For all the above-mentioned systems, the plant size has already been selected so that a maximum number of full load hours is achieved, to ensure low long-run generation costs. In the appendix there are further possible operations of the above-mentioned plants with a higher output and therefore a lower number of full load hours.

Furthermore, for all the above-mentioned systems, only the coverage of the base load of the heat demand was shown as a possible operating mode. In principle, the above-mentioned calculations are also valid for other operating modes, as long as the number of full load hours is the same.

It is also conceivable that the above-mentioned systems are combined with each other and with heat storages as shown in Figure 91. The combination in Figure 91 is an example of a combination of the different systems and heat storages. In addition to this combination, there are also other combinations possible. To determine the long-run generation costs of the individual systems in such a combination, the number of full load hours of the individual systems must be determined. The calculations of the individual systems and the determination of the long-run generation costs are then carried out with the adjusted full load hours according to the presented schemes. The average long-run generation costs are then calculated from the individual long-run generation costs.

Nevertheless, it can be generalized that the reduction in full load hours leads to an increase in long-run generation costs for the generation of heat for all systems. This characteristic can be seen in all sensitivity analyses of the systems.

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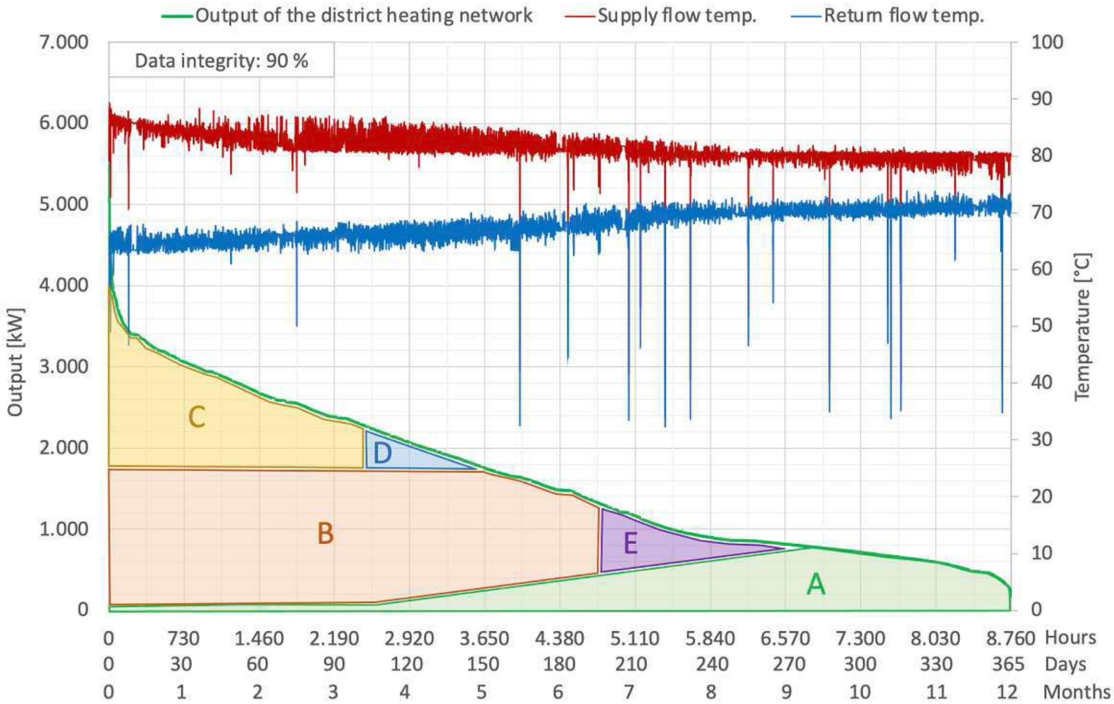

Figure 91: Combination of different systems and heat storages [269]

[269] Annual duration curve of the year 2023

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7 Conclusion and summary

The master's thesis explained the reasons for the necessity of an energy transition – away from fossil fuels towards renewables – from a climate change perspective. Moreover, it was shown on the basis of energy analyses why the space heating sector can make a significant contribution to the energy transition. The focus of the master's thesis was, on the one hand, to explain the district heating sector as it is known today. On the other hand, the master's thesis explained what the district heating sector could look like in the future.

In summary, it can be said that the district heating sector is a very dynamic energy sector that will be affected by numerous changes from a technical, economic and regulatory perspective in the future. In this context, it is worth to mention that the district heating sector is influenced by numerous factors, which also interact with each other.

In the course of the master's thesis, numerous technologies were presented which can be used for the generation of renewable district heat in the future. Within the master's thesis, only technologies that are independent of the location were presented. Other technologies that can only be implemented in appropriate locations (such as geothermal heat utilization, waste heat utilization, etc.) were only roughly outlined. In addition to the technologies, also methods were shown to increase the efficiency of existing district heat generation systems. Besides the change and adaptation of the generation technologies, it will also be necessary to adapt the consumer side so that heat sources with lower temperature levels can be integrated into the district heating systems of the future.

In addition to the technical discussion of the generation technologies, the focus was also put on sector coupling. The ongoing energy transition and the increase in volatile energy sources in the entire energy system will require the coupling of the energy sectors in the future. On the one hand, the heating sector can make a contribution to the stabilization of the electricity grid by using power-to-heat solutions and, on the other hand, contribute to a resilient renewable electricity generation by using CHP plants, especially in situations where other fluctuating renewable energy sources such as photovoltaics or wind generate little or no electricity during the night, in the winter months or during wind lulls.

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The discussed generation technologies were then subjected to investment calculations to be able to compare the generation technologies with each other. In this context, it should be highlighted that the results of the investment calculations do not correspond to the heat price that can be charged to a heat consumer, especially as the investment calculations did not take into account the heat distribution and any long-term heat storage (for systems with long-term heat storage). To ensure a comparability of the results, all subsidies that can currently be obtained were also neglected. Furthermore, the aim of the investment calculations was not to favor a particular technology. Each technology has its strengths and weaknesses. A detailed description of these strengths and weaknesses would go beyond the scope of this master's thesis. Also, several assumptions and simplifications were made in the master's thesis making it almost impossible to determine a preference for one of the technologies. The investment calculations for the different generation technologies show clearly which parameters have an influence on the long-run generation costs for the generation of heat. The heat provision costs of the district heat supply, which consist of the heat costs for the district heat generation, the heat distribution costs, and the heat storage costs (for systems with long-term heat storage), are in direct competition with the heat provision costs of other heat supply technologies. In this context, the individual heat provision based on natural gas is the strongest competitor. To ensure that the district heat supply can be expanded in the future, it is necessary to keep the heat provision costs of the district heat supply at a low level or to create acceptance among the end customers that the supply with renewable district heat has a slightly higher price than the heat provision based on natural gas. In general, it should be tried that the end customer accepts higher prices when renewable energy is supplied, as renewable energy does not only contribute to the protection of the climate and the creation of regional value, but also supports the independence from fossil fuels from abroad. Another way to phase out the provision of heat from fossil fuels is to use legal standards such as laws and regulations. The master's thesis has provided a good overview of the technical and economic framework conditions of the various generation technologies. The generation technologies were only analyzed in a static way during the master's thesis. In order to be able to make a statement about the optimum combination of generation technologies, as well as the use of heat storage systems, it is necessary to analyze the whole system dynamically and assess the strengths and weaknesses of the individual technologies. Furthermore, the subsidies that can be obtained must be taken into account for all systems.

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Future perspectives

The district heat supply will undoubtedly play a central role in the sustainable supply of heat in the future. As already mentioned, the district heat supply will be subjected to numerous changes in the future.

One significant development in district heat generation in the future is the increased use of renewable energy sources. Combined heat and power generation plants, solar thermal plants, geothermal heat utilization, waste heat utilization and the utilization of industrial waste heat will be integrated more and more into district heating systems. These sources will provide a CO_2-neutral or a CO_2-negative heat supply. In addition to this, innovative storage technologies will play a key role to store surplus heat from times of low demand and make it available again when it is needed. Above all, this increases the flexibility, but also the reliability of district heating systems. For the heating sector, as for all other energy sectors, the energy transition will be a matter of storage.

Another important trend is digitalization and the use of smart grids. The use of intelligent grid management systems makes it possible to optimize the efficiency of district heat distribution and the use of district heat. Real-time data enables precise control and adjustment of the heat generation to the actual demand and makes it possible to avoid peak loads as far as possible.

It can be assumed that the generation of district heat within a district heating network will not be produced by one technology, but by several technologies that use flexible generation strategies. Currently, it is not possible to assess if there will be a cannibalization of renewable energy sources in the heating sector in case of low heat generation costs, but it cannot be excluded. It also cannot be excluded that one day the heat consumed by heat consumers will be billed based on hourly or quarter-hourly consumption. This type of billing model is already familiar and common in the electricity market. In the heating sector, such a billing method cannot be excluded in the future, especially in cases where the district heat is generated with different technologies whose long-run generation costs are very different. Nevertheless, it should be mentioned that this type of billing method causes a lot of effort.

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List of abbreviations

Table 25: List of Abbreviations

Abbreviation	Explanation
°C	Degrees Celsius
a	Year (from annus)
aFRR	Automatic frequency restoration reserves
BU	Bottom-up
C	Carbon
CCS	Carbon capture and storage
C_2H_4	Ethylene
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of Performance
d	Day
DHN	District heating network
EUR	Euros
g	Gram
GWh	Gigawatt hour
GWP	Global Warming Potential Greenhouse Warming Potential
h	Hour

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H_2	Hydrogen
H_2O	Water
HOB	Heat-only boiler
K	Kelvin
kg	Kilograms
kJ	Kilojoule
km	Kilometer
kW	Kilowatt
kWh	Kilowatt hour
LCV	Lower Calorific Value
m	Meter
m^2	Square meter
m^3	Cubic meter
mFRR	Manual frequency restoration reserves
min	Minute
MJ	Megajoule
mm	Millimeter
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous oxide
NPV	Net Present Value
OR	Operating reserve
ORC	Organic Rankine Cycle

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Pa	Pascal
PJ	Petajoule
P2H	Power to heat
R&D	Research and Development
s	Second
t	Tons
TD	Top-down
TSO	Transmission system operator
TWh	Terawatt hours
UCV	Upper Calorific Value
W	Watt
wk	Week

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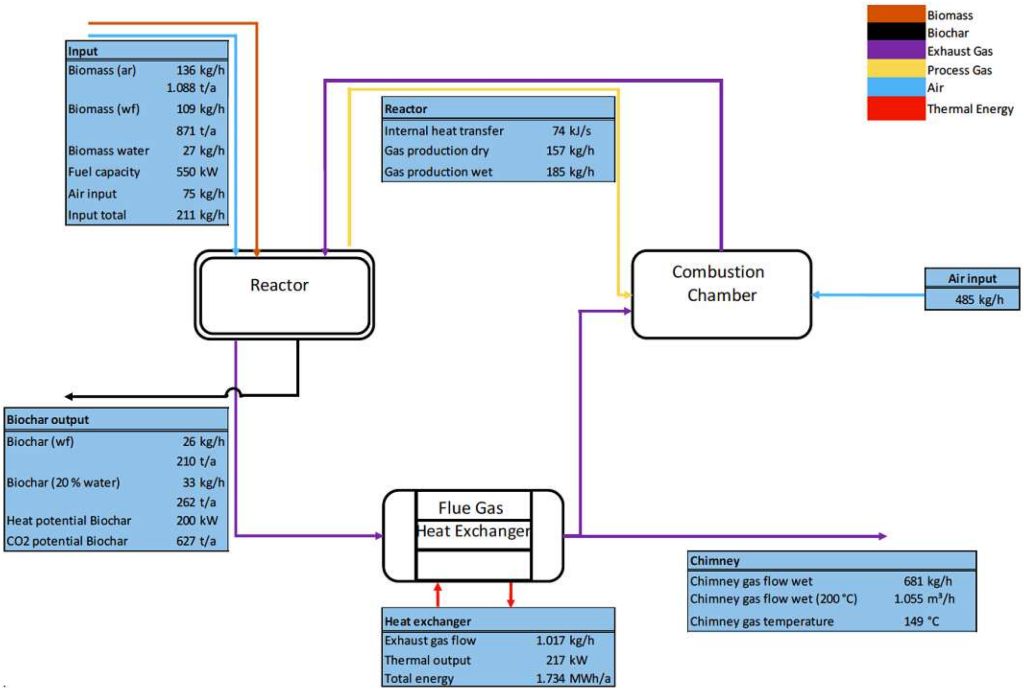
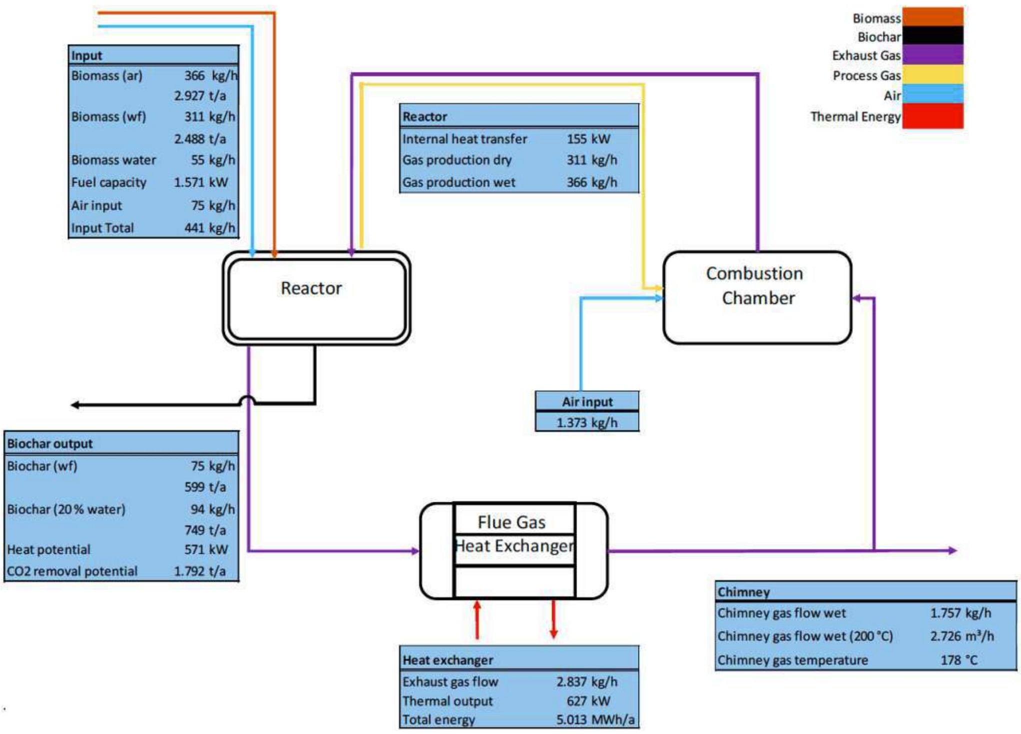
Appendixes



Appendix 1: Energy and mass balances for PYREG PX500 for residual forest wood [270]



Appendix 2: Energy and mass balances for PYREG PX1500 for residual forest wood [271]

[270] (Pyreg, 2023b p. 2)
[271] (Pyreg, 2023b p. 3)

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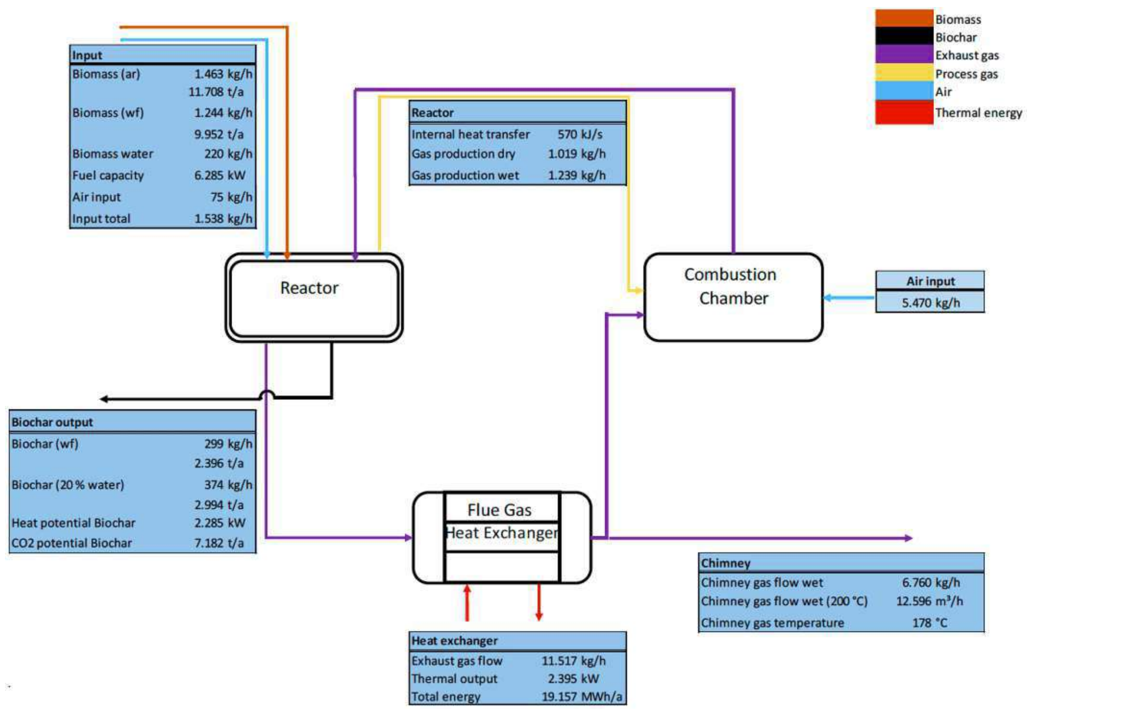

Appendix 3: Energy and mass balances for PYREG PX6000 for residual forest wood [272]

Von: Philipp Reichardt <p.reichardt@pyreg.com>
Gesendet: Dienstag, 25. Juli 2023 13:52
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: RE: Unverbindliche Anfrage I Einsatz der Pyrolysetechnologie zur Biokohle-, Wärme- und Stromerzeugung aus holzartiger Biomasse

Guten Tag Herr Wöss,

bitte entschuldigen Sie vielmals, die letzte Email von Ihnen ist bei mir irgendwie untergegangen.

Anbei finden Sie für alle unsere Anlagen (PX500, PX1500 und PX6000 (noch in Entwicklung)) beispielhafte Energie- und Massenbilanzen mit dem Referenzbrennstoff Waldrestholz. Daraus können Sie die wichtigsten Kennzahlen ableiten. Die Investitionskosten betragen ca. 1 Millionen (PX500), ca. 2,2, Millionen (PX1500) und vsl. ca. 5,5 Millionen (PX6000).

Unabhängig von der Anlagengröße muss jedes Inputmaterial folgende Anforderungen erfüllen:

- Partikelgröße kleiner 30mm
- Restfeuchte maximal 20 %
- Heizwert mindestens 10 MJ/kg

Die Anlagen müssen immer mit wenigstens 70 % Teillast betrieben werden, um immer sicher zu gehen, dass genug Prozessgas entsteht, um den Prozess thermisch autark Aufrecht erhaltenen zu können.

Typischerweise kalkulieren wir mit 2,5% pro Jahr (bezogen auf Investitionskosten) für Service und Wartung.

Ich hoffe damit alle Ihre Fragen beantwortet zu haben und stehe für weitere Fragen gerne zur Verfügung.

Mit freundlichen Grüßen / kind regards

PYREG
NET ZERO TECHNOLOGY

Philipp Reichardt
Sales Manager

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Appendix 4: Additional information for the PYREG plants [273]

[272] (Pyreg, 2023b p. 4)
[273] (Reichardt, 2023)

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Von: Philipp Reichardt <p.reichardt@pyreg.com>
Gesendet: Montag, 15. Jänner 2024 15:46
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: RE: Unverbindliche Anfrage I Einsatz der Pyrolysetechnologie zur Biokohle-, Wärme- und Stromerzeugung aus holzartiger Biomasse

Hallo Herr Wöss,

für die PX500 werden wir keine Möglichkeit zur Verstromung mit einer Dürr-ORC anbieten. Die zur Verfügung stehende thermische Leistung (nur ca. 200 kW) ist zu gering, dass es sich lohnen würde eine Verstromung wirtschaftlich tragbar zu machen.

Die Kosten für eine PX1500-ORC (Cyplan 120) betragen ca. 2,8 Millionen Euro, für eine PX6000-ORC (vsl. Cyplan 350) rechnen wir mit ca. 6,5 Millionen Euro.

Sie können die technischen Daten aus unserem allgemeinen Flyer nutzen und dabei für die ORC-Lösung die Wärmeleistung in 15 % Strom und 85 % Wärme teilen. Für eine PX1500 von 600 kW thermisch also bis zu 90 kW elektrisch und ca. 500 kW thermisch (Gesamtwirkungsgrad >95 %).

In den zusätzlich beigefügten Broschüren finden Sie auf Seite 15 jeweils ein Prozessdiagramm.

Mit freundlichen Grüßen / kind regards

PYREG
NET ZERO TECHNOLOGY

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pyreg.com

Appendix 5: Additional information for the PYREG plants [274]

Von: Thomas Besendörfer <thomas.besendoerfer@syncraft.at>
Gesendet: Mittwoch, 31. Jänner 2024 16:45
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: AW: Anfrage von Informationen

Sie erhalten nicht oft eine E-Mail von thomas.besendoerfer@syncraft.at. Erfahren Sie, warum dies wichtig ist

Sehr geehrter Herr Wöss,

Herr Huber hat mir Ihre E-Mail mit der Bitte um Bearbeitung übergeben und möchte sich für die Verzögerung entschuldigen.
Ihre Fragen möchte ich wie folgt beantworten:

1. Die Investitionskosten für eine CW1200-400 betragen ca. € 3,4 Mio. eine CW1800-500 ca. € 3,7 Mio und eine CW1800x2-1000 ca € 6,3 Mio. Die CW700-200 wird nicht mehr gebaut.
2. Teillastfähigkeit zwischen 75 und 80 % der Nennleistung.
3. Siehe Brennstoffspezifikation anbei
4. Ca. 8 %
5. Siehe Datenblätter anbei
6. Siehe Kurzbeschreibung Prozess anbei

Freundliche Grüße

Thomas Besendörfer
Technischer Vetrieb / Technical sales

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Falls Sie diese E-Mail irrtümlich erhalten haben, leiten Sie sie bitte weiter an: office@syncraft.at Vielen Dank für Ihre Bemühungen.

Appendix 6: Additional information for the SYNCRAFT plants [275]

[274] (Reichardt, 2024)
[275] (Besendörfer, 2024a)

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Von: Thomas Besendörfer <thomas.besendoerfer@syncraft.at>
Gesendet: Freitag, 2. Februar 2024 13:14
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: AW: Anfrage von Informationen

Sie erhalten nicht oft eine E-Mail von thomas.besendoerfer@syncraft.at. Erfahren Sie, warum dies wichtig ist

Hallo Herr Wöss,

kurz zu Ihrer Frage:

Die Pflanzenkohle besitzt im trockenen Zustand eine Dichte von 120 bis 250 kg/m3 stark abhängig vom eingesetzten Brennstoff. (Holzart).

Freundliche Grüße

Thomas Besendörfer
Technischer Vetrieb / Technical sales

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Appendix 7: Additional information for the SYNCRAFT plants [276]

[276] (Besendörfer, 2024b)

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Von: andre.flemming@steamergy.de <andre.flemming@steamergy.de>
Gesendet: Dienstag, 6. Juni 2023 11:48
An: WÖSS Dominic <d.woess@linzag.at>
Cc: robert.duschl@steamergy.de
Betreff: Vorschlag & Richtpreise für komplette Kraftwerke in Puchenau, Asten & Haid

Sehr geehrter Herr Wöss,

den Besichtigungstermin für das Kraftwerk in Eging am See vereinbaren wir hiermit auf den **01.08.2023 um 10.00 Uhr**.
Ich würde vorschlagen, dass wir uns dann gleich vor Ort treffen bei:

meusburger Fahrzeugbau GmbH
Kollmering 7
D-94535 Eging am See
Deutschland

Des Weiteren sende ich Ihnen die Richtpreise für komplette Kraftwerke inkl. der Feuerung. Für die Kalkulation ohne Feuerung benötigen wir noch einige Tage.
Die Jahresdauerlinie Puchenau und Haid fallen schnell steiler ab mit weniger Laufzeit übers Jahr. Deshalb hatte ich hier aus Kostengründen prozentual eine höhere Wärmeproduktion angenommen. Anforderungen wieviel Strom Sie an dem jeweiligen Standort produzieren möchten, hatten Sie bisher nicht geäußert. Als Vollbetriebsstunden hatte ich 4.800h angenommen.

1. Biomasseheizwerk Puchenau 2022: 9.768.000 kWh (= 9.768 MWh)
    1. **3-motoriges Kraftwerk – Richtpreis = 4.080.000,- EUR**
        1. 600 kW elektr. - Nennleistung
        2. 2.250 kW thermisch – Nennleistung
        3. Bis 20% Teillastbetrieb mit Stromproduktion möglich
        4. Spitzenlast nach Jahresdauerlinie 2022 aus Wärmespeicher-Salzbad entnehmbar
2. Biomasseheizwerk Asten 2022: 14.128.000 kWh (= 14.128 MWh)
    1. **5-motoriges Kraftwerk – Richtpreis = 6.400.000,- EUR**
        1. 1.000 kW elektrisch - Nennleistung
        2. 3.000 kW thermisch - Nennleistung
        3. Bis 20% Teillastbetrieb mit Stromproduktion möglich
        4. Spitzenlast nach Jahresdauerlinie 2022 aus Wärmespeicher-Salzbad entnehmbar
3. Biomasseheizwerk Haid 2022: 25.010.000 kWh (= 25.010 MWh)
    1. **8-motoriges Kraftwerk – Richtpreis = 9.760.000,- EUR**
        1. 1.600 kW elektrisch - Nennleistung
        2. 6.000 kW thermisch - Nennleistung
        3. Bis 20% Teillastbetrieb mit Stromproduktion möglich
        4. Spitzenlast nach Jahresdauerlinie 2022 aus Wärmespeicher-Salzbad entnehmbar

Bitte verstehen Sie die Angabe der Leistungswerte und Anzahl der Motoren als ersten Vorschlag. Falls Sie doch anders planen möchten, können wir dies gerne tun.
Mit der Steamergy-Kraftwerkstechnologie haben Sie eine sehr hohe Flexibilität und können auch die Teilastbereiche wärmetechnisch komplett abdecken.

Für weitere Fragen vorab, stehe ich Ihnen gerne zur Verfügung.

Mit freundlichen Grüßen

André Flemming
Geschäftsführer

STEAMERGY

STEAMERGY Stralsund GmbH
An der Werft 5
18439 Stralsund
Germany

Telefon: +49 3831-2356703
Mobiltelefon: +49 179 43 44 988
E-Mail: andre.flemming@steamergy.de
Web: www.steamergy.de

Geschäftsführung: André Flemming, Robert Duschl, Amtsgericht Stralsund: HRB 22024

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Appendix 8: Additional information for the STEAMERGY plants [277]

[277] (Flemming, 2023c)

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Von: Flemming Andre <andre.flemming@steamergy.com>
Gesendet: Mittwoch, 20. Dezember 2023 13:29
An: WÖSS Dominic <d.woess@linzag.at>
Cc: Memic Semira <semira.memic@steamergy.com>; Duschl Robert <robert.duschl@steamergy.com>
Betreff: AW: Besichtigung der Referenzanlage I Meusburger Fahrzeugbau GmbH

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Sehr geehrter Herr DI Wöss,

sehr gerne senden wir Ihnen die Richtpreise für die weiteren Leistungsklassen:

1-motoriges Kraftwerk – Richtpreis = **1.440.000,- EUR ohne** Feuerung - **> 1.730.000,- EUR mit Feuerung**

2-motoriges Kraftwerk – Richtpreis = **2.550.000,- EUR ohne** Feuerung - **> 2.990.000,- EUR mit Feuerung**

10-motoriges Kraftwerk – Richtpreis = **9.900.000,- EUR ohne** Feuerung - **> 11.830.000,- EUR mit Feuerung**

12-motoriges Kraftwerk – Richtpreis = **11.720.000,- EUR ohne** Feuerung - **> 14.200.000,- EUR mit Feuerung**

Wie schon besprochen, sind dies Richtwerte. Wenn die Projekte konkret kalkuliert werden können, werden die Anlagen ganz spezifisch kalkuliert und Sie erhalten ein detailliertes Angebot.

Ich hoffe wir können Ihnen so vorab weiterhelfen und wenn Sie weitere Fragen haben, sprechen Sie uns gerne an.

Vielen Dank und Ihnen wünsche ich ebenfalls ein gesegnetes Weihnachtsfest und einen guten Rutsch ins nächste Jahr!

Mit freundlichen Grüßen

André Flemming
Geschäftsführer

STEAMERGY

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Geschäftsführung: André Flemming, Robert Duschl, Amtsgericht Stralsund: HRB 22024

Besuchen Sie uns auf der Messe Nürnberg vom 28.11.-30.11.2023:

Brau '23 Beviale
28. - 30. November 2023 / Nürnberg, Germany

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Appendix 9: Additional information for the STEAMERGY plants [278]

[278] (Flemming, 2023a)

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Von: Erich Temper <erich.temper@gasokol.at>
Gesendet: Mittwoch, 7. Februar 2024 09:06
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: AW(6): Solare Abdeckung der Sommerlast bei Wärmenetzen

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Hallo Hr. Wöss,

ich kann Ihnen dazu folgende Kenngrößen geben:
Flächenbedarf:
Wenn es sich um eine ideale Geometrie handelt (rechteckige Grundfläche) dann, sind pro m² Kollektorfläche etwa 2,5 m² Aufstellfläche erforderlich, damit sich die Reihen zueinander nicht wesentlich verschatten.

Kosten:
Wenn sich die Kollektorfläche in der Nähe des Puffers befindet, dann kann man als Kostenschätzung (Kollektorfeld, Unterkonstruktion, Pufferanschluss, Planung - ohne Puffer) etwa 400-550,- €/m² ansetzen Die Förderung beträgt etwa 30% (wobei sich hier ständig was ändert)

Wartung:
Da es in der Regel bei Wärmenetze ein geschultes Betreuerpersonal gibt, die nach einer Einschulung die Bedienung und Wartung erledigen können, gehen wir von jährlich etwa 500,- bis 1.000,-€ pro Anlage aus. (je nach Anlagengröße)

Mit freundlichen Grüßen

Erich Temper
Leitung Technik

GASOKOL GmbH
Solarpark 1, A-4351 Saxen

T +43 (0)7269 / 76600-0
erich.temper@gasokol.at
www.gasokol.at

Appendix 10: Additional information for the solar thermal systems [279]

[279] (Temper, 2024b)

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Von: Erich Temper <erich.temper@gasokol.at>
Gesendet: Dienstag, 6. Februar 2024 13:57
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: AW(4): Solare Abdeckung der Sommerlast bei Wärmenetzen

Sie erhalten nicht oft eine E-Mail von erich.temper@gasokol.at. Erfahren Sie, warum dies wichtig ist

Hallo Hr. Wöss,

anbei ein Dimensionierungsvorschlag zu den angefragten Wärmenetzen.
Zu den Kosten:
Reicht die Kostenschätzung zu den Solarfeld + Speichereinbindung in den Puffer?

Zur Info ein Video zu einem ähnl. Projekt:
GASOKOL Nahwärme St. Ruprecht (youtube.com)

Mit freundlichen Grüßen

Erich Temper
Leitung Technik

GASOKOL GmbH
Solarpark 1, A-4351 Saxen

T +43 (0)7269 / 76600-0
erich.temper@gasokol.at
www.gasokol.at

Appendix 11: Additional information for the solar thermal systems [280]

Von: Schramm, Sebastian <Sebastian.Schramm@greenonetec.com>
Gesendet: Dienstag, 27. Februar 2024 13:52
An: WÖSS Dominic <d.woess@linzag.at>
Betreff: AW: Solare Abdeckung der Sommerlast bei Wärmenetzen

Sehr geehrter Herr Wöss,

ich bitte die lange Wartezeit zu entschuldigen! Finden Sie bitte anbei meiner erste Ausarbeitung. Ich bin auf Ihr Feedback gespannt bzw. kann ich Ihnen auch gerne anbieten, zur Ergebnisdiskussion nach Linz zukommen.

Ich freu mich über eine Rückmeldung!

Mit freundlichen Grüßen / Best regards

Dr.-Ing. Sebastian Schramm
Business Development
Large-scale solar thermal systems

GREENoneTEC
SOLAR INDUSTRY

GREENoneTEC Solarindustrie GmbH
Industriepark St. Veit, Energieplatz 1, A - 9300 St. Veit/Glan
M: +43 664 88955611 I T: +43 4212 28136221
www.greenonetec.com

Appendix 12: Additional information for the solar thermal systems [281]

[280] (Temper, 2024a)
[281] (Schramm, 2024)

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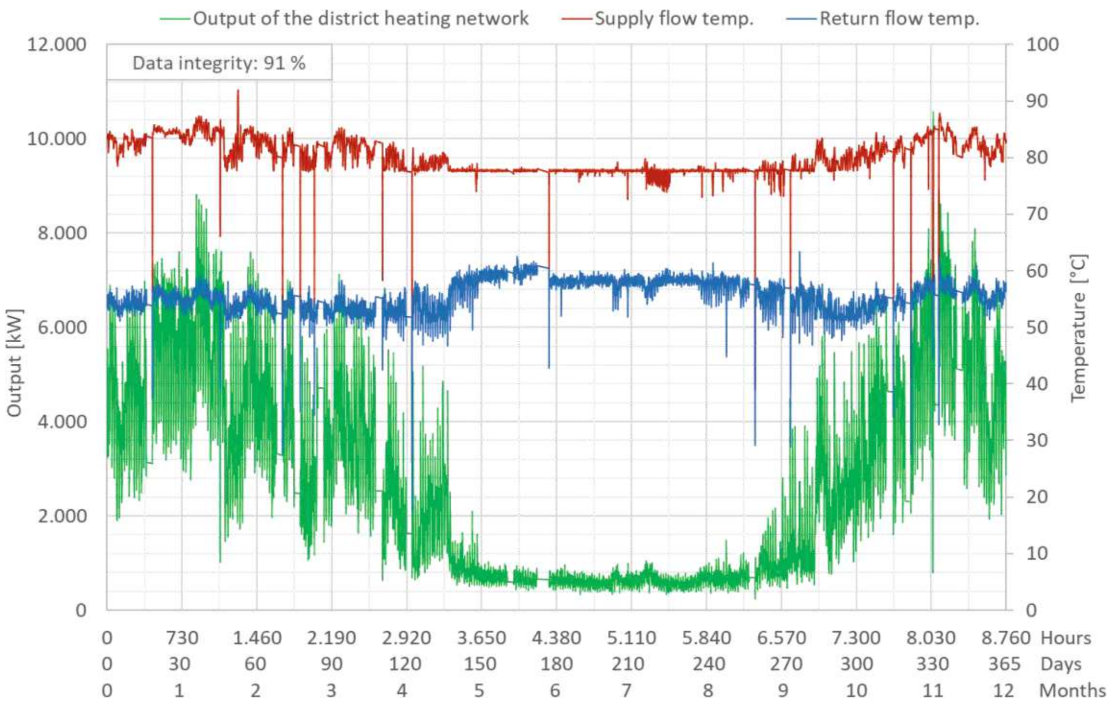
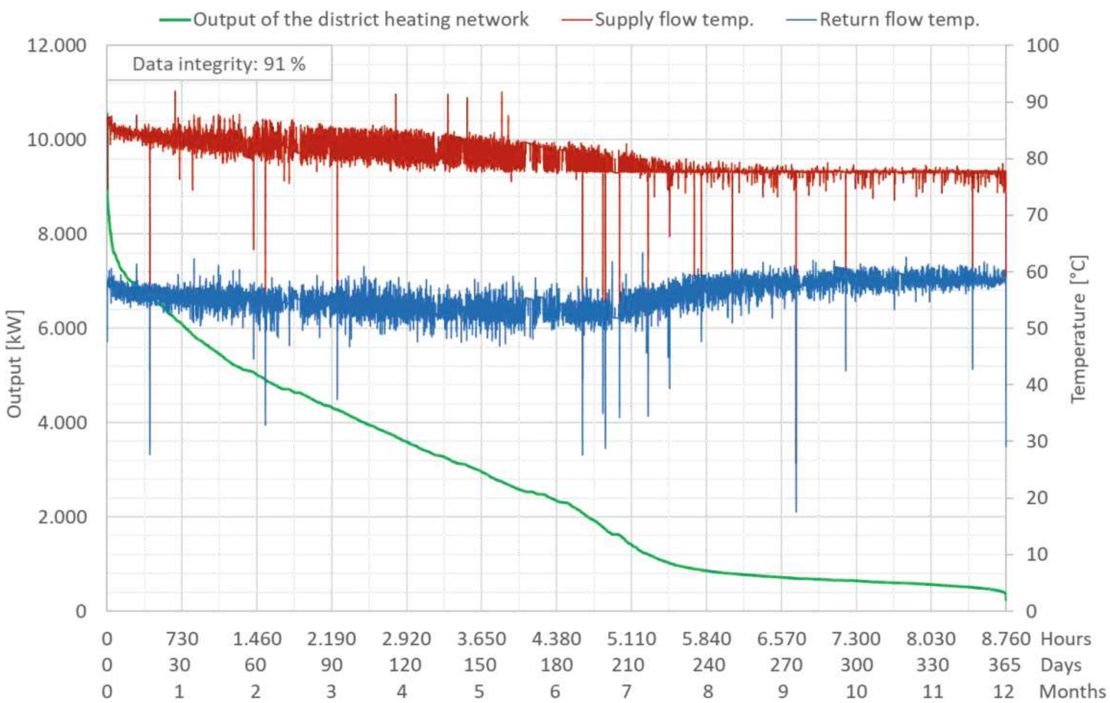


Appendix 13: Unsorted output and temperatures of the DHN in Haid [282]



Appendix 14: Sorted output and temperatures of the DHN in Haid [283]

[282] For the year 2023
[283] For the year 2023

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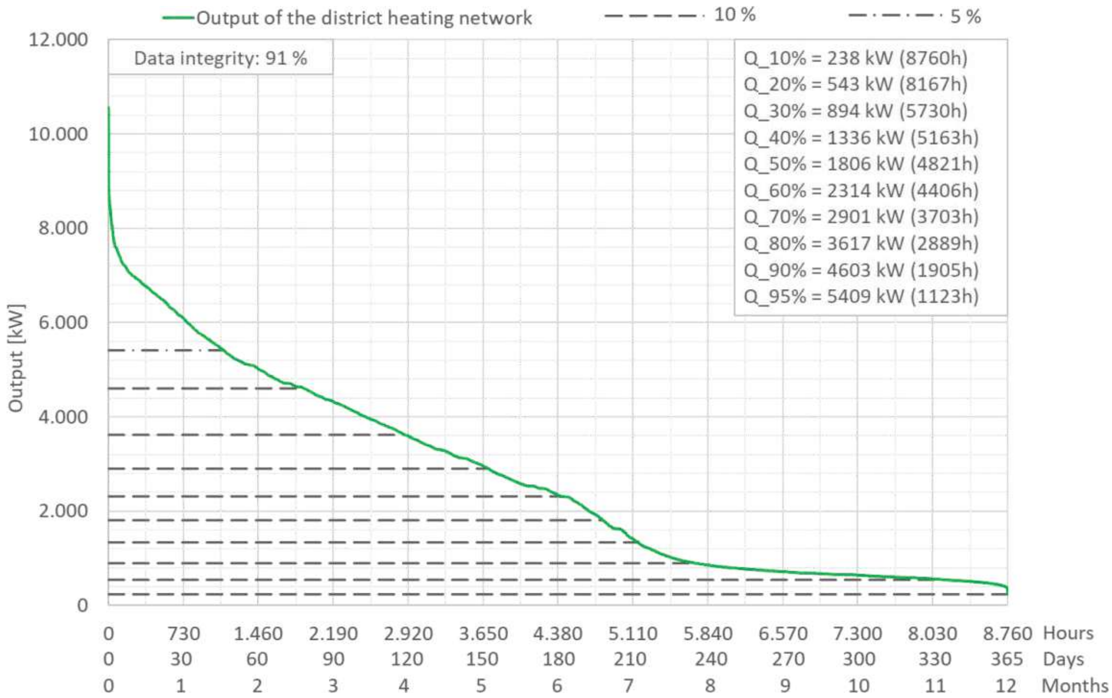
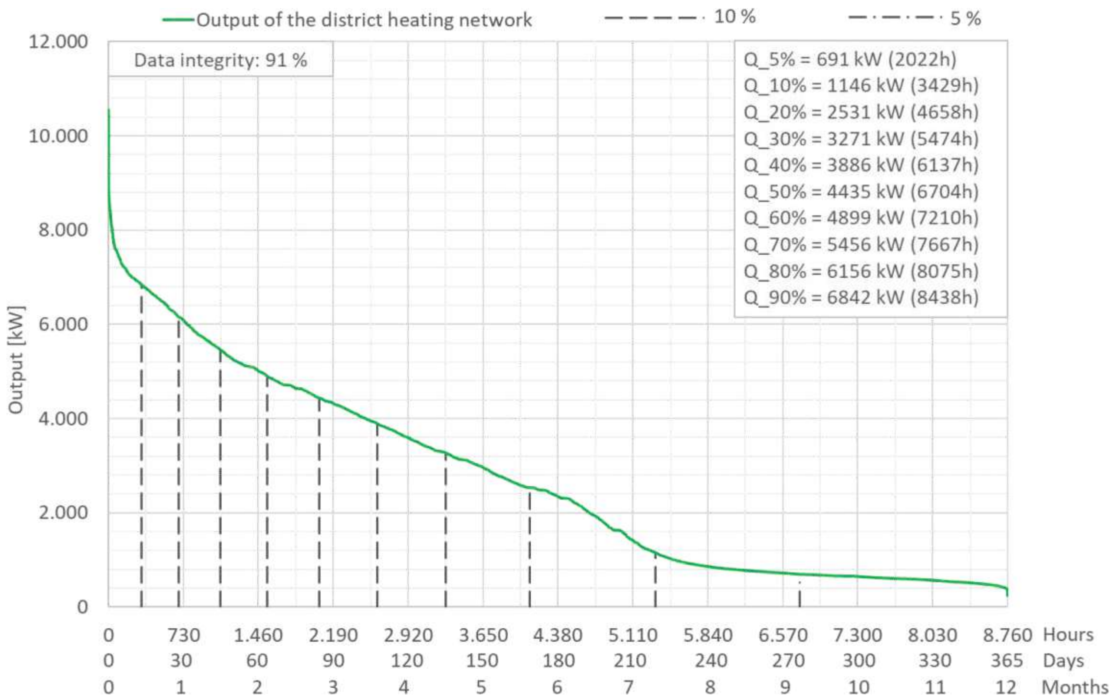


Appendix 15: Duration curve with horizontal subdivisions of the DHN in Haid [284]



Appendix 16: Duration curve with vertical subdivisions of the DHN in Haid [285]

[284] For the year 2023
[285] For the year 2023

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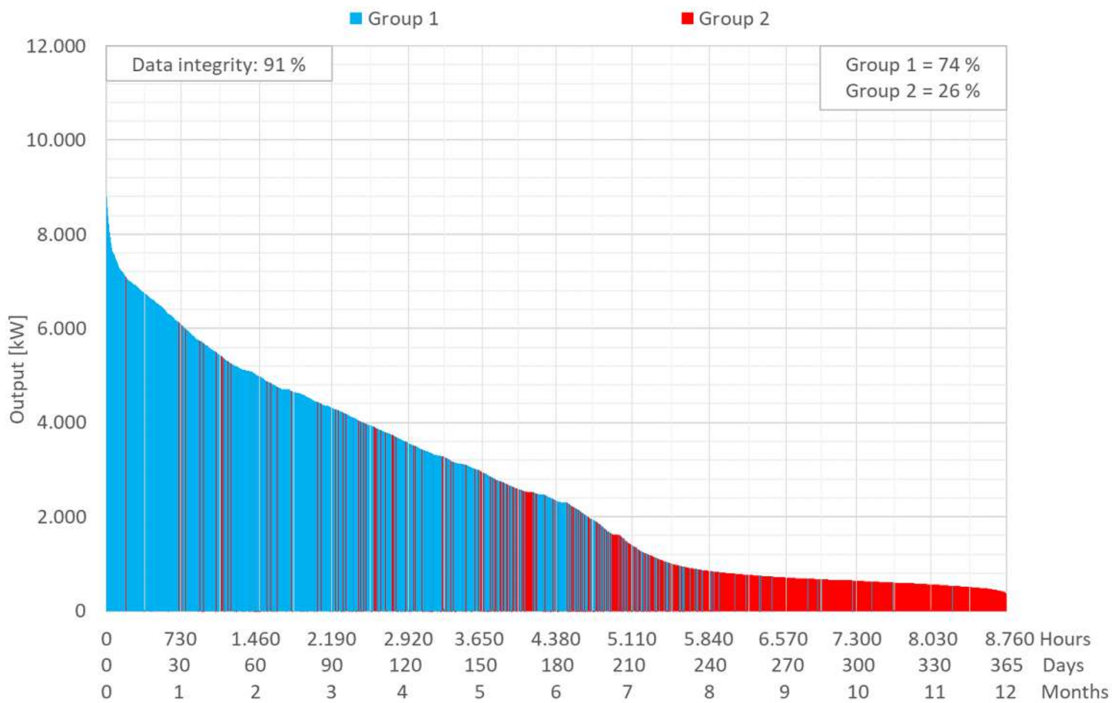
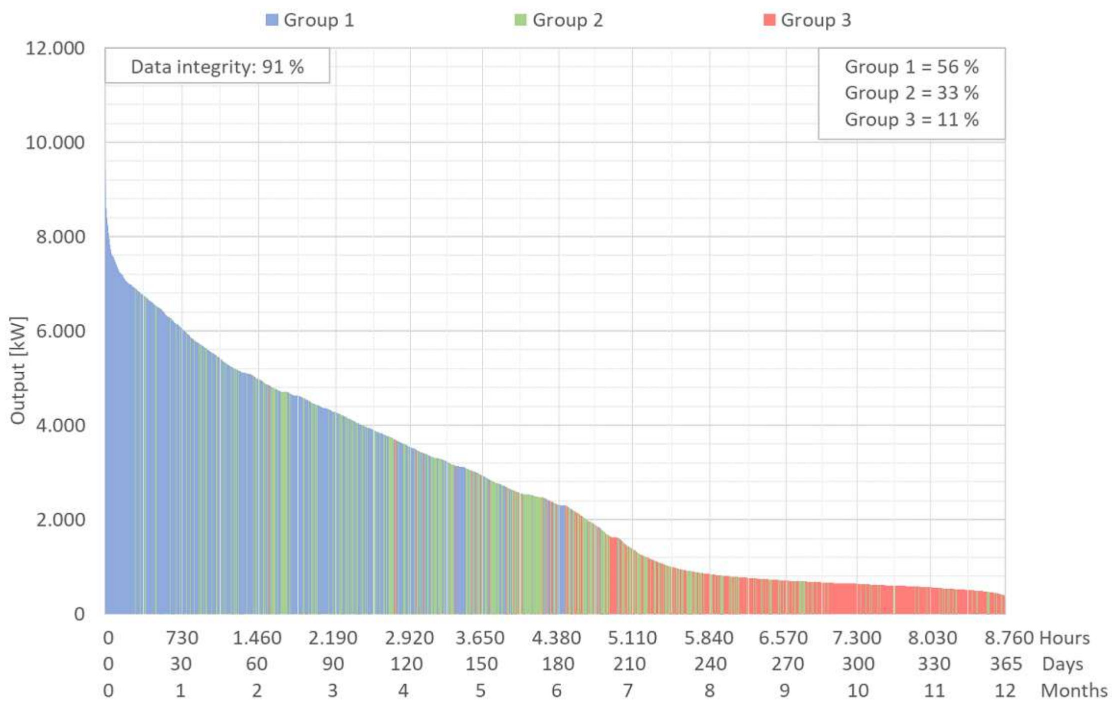


Appendix 17: Duration curve with dual-group allocation of the DHN in Haid [286]



Appendix 18: Duration curve with triple-group allocation of the DHN in Haid [287]

[286] For the year 2023
[287] For the year 2023

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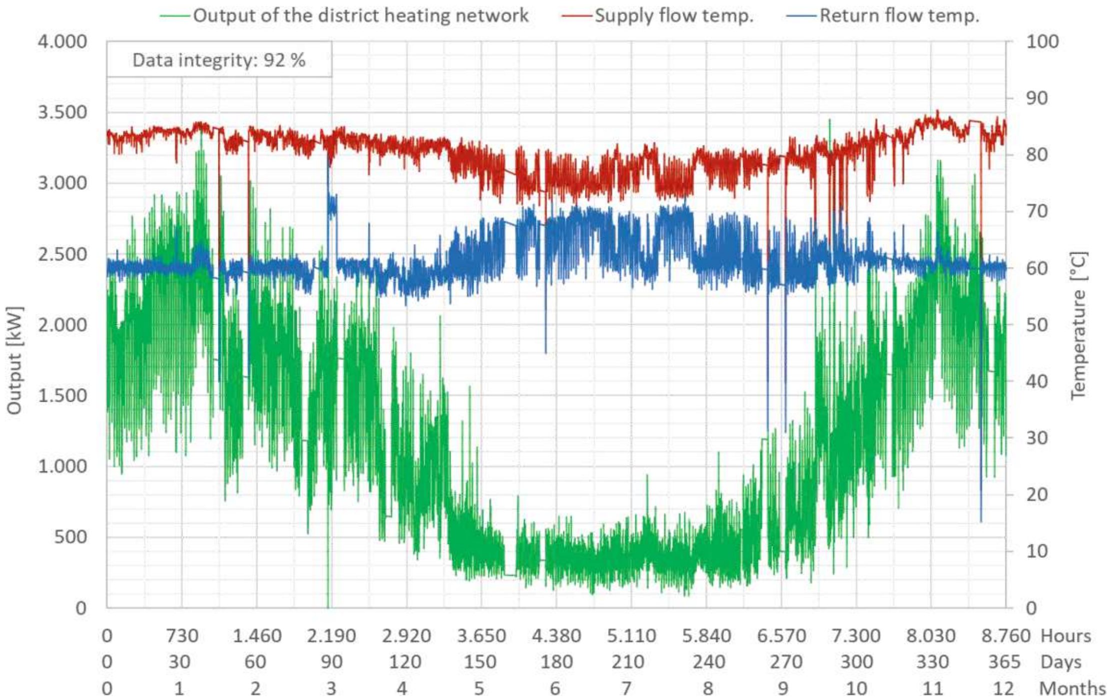
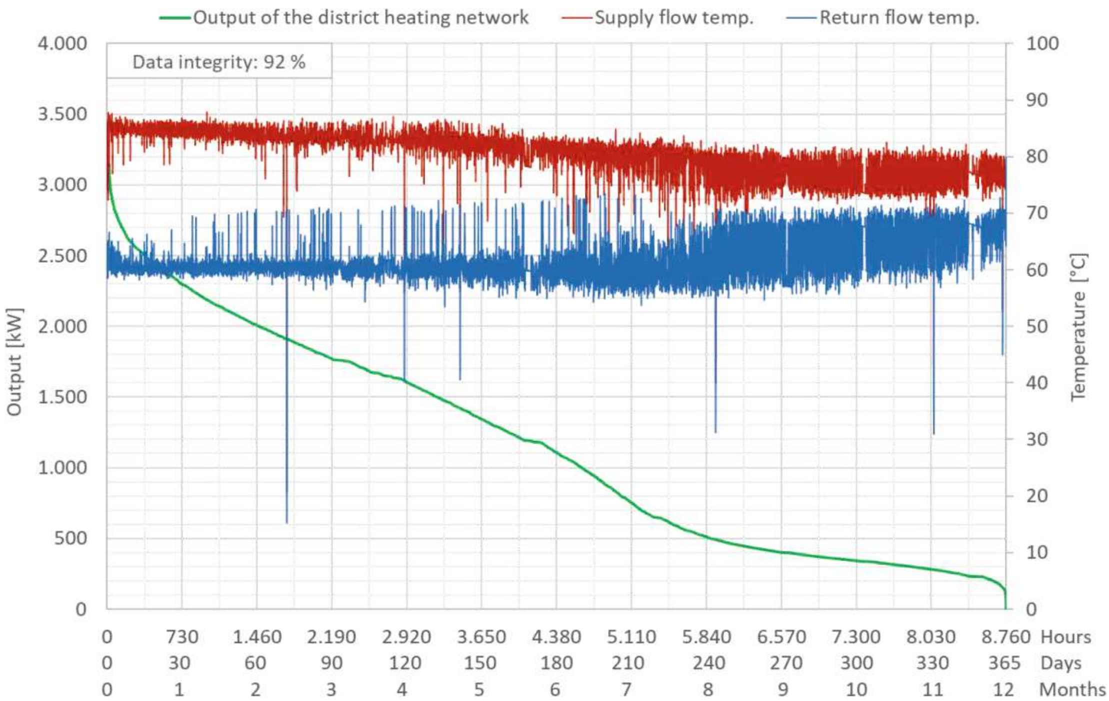


Appendix 19: Unsorted output and temperatures of the DHN in Marchtrenk [288]



Appendix 20: Sorted output and temperatures of the DHN in Marchtrenk [289]

[288] For the year 2023
[289] For the year 2023

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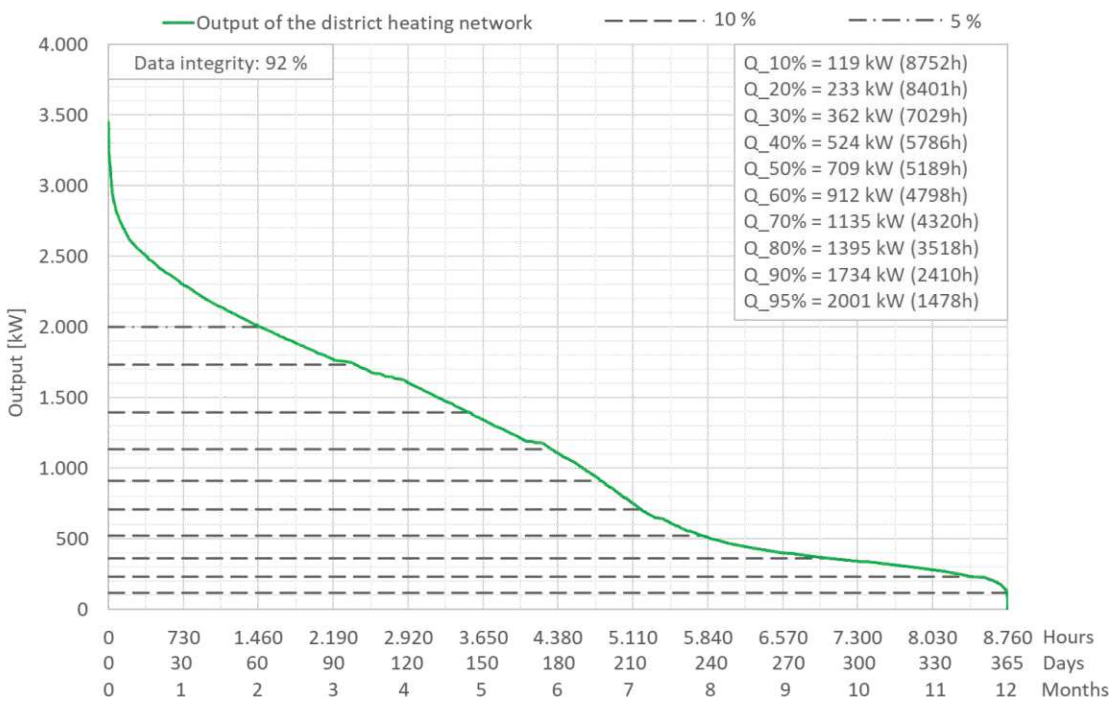
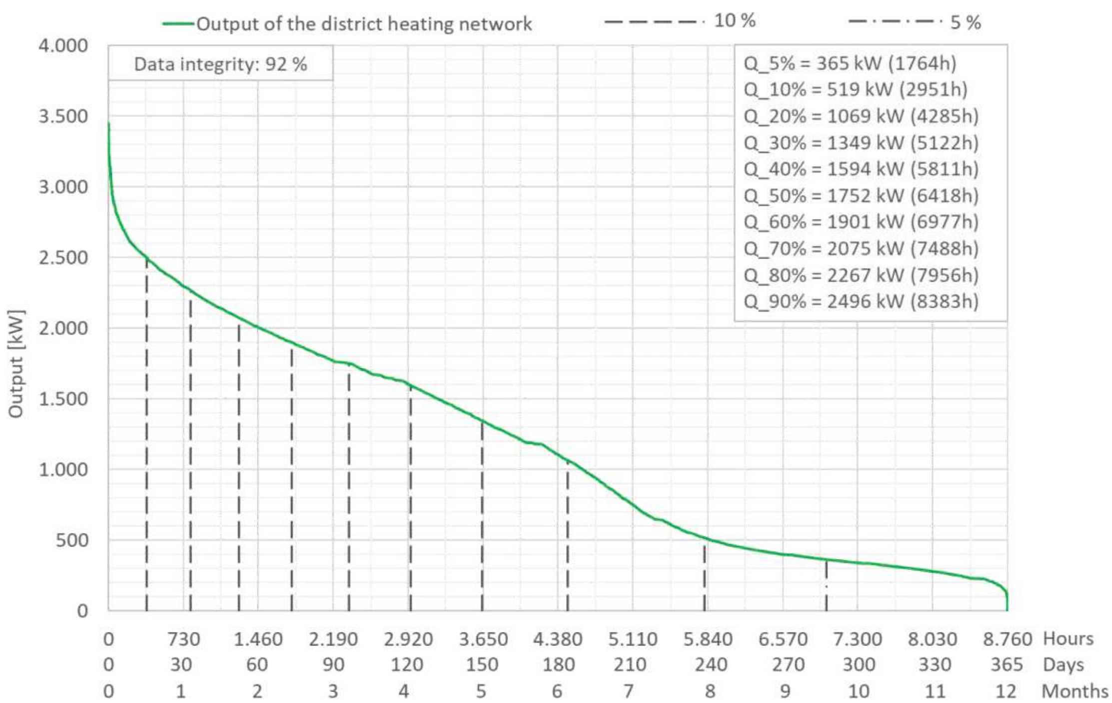


Appendix 21: Duration curve with horizontal subdivisions of the DHN in Marchtrenk [290]



Appendix 22: Duration curve with vertical subdivisions of the DHN in Marchtrenk [291]

[290] For the year 2023
[291] For the year 2023

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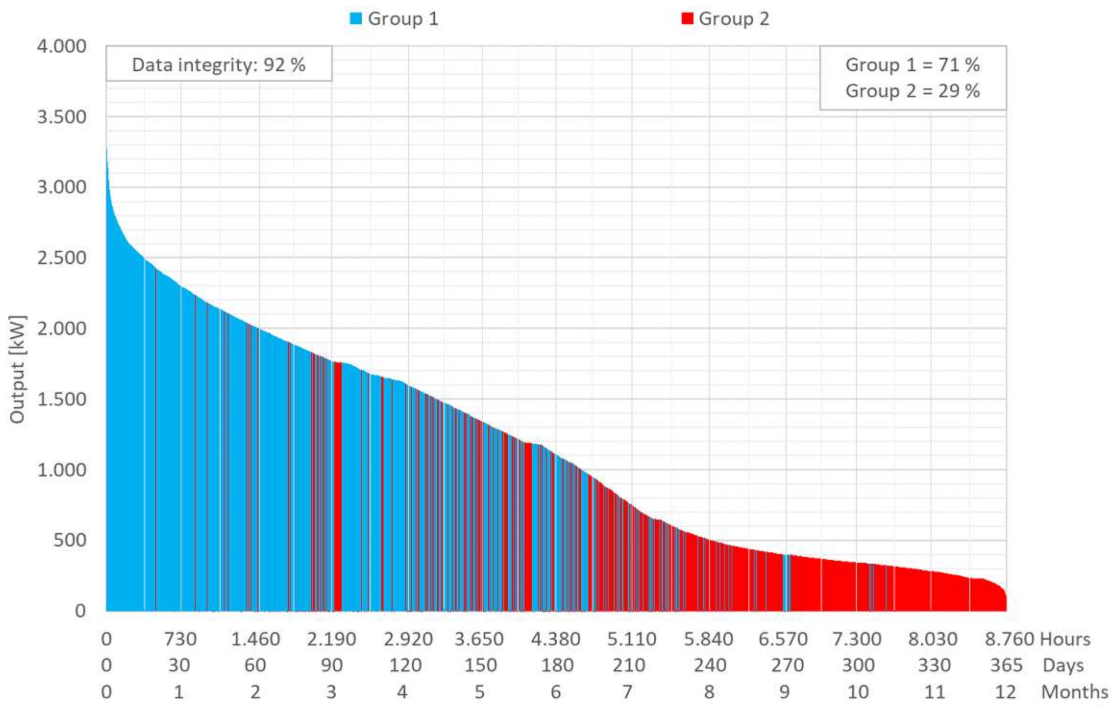
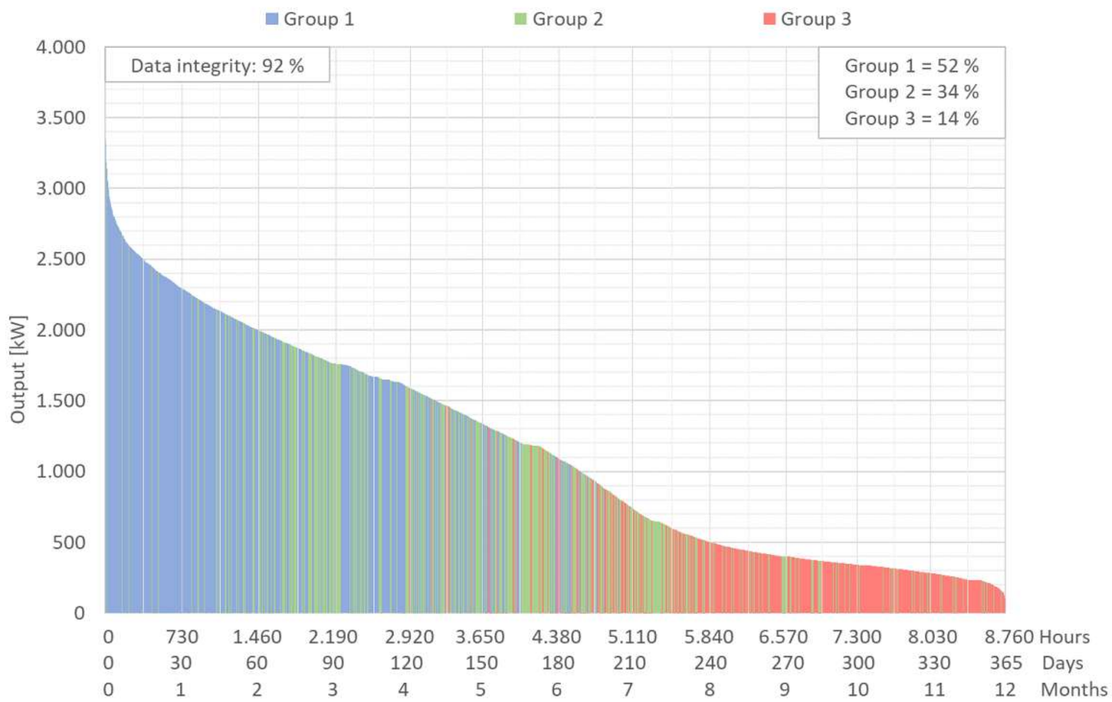


Appendix 23: Duration curve with dual-group allocation of the DHN in Marchtrenk [292]



Appendix 24: Duration curve with triple-group allocation of the DHN in Marchtrenk [293]

[292] For the year 2023
[293] For the year 2023

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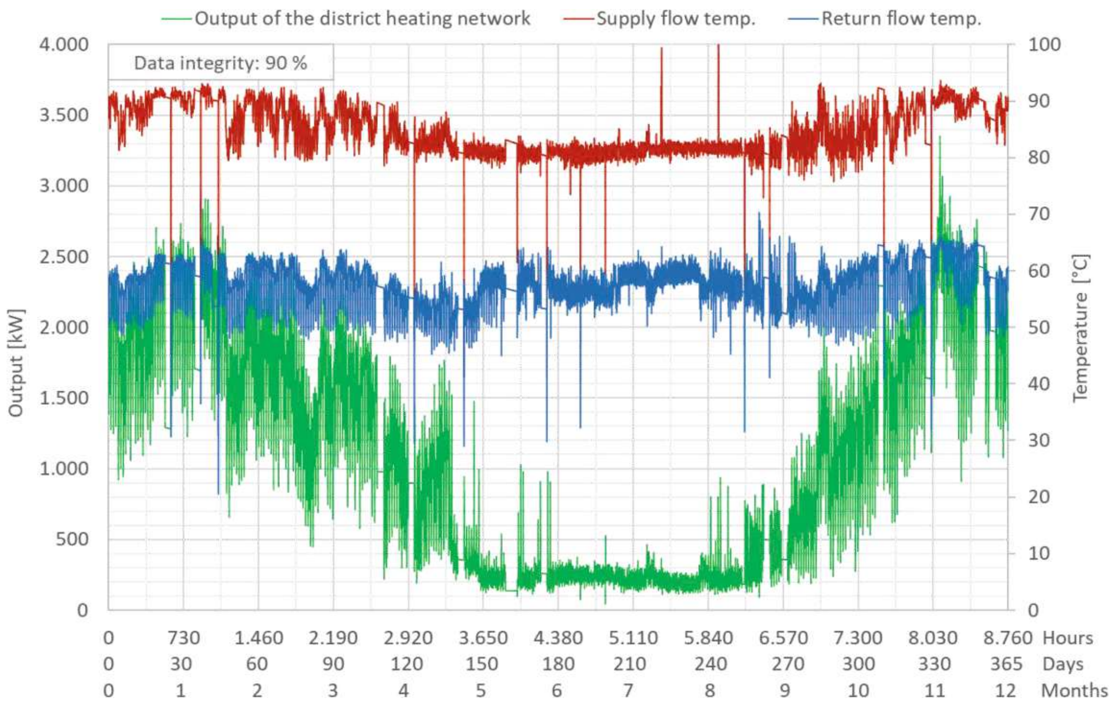
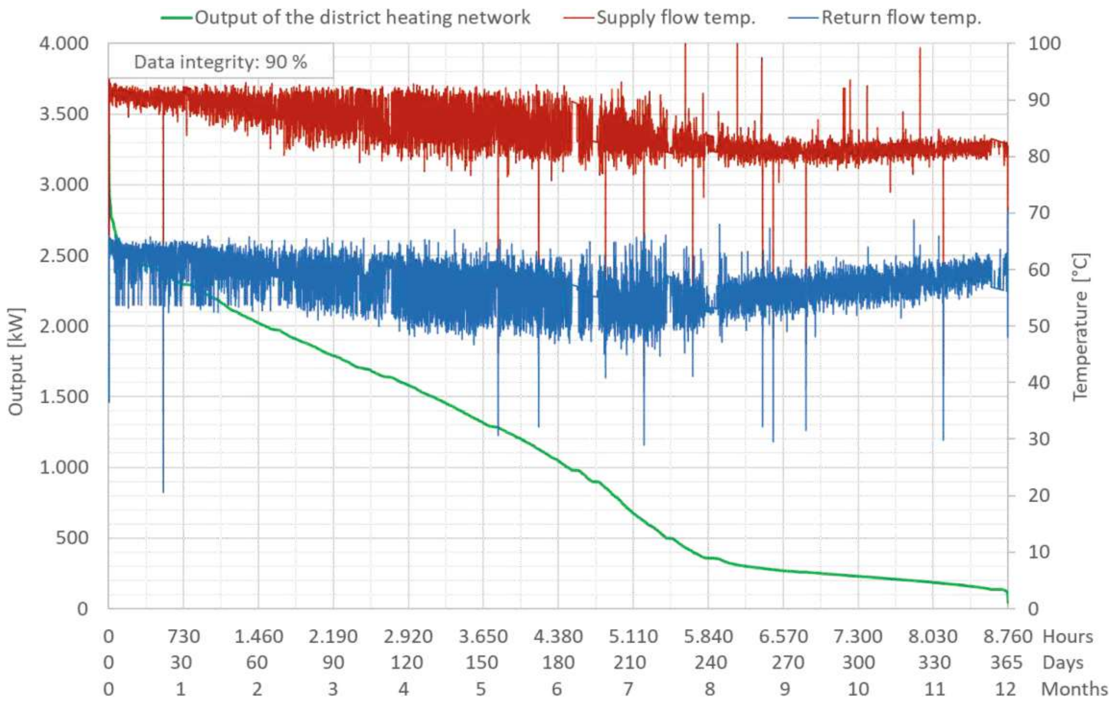


Appendix 25: Unsorted output and temperatures of the DHN in Puchenau [294]



Appendix 26: Sorted output and temperatures of the DHN in Puchenau [295]

[294] For the year 2023
[295] For the year 2023

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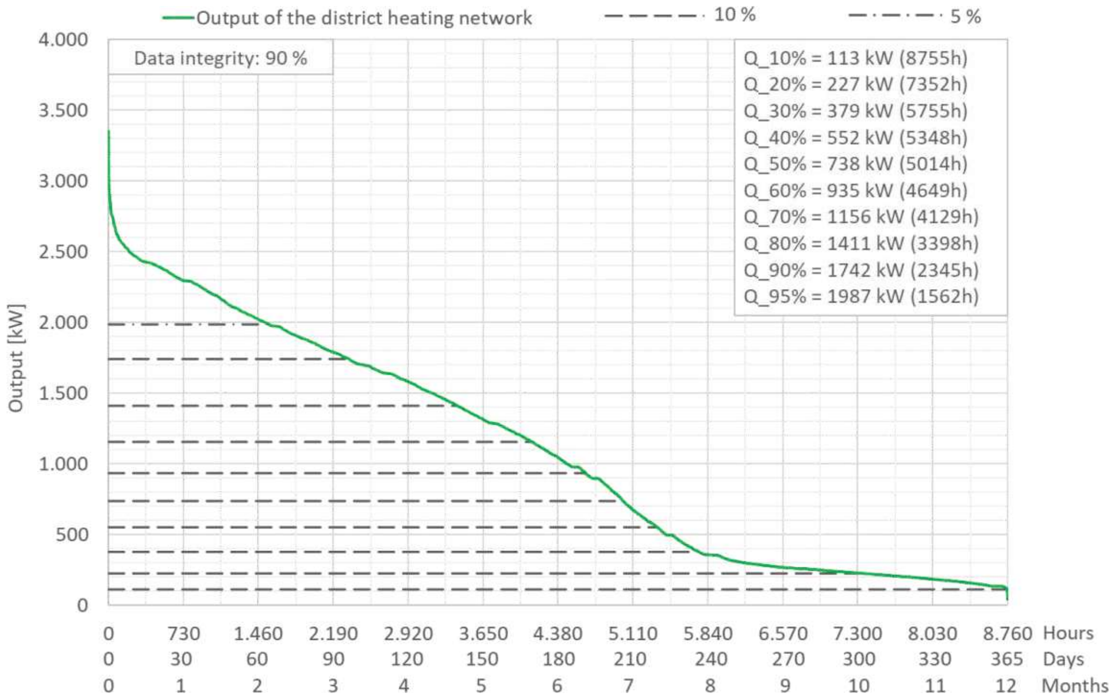
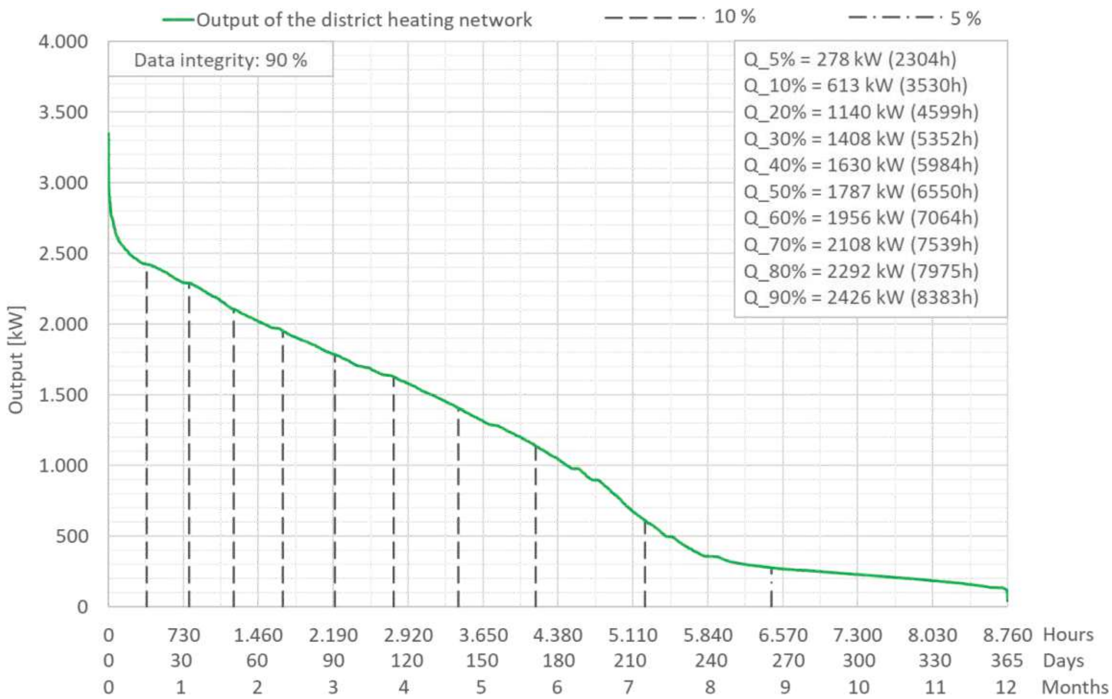


Appendix 27: Duration curve with horizontal subdivisions of the DHN in Puchenau [296]



Appendix 28: Duration curve with vertical subdivisions of the DHN in Puchenau [297]

[296] For the year 2023
[297] For the year 2023

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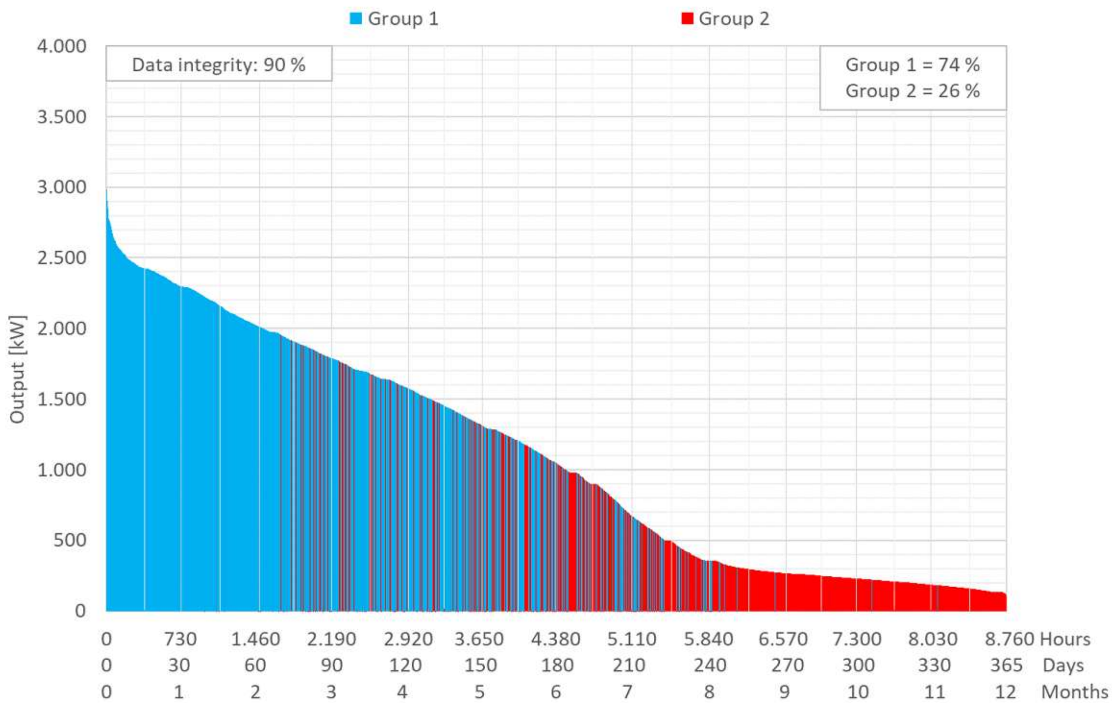
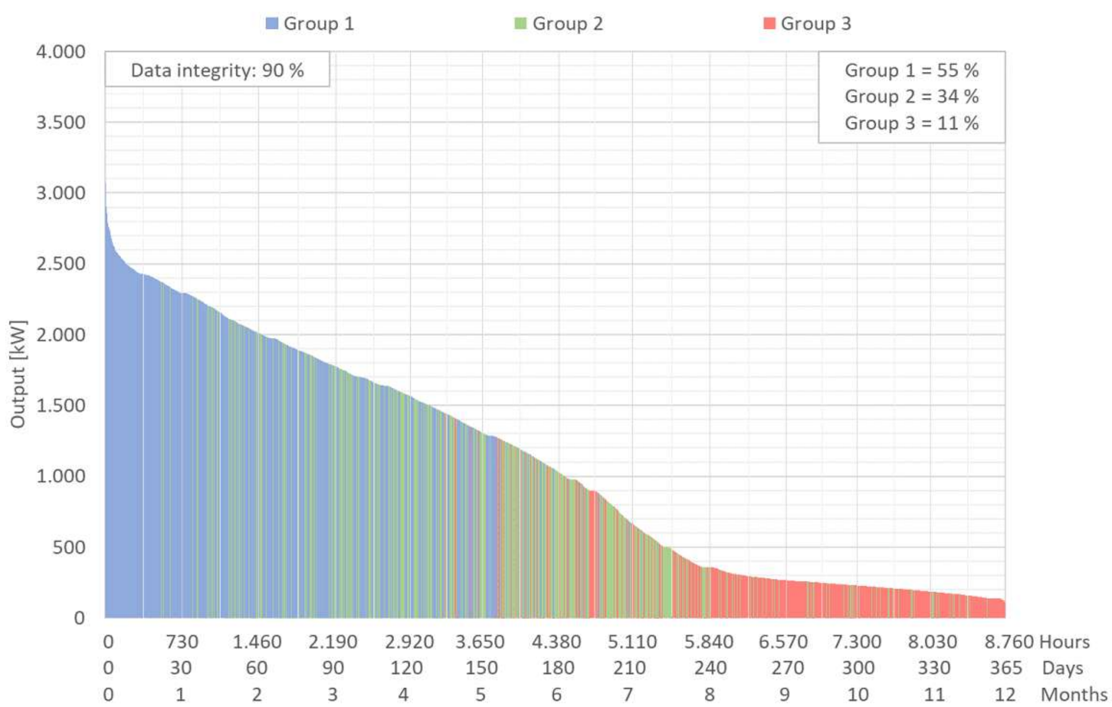


Appendix 29: Duration curve with dual-group allocation of the DHN in Puchenau [298]



Appendix 30: Duration curve with triple-group allocation of the DHN in Puchenau [299]

[298] For the year 2023
[299] For the year 2023

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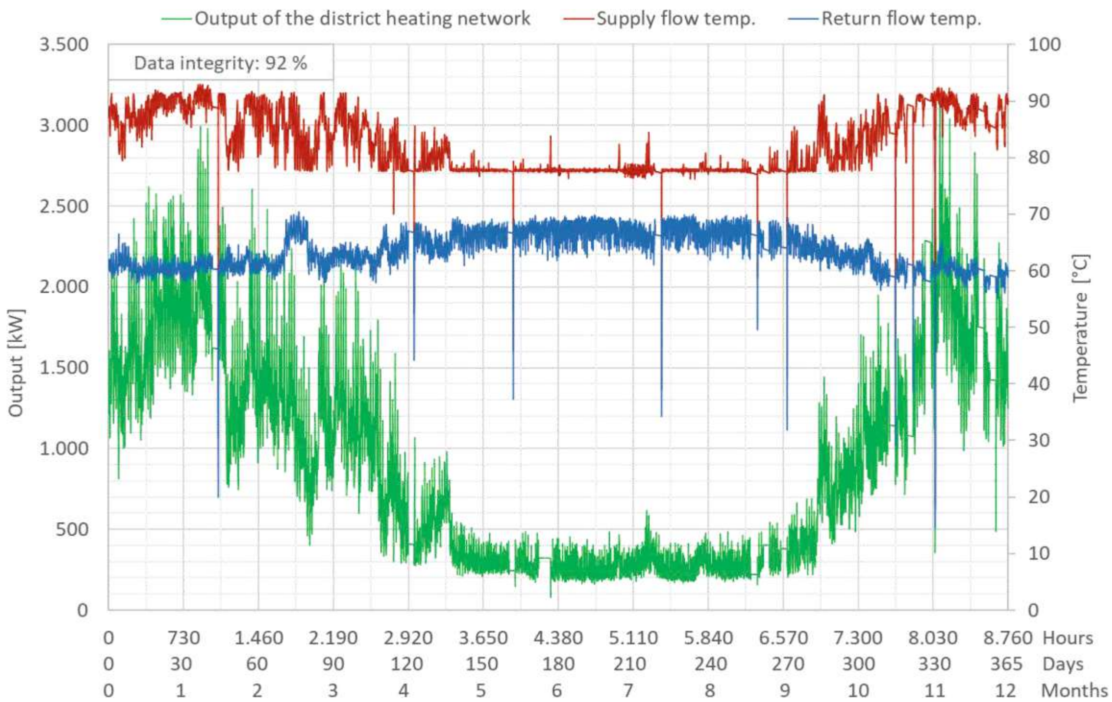
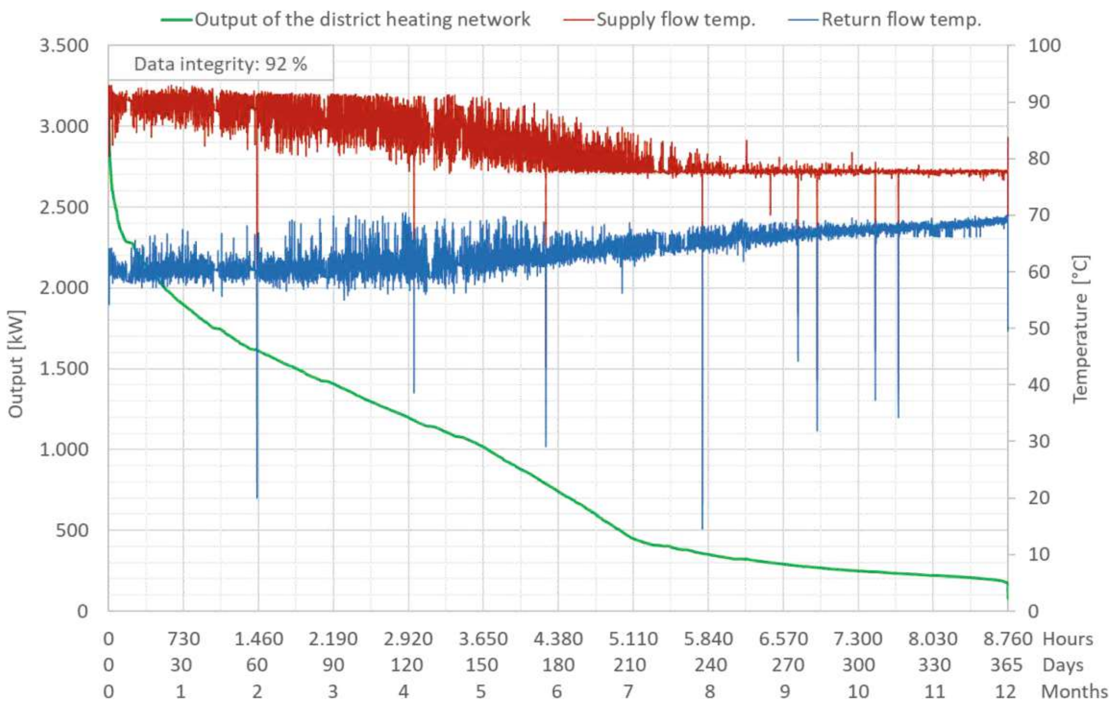


Appendix 31: Unsorted output and temperatures of the DHN in Steyregg [300]



Appendix 32: Sorted output and temperatures of the DHN in Steyregg [301]

[300] For the year 2023
[301] For the year 2023

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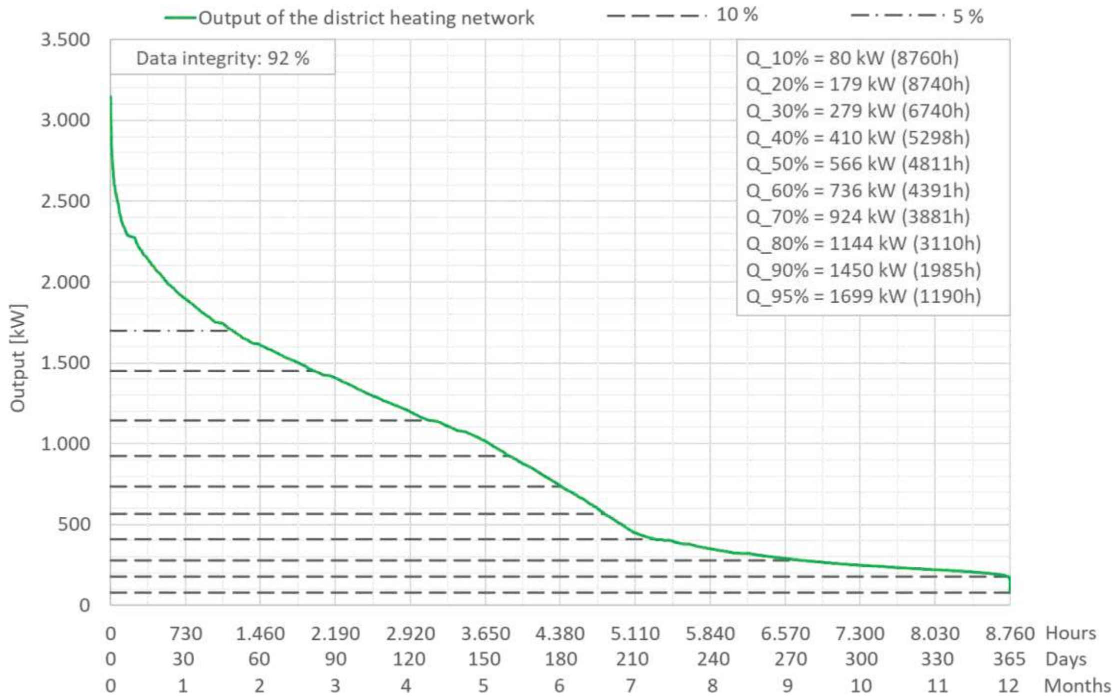
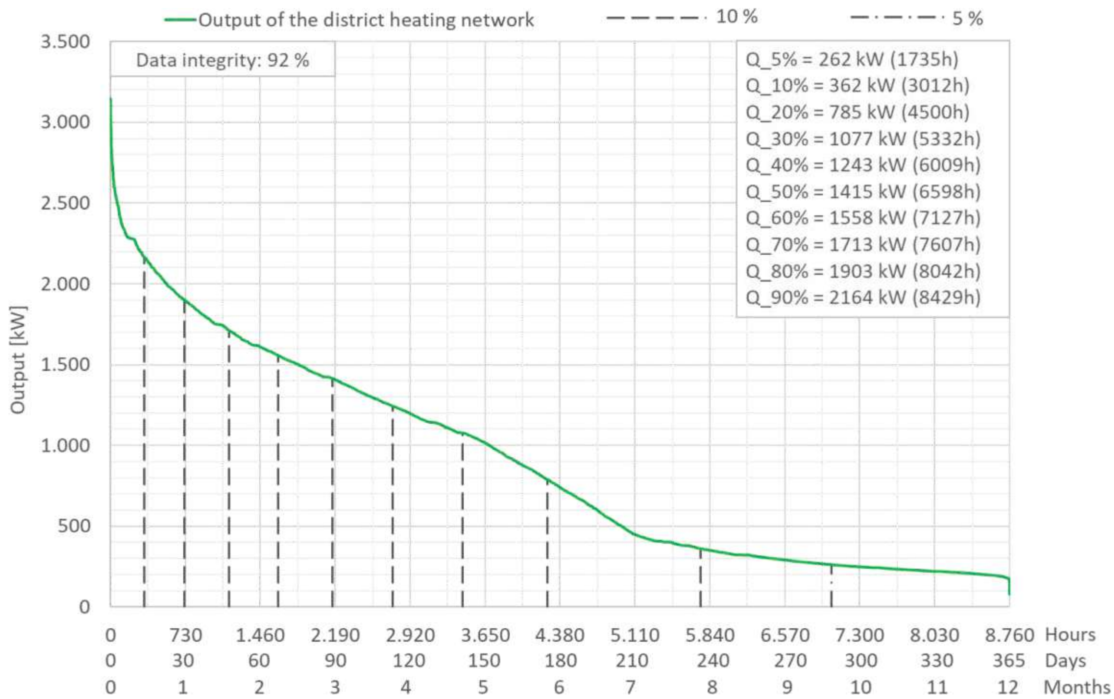


Appendix 33: Duration curve with horizontal subdivisions of the DHN in Steyregg [302]



Appendix 34: Duration curve with vertical subdivisions of the DHN in Steyregg [303]

[302] For the year 2023
[303] For the year 2023

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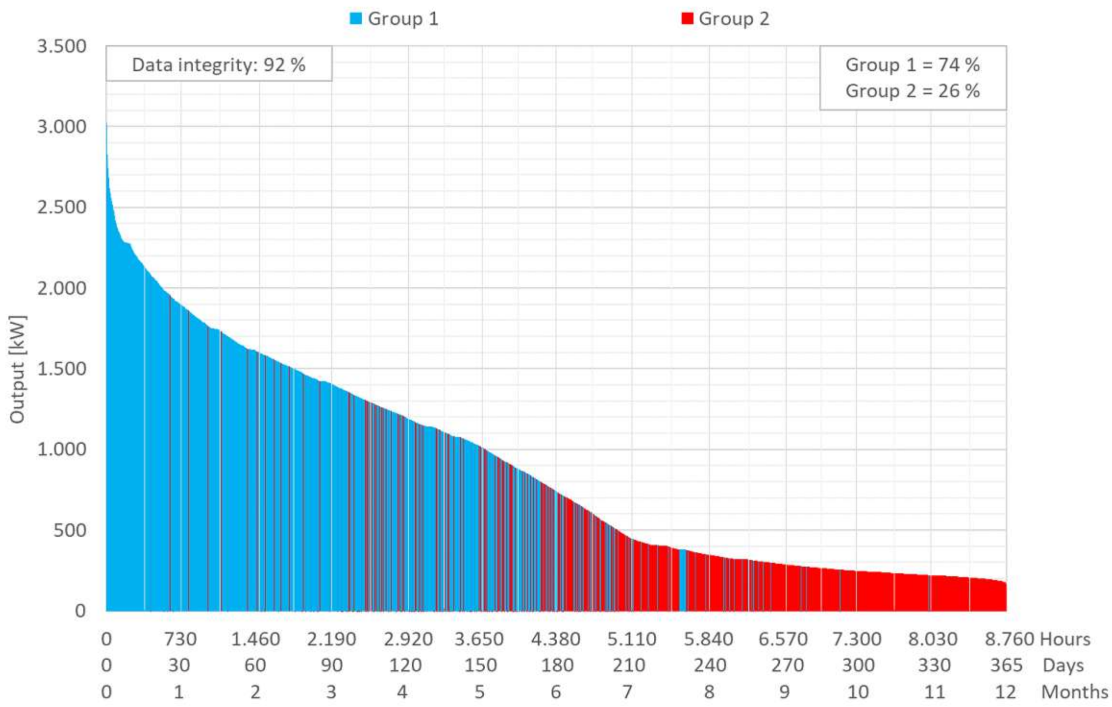
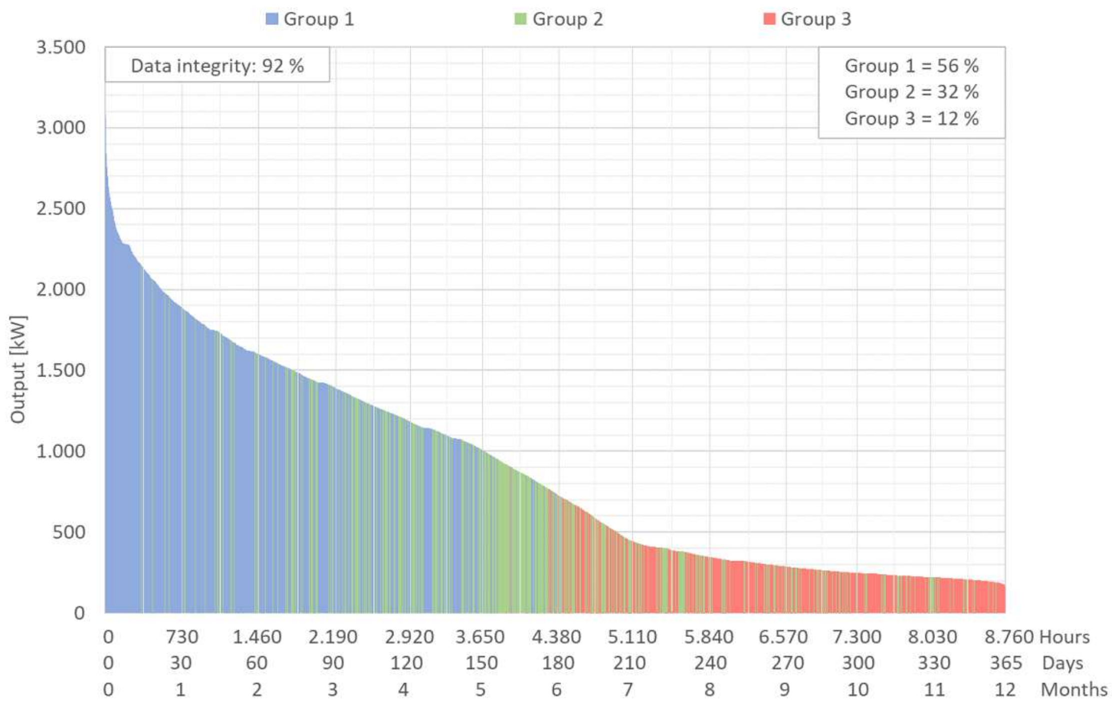


Appendix 35: Duration curve with dual-group allocation of the DHN in Steyregg [304]



Appendix 36: Duration curve with triple-group allocation of the DHN in Steyregg [305]

[304] For the year 2023
[305] For the year 2023

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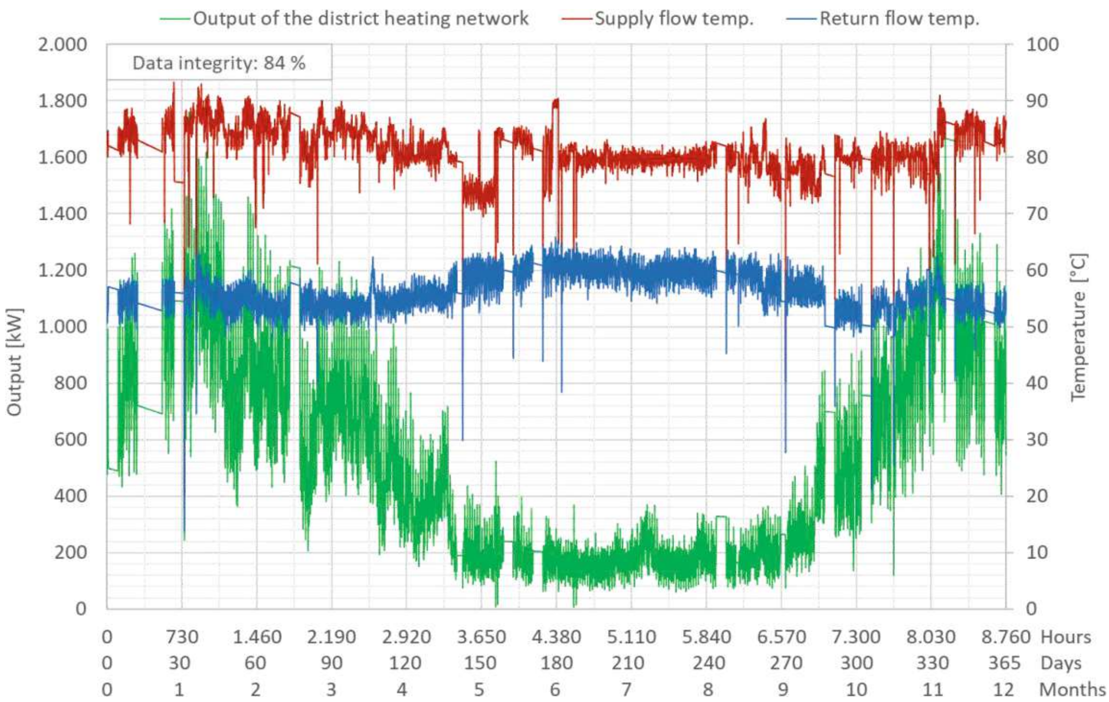
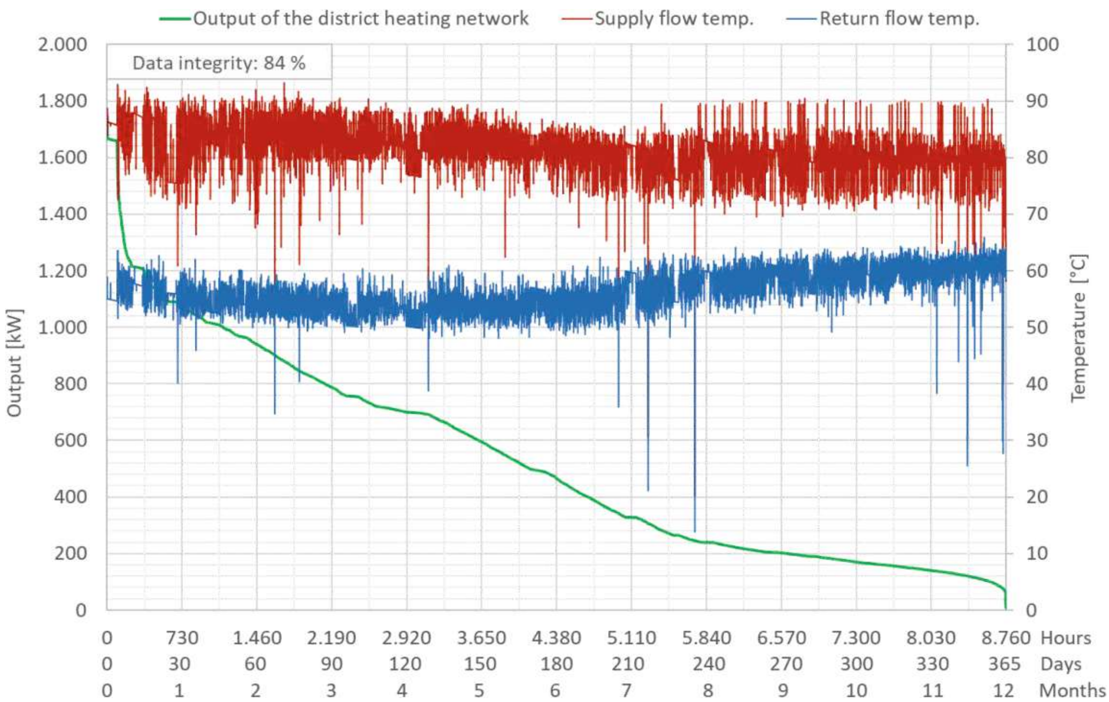


Appendix 37: Unsorted output and temperatures of the DHN in Tragwein [306]



Appendix 38: Sorted output and temperatures of the DHN in Tragwein [307]

[306] For the year 2023
[307] For the year 2023

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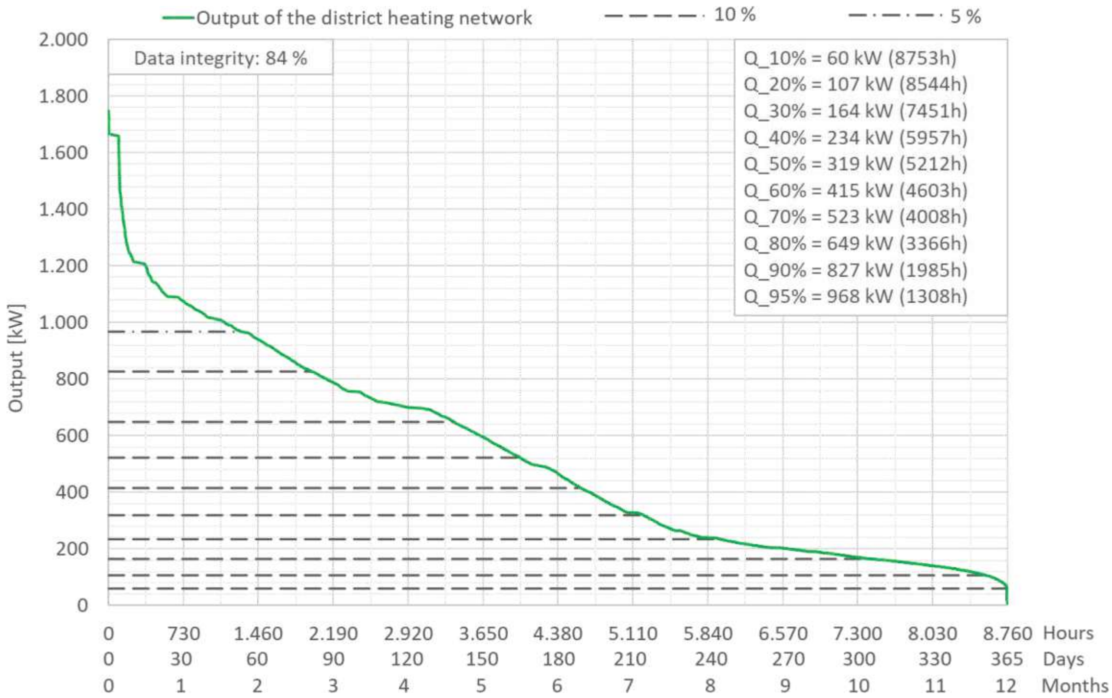
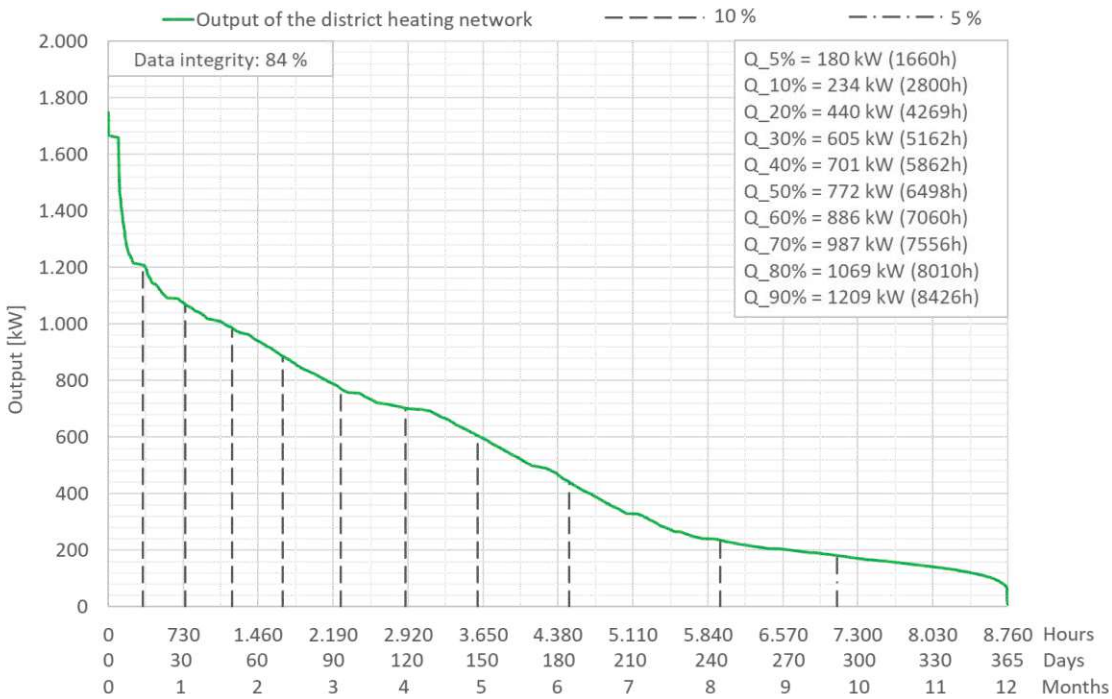


Appendix 39: Duration curve with horizontal subdivisions of the DHN in Tragwein [308]



Appendix 40: Duration curve with vertical subdivisions of the DHN in Tragwein [309]

[308] For the year 2023
[309] For the year 2023

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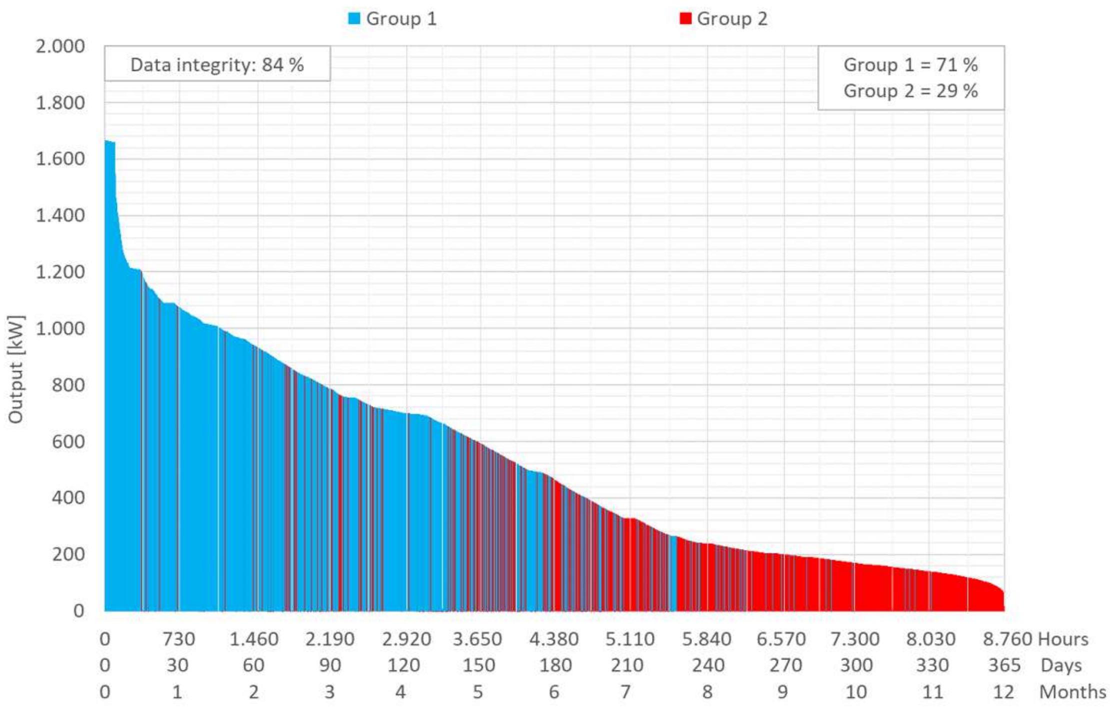
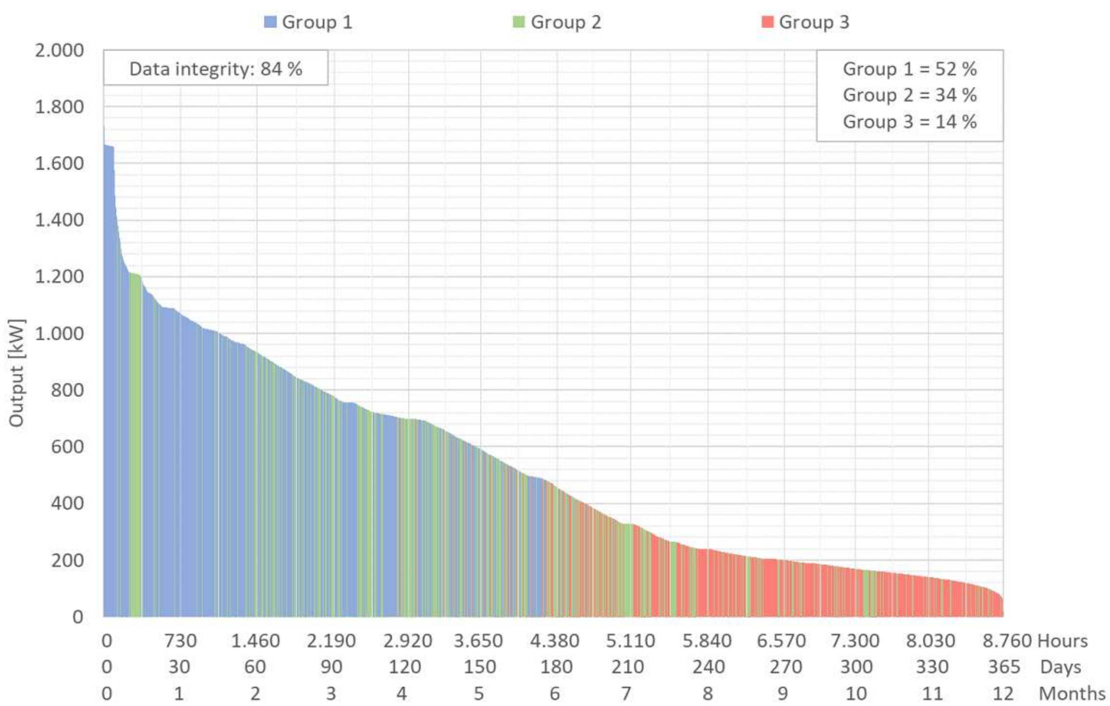


Appendix 41: Duration curve with dual-group allocation of the DHN in Tragwein [310]



Appendix 42: Duration curve with triple-group allocation of the DHN in Tragwein [311]

[310] For the year 2023
[311] For the year 2023

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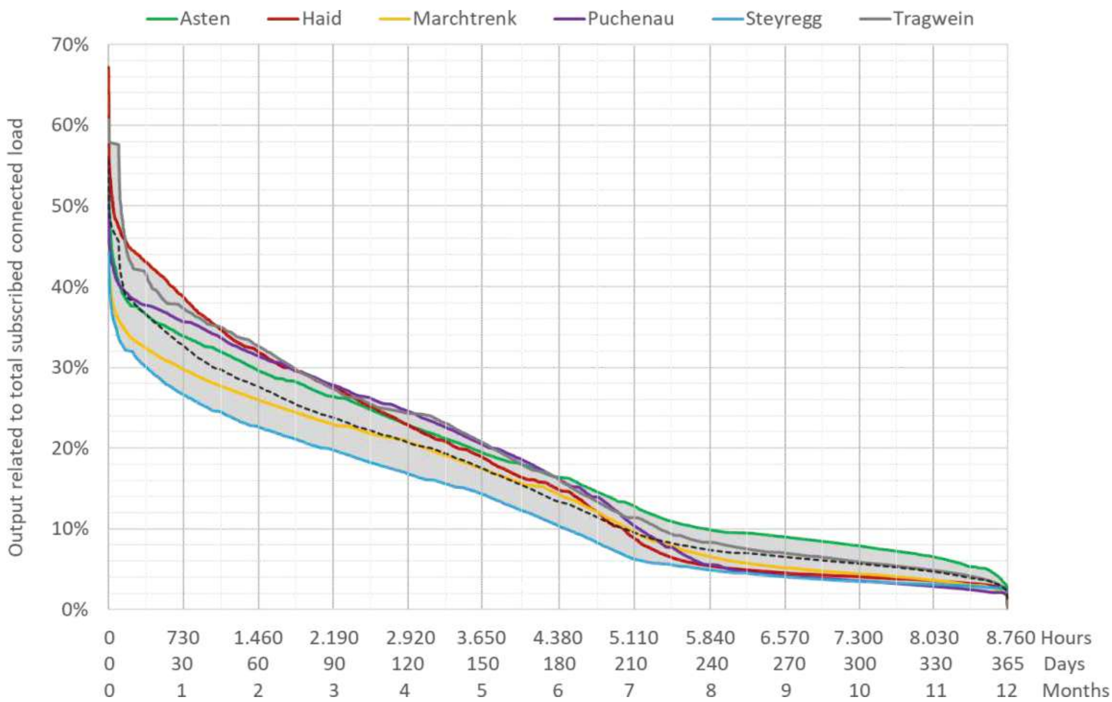
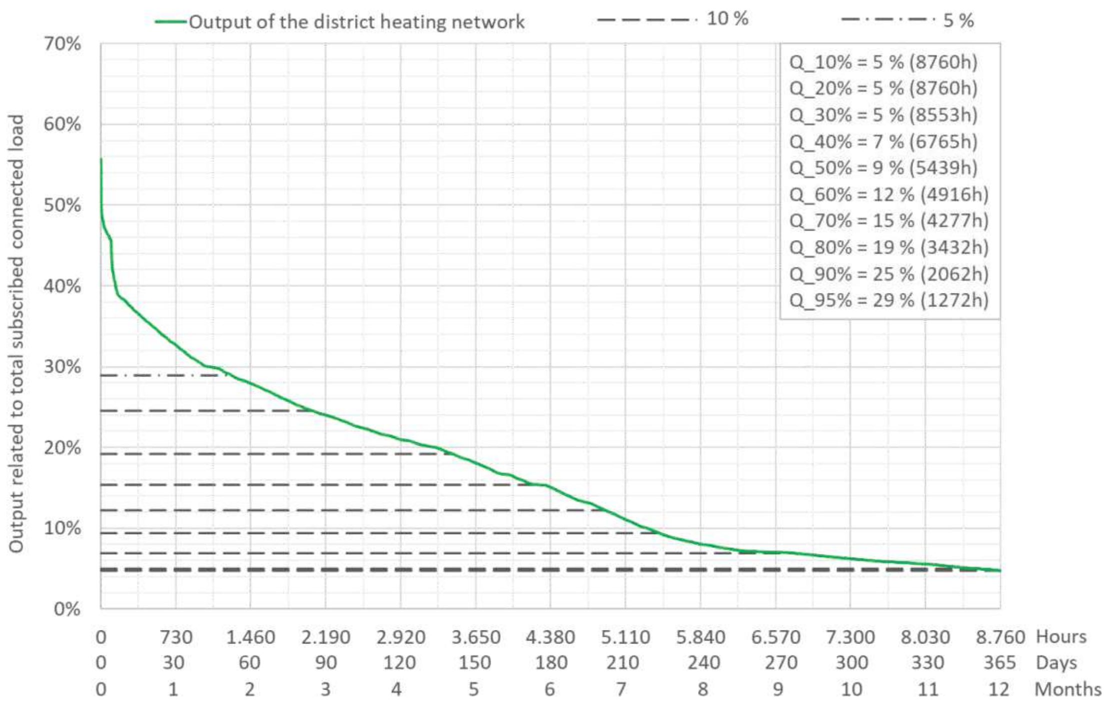


Appendix 43: Relative duration curve of different district heating networks [312]



Appendix 44: Mean relative duration curve with horizontal subdivisions [313]

[312] Measured output related to total subscribed connection load, for the year 2023

[313] Measured output related to total subscribed connection load, for the year 2023

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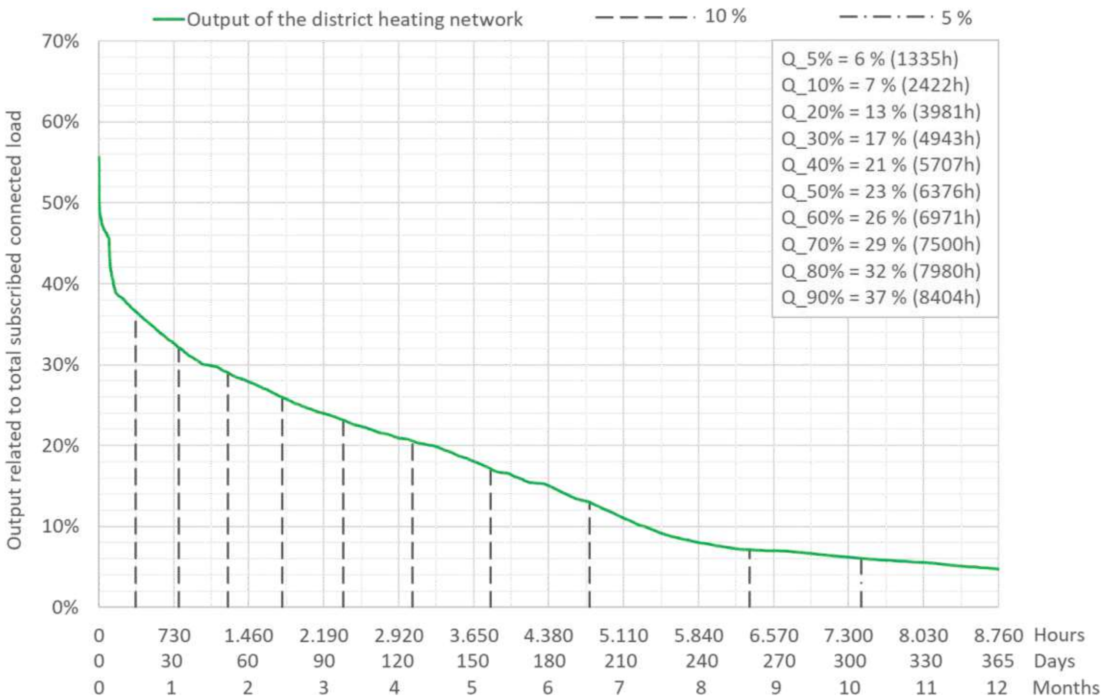

Appendix 45: Mean relative duration curve with vertical subdivisions [314]

[314] Measured output related to total subscribed connection load, for the year 2023

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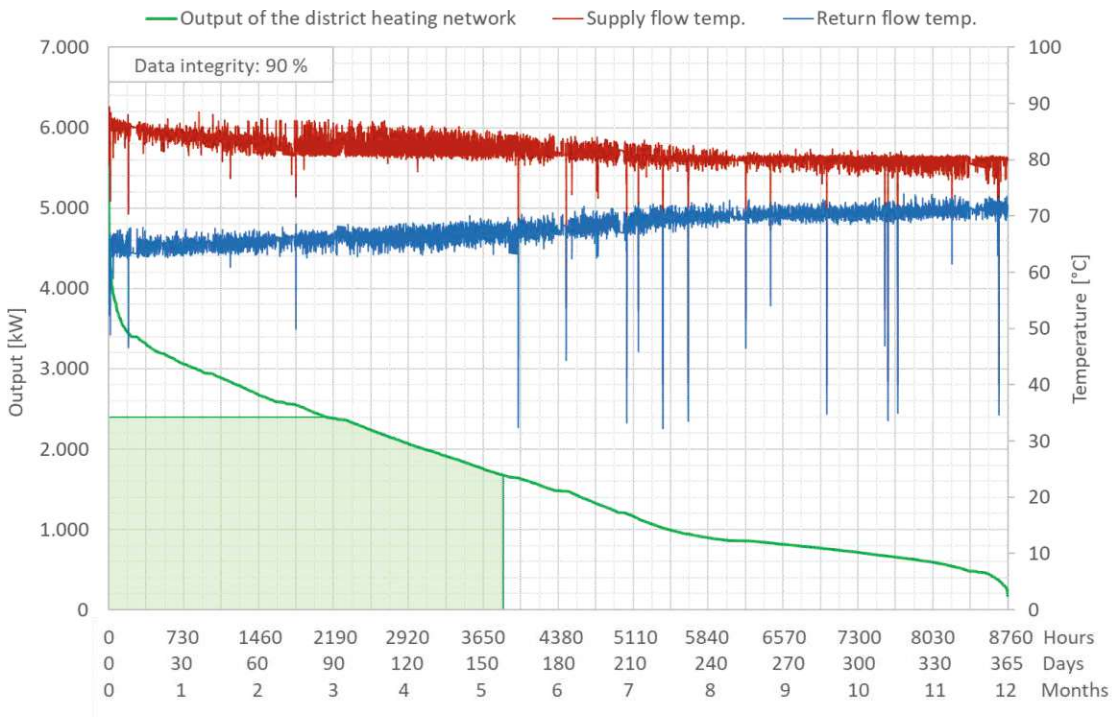
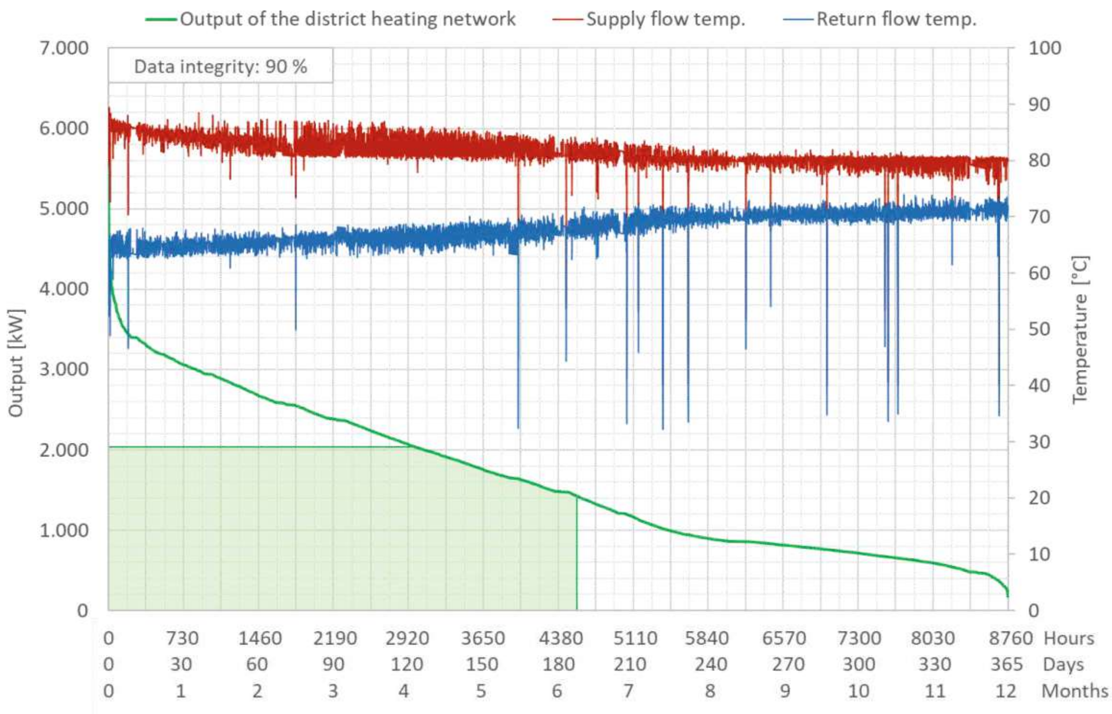


Appendix 46: Exemplary operation of the biomass pyrolysis plant – PYREG [315]



Appendix 47: Exemplary operation of the biomass CHP plant – PYREG [316]

[315] Annual duration curve of the year 2023 with PYREG PX6000, FLH = 3.600 h
[316] Annual duration curve of the year 2023 with PYREG PX6000 CHP, FLH = 4.320 h

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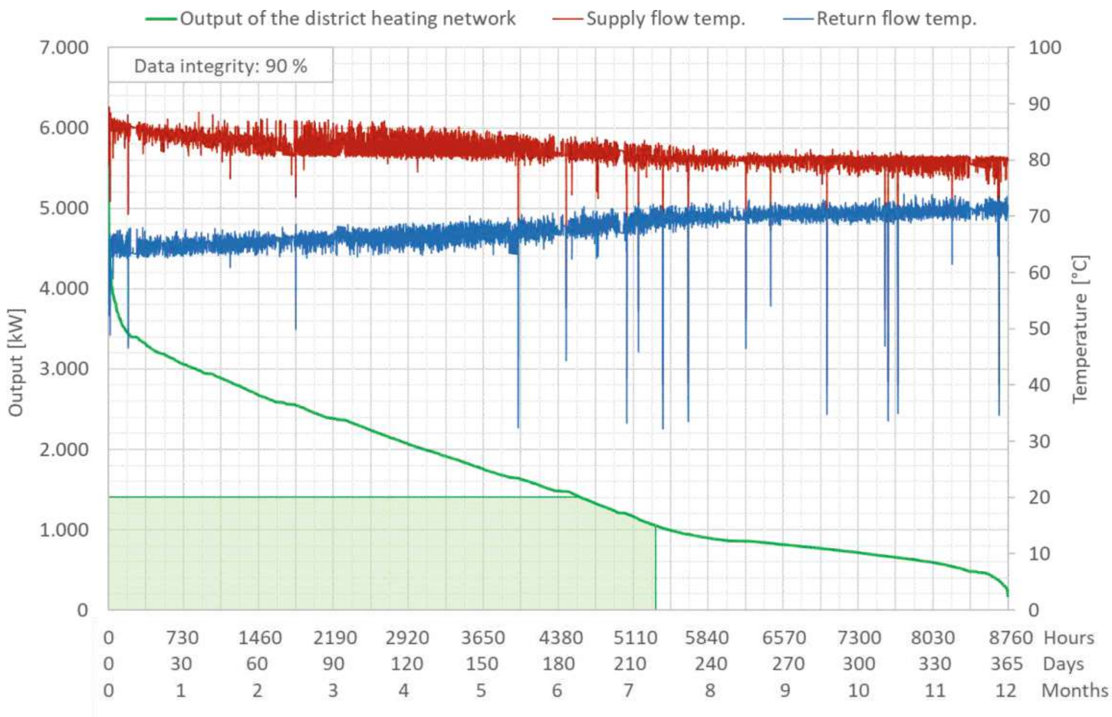
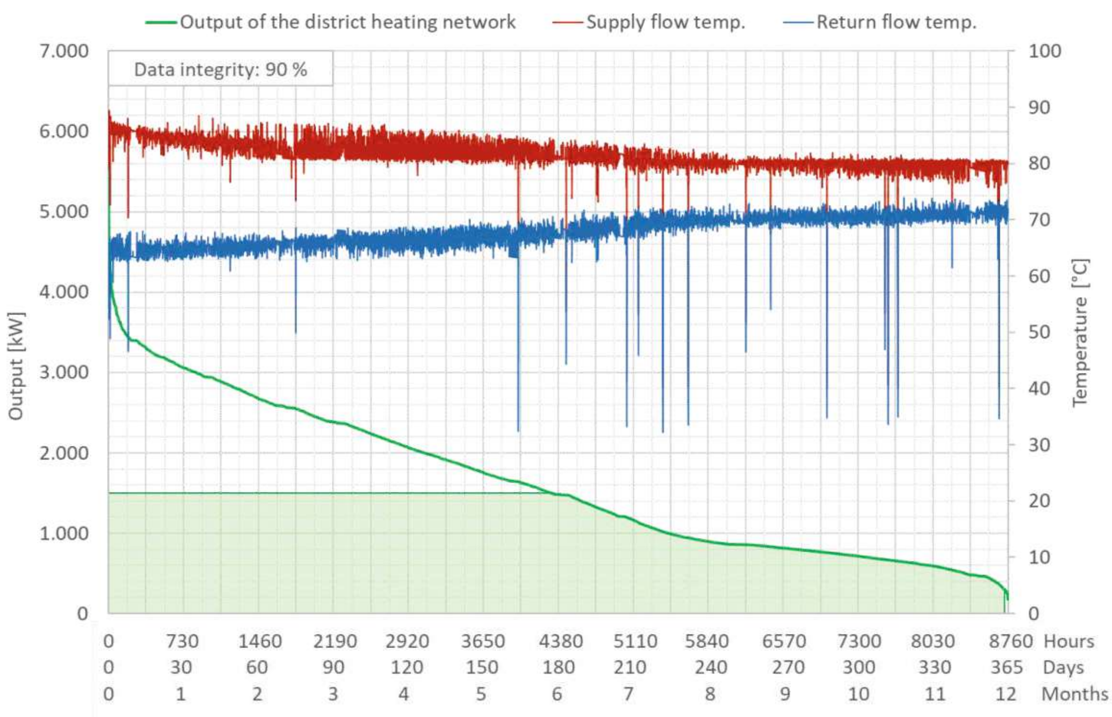


Appendix 48: Exemplary operation of the biomass CHP plant – SYNCRAFT [317]



Appendix 49: Exemplary operation of the biomass CHP plant – STEAMERGY [318]

[317] Annual duration curve of the year 2023 with SYNCRAFT 2 x CW1800-500, FLH = 5.240 h
[318] Annual duration curve of the year 2023 with STEAMERGY with 2 engines, FLH = 6.850 h

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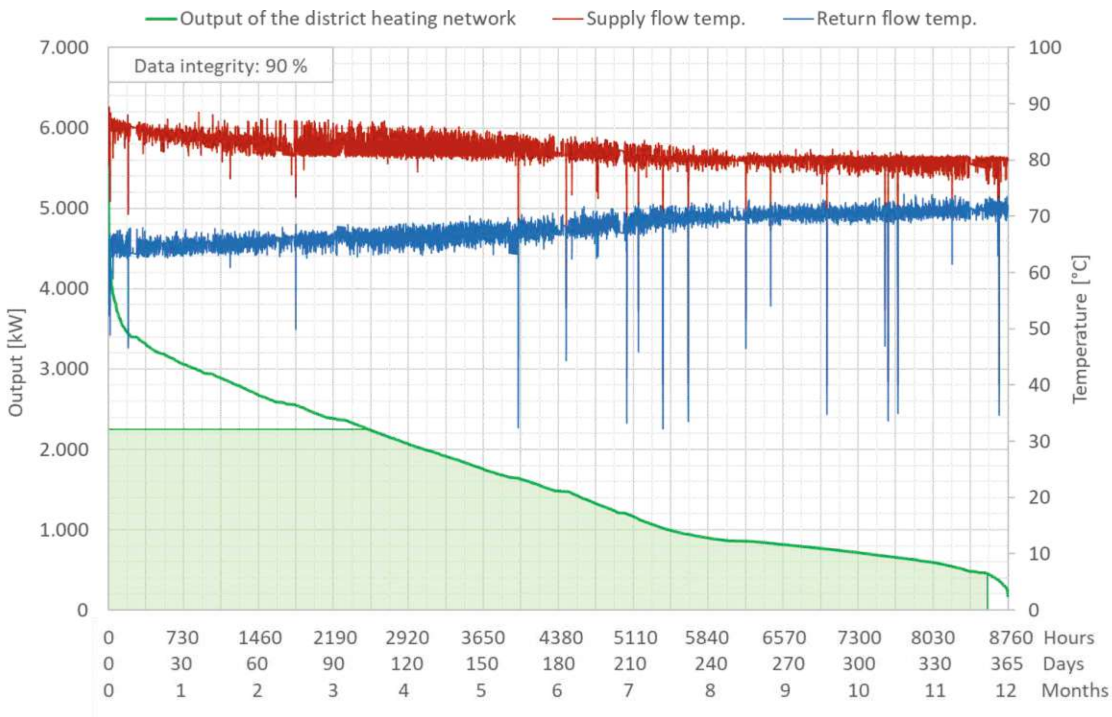
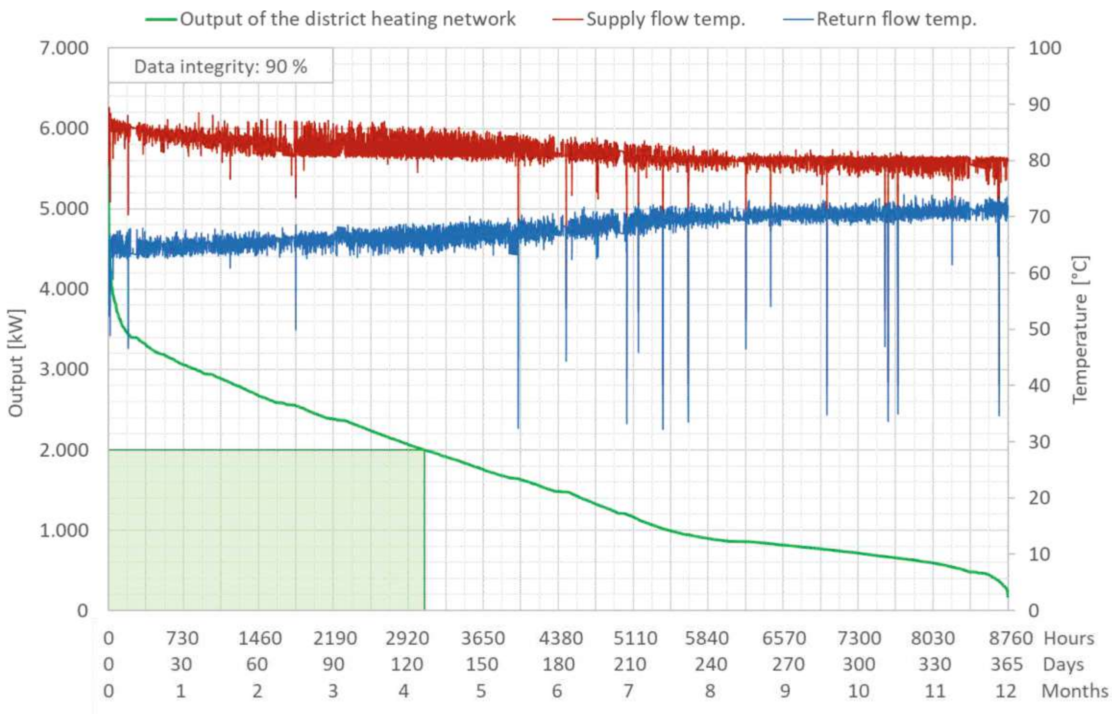


Appendix 50: Exemplary operation of the biomass CHP plant – STEAMERGY [319]



Appendix 51: Exemplary operation of the electric boiler system – control reserve [320]

[319] Annual duration curve of the year 2023 with STEAMERGY with 3 engines, FLH = 5.670 h
[320] Annual duration curve of the year 2023 for electric boiler with 2.000 kW, FLH = 3.080 h

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