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Techno-economic analysis on wind thermal energy converters and renewable heating technologies for process heat in Germany

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Abstract

Process heat accounts for one-sixth of the EU28's final energy consumption. Currently, industrial processes mostly rely on conventional heating systems such as combustion boilers. With the urge to mitigate climate change, German regulators introduced a carbon pricing mechanism, which gradually increases prices for fossil fuels in all sectors.

This thesis investigates alternative heating technologies for low- and medium-temperature process heat, potentially substituting combustion boilers and reducing the industrial carbon footprint. The chosen methodology was the techno-economic analysis. First, the technologies were identified and described; second, their levelized cost of heat was calculated; third, the Analytic Hierarchy Process was applied to determine the best technologies under given criteria.

The levelized cost of heat calculation proves that renewable heating technologies such as solar thermal systems, wind thermal energy converters, and electric heating systems can perform similar or better than fuel-based heating systems.

Based on the Analytic Hierarchy Process, it was concluded that combustion boilers are the most favorable heating technology closely followed by electric heating systems. However, depending on the use case and available renewable energy sources, renewable electricity or a hybrid system consisting of solar thermal and wind thermal converters are alternatives for conventional heating systems.

DECLARATION

I hereby confirm that this thesis is entirely my own work. I confirm that no part of the document has been copied from either a book or any other source – including the internet – except where such sections are clearly shown as quotations, and the sources have been correctly identified within the text or in the list of references. Moreover, I confirm that I have taken notice of the ‘Leitlinien guter wissenschaftlicher Praxis’ of the University of Oldenburg.

Oldenburg, 31st July 2021

Robin Adriano Marques Pais

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ABBREVIATIONS

AHP	Analytic Hierarchy Process
BEHG	Brennstoffemissionshandelsgesetz
CF	Capacity factor
CHTech	Conventional heating technology
DNI	Direct normal irradiance
EU28	The 28 member states of the European Union
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
LTPH	Low-temperature process heat
MTPH	Medium-temperature process heat
RE	Renewable energy
RHTech	Renewable heating technology
TEA	Techno-economic analysis
WTESS	Wind thermal energy storage system
WTESS-RET	Wind thermal energy storage system retarder
WTESS-MHP	Wind thermal energy storage system mechanical heat pump

1 Introduction

1.1 Motivation

Earth's climate is changing. And it is changing at a pace, which is projected to become a significant threat to humanity. The Intergovernmental Panel for Climate Change (IPCC) assesses the science related to climate change. In 2014 the IPCC's published its 5th Assessment Report [1]. International scientists write the report to provide governments and stakeholders with information about climate change. The report includes observed changes, possible projections, risks, and future pathways for adaptation and mitigation to climate change. Some of the information presented in the 5th Assessment Report will be summarized to explain climate change briefly.

Over the period from 1880 to 2012, the average global surface temperature increased by 0.85 °C. Most of that thermal energy is stored in the oceans, warming them up. Because of the warmer oceans, sea ice has been melting, resulting in a rising global sea level. The report states that it is highly likely that the concentration of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide in the atmosphere is the dominant cause for the observed warming. Human activities such as deforestation, large-scale agriculture, and burning fossil fuels further enrich the atmosphere with the gases mentioned earlier. Economic and population growth are considered the main drivers for GHG emissions. If there are no efforts to constrain GHG emissions, the report's baseline scenario expects that by 2100 the global mean surface temperature increases in range from 3.7 - 4.8 °C compared to 1850 - 1900. The report suggests that global warming should be kept below 1.5 °C as the natural ecosystem could take severe damage.

The findings of the 5th IPCC report were presented at the United Nations Framework Convention on Climate Change in Paris in 2015. On that event, 196 parties signed the "Paris Agreement", a legally binding treaty on climate change to limit global warming below 2 °C compared to pre-industrial levels. In addition, the parties agreed to report on and reduce their national GHG emissions [2].

Economic and population growth are the main drivers for greenhouse gas emissions as energy is a fundamental component for growth. Figure 1 displays the global primary energy consumption by fuels in 2018. The most consumed resources in 2018 were fossil fuels, namely oil, followed by coal and natural gas.

Those three fossil fuels together represented 84 % of global primary energy consumption. However, only 16 % of the global primary energy came from low-carbon sources such as nuclear energy, hydroelectricity, and renewables. The figure clearly emphasizes the importance and potential to shift global primary energy consumption towards low-carbon energy sources.

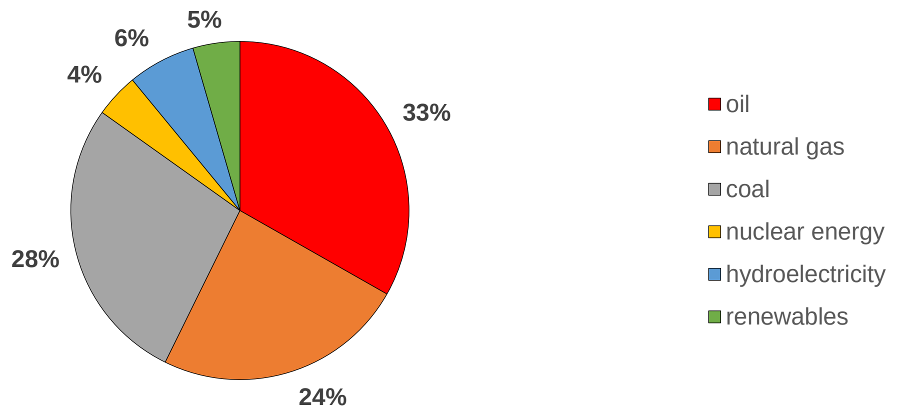

Figure 1: Global primary energy consumption by fuels in 2018 with a total of 583.90 EJ (source: [3])

Primary energy is the energy available in a resource such as unprocessed coal. Before a consumer can use it, several conversion processes are needed. Throughout the conversion process, conversion losses occur. The energy which is delivered to the consumer is called final energy.

In 2018, the total final energy consumption shares were 50 %, 29 %, and 21 % for heat, transport, and electricity, respectively [4]. As the biggest final energy consumer, heat is accountable for 40 % of global GHG emissions [4], making it worth further analyzing heat consumption and its applications.

In the same year, the global heat consumption was estimated to be at 208 EJ. Figure 2 presents the fuels consumed for heat generation. Three-quarters of global heat consumption heavily depended on fossil fuels such as coal, natural gas, and oil. The last quarter, which can be considered as low-carbon sources, is almost evenly shared between traditional biomass and modern renewables. The high share in fossil fuels shows the need and potential to decarbonize heat consumption.

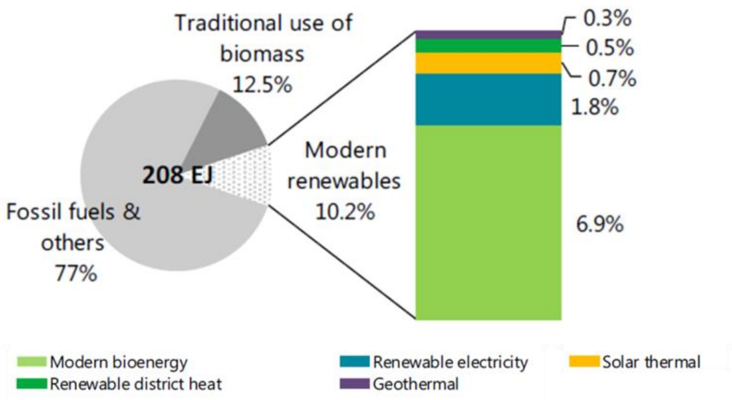

Figure 2: Global heat consumption by fuels in 2018 with a total final energy of 208 EJ (source: [4])

The next step is to find out which activities are relevant for global heat consumption. The International Energy Agency concluded that “about 50 % of total heat produced was used for industrial processes, another 46% was consumed in buildings for space and water heating and, to a lesser extent, for cooking, while the remainder was used in agriculture, essentially for greenhouse heating” [4]. Similar figures are found for the European Union. The European Commission conducted a study across its 28 member states (EU28) on the heat and cooling demand for the year 2012. The study presented that 51 % of the total 12,821 TWh final energy was used for heating and cooling. Figure 3 illustrates the final energy consumption by application.

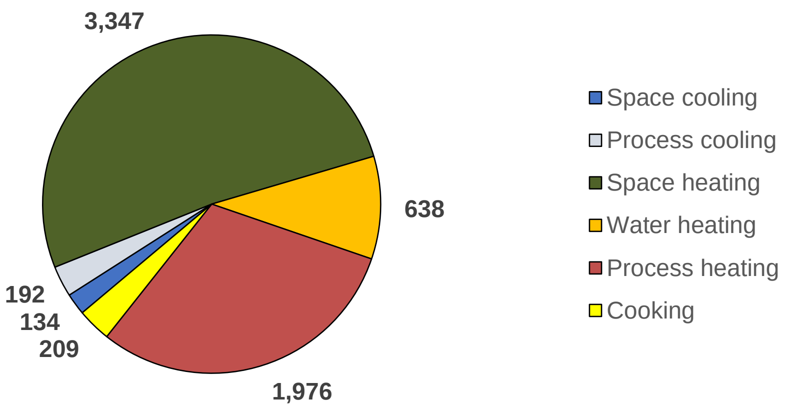

Figure 3: EU28’s final energy consumption of 6,496 TWh by application for heating and cooling in the year 2012 (source: [5])

Space heating, process heating, and water heating accounted for 50 %, 30 %, and 10 % of final energy consumption. The remainder was consumed for cooking and cooling purposes. The differences between process, space, and water heating are briefly explained.

Process heat is the heat consumed for industrial processes. The temperature of process heat varies according to the industry needs above 500 °C [5]. Space heating refers to heating buildings to room temperature for the thermal comfort of occupants. Finally, water heating covers warm water for sanitary purposes, particularly dominant in the residential sector.

All industries consume heat either for processes or for space and water heating. Different European industries and their respective heat consumption is shown in Figure 4. The illustration shows that the iron and steel, the chemical and petrochemical, and the non-metallic minerals industry are the most energy demanding industries in the EU28. Including non-ferrous metals, all four industries have a significantly high share in high-temperature process heat. The other presented industries show a lower total final energy demand thermodynamically correlated by the required temperatures.

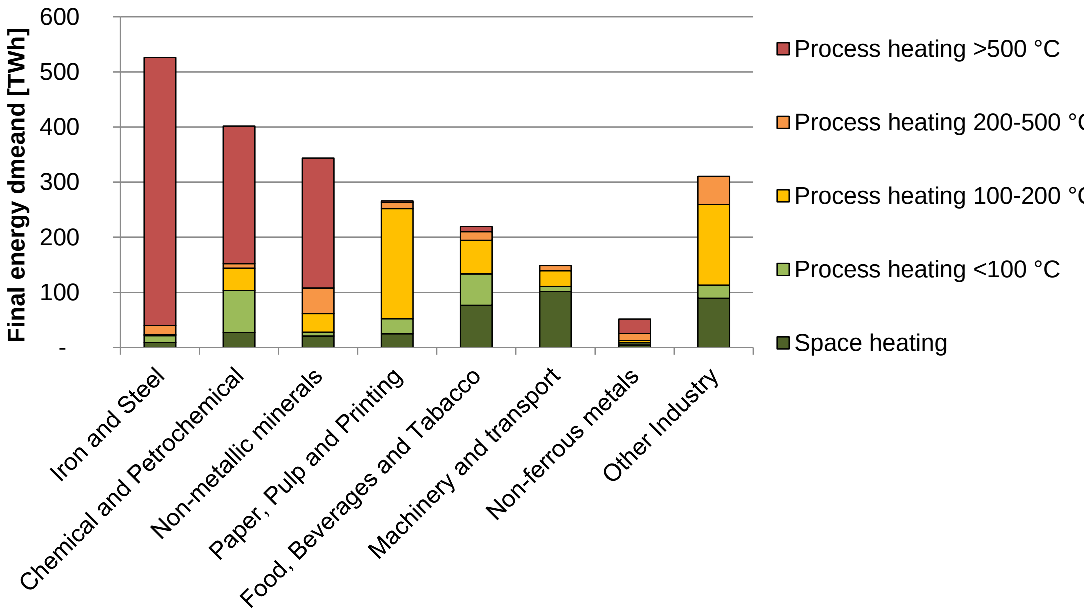

Figure 4: Final energy demand for EU28 industries by temperature level and sub-sector for heating in 2012 (source: [5]; adjusted)

For the further course of this work, the different temperature levels are categorized. High-temperature process heat above 500 °C, medium-temperature process heat (MTPH) between 100 - 500 °C, and low-temperature process heat (LTPH) < 100 °C. LTPH technologies and space heating technologies will be considered equivalents, as both technologies aim to provide heat at temperatures below 100 °C. Different heating technologies are available on the market, which generate the process-required temperature. In general, industries are considered heavily dependent on fossil fuel-based and electric heating technologies [6, 7].

The European Commission assessed that within the EU28 85 % of the total deployed heating technologies were furnaces for high-temperature process heat, steam generators for MTPH, combined heat and power units for steam and hot water, and a small share of process cooling technologies. The remaining 15 % are primarily individual furnaces providing high-temperature process heat [8]. 45 % of the final energy demand for heating and cooling was provided by natural gas, followed by electricity, fuel oil, and biomass accounting for 12 % each [5].

Two things should be noted about the temperature categories and heating technologies. The described temperature levels are roughly aligned with the technology-specific maximum temperature. It should be considered that heating technologies can provide heat at temperatures below their maximum, basically down to ambient temperature. In the case of steam generators or combined heat and power units, they can generate steam above 600 °C and exceed the upper boundary of MTPH. This thesis focuses on MTPH and LTPH technologies due to the current limitation of renewable thermal systems to provide high-temperature heat; hence furnaces are not further discussed.

Despite knowing which energy sources are used for the respective applications, the decarbonization of process heat is challenging. Following [9], research and development have to address four pillars: zero-carbon fuels, zero-carbon heat sources, electrification of heat, and better heat management. The electrification of heat is achieved through renewable energies (RE). The electrification of heat originates in the concept of ‘sector coupling’, which targets to optimize the interaction between different sectors. In a broad scope, sector coupling can refer to “a more integrated approach of the whole energy system” down to a strict scope describing it “as solution for the use of temporary excess electricity from variable RE for renewable heat and gas production” [10]. Renewable electricity can either directly or indirectly be used. The direct use is called ‘power to heat’, in which heat pumps or electric boilers convert the renewable electricity into heat. Indirectly the renewable electricity is converted into gaseous or liquid combustible fuels such as methane or hydrogen, respectively named ‘power to gas’ or ‘power to liquid’ [10]. The generated fuels can then be combusted in respective combustion technologies to provide heat.

The transition from conventional fuels towards sustainable energy carriers requires the further penetration of REs into the energy mix. In the last decades, wind and solar energy became the primary sources of renewable electricity. Both are intermittent energy sources that result in variable electricity generation and supply to the power grid. One exemplary challenge is that today's wind turbines can be decoupled from the grid through their power electronics to meet the grid capacity and avoid power imbalances [11]. Decoupling implies that the low-carbon power is 'wasted' due to insufficient grid capacity. The variability and uncertainty of REs require system flexibility and power system reserves [12]. The costs for power grid extension, high upfront investment cost for REs, and the lack of supportive government policies lead to a moderate deployment of RE technologies [13-15].

Given the challenges of decarbonizing the heat sector and integrating renewable electricity into the power grid, a relatively novel zero-carbon heat technology is introduced. The technology is called 'wind thermal energy' and is presented in the next chapter.

1.2 Wind thermal energy converter

Following [16], the land use of wind energy dates back to the 10th century where primitive windmills were used to grind grain and lift water. By 1886, Charles F. Brush built the first wind turbine producing electricity. Wind turbines are now commercially available and are installed onshore and offshore, with power ratings reaching up to 14 MW [17]. Wind power plays a vital role in decarbonizing the energy supply as its total life cycle emissions and environmental impact are the lowest amongst known power generation technologies [18].

The wind thermal energy working principle is easily compared to the well-known wind power technology. In wind power, the wind turbine converts the kinetic energy of wind into rotational kinetic energy. The available energy is then converted into electrical energy through a generator. In wind thermal energy converters, the generator is replaced by a heat generator. Studies underline that the direct energy conversion for thermal applications, skipping the electricity generation, yields higher efficiencies [19, 20]. However, the concept of wind thermal energy is given little attention, leading to slow progress in its development. As wind thermal energy is based on the same wind turbine and its respective physics as wind power, scientific activities mainly focus on the heat converter.

The idea of converting the rotational energy of wind turbine blades into heat dates back to 1971, when the first patent by Ashikian was registered [21]. The patent describes a wind turbine powering a “mechanohydrothermal energy converter”. The patent explains that the wind turbine will mechanically drive a pump that will accelerate a working fluid through a small diameter pipe. Due to friction losses, the accelerated fluid’s kinetic energy dissipates into heat. In 1979 another wind heating concept was patented [22]. The inventor registered a windmill that will rotate a submerged impeller within a tank, referred to as ‘Joule machine’. The tank is equipped with ribs so that when the impeller rotates the working fluid against the baffles, the fluid’s kinetic energy is converted into heat through friction. The first scientific papers were published around the 1980s in the United States. Given the 1973 oil and 1979 energy crisis, American researchers investigated the potential of wind thermal energy systems as an alternative to fossil fuel-based heating. The studies involved theory-based assessments and prototypes using vertical-axis wind turbines mechanically driving the compressor of a heat pump for heating and cooling in agriculture. Despite facing the problem of matching the heat generation with its demand, the studies concluded that wind thermal energy is a feasible solution to reduce electricity and fuel consumption [23-25]. After that, it took almost 20 years for further publications. By the beginning of the 2000s, research activities slowly started again. By now, three main conversion principles for wind thermal energy exist. Those are based on compression, induction, or friction.

Compression

Compression-based wind thermal energy uses the rotational energy of the wind turbine to power a pump or compressor mechanically. The compressor increases the working fluid's pressure. Suppose the working fluid is a gas, the fluid's temperature increases due to compression as defined by the ideal gas law. On the other hand, suppose the working fluid is a liquid, the fluid's temperature increases due to friction losses.

Taiwanese researchers performed three experiments with two on an eight-vane horizontal axis wind turbine. The turbine and heat pump's compressor was coupled through a shaft [20, 26]. The experiment showed that the prototype cooled 6 liters of water down from ambient temperature by 8 to 13 K within 30 minutes, starting the conversion efficiency from wind energy to heat under different starting points between 10 and 33 % [20]. In the second experiment, the wind-powered refrigeration process cooled 30 liters of water down from ambient temperature by 6 to 9 K within 55 minutes [26]. The third experiment was a three-vane horizontal axis wind turbine powering the compressor of a heat pump for heating and cooling 28 liters of water. Within 60 minutes, at average wind speeds of 6 m/s, the water tank was cooled from 23 to 3 °C and heated from 10 to 25 °C. The conversion efficiency from wind energy to heat was between 45 to 61 % [27].

Lithuanian researchers conducted different laboratory experiments on a hydraulic heat system. The compressor was powered by an electric motor that simulated a wind turbine. The experiments included determining the optimal work regime and the influence of varying rotational speed of the motor [28, 29]. The conversion efficiency of the system was from 91 to 94 % [28]. Mujtaba et al. simulated the flow and pressure characteristics related to the position of a throttling valve within a hydraulic heat system [30].

Swinfen-Styles et al. investigated a compressed dry air energy storage concept with wind turbines mechanically powering the compressor. Although the studies are focused on the storage technology and electricity generation, the compressor based on thermodynamic laws increases the dry air temperature up to 700 °C [31].

Induction

Induction-based wind thermal energy uses the rotational energy of the wind turbine to rotate a conductor mechanically within a constant magnetic field. Due to the relative motion between the two components, the magnetic field alternates in the conductor. This alternating magnetic field induces eddy currents in the conductor, which dissipate as heat energy. Alternatively, the magnets rotate around a static conductor, resulting in the same induction heating effect. Induction heating is a well-known heating technology used in metallurgy and home cooking, where the alternating magnetic field is generated by applying alternating current.

A research group based at the University of Bucharest first introduced an "eddy current heater" for wind thermal energy. Three publications were found, which dealt with optimizing the eddy current heater and analyzing the induced power by applying a finite element model. The optimization included determining the number of poles, the stator, the airgap thickness, and the geometry of magnets [19, 32, 33]. Further, the group presented an analysis of an eddy current heater in a simulated wind environment [34]. The latest publication presented a hybrid induction system for wind turbines, which generates electricity and heat. To validate the applied finite element model, a prototype which is powered by a motor was built [35]. Several other publications present numerical analysis induction-based wind thermal energy or prototypes or both [36-40]. In the first experiment, water was heated from 26 to 40 °C at efficiencies from 70 to 91 % [37]. In the second experiment, water was heated from 10 to 16 °C at efficiencies from 96 to 99 % [38]. Okazaki et al. described that an induction retarder reaches temperatures above 600 °C [41].

Friction

Friction-based wind thermal energy uses the rotational energy of the wind turbine to accelerate a working fluid mechanically. The working fluid will convert its kinetic energy into heat due to friction losses. A straightforward construction is to couple the wind turbine to an impeller that stirs a tank's working fluid.

Kim et al. investigated the performance of a Savonius Wind turbine powering a Joule machine, which heated 60 liters of thermo fluid from 16 to 22 °C. The authors concluded that the size of components was not suitable for the test site [42]. Prior experiments using an electric motor with constant rotational speed to power the Joule machine resulted in thermal oil’s temperature 87 °C with conversion efficiencies up to 68 % [43, 44]. Qiu et al. compared the thermal behavior of water, hydraulic oil, and saturated sodium chloride solution as working fluids [45]. Liu et al. compared different working fluids and rotor structures regarding their thermal performance [46]. Mamonov et al. presented a more sophisticated heating unit based on Taylor-Couette flow between independently rotating cylinders. The system's performance was analyzed in the experiments by varying the cylinders’ rotational speed and working fluids [47-50]. Hamakawa et al. reported that multi-cylinder Taylor-Couette heating units achieve conversion efficiencies close to 100 % [51].

Wind thermal energy systems offer several advantages when compared to wind power. The generator and its electrical components become dispensable by producing heat instead of electricity, reducing the system’s total cost [37]. The wind turbine and heating unit can be coupled through a direct drive, eliminating the need for a gearbox [50]. The electrical components and gearbox are the parts with the highest downtime and failure rate [52], making wind thermal energy systems more reliable and cost-efficient [31]. Sobor et al. concluded that a wind thermal induction system’s rated wind speed is higher than the one for wind power. Hence, a wind thermal system generates annually 6 to 18 % (summer and winter) more heat than wind power generating electricity [53]. Wind thermal systems generate more heat in winter, which correlates with the space and water heating demand. These properties make the technology more suitable than solar thermal systems for heating in winter [23].

In terms of the technology's application, different areas are proposed. Most of the presented studies investigated wind thermal energy systems for residential applications. Other studies analyzed the technology's application in the commercial sector, such as agriculture for dairy farming [24, 25] and greenhouses [43, 54], oilfields [55], seawater desalination [56, 57], or cooling of a cold storage plant [58].

The following two paragraphs will present relevant studies from Okazaki et al. and Cao et al., which assessed the costs of wind thermal energy systems including thermal energy storage and their economic potential.

Okazaki et al. were the first to introduce a wind thermal energy storage system (WTESS) as a possible solution for further installing intermittent renewable energies and related grid issues. Following the study, the implementation of further renewable electricity implies either backup capacity or energy storage systems. Based on that, the goal of this study was to compare the levelized cost of electricity (LCOE) of wind power with adjustable thermal backup capacity (e.g., gas turbines), wind power with battery storage systems, and WTESS. The proposed WTESS consists of a wind thermal converter connected to a thermal energy storage, further extended by a steam turbine for electricity generation. The three concepts have a capacity factor (CF) of 0.3, with the size of the energy storage system being the changing variable. The size of the energy storage system was designed for sufficient energy supply for wind patterns between 6 to 48 hours. The LCOE, assuming a system lifetime of 10 and 20 years, was calculated with a simplified method, which excluded elements "such as maintenance and finance". The author group concluded that WTESS "become the most economical system in these three systems," costing below 0.04 EUR/kWh[1]. They further added that WTESS come with few hazardous materials, low noise and vibrations, low environmental impact, and the ability to store surplus energy from the grid [41].

Cao et al. conducted a techno-economic analysis (TEA) on wind thermal energy systems by calculating the levelized cost of heat (LCOH). The research group considered five different heating concepts for space heating. Two concepts used wind power to run an electric boiler or an electric heat pump. The three other

[1] The source presents 5 JPY/kWh which is converted at the average exchange rate in year of publication (2015) of 0.0074 EUR/JPY (source: https://www.exchangerates.org.uk/JPY-EUR-spot-exchange-rates-history-2015.html).

considered WTESS concepts were based on the following heating unit: mechanical heat pump, hydrodynamic retarder, hydrodynamic retarder coupled to an absorption heat pump. The study encompassed three different scenarios assuming a small WTESS, a state-of-the-art multi-megawatt WTESS, and a WTESS farm providing heat for a single-family household, a village with 2,000, and a city with 20,000 inhabitants. The CF was varied to account for possible wind site conditions. The results show two things. First, the LCOH of all concepts decreases with increasing size, which is reasoned in the economies of scale. Or the LCOH decreases with increasing CF, which means that more heat is generated. WTESS with a mechanical heat pump have the lowest LCOH between the five concepts across the different scenarios. The authors noted that the heat pump's seasonal coefficient of performance "strongly influences the competitiveness in terms of cost efficiency for heat supply". The study determined that WTESS with a high CF present a LCOH below 5 €ct/kWh, which is lower than the one for gas or wood chip boilers for district heating. The assessment further evaluated the LCOH of WTESS with mechanical heat pump concerning the heat transport distances, indicating the shorter the heat transport distance, the lower the LCOH. It was concluded that WTESS with a mechanical heat pump are "the most cost-effective realization", especially if deployed close to the demand site. Capacity factors above 0.25 enable other WTESS concepts to reach a similar LCOH like the proposed gas and wood chip boilers [59].

WTESS are virtually non-existent due to its early stage of development, which implies high system costs and little engineering knowledge in this area. But the presented literature summary shows that a technological and economic potential for WTESS exist. Furthermore, Okazaki et al. and Cao et al. proved WTESS theoretical potential as an economically feasible low-carbon technology for electricity and heat generation.

So far, studies have focused on the application for space heating which requires fluid temperatures below 100 °C, neglecting WTESS's as technology to decarbonize process heat. However, given that WTESS potentially generate and store temperatures up to 600 °C, it becomes a suitable technology for several industries. Therefore, the research goal is to identify the potential role of WTESS in the context of process heating technologies.

1.3 Research goal

Industries require that process heating technologies reliably and continuously provide energy to its processes at the lowest possible costs, enabling businesses to produce competitive market products. Yet, industries have an energy price advantage compared to residential consumers. This price advantage allows purchasing fossil fuels at a reasonable low cost, resulting in combustion technologies being the most economical. However, low fossil fuel prices strongly endanger the implementation of low-carbon energy technologies like WTESS, which are relevant to achieving the Paris Agreement's goals.

Governments are introducing financial mechanisms to continuously increase the costs of fossil fuels, which plays a significant role in mitigating climate change. The increasing costs make the use of fossil fuels unattractive, simultaneously supporting the development and deployment of cost-competitive RE technologies. In this thesis, the German national regulation “Brennstoffemissionshandelsgesetz” is considered to determine the national natural gas price development. The regulation was introduced by 2021 to price carbon emissions not accounted for by the European Emissions Trading System.

This thesis intends to investigate the current use and future deployment of heating technologies in industrial processes. It mainly focuses on fossil fuel-based and renewable heating technologies (RHTech), which can potentially be substituted through WTESS systems. The comparison between the different technologies is achieved by applying a TEA. Aligned with the methodologies of Okazaki et al. and Cao et al., the LCOH for all relevant technologies is calculated with particular regard to the future fossil fuel costs. By the end of this work following research questions are answered:

a) *Which are currently used or other available heating technologies for industrial processes?*
b) *Which are the respective LCOH for the assessed heating technologies?*
c) *Assuming that today an expert has to choose a new heating system for process heat, which of the presented technologies is the best choice?*

The results of this work put WTESS into the context of process heat applications and indicate if it is reasonable to support its further development.

2 Techno-economic analysis

2.1 Introduction

A holistic approach to answer the defined research questions is the TEA. “TEA is a methodology framework to analyze the technical and economic performance of a process, product or service” [60]. other denominations are techno-economic assessment or techno-economic evaluation. In this thesis, the most common denomination ‘techno-economic analysis’ is used [61].

TEAs have already been applied for almost 40 years across several sciences (e.g. [62-64]), but methodologies are either unspecified or vary significantly between authors. As an example, Khraiwish’s and Cao’s et al. TEA methodologies are compared. Both studies present a TEA without clearly defining the associated method. In terms of technical analysis, Khraiwish covers the mathematical modeling of a wind turbine’s power output at a specific wind site [64]. In contrast, Cao et al. describe and compare WTESS setups for different heat demands [59]. In both cases, the economic analysis encompassed the calculation of levelized cost of energy for different input variables. The applied equations differ, and some parameters are not explicitly presented. Although both authors name their studies a TEA, the lack of uniformity becomes clear. Different scientific literature search engines were used to find a TEA framework for RE technologies without success.

Van Dael et al. conducted a literature review in 2015, which underlined that TEA definitions exist, but sciences have lacked a comprehensive and concise methodology guideline. In the same study, Van Dael et al. presented a general methodology for TEA consisting of four iterative phases:

1. market study,
2. process flow diagram and mass and energy balance,
3. economic evaluation,
4. risk analysis.

The market study identifies potentials for the investigated technology such as the market size, market needs, and alternatives. The process flow diagram and mass and energy balance facilitate understanding system boundaries and system processes. The economic evaluation references if a technology is economically feasible, which reasons to continue or stop further investigation. The risk analysis intends to disclose possible risks due to the uncertainty of variables. The framework presented by Van Dael et al. explains the importance of the individual phases. Different assessment methods are suggested to execute the phases. The study recommends using a method that is aligned with the goal of the TEA [61].

Zimmermann et al. developed a comprehensive and detailed guideline that addresses carbon capture and utilization technologies [60]. Following the guideline's related journal article, the published guideline tackles the "lack of transparency in assumptions and intermediate results as well as the lack of generally accepted TEA standard". The guideline was developed in 7 phases: literature analysis, two workshops, preparing drafts, and an expert review with participants from academia, industry, and policy [65].

This work follows the guideline of Zimmermann et al. for several reasons. The use of a guideline helps to standardize TEA and therefore increases comparability and transparency of the results. The TEA guideline is the only identified document that was developed together with experts from industry and policy. Including experts' opinions improve the TEA's readability outside of academia. Finally, the guideline's level of detail and information allows the TEA apart from carbon capture and utilization technologies.

The methodology consists of four iterative steps: goal and scope, inventory, calculation of indicators, and interpretation, as shown in Figure 5. The overall goal, system boundaries, and assessment scope are determined in the goal and scope step. The inventory step refers to the collection of relevant data. Based on the collected data, the calculation of indicators is done. The interpretation of steps is essential to assess whether the individual steps are aligned with the goal and scope of the analysis. If not, iterations of the TEA steps are recommended. The steps are described in detail in the following subchapters.

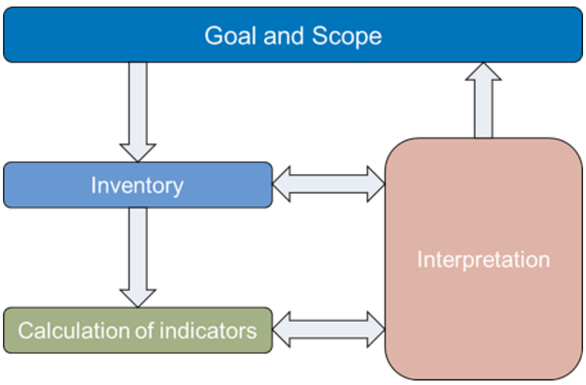

Figure 5: The four iterative steps of TEA (source: [60])

2.2 Goal and scope

This TEA aims to answer the three following research questions presented in chapter 1.3 Research goal.

a) *Which are currently used or other available heating technologies for industrial processes?*
b) *Which are the respective LCOH for the assessed heating technologies?*
c) *Assuming that today an expert has to choose a new heating system for process heat, which of the presented technologies is the best choice?*

Based on the research questions, the scope of this study is determined. This study will encompass process heating technologies whose primary purpose is to provide heat. The requirement to provide heat only dismisses combined heat and power plants from the study. For MTPH, the technologies shall provide heat at temperatures above 500 °C. For LTPH, the technologies shall provide heat at least above 50 °C. The conversion process shall be direct, meaning that the respective energy source is directly converted into heat, excluding intermediate energy forms such as electricity. The allowed energy sources are either supplied from the grid (e.g., natural gas or electricity) or RE sources such as wind, solar and geothermal. This thesis focuses merely on natural gas as fossil fuel due to it being the most consumed and cheapest fossil fuel for heating.

The study takes place in Germany. Therefore, the financial analysis is conducted in Euro (EUR), considering national market prices for natural gas and electricity, product prices, inflation rate, and carbon pricing mechanism, where applicable. The study excludes incentives or subsidies. The base year is 2020, and the time frame is set to 30 years, which corresponds to the maximum technology-specific lifetime. In addition, the technical potential of renewable heating technologies is determined by the available national RE sources such as wind and solar. If national information is unavailable, other references are used and indicated.

2.3 Inventory

In the inventory step, all relevant data for the TEA is collected. The collected data should be up-to-date, reproducible, and consistent [60]. The purpose of those requirements is to enable a comparison between the different heating technologies.

In a first step, online sources were consulted to identify process heating technologies. Organizations such as the Australian Energy Agency, the United States Department of Energy, the Danish Energy Agency, and the International Renewable Energy Agency provided the first information on process heating technologies. The technologies are combustion steam and water boilers, wind thermal energy systems, solar thermal systems, electric steam and water boilers, and geothermal systems.

Since 2016, the Danish Energy Agency provides regularly updated technology data catalogs that are freely accessible [66]. There are six catalogs available: "*generation of electricity and district heating"*, "*individual heating plants"*, "*renewable fuels"*, "*transport of energy and CO2"*, "*energy storage",* as well as "*industrial process heat and carbon capture"*. Following [67], the catalogs are developed based on "well-documented and public information" and on "invited expert advice". The objective of the catalogs is "to establish a uniform, commonly accepted and up-to-date basis for energy planning activities, […] as well as technical and economic analyses, […]". By using the Danish Energy Agency's dataset, a certain level of uniformity is given. The uniformity reduces the number of required sources and facilitates the comparison between different technologies. However, the Danish Energy Agency's catalogs lack data, especially for concentrated solar heating and WTESS. In that case, other sources are used as references. The sources have to include technical or economic information on the heating technologies. The reader should be aware that the comparison between the different technologies' LCOH is limited. The limitations are given due to assumptions made in the referenced studies. The collected data is presented in Appendix A.

2.4 Calculation of indicators

Before any indicator is calculated, a fictive use case is introduced to compare the different heating technologies. It is assumed that the heating technologies are deployed to provide heat to a paper and pulp factory in Germany. The paper and pulp industry is chosen because it consumes MTPH, which can be fully supplied through WTESS. Based on the assumption that 70 % of primary energy is converted into final energy in European paper and pulp factories [68], the annual average heat demand of a single factory is estimated to $E_{demand} = 250{,}000\ MWh$. Further it is assumed, that the factory runs a continuous production, meaning it operates 24 hours, 365 days a year at rated capacity. The continuous production presumes that the conventional heating technologies (CHTech) are working at their respective rated system efficiency. The operational time for continuous production is approximated to 8,000 hours a year [67]. It should be noted that the assumption is made to facilitate the calculation and comparison of technologies.

2.4.1 Levelized cost of heat

The main parameter in the financial analysis is the levelized cost of energy which is commonly used to compare different energy technologies. “The levelized cost of energy allows alternative technologies to be compared when different scales of operation, different investment and operating periods, or both exist” [69]. In general, the levelized cost of energy represents the attributed cost to generate one unit of energy by the analyzed system. The denomination for the levelized cost of energy varies in sciences. Some refer to the levelized cost of energy, and others refer to LCOE or LCOH depending on the provided form of energy. However, the mathematical expression for all three is the same. Given that the assessment focuses on heating technologies, the term LCOH is used.

Due to the simplicity of the model, some limitations and criticism exist. The levelized cost of energy is not recommended for investment decisions as investment size, and returns are neglected [69]. The cost or benefit for externalities is not accounted for either [70]. Furthermore, there is criticism about the levelized cost of energy studies' comparability due to the lack of assumptions [71]. Depending on the level of detail, more variables such as depreciation and tax rates can be included into the levelized cost of energy calculation (e.g. [69]). Research institutes across the globe use the LCOE to compare different power technologies, such as the International Renewable Energy Agency [70] or Fraunhofer Institute [72]. Despite the limitations and criticism, the LCOH is an indicator aligned with the goals of this study.

The LCOH equation is obtained from [69] as shown in Eq. 1. The LCOHs were calculated using a Microsoft® Excel® spreadsheet.

$$LCOH = \frac{total\ lifecycle\ cost}{energy\ produced} = \frac{\sum_{n=0}^{N} \frac{EXP_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+r)^n}}\ [\frac{EUR}{MWh}]$$ *Eq. 1*

Where:

EXP_n: expenditure in year n

Q_n: heat output in year n

r: real discount rate

N: project lifetime

For all technologies, capital expenditure (CAPEX) is accounted into year 0. Operational expenditure (OPEX) and heat generation are accounted for starting from year 1. The total lifecycle cost is broken down into three variables as presented in Eq. 2. More detailed calculations are presented in Appendix A.

$$LCOH = \frac{CAPEX_0 + \sum_{n=1}^{N} \frac{(OPEX_n)}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+r)^n}}\ [\frac{EUR}{MWh}]$$ *Eq. 2*

Where:

$CAPEX_0$: capital expenditure in year 0

$OPEX_n$: operational expenditure in year n

Q_n: heat output in year n

r: real discount rate

N: project lifetime

The variables are further elaborated.

- *Capital expenditure* $CAPEX_0$ corresponds to the capital expenditure for the total heating system in year 0. Given that different sources are used, the components to determine the CAPEX might vary. The CAPEX shall at least include all costs related to the relevant technical components. Expenses related to buy or lease property are not considered.
- *Operational expenditure* $OPEX_n$ accounts for the annual expenditure for energy and operations and maintenance (O&M). Energy cost plays an important role in CHTechs. The costs for O&M are calculated based on the available data, such as heat output, rated power, and auxiliary electricity consumption.

- *Energy output* Q_n is the annually generated heat by the heating technology. It is equal to $E_{demand} = 250{,}000\,MWh$ as required for the paper and pulp factory.
- *Real discount rate* r is used to determine the present value of a future payment, including the inflation rate. It is a great challenge to determine the appropriate discount rate. The discount rate is "determined by a wide variety of factors, such as the investor's rate of return, risk premium, planning horizon, interest rates, and income and property taxes" and "vary from state to state, industry to industry, and company to company" or equal to the weighted average cost of capital [69]. Technologies established in the market are subject to low discount rates due to their low perceived risk in performance. Renewable heating technologies, especially for MTPH, are calculated based on higher discount rates. The discount rates are assumed for an investment in Germany, which offers "favorable framing conditions for investments in renewable energy" [73].
- *Project lifetime N* is the expected maximum lifetime of the system running under acceptable performance.

Technology-specific data is required to calculate the individual heating technology's LCOH. The considered variables are described and their respective equations are presented in Table 1.

- *Total system efficiency* η_{system} represents the system's conversion efficiency from an energy source to useful energy.
- *Total primary energy consumption* $E_{primary}$ is in particular important for non-renewable technologies. Conventional technologies combust fuels or consume electricity to generate heat. The total energy required is calculated based on the total system efficiency. Thus, the required energy determines the fuel consumption and related fuel expenditure.
- *Forced outage* t_{forced} refers to the time of an unexpected breakdown of the system or its transmission lines.
- *Planned outage* $t_{planned}$ refers to the time when the heat supply is shut down due to planned activities like maintenance and repairs.
- *System availability* A_{year} is the operational time of the heating system in a year. The system availability accounts for forced and planned outages. Based on the system availability and energy output, the rated power of the

system is calculated. The system's availability can be expressed by the CF, too. The CF is the ratio of annually generated energy to annually generated energy under the constant rated power of the system.

- *Rated power* P_{rated} is the maximum available power from the heating system. The rated power is crucial to determine the CAPEX.

Table 1: Summary of applied equations to calculate technical data

Variable	Equation
$\boldsymbol{E_{primary}}$	$E_{primary} = \frac{E_{demand}}{\eta_{system}}$
$\boldsymbol{A_{year}}$	$A_{year} = \frac{8{,}760\,\frac{h}{a} - t_{forced} - t_{planned}}{8{,}760\,\frac{h}{a}}$
$\boldsymbol{P_{rated}}$	$P_{rated} = \frac{E_{demand}}{A_{year} * 8{,}760\ h}$

2.4.2 Natural gas price development

Most of the currently deployed heating technologies are based on the combustion of fossil fuels. Fuel cost represents 96 % of the lifecycle cost of a steam boiler, while the remainder accounts for installation and OPEX [74]. Despite the high share of fuel cost on the total lifecycle, the combustion of fuels remains economically viable due to the low fuel prices.

Starting from 2021, the German government introduced the Brennstoffemissionshandelsgesetz (BEHG), a national regulation to price GHG emissions based on a cap and trade system. The BEHG applies to all industries such as the paper and pulp factory, except for energy-intensive companies already part of the European Emissions Trading System. Companies purchase emission certificates to compensate for their GHG. The certificates correspond to one ton CO_{2eq}. GHG emissions which are not offset are fined [75]. Pricing carbon emission will substantially increase fossil fuel prices and support the deployment of renewable heating technologies.

In the first step, the individual price components for natural gas for German industries are introduced. The natural gas price is subdivided into three main categories: procurement and sales, grid charges, and levies. Levies include license fees, metering operations, and natural gas tax. Procurement and sale are defined by the wholesaler, whereas grid charges and levies are regulated. The natural gas price composition is shown in Figure 6. Procurement and sale account for 63 %, natural gas tax for 21.5 % and grid charges for 14.5 % [76]. The license fee and metering operation contribute less than 0.1 % to the total cost structure and are neglected in further price development.

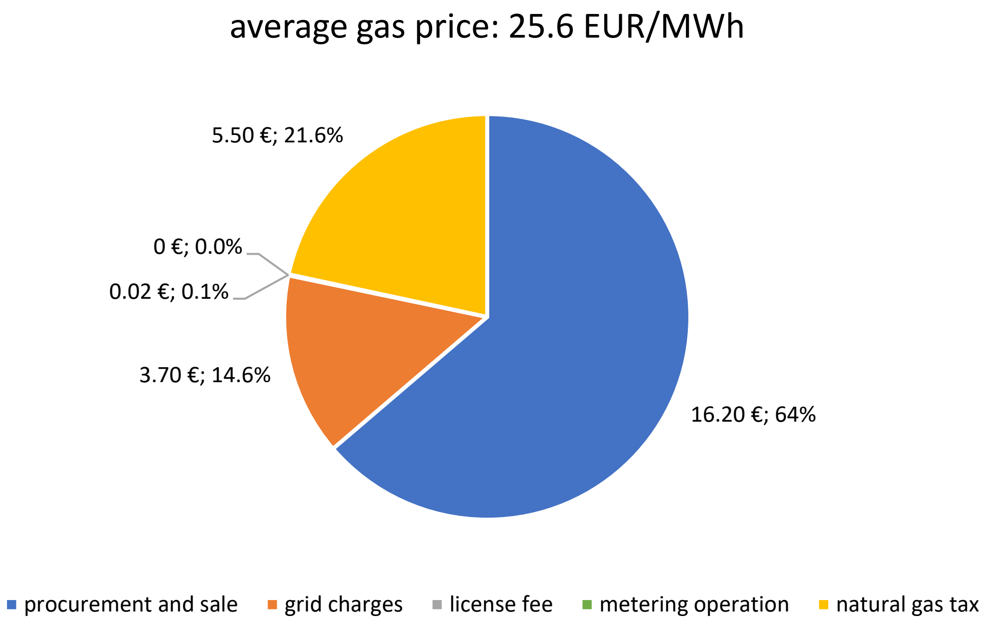

Figure 6: Average natural gas price components for industries in Germany in the year 2020 (source: [76], adjusted)

The BEHG indicates the certificate prices for the years 2021 to 2026. For the year 2026, the certificates are auctioned at a price between 55–65 EUR. The impact on fuel prices through the BEHG is rounded based on 55.9 tCO_2/TJ ≈ 200 kg/MWh [77] and shown in Table 2.

Table 2: Indicated certificate price and impact on fuel prices for the years 2021 to 2026 (source: [75])

Year	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Price [EUR/tCO_2]	25	30	35	45	55	55–65
Price [EUR/MWh]	5	6	7	9	11	11–13

Further predictions of the future natural gas price are required to address the timeframe of 25 years. However, predicting future prices is a complex task and subject to many uncertainties, making it almost impossible to do correctly. For example, one study ordered by the German ministry expected the natural gas cross-border price in 2020 to be above 37 EUR/MWh [78], which has to be below the 16.20 EUR/MWh natural gas procurement and sale component.

Despite the uncertainties, assumptions are made for the development of the natural gas price components. The relevant factor on the price for procurement and sale are wholesale prices. Average wholesale prices until 2024 are taken from [79] as shown in Table 3, with the price being derived from natural gas futures. Futures are a legal agreement to buy or sell an asset at a specified time in the future. It is further assumed that the wholesale price develops with an annual growth rate of 1.8 %, as it did between 2023 and 2024. A 30 % profit margin is added to the wholesale price. It is expected that the natural gas tax remains constant as the primary regulatory measure is carbon pricing.

Table 3: Average natural gas wholesale price derived from natural gas futures (source: [79])

Year	2020	2021	2022	2023	2024
Wholesale price [EUR/MWh]	11.6	14.1	15.7	16.4	16.7

Carbon pricing plays a significant role in the energy transition, especially given that natural gas prices are at the same price level as 2013 and probably remain cheap in the future. Two models, “business as usual” and “climate neutral”, are introduced to assess the current carbon pricing role.

In “business as usual”, the government fails to strengthen the BEHG after 2026, resulting in certificate prices remaining constant at 65 EUR/tCO_2. In “climate neutral”, the government strengthens the BEHG and significantly increases carbon certificate prices so that in the year 2050, national GHG emissions are reduced by 85–90 % compared to 1990. The necessary carbon certificate prices were modeled by Kemmler et al. and are taken as a reference [80]. The study suggests that the certificate price should reach a nominal 220 EUR/tCO_2 at some point after the year 2030. The certificate prices are calculated based on an inflation of 1.41 %. This value corresponds to the average inflation in Germany between 2000 and 2020 [81]. The applied natural gas prices for the investigated period of 25 years are presented in Appendix B.

2.4.3 Cost of electricity

The cost of electricity is relevant in two different ways. First, the LCOH calculation includes the cost for powering auxiliary equipment, which requires electricity. Second, power-to-heat technologies are included, which are powered by electricity. The electricity is either purchased from a power facility or self-generated through renewable power technologies.

The industrial price for electricity in the base year 2020 is 165.4 EUR/MWh [76]. The price for electricity for auxiliary equipment is considered constant. To keep the price constant is reasonable given that Kemmler et al. expects the future industrial electricity price to vary between 150–200 EUR/MWh under different scenarios [80]. On a side note, energy-intensive industries purchase electricity at much lower prices, around 70 EUR/MWh [79].

In terms of self-generated renewable electricity, the costs are derived from current studies. Power technologies with the lowest LCOE in Germany are photovoltaics and onshore wind [72]. Large-scale photovoltaics with battery storage have an LCOE between 52.4–99.2 EUR/MWh [72]. Own calculations result in an LCOE around 60 EUR/MWh.

2.5 Interpretation

The interpretation is conducted in parallel to all phases. It reviews if the phases and their results successfully address the study's goal. If the interpretation proves deviations to the goal, the step, and the TEA are iterated. If the interpretation confirms the "consistency, completeness and reliability of model and input parameter", the TEA is completed [82].

Part of the interpretation is to conduct a sensitivity analysis. The sensitivity analysis assesses the dependency of the LCOH on several variables. The third research question is answered by interpreting the results through the Analytic Hierarchy Process (AHP).

2.5.1 Sensitivity analysis

The sensitivity analysis is a method to determine the contribution of uncertain input variables to the model output. The sensitivity analysis identifies "key variables that need to be focused on" [60]. Two sensitivity analyses exist, a local and a global one. The local one analyzes the impact by changing one input variable at a time. The global sensitivity mathematically investigates the effect on model output from all input variables [60].

For the global sensitivity analysis, the multi linear regression analysis is applied. It is assumed that a random sample of data consisting of n number of samples from a larger population satisfies a linear relationship as presented in Eq. 3 [83].

$$y_i = \beta_0 + \beta_1 * x_{1i} + \cdots + \beta_p * x_{pi} + \varepsilon_i \quad (i = 1, \ldots, n) \qquad \textit{Eq. 3}$$

Where:

y_i:	dependent variable
β_p:	unstandardized regression coefficient
x_{pi}:	independent variable
ε_i:	random error
p:	number of regressors
n:	number of samples

One thousand samples for regression analysis are randomly generated under the uniform distribution. The variables' boundaries are given either by a percentage around the mean value or a minimum and maximum value in a determined range. A summary of variables and their boundaries is presented in Table 4.

Table 4: Summary of variables subject to sensitivity analysis

Technology	Independent variable	Change or Min–Max
Electric boiler Electric heat pump Geothermal	Discount rate	±50 %
	Cost of electricity	60–200 EUR/MWh
	CAPEX	±20 %
	OPEX	±20 %
WTESS	Discount rate	±50 %
	Capacity factor	0.15–0.30
	Retarder	
	CAPEX [59]	0.82–1.72 MEUR/MW
	OPEX [59]	18,250–32,750 EUR/(a*MW)
	Mechanical heat pump	
	CAPEX [59]	1.50–2.67 MEUR/MW
	OPEX [59]	21,300–38,300 EUR/(a*MW)
Solar thermal systems	Discount rate	±50 %
	Direct Normal Irradiance	0.8–1.2 MWh/(a*m²)
	CAPEX	±20 %
	OPEX	±20 %

The conventional steam and water boiler are excluded from the sensitivity analysis given that the fuel costs mainly influence the LCOH. The two natural gas price developments address the variation of costs.

After generating the defined number of samples for each technology, the multi linear regression analysis is calculated using Microsoft® Excel® inbuild regression analysis tool. Finally, the calculated regression function and its unstandardized regression coefficients are standardized to become comparable. The expression is shown in Eq. 4 [84].

$$b_p = \beta_p * \frac{\sigma_p}{\sigma_y} \qquad \textit{Eq. 4}$$

Where:

b_p:	standardized regression coefficient
β_p:	unstandardized regression coefficient
σ_p:	standard deviation of regressor
σ_y:	standard deviation of dependent variable

2.5.2 Analytic Hierarchy Process

"Multi-criteria decision analysis methods have been developed to support the decision-maker in their unique and personal decision process" [85]. One of those methods is the AHP [85], which Saaty developed. The AHP is used to answer which heating technology for MTPH and LTPH is the most suitable, considering different criteria. Within the AHP framework, the goal, criteria, and alternatives are leveled in a hierarchy [86]. The goal is to find the most suitable technology under the criteria of investment size, LCOH, continuous heat supply, Technology Readiness Level, and customer perception choosing from the alternative heating technologies, see Figure 7. Of course, further criteria such as space requirements, noise, installation time, and others could be added, but this would substantially require more data.

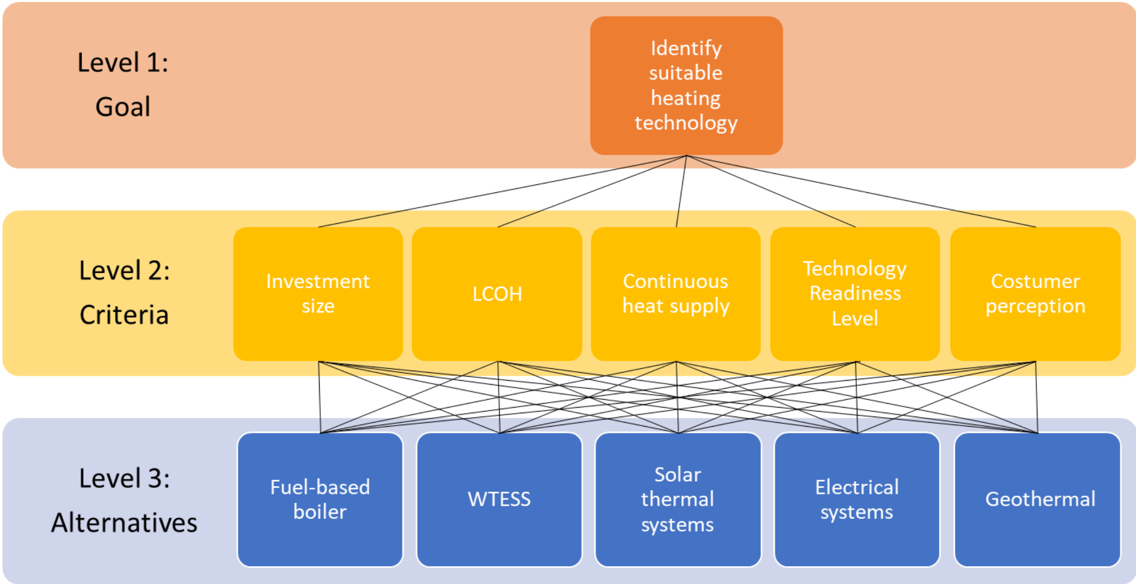

Figure 7: Hierarchic structure for the Analytic Hierarchy Process to identify a suitable heating technology

After setting up the hierarchy, a pairwise comparison for the options in every level concerning its higher level is required. The results are expressed in a pairwise comparison matrix $\boldsymbol{A}$ such as in Eq. 5 [86]. The pairwise comparison leads to reciprocal entries within the matrix. A scale for pairwise comparison of criteria and alternatives with respect to their higher level is applied, as shown in Table 5. The comparison matrix requires consistency which is defined as consistency ratio CR < 0.1. The consistency ratio is calculated as shown in Eq. 6 [86].

$$\boldsymbol{A} = (a_{ij})_{n \times n} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & 1 & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \qquad \textit{Eq. 5}$$

$$CR = \frac{\lambda_{max} - n}{\mu * (n-1)} \qquad \textit{Eq. 6}$$

Where:

CR	consistency ratio
λ_{max}	matrix's maximum eigenvalue
μ	measure of inconsistency from [87]

Table 5: Pairwise comparison scale by Saaty (source: [87])

Intensity of importance	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between two adjacent judgments

The weight of the alternatives' LCOH is calculated by entering the actual numbers into the pairwise comparison matrix [88]. The matrix is then converted into a priority vector $\boldsymbol{w} = (w_1, \dots, w_n)^T$ by the geometric mean method as in Eq. 7 [86]. The last step is to determine the global priority $\boldsymbol{W}$ of all alternatives in respect to the criteria as in Eq. 8 [89].

$$\boldsymbol{w_i} = \left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \Bigg/ \sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}} \qquad \textit{Eq. 7}$$

$$W_k = \sum_{i} w_i * p_{ik} \qquad \textit{Eq. 8}$$

Where:

W_k: global priority of alternative

w_i: weight of criterion

p_{ik}: priority of alternative concerning criterion

According to [90], the AHP is based on experts' judgment. They evaluate and compare the criteria and alternatives. In the context of this work, the expert's interest is focused on identifying the best heating technology for the paper and pulp factory. The author of this thesis is the AHP's expert. A brief introduction to the expert's opinion is given.

Investment size (INV)

The investment size is an important criterion for the expert. Following [68], the average annual investment per paper and pulp factory is 5 MEUR. In general, the smaller the investment size, the better. The problem with high investment sizes is that it ties a lot of financial resources. The financial resources might not be available directly to the business, requiring a bank loan subject to interest.

LCOH

As already described in 2.4.1, the LCOH is not helpful for investment decisions. Nevertheless, the expert is interested in using a cost-efficient technology. The smaller the LCOH, the better.

Continuous heat supply (CHS)

Considering that the paper and pulp factory is working in continuous production, a reliable and continuous heat supply is mandatory. That's the reason for the expert to consider the continuous heat supply as the most important criteria.

Technology Readiness Level (TRL)

The Technology Readiness Level describes the maturity of a technology. The Technology Readiness Level is defined in the United States Department of Energy framework [91]. Immature and young technologies are perceived as risky. The expert is interested in mature technologies. Therefore, the Technology Readiness Level is an essential criterion as the expert wants to reduce risks to a minimum.

Customer perception (CP)

In terms of customer perception, the use of low-carbon technology creates a positive impression on the customer as it contributes to mitigating climate change. As a result, the company's image positively influences sales of the company's product. However, the expert gives the customer perception less importance.

Following the explanations, the criteria matrix $A_{criteria}$ and $w_{criteria}$ with $CR = 0.060$ are:

$$A_{criteria} = \begin{array}{c|ccccc} & INV & LCOH & CHS & TRL & CP \\ INV & 1 & 2 & 1/5 & 1/3 & 2 \\ LCOH & 1/2 & 1 & 1/3 & 1/3 & 1 \\ CHS & 5 & 3 & 1 & 3 & 3 \\ TRL & 3 & 3 & 1/3 & 1 & 3 \\ CP & 1/2 & 1 & 1/3 & 1/3 & 1 \end{array} \rightarrow w_{criteria} = \begin{array}{c} 0.126 \\ 0.092 \\ 0.437 \\ 0.254 \\ 0.092 \end{array}.$$

3 Process heat technologies

This chapter presents the identified technologies which are subject to further analysis. The technologies are grouped in conventional and renewable heating technologies and their MTPH or LTPH application, as depicted in Figure 8. CHTechs use fuels or electricity as energy sources. They are connected to the respective energy supply grids, enabling the CHTech to operate continuously. Due to the consumption of fuels or electricity, conventional technologies emit GHGs, which endanger the goals of the Paris Agreement. Renewable heating technologies convert RE from the ground, wind, or sun into emission-free heat. The availability of RE sources is site-specific, and the potential is identified through site assessments. Thermal storage technologies are considered to account for the intermittency of solar and wind energy. The assessed technologies are described briefly to provide a general understanding of their current development.

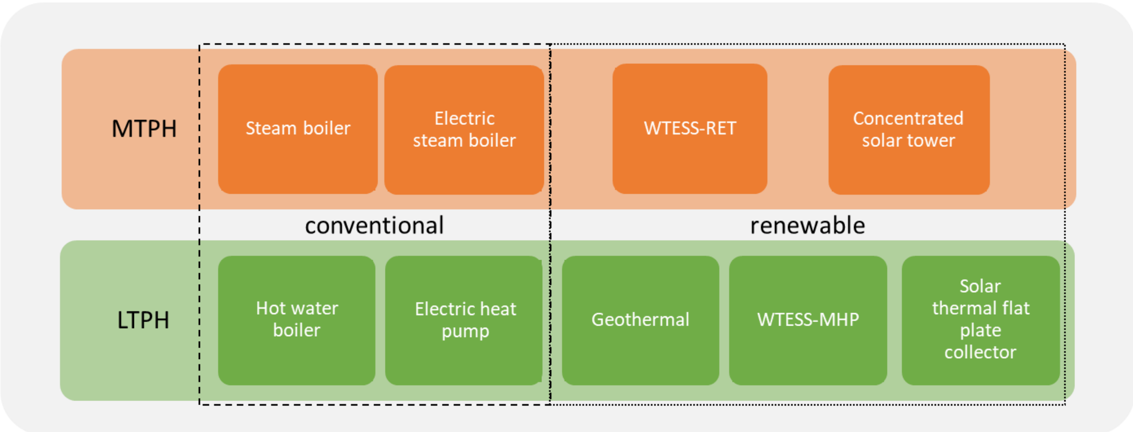

Figure 8: Overview of the assessed conventional and renewable heating technologies

3.1 Conventional process heat technologies

3.1.1 Combustion steam and water boiler

Boilers, in general, are closed vessels used to heat a fluid, not necessarily boiling it [92]. Steam is generated by heating the fluid above its boiling point. The required heating energy is provided through fuel combustion (e.g., natural gas, oil, coal, biomass) or electricity. Different fuels such as natural gas, oil, coal, and biomass are combustible in the burning chamber. The most combusted fuel in the EU28 for industrial processes is natural gas [5]. Using other fuels results in lower efficiency due to the higher contents of moisture [93] or are just more expensive.

Fuel-based steam boilers are mainly divided into water-tube and fire-tube boilers. Inside the boiler, a combustion unit and several metal tubes are installed. In the case of fire-tube boilers, flue gas runs through the metal tubes. In the case of the water-tube boilers, water runs through the metal tubes. The schematic principle is shown in Figure 9. Current boilers are limited to 550 °C due to material property limitations [93].

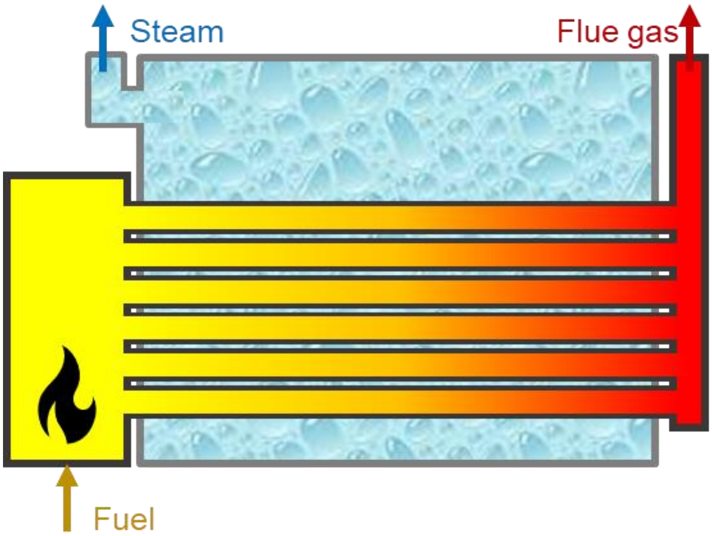

Figure 9: Schematic working principle of a fire-tube boiler

The dominance of steam boilers is given due to their simple construction, which leads to low investment costs and high conversion efficiencies close to 100 %. The system availability is around 94 % [74], making the steam boiler a reliable MTPH technology. A further advantage is the load response and the possibility to combust different fuel types [67]. Hot water boilers for LTPH have a slight performance advantage compared to steam boilers when flue gas condensation due to low return water temperatures is possible [67]. Steam and water boilers, their required fuel supply, and fuel supply network are mature systems [94]. The main disadvantage of boilers is the emissions related to the combustion of fuels. The fuel costs mainly determine the total cost of a boiler system. Fuel costs alone account for 96 % of the TLCC of a steam boiler [74].

3.1.2 Electric heating

Using electricity as an energy source enables efficient process heat for all kinds of temperature levels. Different electric heating principles exist, but they are mainly divided into direct and indirect heating. Steam generation and hence

MTPH is provided by electrode steam boilers. The electrodes are submerged into pressurized water, heating it to the required steam temperature.

Electric steam generators have similar characteristics to the fuel-based boiler, such as very high conversion efficiency, high availability, and full technological maturity [94, 95]. The continuous access to electricity is secured through the power network. The electrode steam boiler has some further advantages, such as higher load flexibility, lower maintenance costs, and the elimination of local air pollution [94-96].

Nevertheless, the environmental impact of the electrode steam boiler is directly linked to the electricity generation mix [94]. The higher the share in renewable electricity, the lower the environmental impact. The choice to use a fuel-based or electrode steam boiler depends on the specific energy costs.

When using electric heating for LTPH, a heat pump should be preferred over an electric hot water boiler due to its higher efficiency. A heat pump is a technology that runs a thermodynamic cycle for heating or cooling purpose. By adding work into the cycle, thermal energy from a low-temperature heat source to a higher temperature heat sink is transferred. The heat pump consists of five main components. Those are the compressor, the condenser, the expansion valve, evaporator, and refrigerant. Heat pumps are a well-known technology for space and water heating. Its coefficient of performance determines the efficiency of a heat pump. The coefficient of performance is the ratio between the heat transferred from the source to the sink and consumed electricity.

Depending on the temperature lift and type of heat sources such as air or water, the coefficient of performance for heat pumps ranges from 2–5 [97]. Those values mean that the heat pump converts the consumed energy into 2–5 times heat. This characteristic makes heat pumps very efficient. Similar to the electrode steam boiler, the electricity generation mix determines the heat pump's carbon emission.

Current commercially available heat pumps lift temperatures depending on the used refrigerant up to 165 °C with a maximum temperature lift of 130 K [98], proving the technology fully mature for LTPH.

Current research focuses on developing suitable energy-efficient heat pumps for industrial processes. For example, the heat pumps are used to recover waste heat, lift it to higher temperatures, and reuse it, increasing the total energy efficiency in industrial processes [99]. One conceptual study introduced a carbon dioxide based heat pump that lifts molten salt from 270 to 480 °C at a coefficient of performance below 1.35 [100], which could be used for MTPH.

3.2 Renewable process heat technologies

3.2.1 WTESS

Research activities about WTESS are already described in 1.2 Wind thermal energy. For the assessment, two different WTESS are considered. For the case of MTPH, a retarder (WTESS-RET) and for the case of LTPH, a mechanical heat pump (WTESS-MHP) is considered.

As presented studies showed, the conversion efficiency of a retarder is close to 100 % [41, 51]. In the mechanical heat pump case, a coefficient of performance of 3.26 is assumed [59].

WTESS converts the wind's kinetic energy into heat. Given the intermittency of the wind resource, an adequate site assessment before installing a WTESS is required. The site assessment's information is used to correspondingly dimension WTESS to maximize the energy production and predict the annual energy generation. The CF for wind turbines in Germany increases geographically from South to North from 5–30 % onshore with its maximum up to 50 % offshore in the North Sea [101].

The CF already enables the required LCOH calculation, but as other requirements such as the continuous heat supply for production exist, the annual wind pattern is briefly addressed. In Europe, wind turbines' power generation tends to be higher in winter (September to March) than in summer [102]. This effect is directly correlated to the available average wind speeds in the respective months. Along with the seasonal power generation pattern, low-wind speed events occur less likely in winter than in summer [103]. In extreme events, it is expected that the wind turbine's mean CF is below 10 % for five consecutive days every year [103]. That is why thermal storages are essential to WTESS.

3.2.2 Solar thermal systems

Solar thermal technologies convert solar radiation into useful thermal energy. Different solar thermal technologies exist which provide different working temperatures. The systems are shown in Table 6. Given the operating temperatures, stationary collector systems are suitable for LTPH, whereas concentrating collector systems are suitable for MTPH. Flat-plate collectors for LTPH and concentrated solar towers for MTPH are further described.

Table 6: Solar collectors types for process heat (source: [104, 105])

Tracking	Collector type	Working temperature [°C]
None	Flat-plate collector	30–90
	Evacuated-tube collector	50–130
	Improved stationary collectors	80–150
Single axis	Linear Fresnel collector	60–400
	Parabolic trough collector	100–450
Two-axes	Parabolic dish collector	100–500
	Concentrated solar tower	150–2000

Flat plate collectors are a simple construction to absorb direct beam and diffuse solar radiation, and convert it into heat. The collectors consist of blackened absorbing material within an insulated panel. Channels for the working fluid, mostly water, are installed within the panel for heat transfer. Figure 10 presents a glazed flat-plate collector. If the flat-plate collectors are enhanced by evacuating the air gap, they are referred to as an evacuated-tube collector. Flat-plate and evacuated-tube collectors are operated globally and are considered a simple, robust, and mature technology [67, 105].

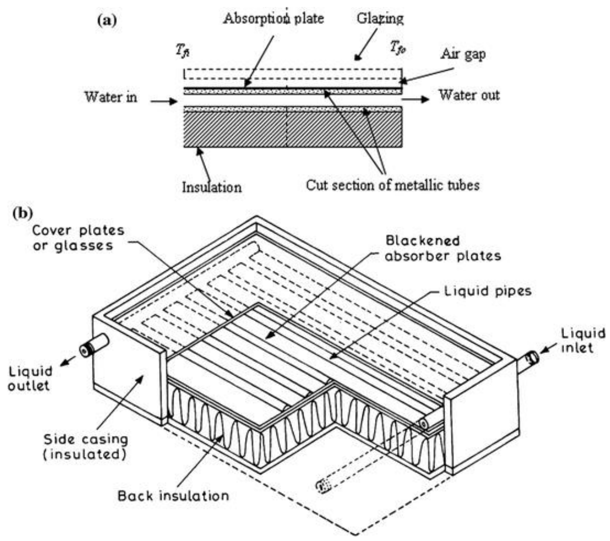

Figure 10: (a) Side cross-section view of single glazed flat-plate collector. (b) Front and cut view of glazed flat-plate collector (source: [106])

Concentrating solar technologies are improved stationary collectors with a single axis or two axes tracking systems. Concentrating solar technologies reflect the solar radiation towards a receiver, increasing the radiant flux density and, therefore, the working fluid temperature [104]. The concentrated solar tower is a two axes tracking system, as depicted in Figure 11. The heliostat reflectors continuously track the sun's direction and reflect its radiation towards the central receiver mounted on top of a tower structure.

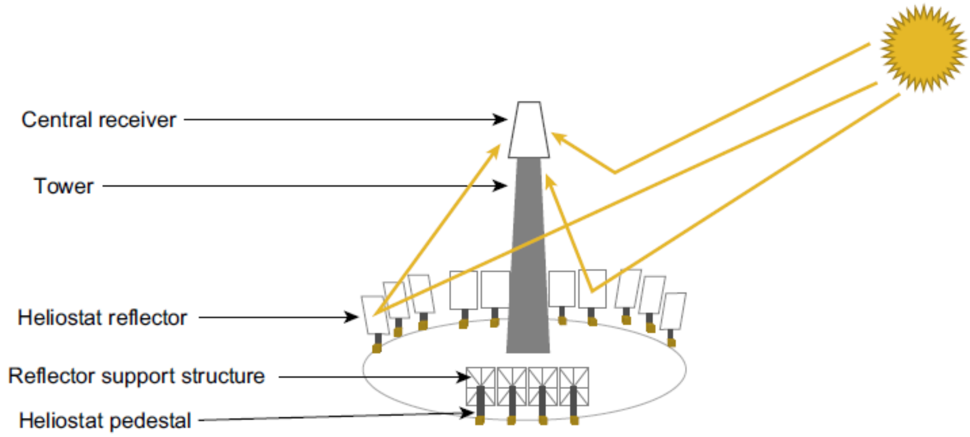

Figure 11: Concentrated solar tower system (source: [107])

Depending on the temperature, the working fluid is steam, thermal oil, air, or molten salt [104]. Current concentrated solar towers and their storage systems reach maximum temperatures up to 565 °C [108]. There is increasing demand for concentrated solar towers due to the system's higher temperature, despite only accounting for 5 % of current commercially installed concentrated solar power plants [107]. According to [108], concentrated solar towers are "recently commercially proven" and subject to further development.

The main limitation of solar technologies is that they can only generate heat during sun hours and are therefore dependent on the site's solar exposure. For example, 80 % of the annual heat is generated for Danish district heating networks during the summer months [67]. Therefore, the seasonal heat production strongly endangers the required continuous heat supply.

For a geographical location in Germany, long-term annual direct normal irradiation ranges between 800–1,200 kWh/m² [109] with long-term annual sun hours roughly between 1,300–1,900 hours [110]. Therefore, Germany is considered unsuitable for concentrated solar technologies as a power technology due to the low direct normal irradiation, resulting in a very high LCOE [111].

3.2.3 Geothermal

Geothermal energy is the thermal heat stored in the Earth's crust. Geothermal energy is used for either heat or electricity generation. The thermal reservoir is accessed by drilling holes several hundred to thousands of meters into the ground, as depicted in Figure 12.

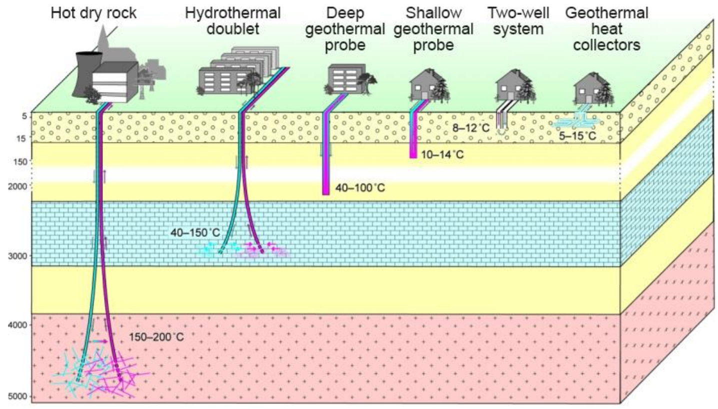

Figure 12: Overview of geothermal systems including supplied temperature and borehole depth (source: [112])

In general, the temperature of the heat reservoir increases with depth. The geothermal gradient is between 20–30 K/km on continental crust, with the highest gradient between 40–80 K/km in areas where magma is close to the surface [113]. Accessible geothermal heat sources are at temperatures between 50–350 °C [114]. Transferring the stored underground heat to the surface is subject to heat losses, resulting in usable temperatures below 200 °C in respect to a 350 °C source [115]. In terms of the globally available heat sources, around 68 % of them are expected to be below 130 °C [116]. In Germany, geothermal resources are available in three main regions the Upper Rhine Graben, the North German Basin, and the South German Molasse Basin, with temperatures between 59–165 °C at 2,500 meters depth [117]. The current state-of-the-art geothermal systems and available national resources are not suitable to provide the required MTPH, but the system is a reasonable technology to provide LTPH. Geothermal systems are already established for district heating networks [67]. The application of geothermal systems for industrial processes at temperatures below 200 °C has been used in several countries but experienced a decline in operational geothermal systems [118].

Compared to other renewable technology, the most significant advantage of geothermal systems is the continuously available and weather-independent heat supply [95]. This type of heat source is used in combination with a heat pump to increase efficiency further. Once in operation, the operational and variable costs are low [67]. Barriers are the high investment costs and identifying a suitable heat reservoir that has to be drilled and tested [67]. In addition, the installation of deep geothermal systems can cause seismic activities, which occasionally were measurable at surface level [119]. Therefore, geothermal systems are subject to further development, potentially reducing costs and associated risks [67].

3.2.4 Thermal energy storage technologies

Renewable heating technologies convert intermittent energy sources into heat. In particular, WTESS and solar thermal systems require storage technologies to store and evenly distribute the generated heat throughout a given time frame. The type of thermal storage depends on the requirements, such as temperature and storage time. Three types of thermal energy storage exist: sensible heat, latent heat, and chemical [120].

Sensible heat storages refer to a system in which a medium stores thermal energy by heating or cooling it. The most popular medium for sensible heat storage is water, commonly used for residential, commercial, and industrial applications [120]. Water is suitable for several applications in temperatures below its boiling point as it possesses a comparably high specific heat value and low price [120]. The water is stored in an insulated tank which can be used for heating and cooling at any time.

Sensible heat storages are as well used as seasonal storage. Most seasonal storages use ground material to store heat or cooling energy [120]. Further ground storages are aquifers, underground stored freshwater sources with several million cubic meters in volume [121]. Aquifers store excess heat from solar thermal systems in the summer months and dispatch the thermal energy when needed in winter [121]. Due to the immense size of an aquifer, they cannot be insulated and are limited to small temperature changes [120].

Storage solutions for MTPH are already available for concentrated solar technologies. Molten salt is the most widespread storage medium for concentrated solar systems [108]. The maximum temperature of molten salt storage is 565 °C, its decomposition temperature [122]. Research is conducted to develop new working fluids based on liquid metals which achieve higher temperatures than molten salt [122]. The most significant advantage of thermal storage is its economic feasibility for large-scale applications compared to electrical storage [41, 108].

A storage capacity of 12 hours (342 MWh) is considered for any intermittent RHTech. For LTPH, hot water storage is accounted for at the cost of 9,000

EUR/MWh [59]. For MTPH, molten salt storage is accounted for at the cost of 22,400 EUR/MWh[2] [111].

[2] The source presents 26.4 USD/kWh which is converted at the average exchange rate in year of reference (2018) of 0.8475 EUR/USD (source: https://www.exchangerates.org.uk/USD-EUR-spot-exchange-rates-history-2018.html).

4 Results and discussion

This section presents the results and discussion associated with heating technologies. For comparison reasons, the technologies are divided into MTPH and LTPH technologies. It should be noted that the lower and upper LCOH is derived from different assumptions. The LCOH is determined through the two natural gas price models for the steam and hot water boiler. The mean value and two times the standard deviation (2SD) based on the conducted sensitivity analysis are presented for the other technologies.

4.1 Medium-temperature process heat

For MTPH, four technologies are identified and compared in terms of their LCOH. The natural gas steam boiler under business as usual and climate neutral presents an LCOH of 51 and 78 EUR/MWh, respectively. The alternative technologies are the concentrated solar tower, WTESS-RET, and electric steam boiler. First ranked is the concentrated solar tower, which presents the smallest LCOH between 15–32 EUR/MWh with its mean around 24 EUR/MWh, undercutting the LCOH of all considered technologies even under consideration of its 2SD. The WTESS-RET LCOH ranks second, ranging between 30–110 EUR/MWh, with its mean around 70 EUR/MWh. The electric steam boiler ranks last between 50–220 EUR/MWh, with its mean LCOH around 125 EUR/MWh. The respective plot is presented in Figure 13.

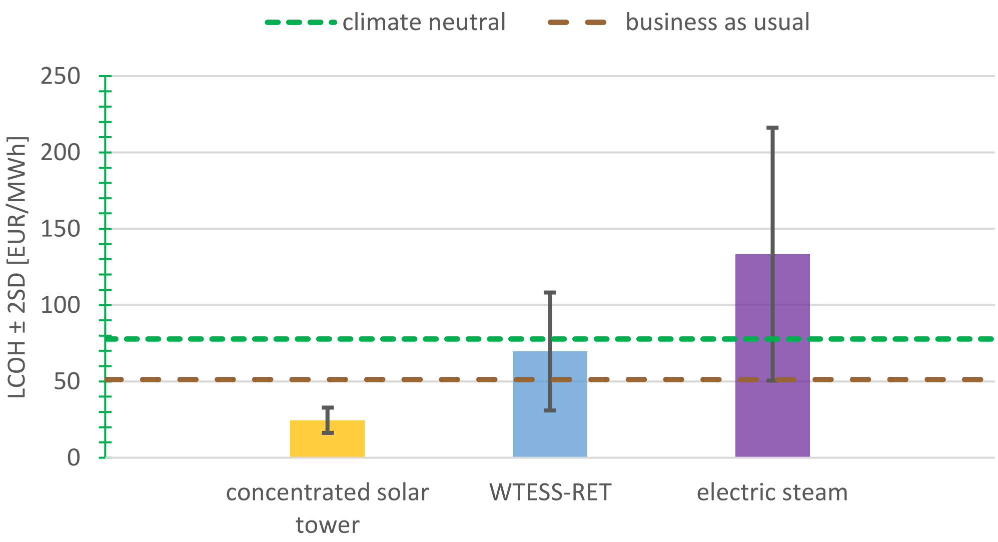

Figure 13: LCOH of assessed MTPH technologies

Following the LCOH ranking, it is highly preferable to choose the concentrated solar tower as MTPH technology. Despite the sensitivity analysis, deviations are relatively small compared to the other two technologies. The solar tower performs so well in its LCOH due to the calculation based on the direct normal irradiance (DNI). The DNI is an annual average value that neglects the intermittency of solar radiation. If a concentrated solar power tower in Germany is taken as a reference, the LCOE is around 280 EUR/MWh [111]. The LCOH is derived from the LCOE through an estimation. The estimation accounts for the power cycle efficiency of 43.5 %. It only considers the thermal energy-relevant structural components such as heliostats, tower, receiver, and thermal storage, which account for 60 % of the overall CAPEX [111]. The respective LCOH results in 73 EUR/MWh. Therefore, the calculated LCOH of 24 EUR/MWh seems too optimistic compared to the estimated LCOH.

Another conflict is that the solar tower's LCOH is close to the flat-plate collector one. According to the sources used, the cost for heliostats (111 EUR/m^2) is significantly cheaper than for the flat plate collectors (187 EUR/m^2). This cost difference seems unreasonable, especially concerning the maturity of both technologies.

The WTESS-RET's LCOH is very similar to the results presented by Cao et al. [59]. Cao et al. calculated the WTESS-RET's LCOH in a range between 50–120 EUR/MWh [59]. Compared to Cao et al., the WTESS-RET sensitivity analysis accounts for a higher CF and lower discount rate. The different assumptions explain why the WTESS-RET reaches a lower LCOH value of 30 EUR/MWh. As suggested by the literature review, the WTESS-RET's LCOH should be below the LCOE for onshore wind turbines. This criterion is fulfilled as current onshore wind turbines in Germany have an LCOE starting from 40 EUR/MWh [72].

The electric steam boiler's LCOH ranges in the same range as the assumed electricity price. Therefore, the LCOH already suggests a strong dependency on the electricity price.

The multilinear regression analysis provides more details on the influence given by the input variables. The standardized regression coefficients are shown in Table 7.

Table 7: Standardized regression coefficients b_p for dependent variable LCOH of MTPH technologies as described in 2.5.1

Technology	**Independent variable**	**Standardized regression coefficient b_p**
Concentrated Solar Tower (R^2 = 0.992)	Discount rate	0.691
	Direct normal irradiance	insignificant
	CAPEX	0.753
	OPEX	unavailable
WTESS-RET (R^2 = 0.960)	Discount rate	0.355
	Capacity factor	-0.677
	CAPEX	0.560
	OPEX	0.107
Electric steam boiler (R^2 = 0.999)	Discount rate	0.001
	OPEX	1.000
	CAPEX	0.001

The concentrated solar tower's LCOH is significantly dependent on the discount rate and CAPEX. If the LCOH equation is recalled, the discount rate discounts the TLCC and generated energy. Given the meager costs related to OPEX for RHTechs, the discount rate only discounts the energy, which finally increases the LCOH.

The standardized regression coefficient for the DNI equals 0.003 but is insignificant for the LCOH calculation due to its P-Value > 0.4. The insignificant DNI contradicts the results from the flat plate collector, for which the DNI is a significant variable and negatively impacts the LCOH. When a simple linear regression is applied to the DNI regarding the LCOH, the resulting standardized regression coefficient is -0.496. The CAPEX is calculated based on the DNI, which implies collinearity and explains the DNI insignificance. The standardized regression coefficient for OPEX is unavailable due to its linear dependency OPEX = 0.015*CAPEX.

The WTESS-RET's most influential variable is the CF, followed by CAPEX and discount rate. The higher the CF is, the higher the annual energy generation and the lower the LCOH. Assessing and choosing the appropriate location for the WTESS-RET to maximize the CF is therefore very important. Like the concentrated solar tower, the WTESS-RET's LCOH strongly depends on the

CAPEX underlined by the standardized regression coefficient's value. The dependency of the WTESS-RET's LCOH on the discount rate is lower than for the concentrated solar tower. OPEX only plays a subordinate role towards the LCOH as such costs are small for RHTechs. The electric steam boiler's LCOH is only dependent on OPEX. This proves the influence mentioned above of the energy cost on the TLCC and LCOH.

The most suitable technology for the paper and pulp factory is determined by applying the AHP. The results are summarized in Table 8. The MTPH technologies rank in the following order starting with the most suitable one: natural gas steam boiler, electric steam boiler, concentrated solar tower, and WTESS-RET. The weights show that the conventional technologies receive the highest weights across the three highest weighted criteria INV, CHS, and TRL.

Table 8: Final weights for MTPH following the Analytic Hierarchy Process (highest weight for each criterion is underlined)

Criteria	INV	LCOH	CHS	TRL	CP	Global priority
Weight	0.126	0.092	0.437	0.254	0.092	
Natural gas steam boiler	<u>0.426</u>	0.199	<u>0.404</u>	<u>0.385</u>	0.067	**<u>0.352</u>**
Concentrated solar tower	0.093	<u>0.518</u>	0.039	0.142	<u>0.495</u>	**0.158**
WTESS-RET	0.056	0.185	0.153	0.087	0.291	**0.140**
Electric steam boiler	<u>0.426</u>	0.097	<u>0.404</u>	<u>0.385</u>	0.148	**0.350**
CR	0.006	0.000	0.012	0.008	0.007	

Natural gas and electric steam boiler share very similar properties. They require very low investments between 1–2 MEUR, offer secured energy supply through the gas or power network, and are fully mature. In addition, the natural gas steam boiler benefits from the low fuel costs, which leads to a considerably low LCOH. The main disadvantage of the natural gas steam boiler is its environmental impact through GHG emissions, which leads to the least weight in terms of CP. In a direct comparison between both steam boilers, the electric steam boiler performs less in the LCOH but better in CP. Under the consideration that the electric steam boiler consumes emission-related electricity from the grid, the electric steam boiler’s CP weight is below the renewable technologies as there are no direct local emissions related to its operations [96].

The concentrated solar tower and WTESS-RET rank last due to their low weight in INV, TRL, and the knock-out criterion CHS. Both technologies are limited in their application for the paper and pulp factory. Despite the consideration of thermal storage, the heat supply remains unreliable. In particular, the concentrated solar tower provides unpredictable heat under the site conditions in Germany. Given the available national sun hours, the CF for solar plants is reported to be between 0.10–0.14 [101]. The availability of wind energy is generally higher in Germany, which benefits the WTESS-RET’s CHS weight.

Although WTESS-RET is based on the knowledge of commercially available components such as wind turbines and retarders, WTESS-RET itself is still a fictive technology. In the case of concentrated solar towers, first commercial projects exist. However, both technologies still require further development to reduce risks associated with maturity and system costs. Those issues lead to the last barrier, the high investment for RHTechs. The investment required for concentrated solar tower and WTESS-RET is 100 and 200 MEUR, respectively, which creates a barrier to purchase. The criteria in favor of RHTechs are the competitive LCOH and the emission-free heat generation. Furthermore, the concentrated solar tower receives a higher weight in CP than WTESS-RET as the general social acceptance for solar technologies is greater than for wind turbines [123].

Despite the first rank for the natural gas steam boiler, choosing the electric steam boiler is recommended. Some measures are available to improve the electric steam boiler's priority and make it the most suitable technology to fit all criteria the best.

4.2 Low-temperature process heat

For LTPH, five heating technologies are identified and compared in terms of their LCOH. The results are displayed in Figure 14. The natural gas water boiler under business as usual and climate neutral presents an LCOH of 46 and 70 EUR/MWh, respectively. The alternative technologies are solar thermal, WTESS-MHP, geothermal, and electric heat pump. Apart from the geothermal system, the mean LCOH of the other RHTechs are situated below the business as usual LCOH. The flat plate collector ranks first with an LCOH between 13–30

EUR/MWh, followed by WTESS-MHP between 17-51 EUR/MWh, and the geothermal system between 40–81 EUR/MWh. The electric heat pump's LCOH ranges between 17–61 EUR/MWh.

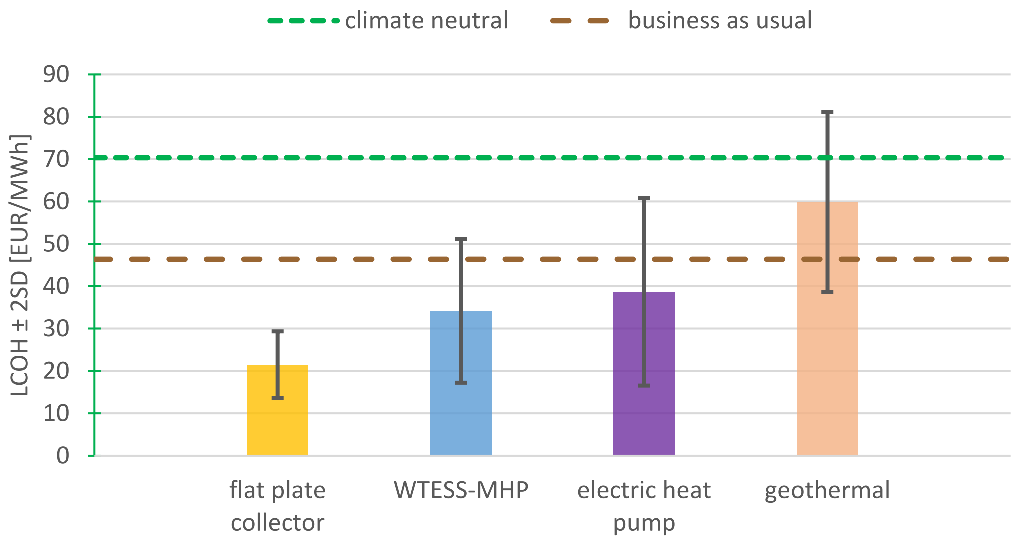

Figure 14: LCOH of assessed LTPH technologies

The flat plate collector ranks first despite the comparably low average annual DNI in Germany. This rank is especially surprising compared to the other heating technologies that benefit from the coefficient of performance of the heat pump systems. Two studies confirm the flat plate collector's calculated LCOH, as the LCOH for solar district heating systems in Denmark is between 20–40 EUR/MWh [124] and for Germany, between 40–70 EUR/MWh [125].

The WTESS-MHP is calculated on the figures presented by Cao et al. [59]. Cao et al. reported the WTESS-MHP's mean LCOH around 60 EUR/MWh, significantly higher than the demonstrated results. The deviation between the reference and own calculation is possibly related to the sensitivity analysis. Cao et al. assessed both WTESS-MHP and WTESS-RET in their study, but both technologies' LCOH only differ slightly by 10 EUR/MWh [59]. In the presented results, the WTESS-MHP's LCOH is half of the WTESS-RET. It is assumed that the mechanical heat pump's coefficient of performance accounts for the significant reduction in the technology's LCOH.

The geothermal system's LCOH is calculated on the assumption that the system includes an electric heat pump. Due to the borehole depth, the heat source's temperature is constantly between 30–70 °C [67]. Those temperatures enable a heat pump to run more efficiently than an air source or ground source electric heat pump.

The difference in LCOH between the heat pump and geothermal system is explained through the much higher CAPEX for geothermal systems. The average LCOE for geothermal systems in Germany is around 235 EUR/MWh [126]. When accounting for a net efficiency of around 10 % [126], the LCOH for geothermal systems could be lower than the calculated result. Indeed, an LCOH of 26 EUR/MWh for Germany based geothermal systems has been presented [127]. This would mean that geothermal systems would rank first concerning the LCOH.

As part of the sensitivity analysis, the multilinear regression analysis is applied. The results are presented in Table 9. Similar to the results for the MTPH technologies, a pattern for the conventional and RHTechs is visible. On the one hand, the RHTechs' LCOH are dependent on the discount rate, CAPEX, and site-specific values such as the DNI and CF. OPEX is insignificant towards the RHTechs' LCOH. On the other hand, conventional technologies' LCOH is mostly dependent on the OPEX.

Table 9: Standardized regression coefficients b_p for dependent variable LCOH of LTPH technologies as described in 2.5.1

Technology	**Independent variable**	**Standardized regression coefficient b_p**
Flat plate collector (R^2 = 0.982)	Discount rate	0.760
	Direct normal irradiance	-0.473
	CAPEX	0.465
	OPEX	0.012
WTESS-MHP (R^2 = 0.963)	Discount rate	0.413
	Capacity factor	-0.733
	CAPEX	0.512
	OPEX	0.094
Electric heat pump (R^2 = 0.999)	Discount rate	0.194
	OPEX	1.000
	CAPEX	0.011
Geothermal (R^2 = 0.999)	Discount rate	0.144
	OPEX	0.967
	CAPEX	0.190

The flat plate collector's LCOH most dependent variable is the discount rate with a coefficient of 0.760. This value is very similar to the one for concentrated solar towers. The negative standardized regression coefficient proves that the LCOH decreases with increasing DNI. This relation is reasonable as higher DNI reduces the required CAPEX. The smaller the CAPEX in general, the smaller the LCOH.

The WTESS-MHP's LCOH shows the most substantial dependency on the CF. The CF is used to calculate the rated power of the WTESS-MHP, which might result in the presented SRC. WTESS-MHP's LCOH is less dependent on the discount rate than the flat plate collector. For both the WTESS-MHP and the flat plate collector, the LCOH's dependency on CAPEX is almost similar. In contrast, the WTESS-MHP discount rate is similar to the flat plate collector's DNI. The flat plate collector's discount rate is similar to the WTESS-MHP CF. Again, it is vital to conduct a site assessment to identify the site's available RE sources to reduce the LCOH.

In terms of the heat pump and geothermal system, the most determining variable for their LCOH is OPEX. The operating principles of both technologies are very similar as they transfer heat from a heat source to a heat sink. The main driver for OPEX is the electricity consumed, which is required to operate the thermodynamic cycle. The cheaper the electricity is generated or purchased, the lower the technologies' LCOH. The discount rate plays a subordinate role for both technologies. In contrast to RHTechs, both the OPEX cost and generated energy are discounted, balancing the impact of the discount rate on the LCOH. The geothermal system's LCOH is slightly determined by the CAPEX, given the high upfront cost for RHTech. The CAPEX for heat pumps is small and hence less influential on the LCOH.

After assessing the LTPH technologies regarding their LCOH, all relevant information exists to finalize the AHP. The summary of the weights for criteria and alternatives is presented in Table 10. The ranking based on global priority for the LTPH technologies starts with the gas boiler, followed by the electric heat pump, geothermal system, WTESS-MHP, and the flat plate collector system. Next, the alternatives' weights concerning the criteria are discussed.

Table 10: Final weights for LTPH following the Analytic Hierarchy Process (highest weight for each criterion is underlined)

Criteria	**INV**	**LCOH**	**CHS**	**TRL**	**CP**	**Global priority**
Weight	0.126	0.092	0.437	0.254	0.092	
Hot water boiler	<u>0.389</u>	0.143	<u>0.328</u>	<u>0.272</u>	0.047	**<u>0.279</u>**
Flat plate collector	0.083	<u>0.260</u>	0.029	<u>0.272</u>	<u>0.439</u>	**0.156**
WTESS-MHP	0.083	0.245	0.114	0.079	0.259	**0.127**
Electric heat pump	0.293	0.213	<u>0.328</u>	<u>0.272</u>	0.088	**0.277**
Geothermal	0.151	0.139	0.200	0.104	0.167	**0.161**
CR	0.008	0.000	0.015	0.013	0.015	

The hot water boiler ranks first for the criterion INV. The hot water boiler is a simple and mature technology that only costs 1.5 MEUR. The electric heat pump requires investments of around 20 MEUR, followed by the geothermal system with 80 MEUR, and finally, both wind and solar technologies with approximately 100 MEUR. The weights in terms of LCOH have been distributed according to the presented LCOH results above. Therefore, they are not further commented.

Concerning CHS, CHTechs have a clear advantage again. They are reliable due to their access to the energy supply grids. The heat supply from geothermal systems is ranked third. The available heat supply depends on the heat source and can therefore be limited to meet the factory's heat demand. The WTESS-MHP ranks before the flat plate collector due to the higher CFs than those for solar systems [101]. Three technologies, the two conventional and the flat plate collector rank first in terms of TRL. All three technologies are considered mature. Geothermal systems are already in operation, but they still experience further development. The WTESS-MHP ranks last as the technology has only been tested on a small scale. Regarding CP, the RHTechs rank in front places, starting with the flat plate collector, followed by WTESS-MHP and geothermal systems. RHTechs, by default, are environmentally friendly, which improves the company's image. The electric heat pump and hot water boiler rank behind due to their potential emissions from energy consumption.

The hot water boiler ranks first, given that it achieves the best weights across three significant criteria, INV, CHS, and TRL. The electric heat pump, which has a lesser weight for INV but a higher weight for LCOH, closely follows the hot water boiler. However, the three other technologies, which are all renewable, fall behind the CHTechs concerning the global priority. The resulting global priorities suggest issues, which need to be addressed to increase the ranking of RHTechs in general.

4.3 General discussion

Some conclusions can be made for both applications when both results for LTPH and MTPH technologies are merged. The LCOH for RHTechs is strongly dependent on the variables discount rate, CAPEX, and available RE sources. The discount rate and CAPEX have a positive, and the available RE sources negatively affect the LCOH. The LCOH for CHTechs is dependent on the OPEX, in particular the energy costs.

Concerning the AHP, conventional technologies rank best, with the fuel-based system ranking first. The electric heating system is closely ranked second, and RHTechs followed far behind in the order of solar and wind. The results support the fact that CHTechs are preferably chosen as heating technology [7]. The advantages of CHTechs are low CAPEX, their maturity, and reliable heat supply. All those three criteria have the highest weighting. In contrast, RHTechs performed better in the LCOH and CP. It is important to substitute fuel-based boilers to mitigate climate change, so it is discussed which measures potentially adjust the AHP ranking in favor of carbon-neutral technologies.

First, the electric systems, steam boiler, and heat pump are discussed. The electric systems miss first place due to their weight in LCOH and CP. By decreasing the OPEX, which is determined by the electricity costs, the LCOH is reduced. There are two ways to do that: either the factory settles a better electricity price with the supplier or generates electricity through its renewable power plant. Running an own renewable power plant cuts down the electricity cost and increases the CP. The CP alone can be increased if the factory purchases renewable electricity.

Based on the AHP, RHTechs require improvement in the three criteria CAPEX, CHS, and TRL. First, the impact of a high TRL is introduced. If the technology is mature, further cost reductions are unexpected. The mature technology is, therefore, at its lowest cost point. The maturity implies too that the technology and its risks are well known. By increasing the TRL through research and development, the CAPEX and associated technological risks are reduced. Another side effect is that knowing or minimizing risks makes an investment more transparent, reducing the discount rate and LCOH. Furthermore, government incentives or low-interest loans for RHTechs can increase the CAPEX weight of the RHTechs. The appropriate site selection is another possibility to decrease the CAPEX and LCOH. Further factors, such as material, labor, knowledge, supply chains, and others, influence the CAPEX [111].

The improvement of RHTechs' weight in CHS is the most challenging. Geothermal systems already have a significant advantage compared to wind and solar systems, but the resources in Germany are geographically limited. Current research activities focus on improving different storage technologies, which might increase the CHS in the near future. The most trivial option to increase the CHS is to find a site with high RE sources. Sufficient wind energy or high solar radiation with many sun hours can already significantly improve the heat supply. Germany might have sites with enough wind energy, but the solar exposure is too little so that solar systems are dismissed due to intermittent heat supply.

From the technical point of view, it can be concluded that the decarbonization of process heat in Germany is mainly achieved through electrification. LTPH might be provided through geothermal systems, which can only operate in some areas of the country. WTESS can be a reasonable solution to provide LTPH or MTPH if a backup heating system is available.

5 Conclusion

This thesis investigated the current and future deployment of process heating technologies in Germany. The thesis considered the recently implemented national carbon pricing regulation. In addition, a new RHTech, WTESS, was introduced into the assessment.

In the first stage, all technologies were assessed in terms of the LCOH. Natural gas based heat systems present an LCOH of around 50 and 80 EUR/MWh for the business as usual and climate neutral gas price development. The results showed that RHTechs for both MTPH and LTPH are already competitive or even overperform conventional heat technologies. The CHTechs' LCOH is strongly dependent on OPEX, whereas RHTechs' LCOH almost evenly depends on the discount rate, site-specific RE sources, and CAPEX.

The interpretation of LCOH results is limited as they exclude the intermittency of RE sources and infrastructure related costs such as grid extensions. For this reason, the LCOH and four other criteria were assessed through AHP. It should be noted that the AHP itself is limited through the study context, the chosen criteria, and a single expert's opinion. More criteria and more experts can be considered to give a more detailed understanding of the decision weights. The results of the AHP indicate that the natural gas heat system is the best option, closely followed by the electric heat systems. Those results underline the fact that conventional heat systems are the most dominant deployed technology. Fuel- and electricity-based technologies strongly benefit from the "endless" supply from the respective supply grids. RHTechs rank last due to their intermittent heat supply, even considering storage technologies.

Further limitations for renewable heating are the high CAPEX and dependency on the available RE sources. In particular renewable MTPH technologies are further limited by the risks associated with their TRL.

In summary, the decarbonization of industries, in particular, process heat, remains challenging. Under the circumstances of continuous production, conventional heating cannot be fully substituted by RHTechs. Storage technologies exist to store and dispatch the generated heat at the required time, but sizing the storage to account for extreme events with days or even months without sufficient heat generation, results in excessively high costs and space requirements. Hence, a conventional backup system is always required to fulfill the needs for continuous production. It is recommended to use a hybrid solar and wind system which potentially ensures the annual heat supply, as the energy generation profiles compensate for each other over the year. Another application would be to use the RHTechs for preheating. Even for industries that are not working continuously, the high investment size for RHTechs is a potential barrier. Financial incentives and low-interest loans help to overcome that barrier. Especially for renewable MTPH technologies, research and development are required to reduce technology-associated risks.

A rather simple option to decarbonize process heat is to opt for electric systems such as the electric steam boiler or electric heat pump. Both systems have ranked closely second to the natural gas boiler. The reasons to miss out in the first place were the high LCOH and low CP. However, both criteria can be addressed at once if the factory generates and self-consumes renewable electricity. Self-generated renewable electricity cuts down the cost for electricity drastically, is great for marketing, and the supply remains secured through the grid connection.

Germany has taken the first step to substitute fuel-based heating with RHTechs through its carbon pricing regulation. Fuel prices would remain too low without any regulation. Current regulation enables RHTechs to be competitive concerning the LCOH. The main issue is that the current regulation is valid until 2026. A clear roadmap for further carbon pricing is needed for an investor so that the regulation is appropriately assessed in the investment decision.

When zooming out from the geographical context of Germany, access to a reliable energy grid might be unavailable. In addition, preferable site conditions such as high direct solar irradiance, high wind speeds, and abundant space might be available, which reasons the deployment of RHTechs. But this is subject to comprehensive site assessments. Therefore, future studies should address an actual use case because only then the strengths and weaknesses of RHTechs and necessary further development steps will be revealed. At the same time, aging and degradation, hourly and daily energy demand and supply, system performance and lifecycle, financing, and others can be investigated and analyzed.

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7 Appendices

Appendix A: Summary of variables and equations used to calculate LCOH

	Steam boiler	Electric steam boiler	Hot water boiler	Electric heat pump	Geothermal
CAPEX [EUR/MW]	55,000	80,000	50,000	730,000	2,710,000
Fixed O&M [EUR/MW]	2,000	1,070	2,000	2,000	22,600
Variable O&M [EUR/MWh$_{out}$]	1.00	0.50	1.00	1.80	5.70
Auxiliary energy consumption [% of MWh$_{out}$]	0.14	0.50	0.14	2.00	4.10
η_{system} [–]	0.93	0.99	1.03	3.88	4.60
Forced outage [%]	–	1.00	1.00	0.00	2.00
Planned outage [weeks per year]	–	0.2	0.7	1.9	2.0
Availability [%]	94.2	98.6	98.3	98.1	94.3
Lifetime [years]	25	25	25	20	25
Real discount rate [%]	2.55	2.55	2.55	2.55	5.00
SOURCES	[74, 94]	[94]	[94]	[94]	[67]

	Solar thermal boiler
Solar collector [EUR/m²]	187
12 hours hot water storage	3,078,000
Fixed O&M [EUR/MWh]	0.09
Auxiliary energy consumption [% of MWh_{out}]	0.30
η_{system} (DNI to thermal energy) [–]	0.45
Forced outage [%]	0.5
Planned outage [weeks per year]	–
Availability [%]	99.5
Lifetime [years]	30
Real discount rate [%]	2.55
SOURCES	[67]

$$Surface_{solar}\ [m^2] = \frac{E_{demand}}{DNI * \eta}$$

$$CAPEX_{solar\ thermal\ boiler} = Solar\ collector * Surface + Storage$$

	Concentrated solar tower
Heliostat [EUR/m²]	111
Solar tower [EUR]	6,872,727
Receiver [EUR/MW]	106,060
12 hours molten salt storage [EUR]	7,660,800
η_{system} (DNI to thermal energy) [–]	0.54
Fixed OPEX	0.015*CAPEX
Lifetime [years]	25
Real discount rate [%]	5.00
SOURCES	[111, 128]

$$Surface_{solar}\ [m^2] = \frac{E_{demand}}{DNI * \eta}$$

$$Power_{solar}\ [MW] = \frac{E_{demand}}{8{,}760}$$

$$CAPEX_{solar\ tower} = Heliostat * Surface + Receiver * Power_{solar} + Tower + Storage$$

	WTESS-RET	WTESS-MHP
CAPEX [EUR/MW]	820,000–1,720,000	1,500,000–2,674,000
12 hours thermal storage [EUR]	7,660,800	3,078,000
OPEX [EUR/MW]	2,000	1,070
η_{system} [–]	1.00	3.26
Capacity factor [%]	0.15–0.30	
Lifetime [years]	20	20
Real discount rate [%]	5.00	5.00
SOURCES	[59, 111]	[59]

Appendix B: Future fuel price for natural gas in nominal EUR with base year 2020

fuel price						**certificate prices**		**future fuel price**	
Year	wholesale gas	margin	Gas tax	Grid charges	Total	CO2 BAU	CO2 Climate	Gas BAU	Gas Climate
base 2020	EUR/MWh	EUR/MWh	EUR/MWh	EUR/MWh	EUR/MWh	EUR/tCO2	EUR/tCO2	EUR/MWh	EUR/MWh
0	12	3	6	4	24	0	0	**24**	**24**
1	14	4	6	4	28	25	25	**33**	**33**
2	16	5	6	4	30	30	30	**36**	**36**
3	16	5	6	4	31	35	35	**38**	**38**
4	17	5	6	4	31	45	45	**40**	**40**
5	17	5	6	4	31	55	55	**42**	**42**
6	17	5	6	4	32	65	65	**45**	**45**
7	18	5	6	4	32	65	95	**45**	**51**
8	18	5	6	4	33	65	125	**46**	**58**
9	18	5	6	4	33	65	155	**46**	**64**
10	19	6	6	4	34	65	180	**47**	**70**
11	19	6	6	4	34	65	189	**47**	**72**
12	19	6	6	4	34	65	206	**47**	**76**
13	20	6	6	4	35	65	225	**48**	**80**
14	20	6	6	4	35	65	243	**48**	**84**
15	20	6	6	4	36	65	260	**49**	**88**
16	21	6	6	4	36	65	278	**49**	**92**
17	21	6	6	4	37	65	295	**50**	**96**
18	21	6	6	4	37	65	299	**50**	**97**
19	22	7	6	4	38	65	304	**51**	**99**
20	22	7	6	4	38	65	308	**51**	**100**
21	23	7	6	4	39	65	312	**52**	**101**
22	23	7	6	4	39	65	317	**52**	**103**
23	23	7	6	4	40	65	321	**53**	**104**
24	24	7	6	4	41	65	326	**54**	**106**
25	24	7	6	4	41	65	330	**54**	**107**