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The Potential of Vapor Compression Heat Pumps Supplying Process Heat between 100 and 200 °C in the Chemical Industry

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Abstract: The supply of process heat in the chemical industry is dominated by fossil fuel combustion. Heat with temperatures up to 200 °C could, however, be supplied by vapor compression heat pumps (VCHPs), allowing for efficient electrification. However, there are still several barriers that need to be overcome before they can be widely implemented. In this work VCHPs are thermodynamically compared to heat-driven heat pumps and heat transformers, exploiting the potential of VCHPs. Moreover, steam production, distillation and drying are found to be of primary interest within the chemical industry, and potential integration points are presented and discussed for these applications. Finally, a financial analysis is performed based on a steam production and a superheated steam drying case study. The analysis calculates the levelized cost of heat (LCOH) of a VCHP, heat transformer, natural gas boiler and electric boiler. Furthermore, a sensitivity analysis of the LCOH to the annual operating hours, carbon pricing and waste heat availability is presented. Generally, when no emissions trading scheme (ETS) is applied, both the VCHP and a combination of a heat transformer with auxiliary natural gas boiler appeared as the most optimal solutions, depending on the energy prices. Due to the limited utilization of waste heat by the heat transformer, an auxiliary natural gas or electric boiler is essential to fully meet the required heating load. When an ETS is being applied the VCHP generally appeared to be most financially attractive technology for both the case studies.

Keywords: industrial heat pumps; high-temperature heat pump; chemical industry; economics; electrification

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Citation: Vieren, E.; Demeester, T.; Beyne, W.; Magni, C.; Abedini, H.; Arpagaus, C.; Bertsch, S.; Arteconi, A.; De Paepe, M.; Lecompte, S. The Potential of Vapor Compression Heat Pumps Supplying Process Heat between 100 and 200 °C in the Chemical Industry. *Energies* **2023**, *16*, 6473. https://doi.org/10.3390/en16186473

Academic Editors: Francesco Nocera and Annunziata D'Orazio

Received: 10 July 2023
Revised: 7 August 2023
Accepted: 4 September 2023
Published: 7 September 2023

1. Introduction

The chemical industry is a growing industrial sector which acts as the backbone of all industrialized countries or economies [1]. Belgium is taken as a representative example, considering its relatively large chemical sector. In 2019, the final energy use of Belgium was about 378 TWh [2]. Within this final energy use, the industrial sector had the most significant contribution with a share of around 32% [2]. One of the reasons for the large contribution of the industrial sector is the strong presence of the (petro)chemical industry. Belgium has, with a yearly turnover of EUR 61,000 M, the fourth-largest chemical industry within Europe, good for 95,500 direct and 220,000 indirect jobs [3]. The importance of the (petro)chemical sector for Belgium is reflected in the industrial energy use data, illustrated in

Figure 1. This figure shows that the (petro)chemical sector is responsible for almost 39% of the total industrial energy use, being double the relative energy use of the (petro)chemical sector in Europe [2].

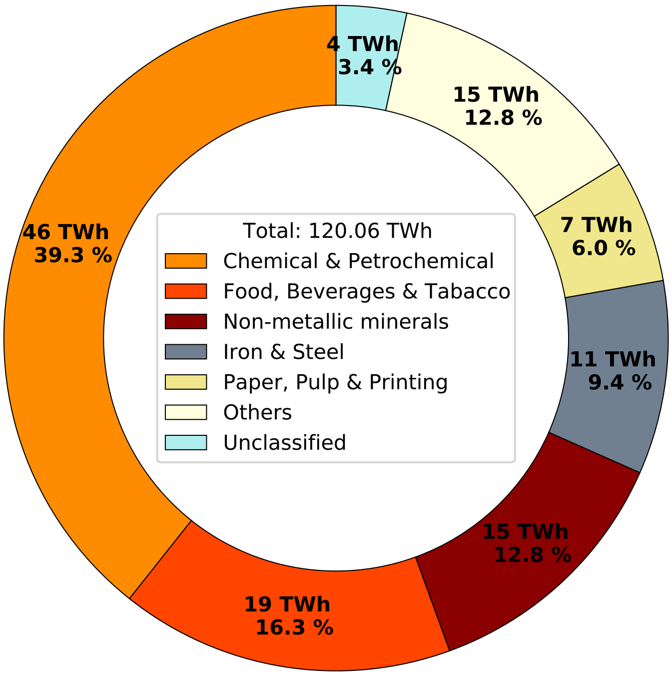

Figure 1. Final energy use in 2019 of each industrial sector in Belgium, data according to Eurostat [2].

The primary energy used by the (petro)chemical industry is mainly provided by fossil fuel combustion. Process heating, in particular, accounting for 66% of the industrial energy use [4], is primarily fossil fuel-driven. It is well-known that fossil fuel combustion results in unsustainable impacts on humans and environment. These impacts are a primary driver for the increasing costs for using fossil fuels, due to emissions trading schemes [5,6]. In contrast, the production cost of renewable electricity is getting cheaper [7], decreasing the renewable electricity to fuel price ratio. Therefore, electrically-driven heating processes are becoming more attractive, both economically and environmentally.

Vapor compression heat pumps (VCHPs), which are predominantly driven by use of electricity, are becoming a promising technology for supplying process heat up to 200 °C. Due to their high thermal performance, the replacement of fossil fuel based heat generation by VCHPs leads to a substantial reduction in emissions, even with the current EU electricity mix [4]. Moreover, in case of favorable electricity to fuel price ratios, VCHPs have the potential to deliver heat at lower costs compared to fossil fuel combustion [8,9].

To obtain optimal VCHP performance, a waste heat stream at a suitable temperature level is required. Marina et al. [10] made a conservative estimate of the European (EU-28) industrial VCHP market potential. Their study used a bottom-up methodology to estimate the heat delivery potential for VCHPs up to 200 °C in the food, paper, chemical and refining sectors. The results showed that VCHPs, supplying heat up to 200 °C, are able to cover 614 PJ/a (171 TWh/a) in the EU-28, with the chemical sector having the largest opportunity (283 PJ/a). The corresponding estimated CO_2 reductions are 52.6 MT CO_2/a. Furthermore, the study showed that beneath a temperature level of 200 °C about 80% of the waste heat available is below 100 °C, whereas more than 80% of the required process heat is in the temperature range of 100–200 °C.

Industrial VCHPs with a technology readiness level (TRL) of 9 have supply temperatures limited to 100 °C [11]. In contrast, the study of Marina et al. [10] shows that the largest potential is in the temperature range of 100–200 °C. By reaching supply temperatures of 200 °C, VCHPs are theoretically able to cover 37% of the European industrial heat demand [11]. It is expected that commercially available VCHPs will reach this barrier in a few years [10]. To achieve widespread deployment of these VCHPs, several barriers must be addressed and overcome:

1. Competition with other heat generation technologies [12].
2. Lack of awareness of industrial VCHP applications and potential integration points in the industrial sector [4,12].
3. Uncertainty about the reliability of coupling heat source and sink by industrial VCHPs, in particular for non-continuous processes [13]. Because extremely high reliabilities are required in the (petro)chemical sector, the heat supply needs to ensure robust and uninterrupted operation.
4. The risk of high payback periods due to the high initial capital cost and/or unfavorable boundary conditions (fossil fuel, electricity and CO_2 prices). Moreover, the uncertainty about these boundary conditions also hinders the implementation of industrial VCHPs [4,12].
5. Limited number of pilot and demonstration cases [4,12,13].

This paper has a closer look at these barriers. First, a thermodynamic comparison between the major classes of heat pump technologies is made. In the literature these heat pump technologies are commonly discussed separately. By providing a thorough comparison of these technologies, their advantages, drawbacks and application areas within the chemical industry can be compared. Secondly, several relevant processes in the chemical industry are discussed and potential integration points are presented. This should increase the awareness of potential VCHP applications and show that these can be conveniently integrated. The reliability is also considered when discussing the applications. Thirdly, the relevant heat generation technologies, including electric and natural gas boilers, are financially compared based on (petro)chemical case studies. This is not comprehensively carried out in the literature. Furthermore, the financial comparison also includes a sensitivity analysis on the investment cost of the heat pump technologies and covers a wide range of energy costs, so that the results will remain relevant over time.

2. Heat Pump Technologies

According to van de Bor et al. [14], large-scale heat pumps can be categorized as VCHPs, heat-driven heat pumps (HDHPs) and heat transformers (HTFs). An indication of the typical energy flows of each heat pump type is given in Figure 2. These energy flows are based on a supply of 1 MW_{th} process heat. In this figure, each arrow color is associated with a different type of energy flow, clarified by the legend at the bottom of the figure. Furthermore, the relative temperature levels are shown for different heat flows. For the estimation of the capacities of the energy flows, typical values for the coefficient of performance (COP) reported within the literature are used [15–17]. For all these technologies, the COP is defined by the ratio of the useful process heat to the amount of primary energy supplied. Moreover, a distinction is made between a medium temperature lift ($\sim$45 K) and a large temperature lift ($\sim$90 K) in order to indicate the dependency of the energy flows on the temperature lift.

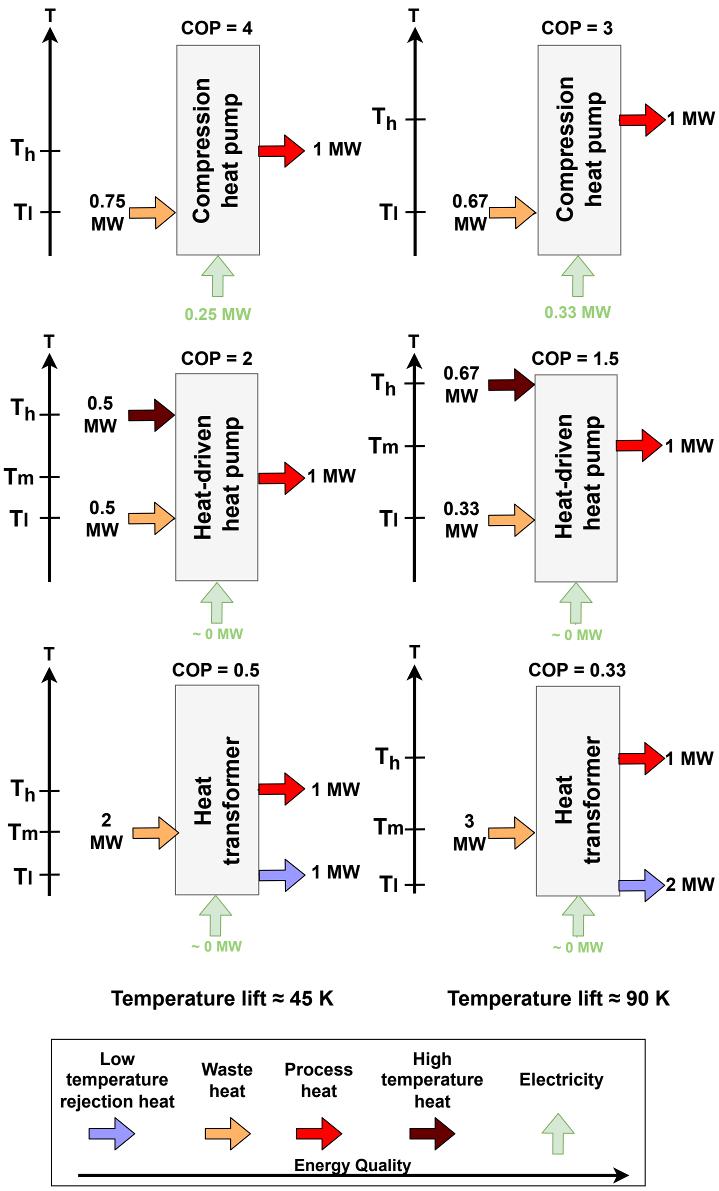

Figure 2. Typical energy flows of a VCHP, HDHP and HTF.

2.1. Vapor Compression Heat Pumps

A VCHP transfers heat from a (waste) heat source ($\dot{Q}_{waste}$) at temperature level T_l to a higher temperature stream ($\dot{Q}_{process}$) at temperature level T_h. This process is possible because of a compressor which uses an amount of work ($\dot{W}_{comp}$). The maximum theoretical ratio of heat delivery to compressor power use is defined by the Carnot COP:

$$COP_{max} = \frac{\dot{Q}_{process}}{\dot{W}_{comp}} = \frac{T_h}{T_h - T_l} \quad (1)$$

In practical applications the COP typically varies between 2 and 5 [11,12]. As the compressor is commonly electrically driven, the VCHP technology is theoretically able to operate entirely emission free. Moreover, due to the addition of compression work in the energy balance, an increased amount of heat is delivered at the heat sink compared to the amount of heat extracted from the heat source ($\dot{Q}_{process} > \dot{Q}_{waste}$). More information on VCHPs can be found in the literature [12,18–23].

2.2. Heat-Driven Heat Pumps

HDHPs transfer heat from two inlet streams to one process heat stream. Next to the low-temperature (waste) heat stream ($\dot{Q}_{waste}$) at temperature level T_l, there is a need for a high-temperature heat input ($\dot{Q}_{high}$) at temperature level T_h. The output of a HDHP system is process heat ($\dot{Q}_{process}$) at an intermediate temperature level T_m. Due to the addition of the high-temperature heat input, a reduced amount of low-grade waste heat is required in order to provide a specific amount of process heat ($\dot{Q}_{process} >> \dot{Q}_{waste}$). The maximum theoretical COP is defined as [24]:

$$COP_{max} = \frac{\dot{Q}_{process}}{\dot{Q}_{high}} = \left(1 - \frac{T_l}{T_h}\right) \cdot \left(\frac{T_m}{T_m - T_l}\right) \quad (2)$$

This COP is essentially a multiplication of a the Carnot heat engine efficiency and the Carnot COP of a VCHP. Consequently, lower COPs are obtained compared to VCHPs. In practical implementations the COP typically varies between 1.3 and 2.2 [17]. However, the primary energy input (high-temperature heat) usually comes at a lower cost than electricity.

The primary energy mainly comes from gas-driven heat sources and to a lesser extent from waste, bioenergy, geothermal or solar heat sources. More information on the operating principles of HDHPs can be found in the literature [16,25–28].

2.3. Heat Transformers

A HTF transfers (waste) heat ($\dot{Q}_{waste}$) at an intermediate temperature T_m to two output flows: a high-temperature flow ($\dot{Q}_{process}$: i.e., upgraded heat) at temperature level T_h and a low-temperature flow ($\dot{Q}_{rej}$: i.e., rejected heat) at temperature level T_l. Consequently, the process requires negligible amounts of electrical energy, or other primary energy sources, being the case for HDHPs and VCHPs. The technology therefore has, with the exception of a small amount of electricity use through operating pumps and auxiliary systems, no operating costs. The maximum theoretical COP is defined as:

$$COP_{max} = \frac{\dot{Q}_{process}}{\dot{Q}_{waste}} = \left(1 - \frac{T_l}{T_m}\right) \cdot \left(\frac{T_h}{T_h - T_l}\right) \quad (3)$$

As a substantial amount of low-grade heat is rejected, HTFs always have a COP below 1. For low temperature lifts, COPs of about 0.5 are reported [15,17,29], whereas for high temperature lifts COPs around 0.23 are reported [15,17,29]. Therefore, only a quarter to half of the waste heat can be valorized. The remaining part is rejected as low-temperature heat, giving rise to a poor waste heat utilization ($\dot{Q}_{process} << \dot{Q}_{waste}$). More information on the operating principles of HTFs can be found in the literature [15,17,25,29–32].

2.4. Comparison of the Heat Pump Technologies

Based on the high-level analysis of the heat pump technologies, VCHPs have some of the most promising characteristics compared to the other technologies.

Firstly, VCHPs are able to operate on completely renewable energy sources, as opposed to HDHPs. HDHPs require a high-temperature heat source and are therefore often fossil fuel-driven. Alternative renewable high-temperature heat sources are: geothermal and solar heat sources, high-temperature waste heat sources or bioenergy. These alternative high-temperature heat sources are, however, rarely available. Geothermal or solar heat sources are not feasible in large parts of Europe. In addition, the distance between geothermal source and industrial site is often a major issue. Although several renewable biofuels exist, they are often not environmental friendly, economically feasible or abundantly available [33]. If biofuels are developed without the above-mentioned drawbacks, they should be firstly used for applications that are hard to decarbonize, such as the transport sector or process heating above 200 °C. This leaves the option of high-temperature waste heat sources. Notwithstanding that these might be a suitable heat source, there is often no, or limited, availability and they should be firstly used for direct heat recuperation at higher temperatures when possible.

Secondly, VCHPs allow for a complete utilization of the waste heat, in contrast to HTFs. In case of a large temperature lift, as illustrated in Figure 2, a HTF requires about six times as much waste heat compared to a VCHP delivering the same duty. This is because two-thirds of the waste heat used is rejected as low-temperature heat. Due to the poor utilization of waste heat and the limitations in available waste heat, HTFs have apparent limitations. HTFs could, however, be interesting in some dedicated industrial sites with excessive amounts of low-grade solar heat, or in industrial sites which have a large imbalance between available low-temperature waste heat and required high-temperature heat.

Thirdly, VCHPs are currently the most mature and robust heat pump technology [34,35]. Robustness and reliability are strict requirements in the chemical industry. Moreover, according to Zhang et al. [36], VCHPs have the lowest investment costs due to their simple cycle layout.

The main drawbacks of VCHPs are related to the fact that they: use refrigerants with potential high global warming potentials (GWPs), use electricity which is often fossil fuel-driven, generate noise and vibrations due to the mechanical compression, and are maintenance intensive [37–39]. However, there is a strong trend towards low-GWP refrigerants [18,40–42]. Furthermore, electricity generation is becoming more renewable. In addition, noise and vibrations are less of an issue for industrial applications.

3. Relevant Applications in the Chemical Industry

Within the chemical industry, several processes have been identified that typically require heat between 100 and 200 °C: distillation, boiling, drying, high-temperature space heating, compression, thermoforming, fluid heating, etc. [12]. Distillation and drying are two of the most relevant direct application processes and will therefore be further discussed. Furthermore, the earlier listed relevant industrial processes are often heated by steam networks [43–47]. Consequently, due to its deep integration and industrial relevance, steam generation is further discussed as an indirect application.

3.1. Distillation

Distillation is of particular importance in the chemical industry. Distillation is commonly used to separate liquid mixtures, by utilizing selective boiling and condensation. As boiling and condensation are energy-intensive tasks, distillation alone globally accounts for about 40% of the energy used in the chemical process industry [48]. In its simplest form, as illustrated in Figure 3a, a distillation column consists of a reboiler at the bottom of the column and a condenser at the top of the column. In the reboiler, high-quality heat is supplied to evaporate the mixture, while in the condenser low-quality heat is rejected as the vapor condenses. The heat released at the condenser is often extracted by means of cooling water, whereas the heat supplied in the reboiler is typically delivered by steam.

In ideal circumstances, no heat is lost in a distillation process but it is degraded to lower a temperature. Moreover, the operation temperatures are often below 200 °C. Hence, heat pumps are an effective method for upgrading the low-temperature heat back to the original high-temperature heat, while simultaneously providing cooling as shown in Figure 3b. Integrating heat pumps in distillation processes is generally an interesting option as the heat availability and demand show similar trends. Moreover, the heat source and sink belong to the same integrated process, thus allowing an easier integration of the heat pump.

Due to the immense potential of heat pumps in distillation processes, heat pump assisted distillation is often studied in the literature [45,49–54] and is therefore not extensively discussed in this paper.

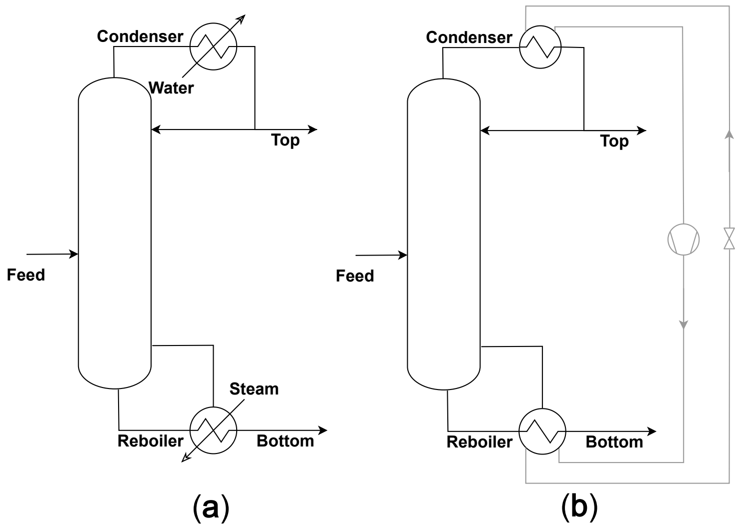

Figure 3. Scheme of a simple distillation column, with (**a**) the conventional heating method and (**b**) the vapor compression heat pump integration.

3.2. Drying

Drying of particulate products is a common process in the chemical industry [43]. It is an energy-intensive process due to the high latent heat of vaporization, and therefore globally accounts for up to 15% of all energy use in industry [55] and 5% in the chemical industry [56].

Within the literature, or research projects, heat pump assisted heat recovery from the exhaust air of spray dryers is often studied [43,57–59]. In these studies, ambient air typically needs to be heated to around 158–210 °C, with most processes operating in the higher temperature range. The outlet temperature of the humid exhaust air for these cases varies between 52 and 76 °C. This exhaust air is typically first used for preheating the ambient inlet air as shown in Figure 4. Air recirculation is often avoided to prevent bacterial growth and reduced drying rates [7]. After the air preheating, the remaining heat from the exhaust air is transferred to the drying air by means of a heat pump in the heat upgrading part. However, some energy is lost to the environment and is transported by the dried product. As a consequence of the air preheating and the energy transferred to the drying product and environment, no energy match can be made between heat source and sink, or unfeasible temperature lifts are needed as indicated in Figure 4. Even with the addition of the compression work, the preheated ambient air can only be partially heated by the heat pump. Therefore, an auxiliary heating system (e.g., electric heater) is necessary. It is clear that HTFs would definitely be out of scope for this application. An alternative option could be to use an external waste heat source with a suitable temperature level and energy content.

Superheated steam drying (SSD) is an emerging closed-loop technology with several advantages over hot air drying [56,60,61]. A particular advantage for the application of heat pumps is that the exhaust of the SSD process is also steam. This allows for convenient latent heat recovery in contradiction to hot air drying. In SSD an exhaust amount of steam, equal to the amount of water evaporated from the dried product, is produced. This slightly superheated excess steam can be used as a waste heat source at constant temperature when condensed. By doing so, an acceptable temperature lift and hence COP of the heat pump can be achieved when heat is transferred from the residual steam to superheat the drying steam, as illustrated in Figure 5. Because SSD shows particularly interesting characteristics this process is further elaborated on in a case study.

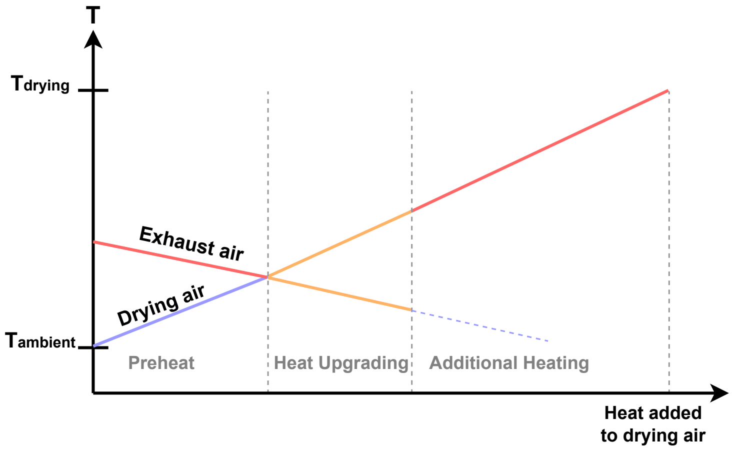

Figure 4. Illustration of theoretic temperature profiles within air drying applications.

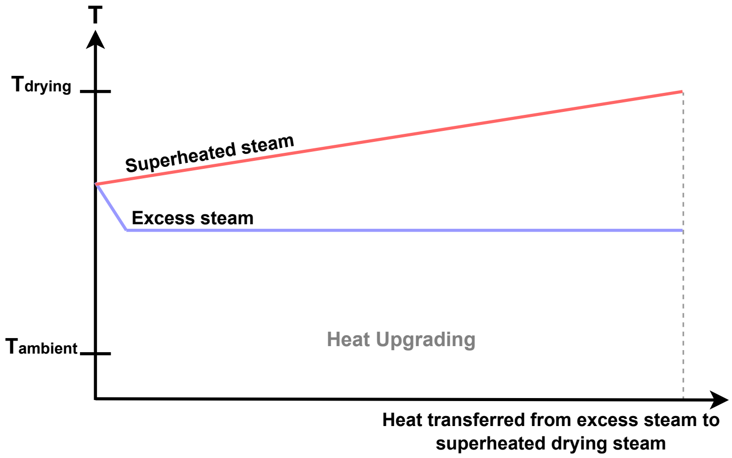

Figure 5. Illustration of temperature profiles within superheated steam drying.

3.3. Steam Production

Steam is one of the main heat transfer media in the industry. In steam networks of energy-intensive industries, steam is typically generated at multiple locations and by multiple sources, e.g., directly by high-temperature waste heat sources or gas-fired boilers. In addition, a back-up might be available. Hence, the reliability requirements of a single steam generating source connected to a steam network can be lower compared to the scenario where it would be directly integrated in the process as the only heat supply. Moreover, a particular advantage of steam production is that it is widely present in energy-intensive industries, allowing for retrofitting and coupling heat sources and sinks at greater distances. These are some of the main reasons why researchers and heat pump manufacturers focus on steam generating heat pumps (SGHPs) [12,62].

In SGHPs steam can either be produced by direct heating of (pressurized) water or by flashing pressurized hot water. Moreover, high pressure steam can be directly generated by the heat pump system or the heat pump system can produce low pressure steam which is further upgraded by mechanical vapor recompression (MVR).

A typical characteristic of steam production is that the heat source can be of any origin (e.g., cooling water) and does not need to be related to the steam production itself, whereas for distillation and SSD the heat source and sink are both part of one integrated process. When the external heat source is sensible heat, some trade-offs have to be made. From a performance point of view, the heat source should ideally have no temperature glide, allowing for higher COPs. From an energy utilization point of view, however, this is less interesting as the available waste heat is poorly utilized. For practical implementation a financial trade-off is required.

3.3.1. Direct Steam Production

In direct steam production, pressurized water is heated until it evaporates. Additional heat may be supplied when superheated steam is needed. However, as the difference in density between the liquid and vapor phase is significant for water, extremely large heat pump condensers would be needed. A potential solution to avoid large condensers can be found by directly integrating the VCHP in a boiler as illustrated in Figure 6. In this configuration the generated saturated steam is extracted at the top of the boiler, while at the bottom an equal amount of feed water is supplied. The temperature of the boiler can be set by controlling the pressure in the steam boiler.

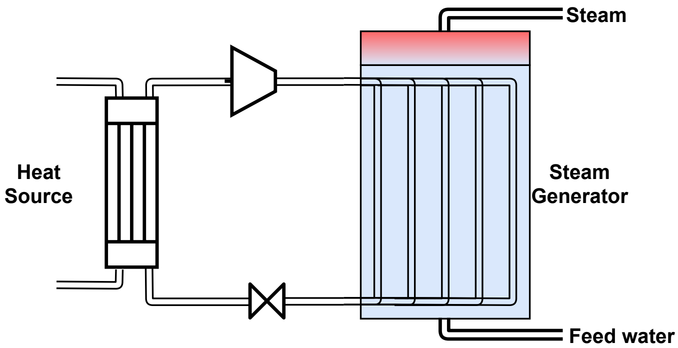

Figure 6. Illustration of a VCHP directly generating steam with use of a steam generator.

3.3.2. Steam Flashing

Next to direct steam generation, SGHPs often produce steam through a flashing process [63–65], as shown in Figure 7. In this process the VCHP adds heat to pressurized water, which is flashed afterwards to a liquid–vapor mixture in a flash tank (i.e., phase separator). Consequently, a small fraction of the water becomes steam. The saturated steam can be extracted at the top of the flash tank, while water is collected at the bottom of the tank. The water at the bottom of the tank is then pressurized and recirculated to the condenser by a pump. Because the heat pump solely heats up (pressurized) water in this scenario the disadvantage of large heat pump condensers is avoided as well.

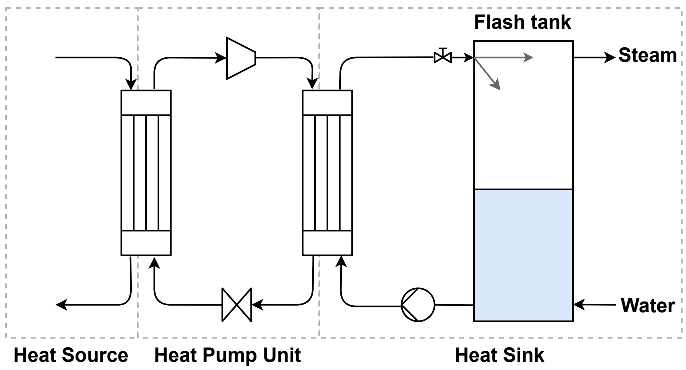

Figure 7. Illustration of a SGHP with flash evaporation.

A trade-off in flash tank inlet temperature is involved in the design of this system [66], as illustrated by Figure 8. In case of relatively low temperatures (blue cycle) the quality and consequently the steam yield will be low. As a result, a high mass flow rate will be needed to meet a specific steam demand, resulting in over-sizing of the equipment. However, due to the overall lower heat sink temperatures, the heat pump will operate at a relatively high COP. For a high flash tank inlet temperature (orange cycle) the opposite will occur, namely that the yield will be high while the COP will be reduced.

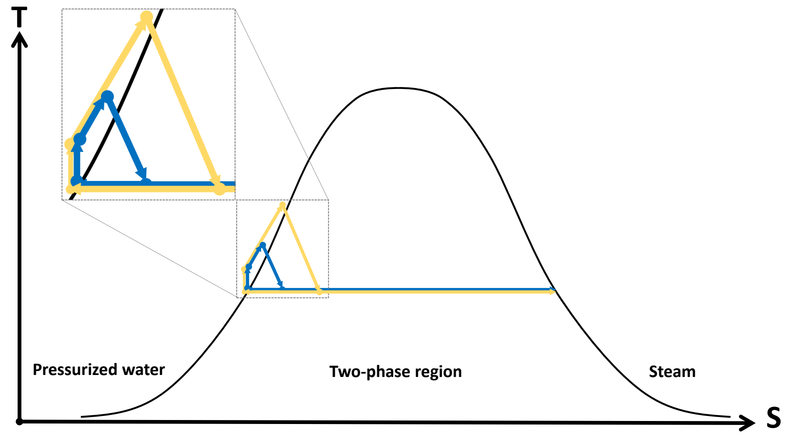

Figure 8. Illustration of the flash tank inlet temperature trade-off, based on the T-s diagram of water.

3.3.3. Mechanical Vapor Compression

In practice, direct steam production and steam flashing often produce low-pressure steam. The pressure and temperature are then increased by mechanically compressing the generated steam. MVR is often employed because it allows for lower energy use. Bless et al. [62] found an energy use reduction of about 40% when comparing a VCHP with MVR to a VCHP without MVR. However, high compression ratios are required for steam compression and the steam strongly superheats during compression. Therefore, three water-injected compression stages were required next to the VCHP. Furthermore, the density of water vapor is low, so that large and therefore more expensive compressors are required. On top of that the need for multiple compression stages and cooling techniques decreases the reliability and increases the maintenance cost. Hence, use of MVR involves multiple trade-offs.

3.4. Case Studies

In this section two relevant case studies are discussed which will act as a baseline for the financial comparison. The selected case studies are superheated steam drying and steam production because of their relevance and the high potential of integrating heat pumps.

3.4.1. Superheated Steam Drying: Case Study

The selected drying case study is based on the work of Bang-Mller et al. [67]. In this work the performance of biomass-fueled combined heat and power plants is studied, starting from wet biomass in the form of wood. The data used in their work is obtained from a demonstration plant. The first process of the plant is drying of wet wood (42% water) by means of SSD. In this work, all other processes are left out and the SSD is considered as stand-alone, where VCHP integration is considered.

A schematic of the SSD process is shown in Figure 9, with the data of each state given in Table 1. The states 'a–b' refer to the wood, while the states '1–5' refer to the steam. It must be noted that in the actual plant some steam is mixed with the dry wood, as is also found in other literature [68]. In this study, however, it is assumed that all steam can be recuperated from the dried product, which should be possible if air infiltration is avoided [56].

In the proposed heat pump concept, heat from the excess steam is extracted by the heat pump. This heat is upgraded and transferred by the heat pump to the superheated drying steam, increasing its temperature from 115 °C to 197 °C. If the excess steam is cooled down to its saturated liquid state, about 298 kW_{th} can be extracted, whereas about 370 kW_{th} is needed for heating the superheated steam. Taking the compression work into consideration, subcooling of the excess steam will be prevented when the COP is below 5.13, which is the situation in a realistic scenario. If not all steam can be recuperated from the drying wood, the available waste heat might not be sufficient to match the heat demand of the SSD process, even in the scenario of VCHPs. In this scenario, the superheated steam can be preheated by the heat pump, while additional heat can be supplied by the conventional heating method, or a small auxiliary electric heater.

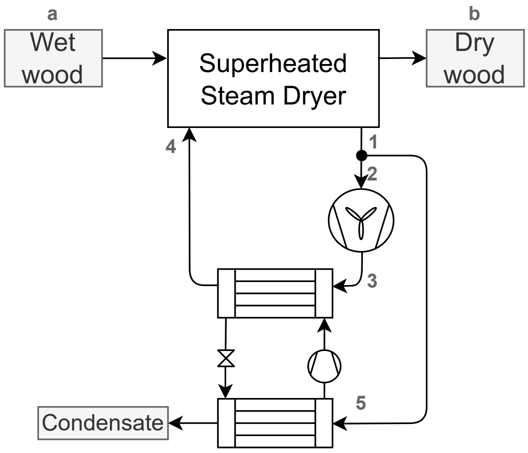

Figure 9. Proposed schematic of the heat pump assisted superheated steam dryer.

Table 1. Mass flow rate $\dot{m}$, pressure p, temperature T and specific enthalpy h of each state indicated in Figure 9, data according to Bang-Mller et al. [67].

State	$\dot{m}$ [kg/s]	p [bar]	T [°C]	h [kJ/(kg·K)]
a	0.32	1.013	15	-
b	0.19	1.008	115	-
1	2.40	1.008	115	2706
2	2.27	1.008	115	2706
3	2.27	1.018	116	2708
4	2.27	1.013	197	2869
5	0.13	1.008	115	2706

3.4.2. Steam Production: Case Study

The case study selected for steam production is based on data retrieved from industry. The corresponding process parameters can be found in Table 2. In this case study, steam is produced directly by integrating a heat pump in a steam generator as explained in Section 3.3.1 and shown in Figure 6. Steam in a saturated liquid ($x_{in} = 0$) at a pressure of 1.5 bar (saturation temperature of 111.4 °C) is directly heated up to the saturated steam state ($x_{out} = 1$) in the steam generator. No MVR as toping stage is considered. At the top of the boiler about 474 kW_{th} of steam is demanded, corresponding with a steam production rate ($\dot{m}$) of 0.213 kg/s. The heat source is a cooling water circuit at a pressure of 1 bar with a supply temperature of 78 °C and a return temperature of 60 °C. This water stream has a mass flow rate of about 9.32 kg/s, meaning that 702.3 kW_{th} of waste heat is available.

Table 2. Information on the heat source and heat sink for the steam production case study, with p the pressure, $\dot{m}$ the mass flow rate, T the temperature and x the quality.

Heat Source					Heat Sink				
Fluid	p [bar]	$\dot{m}$ [kg/s]	T_{in} [°C]	T_{out} [°C]	Fluid	p [bar]	$\dot{m}$ [kg/s]	x_{in} [-]	x_{out} [-]
Water	1	9.32	78	60	Water	1.58	0.213	0	1

4. Financial Analysis Case Studies

In order to determine the most suitable heat upgrading technology, a high-level financial comparison between a VCHP and a HTF is performed for the selected cases. In the scenario where not enough waste heat is available to supply the amount of heat demanded, additional heat can be delivered by use of electric boilers or natural gas boilers. Both options are considered in this analysis. Moreover, these heat pump technologies are also benchmarked against electric boilers and natural gas boilers as stand-alone technologies. The use of HDHPs is excluded from this analysis since a market study of the available technologies showed that this technology is not available in the temperature range of interest. Moreover, the financial performance of HDHPs is hard to generalize since it strongly depends on the temperature level of the high-temperature heat source and whether or not this heat source is freely available or needs to be generated at a certain cost.

In this section the performance estimation of each technology is first discussed. Afterwards, the financial framework, which is based upon the estimated performance of each technology, is explained. Finally, the financial framework is applied to the case studies given in Section 3.4 and the results are discussed.

4.1. Performance Estimation

The COP of the heat pump technologies is estimated based on data available in the literature rather than thermodynamic calculations. This allows for the use of performance data of (near-)commercial heat pumps reported in the literature. In this analysis the COPs of the different heat pump technologies are plotted as a function of the gross temperature lift (GTL). The GTL is defined as the difference between the outlet temperature of the heat sink and the outlet temperature of the heat source. For the electric and natural gas boilers on the other hand a fixed efficiency is chosen, independent of the GTL.

4.1.1. Vapor Compression Heat Pump

The COP for VCHPs is estimated based on manufacturer data reported in the framework of the International Energy Agency Heat Pump Technology Annex 58 on high-temperature heat pumps [11]. Within this Annex, data of well-known VCHP manufacturers such as Heaten, Mayekawa, MAN, Kobelco, Turboden and Siemens is collected. All reported COPs are for heat sink temperatures above 100 °C. Based on the data, the COP is correlated as a function of the GTL as displayed in Figure 10.

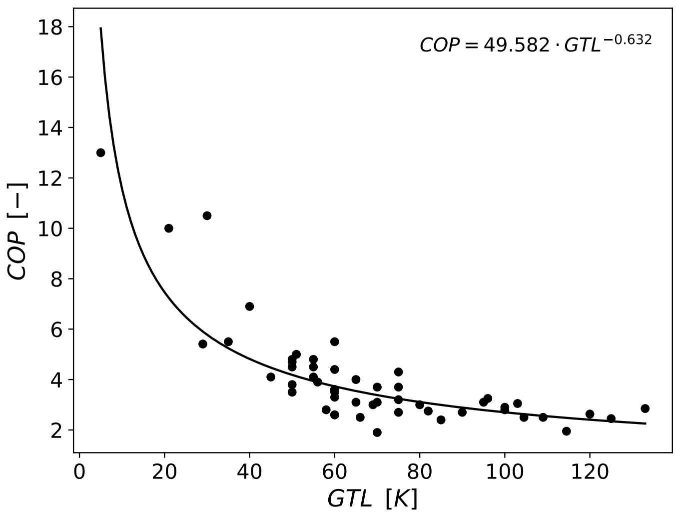

Figure 10. COP of VCHPs as a function of GTL, based on [11].

Based on this data the COP of VCHPs can be fitted as a function of the GTL as shown in Equation (4):

$$COP = 49.582 \cdot GTL^{-0.632} \quad (4)$$

The regression has a coefficient of determination (R^2) of 0.7, a mean absolute deviation of 0.732, a bias of -0.072 and a maximum deviation of 4.930. These are rather large variabilities. However, for GTLs above 40 K, the mean absolute deviation, bias and the maximum deviation reduce to 0.496, 0.0147 and 1.482, respectively. Therefore, this correlation is recommended for GTLs above 40 K.

4.1.2. Heat Transformers

Because HTF technology is less mature and HTFs have lower commercial availability, few manufacturer data are available. Therefore, the COP of HTFs was correlated based on data reported by Donnellan et al. [30], as displayed in Figure 11.

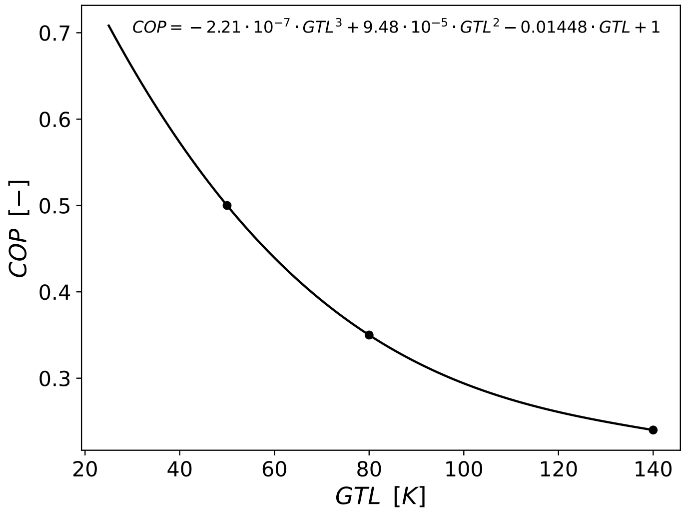

Figure 11. COP of HTFs as a function of GTL, based on [30].

Based on these three data points, the COP can be correlated as shown in Equation (5):

$$COP = -2.21 \cdot 10^{-7} \cdot GTL^3 + 9.48 \cdot 10^{-5} \cdot GTL^2 - 0.01448 \cdot GTL + 1 \quad (5)$$

Because this regression is of the third order, and only three data points are used, the regression perfectly fits these data points. This COP correlation is, however, only valid in the GTL range of 50–140 K, whereas the COP correlation for VCHPs is valid in the range 10–140 K, although recommended for GTLs above 40 K.

4.1.3. Electric and Natural Gas Boilers

For the natural gas boiler an efficiency of 90% [69,70] is assumed whereas an efficiency of 100% is considered for the electric boiler.

4.2. Financial Framework

In the financial evaluation the levelized cost of heat (LCOH) of a VCHP is compared with those of a heat transformer with auxiliary electric boiler (HTF + EB), a heat transformer with auxiliary natural gas boiler (HTF + NGB), a natural gas boiler (NGB) and an electric boiler (EB).

4.2.1. Levelized Cost of Heat

The LCOH is the total cost per unit of heat generated (EUR/kWh_{th}) over the lifetime of the machine. It is defined by the ratio of the discounted expenses and discounted heat production [71]:

$$LCOH = \frac{C_{cap} + \sum_{t=0}^{n} \frac{C_{a,t}}{(1+i)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+i)^t}} \quad (6)$$

with Q_t the amount of heat (kWh_{th}) produced during the year t and $C_{a,t}$ the operational costs during the same year (EUR). Moreover, C_{cap} represents the capital costs (EUR), i the interest rate (%) and n the heat pump lifetime (years).

4.2.2. Financial Boundary Conditions

For all technologies a fixed capital cost (i.e., investment cost) is assumed. According to Arpagaus et al. [12], the specific investment cost for industrial VCHPs varies between 250 and 800 EUR/kW$_{th}$. Meyers et al. [72] reported specific investment costs between 300 and 900 EUR/kW$_{th}$ for industrial VCHPs larger than 100 kW$_{th}$ and showed that the specific investment cost decreases with the heat pump size. Moreover, they reported that the industrial average is about 400 EUR/kW$_{th}$. Schlosser et al. [13] used a specific investment cost of 420 EUR/kW$_{th}$ in their analysis for large-scale industrial VCHPs. In this paper large-scale heat pumps are considered as well. Based on the listed specific investment costs, the total specific investment cost is conservatively assumed to be 550 EUR/kW$_{th}$. This cost is also in line with the data reported by VCHP manufacturers in the framework of Annex 58 [11]. The investment cost of VCHPs is much higher compared to industrial natural gas boilers. These natural gas boilers have a specific investment cost of about 100 EUR/kW$_{th}$ [73]. Electric boilers have an even lower investment cost of about 50 EUR/kW$_{th}$ [74]. In comparison to HTFs, however, the investment cost of VCHPs is low. Within Annex 58 [11], investment costs ranging between 1000 and 2000 EUR/kW$_{th}$ are reported. Lee [75] reports HTF investment costs that are 75–85% higher than for VCHPs. Enslin [76] reported investment costs of about 1300 EUR/kW$_{th}$, based on a breakdown of the costs to the component levels. In accordance with the reported data, an investment cost of 1200 EUR/kW$_{th}$ is chosen. An optimistic HTF investment cost is conservatively chosen because the goal is to fairly benchmark the financial aspects of a VCHP against other technologies. The specific investment cost for each technology is summarized in Table 3. Ideally, these costs are a function of the heating capacity and the supply temperature. However, due to the lower commercial availability of these heat pump technologies at higher temperatures there is a lack of data to develop cost functions. Nevertheless, to illustrate the influence of investment costs, minimum and maximum investment costs for the VCHP and the HTF are also considered, as shown in Table 3. These values are based on the minimum and maximum prices discussed above.

Table 3. Selected specific investment cost of each heating technology.

Technology	Considered Cost [EUR/kW$_{th}$]	Minimum Cost [EUR/kW$_{th}$]	Maximum Cost [EUR/kW$_{th}$]
Vapor compression heat pump	550	250	900
Natural gas boiler	100	-	-
Electric boiler	50	-	-
Heat transformer	1200	1000	2000

The annual operating costs (C_a) are determined by the electricity or gas usage and the maintenance. The yearly maintenance cost is estimated as a percentage of the capital investment cost. For the electricity and natural gas prices, average prices reported by Eurostat [77] between 2016 and 2020 for non-household consumers, with an annual electricity consumption of 500–2000 MWh$_e$ and annual gas consumption of 2778–27,778 MWh$_{th}$, are used. According to Eurostat, most of the EU consumers fall in these bands. The corresponding specific energy costs, excluding VAT and other recoverable taxes and levies, for several EU countries can be found in Table 4.

Table 4. Average electricity and gas prices for several EU countries 2016–2020, excluding VAT and other recoverable taxes and levies [77].

Country	Electricity Price $[\frac{EUR}{kWh_e}]$	Gas Price $[\frac{EUR}{kWh_{th}}]$	Price Ratio [-]
EU-27	0.0792	0.0307	2.58
Belgium	0.0806	0.0235	3.43
France	0.0732	0.0357	2.05
Finland	0.0649	0.0518	1.25
Denmark	0.0612	0.0326	1.88
Germany	0.0799	0.0312	2.56
UK	0.0987	0.0256	3.85

Because the energy prices are dynamic a sensitivity study is presented in this work. The electricity cost will be varied between 0.05 and 0.15 EUR/kWh$_e$, while the natural gas price will be varied between 0.02 and 0.08 EUR/kWh$_{th}$. Due to the increasing importance of carbon neutrality, and inflation, the production cost and cost of using gas and electricity are expected to increase. Hence, the price ranges are predominantly expanded towards the higher prices. Moreover, these numbers do not include the influence of ETS. The cost of ETS in EU went from 30 EUR/tonne CO_2 at the start of 2021 to 80 EUR/tonne CO_2 at the start of 2022 [78]. Since natural gas boilers have specific CO_2 emissions of about 0.22 kg CO_2 per kWh$_{th}$ [69,79], the real natural gas price would increase by 0.0176 EUR/kWh$_{th}$ compared to the values reported in Table 4, due to the cost of carbon. This would increase the gas price in Belgium by about 70%. Albeit this scenario introduces a cost to the usage of natural gas, it still considers a low natural gas price. However, it does not account for a potential increase in electricity generation, which might take place in a realistic scenario.

The selected boundary conditions for the financial calculations are given in Table 5, to represent a heat recovery project in a large-scale chemical site.

Table 5. Boundary conditions for the financial model.

Economic Parameter	Value	Reference
Annual operating time (hour)	8000	[45,46]
Vapor compression heat pump lifetime, n (year)	15	[41,80]
Heat transformer lifetime, n (year)	15	[81]
Natural gas boiler lifetime, n (year)	15	[82]
Discount rate, i (%)	5	[41]
Yearly maintenance cost (% of investment cost)	6	[83]

4.3. Financial Benchmark of the Case Studies

In this subsection the financial framework is applied to the presented case studies. Because for the NGB and the HTF + NGB the electricity use is small, their LCOH is plotted as a function of the natural gas price. Conversely, the VCHP, EB and HTF + EB only directly use electricity. Therefore, the LCOH of these technologies are reported as a function of the electricity price.

4.3.1. Superheated Steam Drying Benchmark

Employing the COP correlations for VCHPs reported in Equation (4) and HTFs in Equation (5), a COP of respectively 3.084 and 0.332 is obtained for a GTL of 81 K. As a result of the HTF COP of 0.332, about 1115 kW$_{th}$ of waste heat is required to deliver the heat duty of 370 kW$_{th}$. However, since only 298 kW$_{th}$ of waste heat is available, the HTF can just supply about 99 kW$_{th}$ of heat. Consequently, 271 kW$_{th}$ of heat needs to be delivered by an auxiliary heating system.

The LCOH for the VCHP, EB and HTF + EB as a function of the electricity price can found in Figure 12. The LCOH for the NGB and HTF + NGB as a function of the natural gas price can be found in Figure 13. In these figures, the solid lines present the LCOH of the technology at the nominal investment cost, while the dashed lines show the LCOH at the minimum and maximum considered investment costs for the heat pump technologies. Since the investment cost is chosen independently of the electricity cost, the dashed lines have a fixed offset from the solid lines.

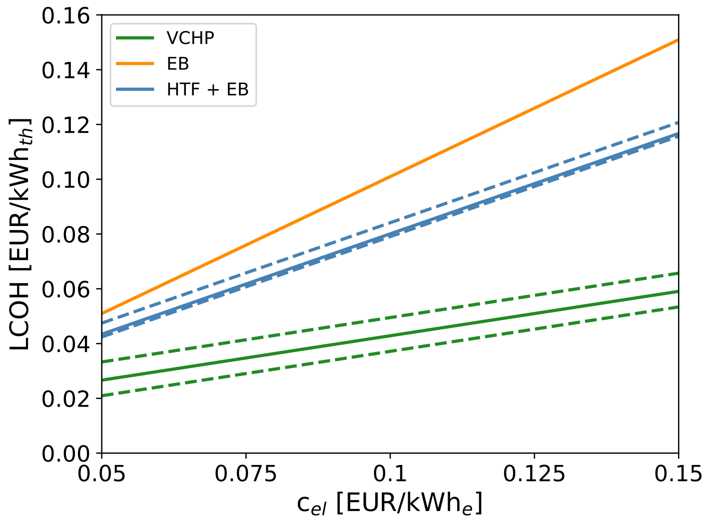

Figure 12. LCOH of EB, VCHP and HTF + EB as a function of the electricity price for the SSD case study, with the dashed lines the sensitivity on the investment cost.

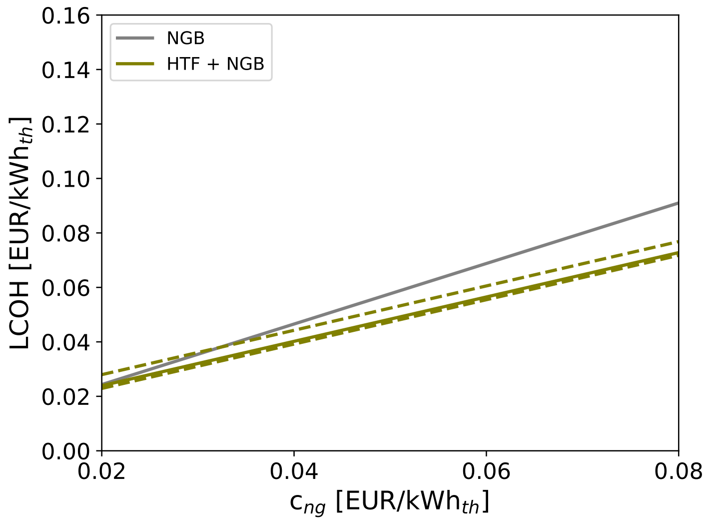

Figure 13. LCOH of NGB and HTF + NGB as a function of the natural gas price for the SSD case study, with the dashed lines the sensitivity on the investment cost.

For the electrical options, VCHPs are by far the most financially interesting over the studied electricity price range. EBs are always the most expensive solution. Using a HTF + EB allows reducing the LCOH compared to EBs. However, for this case study, the decrease is not significant, amongst other reasons because the HTF is only able to deliver a small fraction of the total heat demand. For low electricity prices the LCOH of the HTF + EB and EB even coincide and the optimal technology may shift to the EB. When electricity prices are low, the potential profit from electricity savings is reduced, making it more difficult to pay back the high investment costs of the HTF. The dashed lines in the figure shows that the uncertainty in the LCOH due to the investment costs of the VCHP is relatively high. Considering the maximum investment cost would increase the

LCOH by +0.0066 EUR/kWh$_{th}$, while the minimum investment cost would decrease the LCOH by −0.0057 EUR/kWh$_{th}$. Although the investment cost of the HTF can vary over a wider range, the variation in the LCOH of the HTF + EB as a result of the uncertainty in investment cost is rather small. This is because the HTF only supplies a small amount of heat compared to the total heat demand. For this specific use case, the LCOH can vary by −0.0010 EUR/kWh$_{th}$ to +0.0041 EUR/kWh$_{th}$ as a result of potential differences in investment costs. Overall, for the considered price range, the uncertainty about the investment cost does not influence the technology with the lowest LCOH.

For the natural gas options, the HTF + NGB is on the boundary of being consistently more cost effective then the NGB. When the natural gas price is high, a HTF could reduce the LCOH by about 25%. For lower natural gas prices, NGBs become the best option, again because of the high investment cost of the HTF. For high HTF investment costs, however, the NGB can already become the best option at a natural gas price of 0.0320 EUR/kWh$_{th}$.

Based on the specific electricity and natural gas costs reported in Table 4 and the financial results reported in Figures 12 and 13, the LCOH for each technology in a specific country can be derived. The corresponding results are reported in Figure 14. The uncertainty about the investment cost is not considered in this figure.

Figure 14 shows that, for the three electrical options, the VCHP is the most cost-effective option in all countries. The LCOH of a VCHP is about 1.7–1.8 times lower compared to a HTF + EB and 2.1–2.35 times lower compared to an EB. Although the HTF is able to reduce the costs by about 20% compared to an EB, it is not competitive against the VCHP for this case study. For the natural gas options it can be observed that the HTF + NGB is financially the most competitive for all countries. However, since the averaged gas prices between 2016 and 2020 were quite low, the difference with the NGB is often low, usually in the order of 10%.

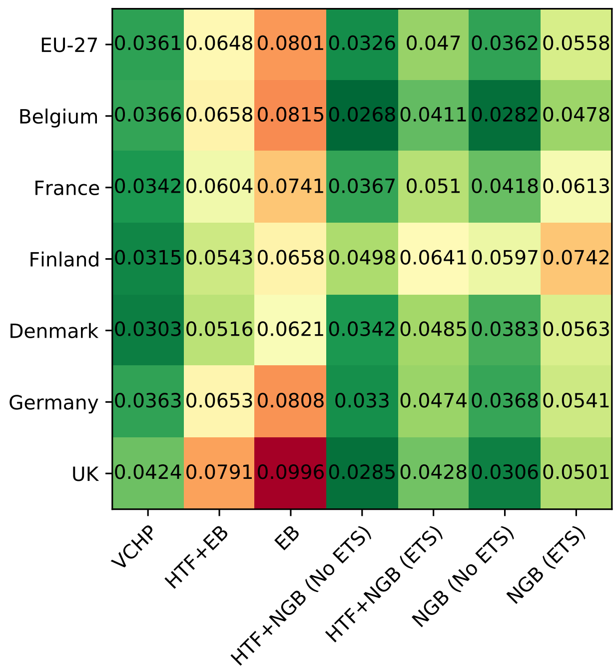

Figure 14. LCOH (EUR/kWh$_{th}$) for the SSD case for each considered technology and country, with and without ETS for natural gas boilers, with green a low LCOH and red a high LCOH.

When considering both electricity and natural gas as an energy carrier, different technologies are candidates for the lowest LCOH. When no ETS cost is considered, a VCHP is only more cost-effective than a NGB in countries with a low or average electricity to natural gas price ratio (i.e., France, Finland, Denmark, Germany and the EU-27 average). In countries with a high electricity to natural gas price ratio (i.e., Belgium and the UK) a NGB is financially more interesting than a VCHP. When comparing a VCHP with a HTF +

NGB, VCHPs are only financially cost effective in countries with low electricity to natural gas price ratios (i.e., France, Finland and Denmark). When an ETS is being applied, the VCHP is for all countries the most interesting option. For some countries such as Finland, an EB becomes even more interesting than a NGB.

4.3.2. Steam Production Benchmark

For the steam production case study, with a GTL of 51.4 K, the developed correlations gave COPs of 4.11 and 0.474 for the VCHP and the HTF, respectively. Now, with a HTF COP of 0.474 and waste heat availability of 702.3 kW_{th}, the HTF is able to deliver a heat duty of 332.9 kW_{th}. As 474 kW_{th} of heat is demanded by the steam production process, the auxiliary boiler should deliver a heat duty of 141.1 kW_{th}. Because two different processes are coupled (i.e., cooling loop and stream network), the HTF is able to deliver about 70% of total heat demand, whereas in the stand-alone process (e.g., SSD) the HTF was only able to deliver about 27% of the total heat demand. Henceforth, more favorable financial aspects may now be expected for the HTF.

The LCOH for the VCHP, EB and HTF + EB as a function of the electricity price is given in Figure 15. The LCOH for the NGB and HTF + NGB as a function of the natural gas price is shown in Figure 16. Again, the influence of a high and low investment cost of the heat pumping technologies is illustrated by the dashed lines. It can now be seen that the variation in LCOH is higher for the HTF, as the HTF now provides 70% of the heat. The difference in LCOH as a result of the minimum and maximum investment cost of the HTF is now −0.0027 EUR/kWh_{th} to +0.0106 EUR/kWh_{th}, whereas for the VCHP this stays −0.0057 EUR/kWh_{th} to +0.0066 EUR/kWh_{th}. In these figures it can also be observed that, when employing an EB or NGB, the same LCOHs are observed as for the SSD case study. Compared to the previous case study, the solutions using VCHPs or HTFs now have lower LCOHs because of the higher COPs and the higher availability of waste heat for the HTF.

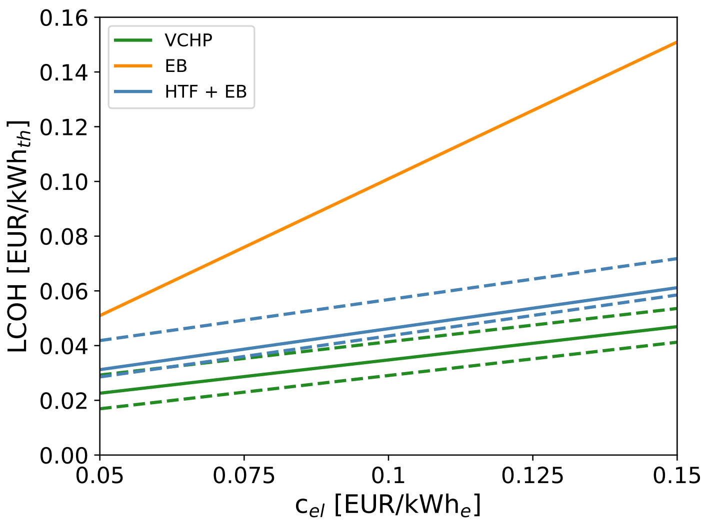

Figure 15. LCOH of VCHP, EB and HTF + EB as a function of the electricity price for the steam production case study, with the dashed lines the sensitivity on the investment cost.

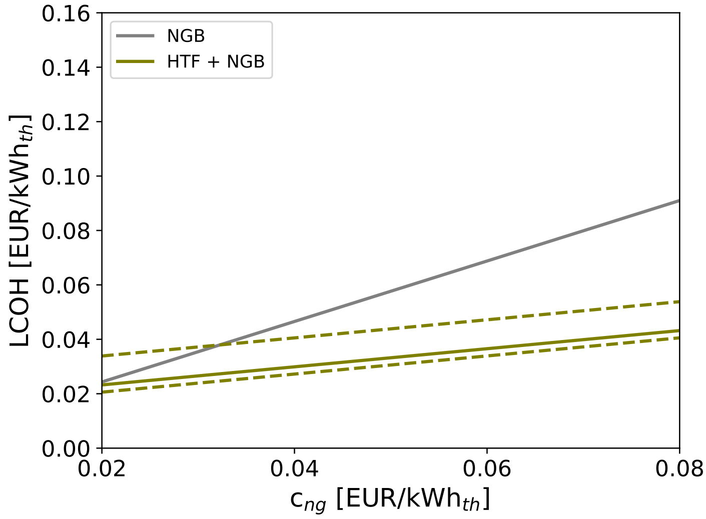

Figure 16. LCOH of NGB and HTF + NGB as a function of the natural gas price for the steam production case study, with the dashed lines the sensitivity on the investment cost.

When using electricity as primary energy carrier VCHPs are the most interesting option while EBs are the least profitable option, whereas for the SSD case study the LCOH of the HTF + EB was close to the LCOH of the EB, now its LCOH is relatively close to that of the VCHP. However, even when considering a high VCHP investment cost and a low HTF investment cost the VCHP is still the best option, although by a marginal difference.

If natural gas is considered as the primary energy carrier, it can be observed that the HTF + NGB is now far more interesting compared to the NGB, especially for high natural gas prices. For low natural gas prices, however, the difference reduces and both technologies become financially equal. If the HTF, however, has a high investment cost, the NGB already becomes the most profitable at a natural gas price of 0.0325 EUR/kWh$_{th}$.

The LCOH of the considered countries for each technology applied to the steam production case, considering their nominal investment cost, can be found in Figure 17. Again, the nominal investment costs of the heat pump technologies are taken into account in this figure.

Figure 17 shows that, for the electrical technologies, VCHPs have a LCOH which is about 26% lower compared to the HTF + EB and about 63% lower compared to the EB. For the technologies using natural gas, it can be observed that the LCOH of a HTF + NGB is about 26% lower compared to the LCOH of the NGB. When taking an ETS cost into account this increases to about 40%. When considering all technologies, it can be observed that, even when no ETS is applied, VCHPs are more cost effective than NGBs with the exception of the UK and Belgium because of the high electricity to fuel price ratio in these countries. When an ETS is applied, VCHPs are financially more cost effective compared to NGBs in all countries. However, for this case study, VCHPs are only competitive against HTFs + NGBs in countries where the electricity to gas price ratio is low (i.e., France, Finland and Denmark) when no ETS is applied. If an ETS is applied they are always more interesting.

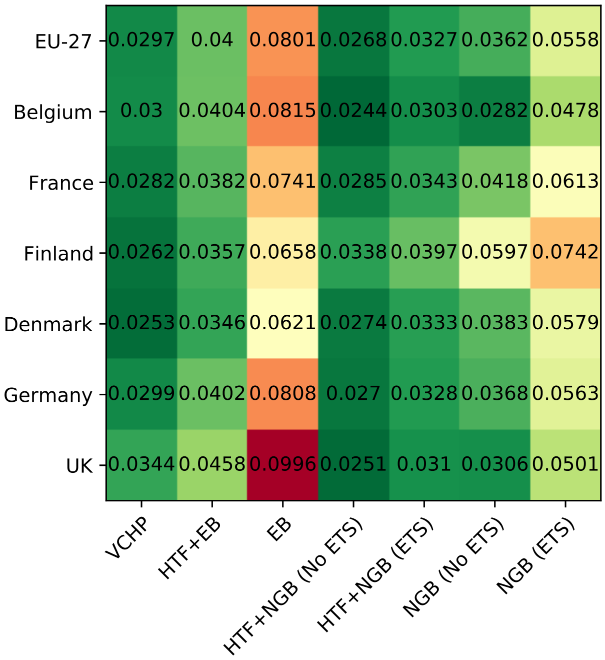

Figure 17. LCOH (EUR/kWh$_{th}$) for the steam production case for each considered technology and country, with and without ETS for natural gas boilers, with green a low LCOH and red a high LCOH.

5. Sensitivity Analysis

This work uses financial constraints that are common in the chemical industry. However, to illustrate the impact of these constraints, a sensitivity analysis is presented. Specifically, the sensitivity of LCOH to changes in annual operating hours, ETS carbon pricing and waste heat availability is examined. The sensitivity analysis is carried out for both case studies presented in this work.

5.1. Influence of the Annual Operating Hours

The annual operating time of the chemical site was set at 8000 h as a representative value. However, this section considers a range of annual operating times from 4000 to 8500 h. It is important to note that the lifetime of the heating system is assumed to be independent of these operating hours. The LCOH values for the different heating technologies and annual operating hours for both the SSD and the steam production case studies are shown in Figures 18 and 19, respectively.

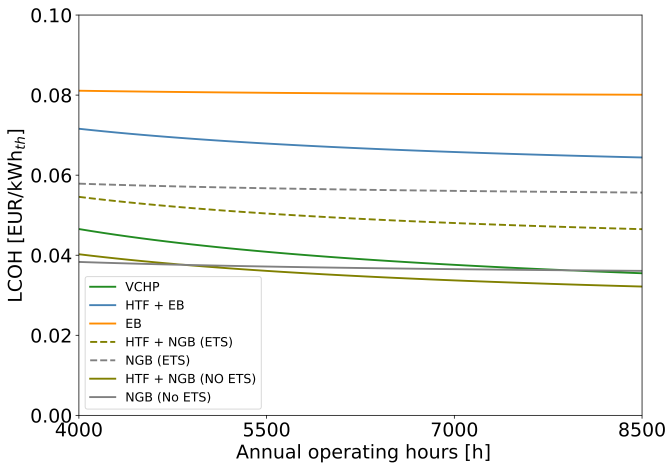

Figure 18. LCOH for the SSD case study for the different technologies as a function of the annual operating hours.

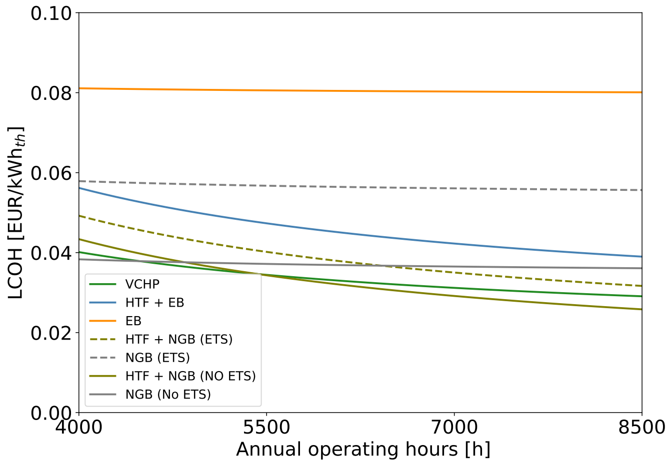

Figure 19. LCOH for the steam production case study for the different technologies as a function of the annual operating hours.

From Figures 18 and 19, it is evident that the LCOH of the EB and NGB shows minimal sensitivity to the annual operating hours. On the other hand, the LCOH of VCHP and HTF shows a higher dependancy on the operating hours, due to their higher investment costs. It should be taken into account that, in both case studies, the HTF can only meet a portion of the total heat demand. As this fraction increases, the dependence on annual operating hours becomes more pronounced, as evident when comparing Figure 19 with Figure 18. Furthermore, the relationship between LCOH and annual operating hours is non-linear for the heat pumping technologies, with a pronounced increase below 5500 operating hours. It is thus crucial for these heat pumping technologies to operate in applications with a high number of operating hours. Although, even at lower operating hours, these technologies may still offer favorable finanicial benefits, particularly when an ETS is considered for the NGB.

5.2. Influence of the ETS Carbon Pricing

In the financial evaluation of the case studies, a carbon price of 80 EUR/tonne CO_2 was considered for the technologies that directly rely on fossil fuel use. To illustrate the sensitivity of this carbon price, it is varied between 0 and 140 EUR/tonne CO_2. The LCOH for the different technologies and the carbon prices for the SSD and the steam production case studies are shown in Figures 20 and 21, respectively.

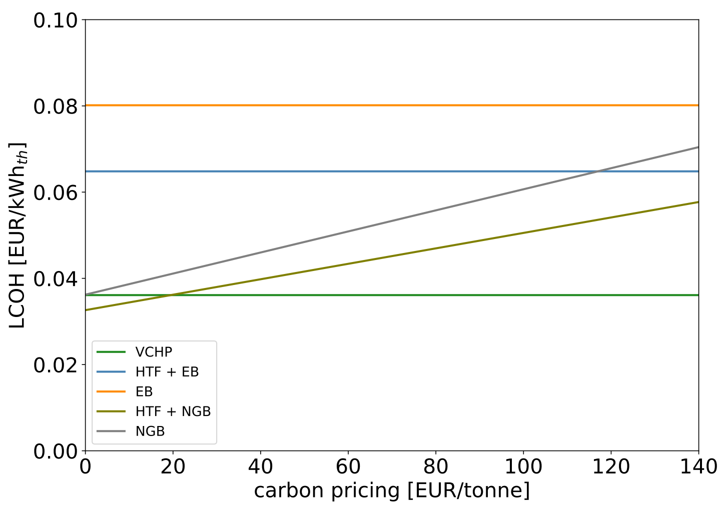

Figure 20. LCOH for the SSD case study for the different technologies as a function of the carbon price for fossil fuels.

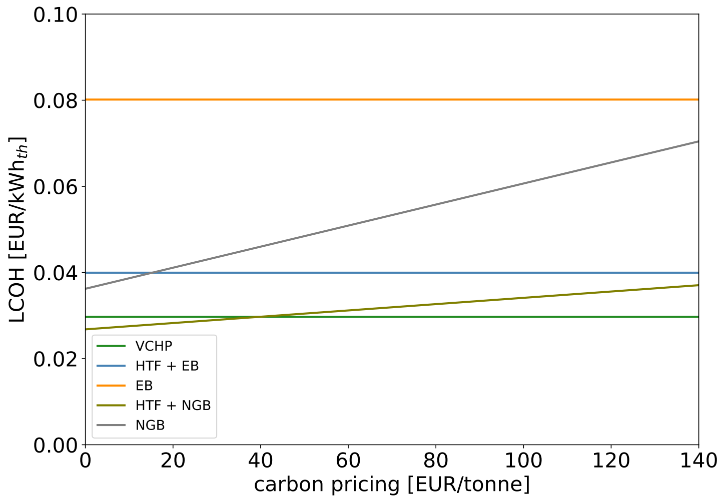

Figure 21. LCOH for the steam production case study for the different technologies as a function of the carbon price for fossil fuels.

As anticipated, both figures indicate that the LCOH of all-electric technologies remains unaffected by the carbon price, whereas that of natural gas-based technologies is influenced. Notably, the stand-alone NGB shows a strong dependency on the carbon price. In both case studies, the LCOH of the NGB nearly doubles when considering a carbon price of 140 EUR/tonne of CO_2 compared to zero carbon pricing. The LCOH of the HTF, on the other hand, is independent of the carbon price. However, due to the potential need for an auxiliary NGB, the overall system is affected. In the SSD case study, where the HTF can supply only 27% of the heating load, the LCOH of the entire system becomes highly dependent on the carbon price, as most of the heat is supplied by the NGB. In contrast, in the steam production case study, where the HTF can supply 70% of the heating load, the overall system is less dependent on the carbon price.

5.3. Influence of the Waste Heat Availability

When coupling different processes, the ratio of waste heat to process heat can vary. Consider the steam case with a heat demand of 474 kW_{th}. To study its effect, the waste heat availability is varied between 0 and 1000 kW_{th}. The LCOH of the different heating technologies as a function of the waste heat availability for the steam production case study can be found in Figure 22.

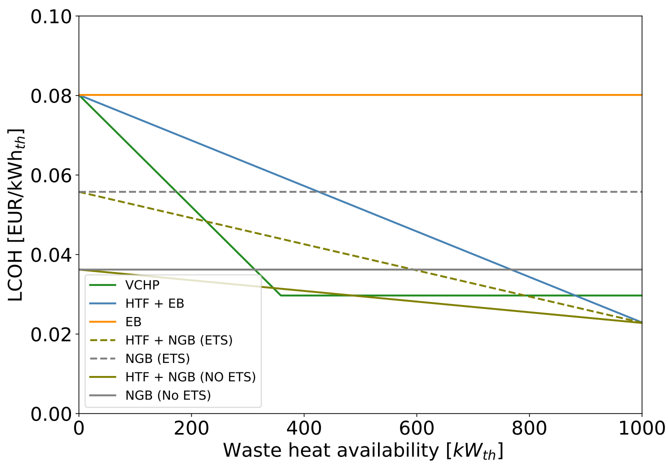

Figure 22. LCOH for the steam production case study for the different technologies as a function of the waste heat availability.

As the EB and the NGB do not require waste heat, their LCOH is independent of waste heat available. For the VCHP 357 kW_{th} of waste heat is required for the LCOH to become independent of the waste heat available. For the HTF 1000 kW_{th} of waste heat is required. If these quantities of waste heat are not available, auxiliary heating will be needed. In such scenarios the LCOH increases for lower waste heat availabilities for both instances, until the waste heat availability becomes zero. At this point the LCOH is the same as for the auxiliary heating technology, as the HTF and VCHP are not able to supply any heat. For high waste heat availabilities the HTF can become more cost effective than a VCHP. Depending on the auxiliary heating system used and whether an ETS is being applied this happens for waste heat availabilities between 500 and 900 kW_{th}.

6. Discussion

The presented work compares the financial performance of the NGB, HTF + NGB, EB, VCHP and HTF + EB. The financial model is applied to two case studies relevant to the chemical industry, namely SSD and steam production. Depending on the case study, energy prices, and whether or not an ETS is applied, either the VCHP or the HTF + NGB shows the lowest LCOH, with the VCHP being a complete electrified option, while the latter one still requires natural gas. Replacing the auxiliary NGB by an EB, to electrify the process, would strongly drive up the LCOH. It should be noted, however, that for other case studies, with higher waste heat availability and/or lower GTLs, an HTF without auxiliary heating system may also appear as the solution with the lowest LCOH, as has been shown in the sensitivity analysis. Furthermore, it should be considered that natural gas costs, electricity costs and ETS costs are highly volatile. Therefore, in a future scenario, the LCOHs reported in Figures 14 and 17 may not be valid. However, in these scenarios, Figures 12, 13, 15 and 16, which show the LCOH of each technology over a price range, can be used.

The study, however, has some limitations. First, there is a lack of detailed cost data of the heat pumping technologies. Therefore, a minimum and maximum cost is considered for each heat pump technology to show the sensitivity of LCOH to investment costs. Second, it could be argued that the financial model assumes the available waste heat to be free heat, as is commonly assumed in the literature [84–87]. However, for high-temperature heat production applications, waste heat at a significant temperature level is required to enable competitive COPs. Heat at these temperatures could already be valuable for pre-heating industrial processes, or for space heating and domestic hot water purposes, e.g., by feeding the heat into a district heating network [88–90]. This potential is not considered in the current study, but it is highlighted. Third, the study does not take into account the integration costs of the technology. As the heat pump technologies require a connection to the heat source in addition to the connection to the process, higher integration costs could be expected. However, it could be argued that the need for cooling infrastructure is reduced or eliminated.

7. Conclusions

Heat pumps have a large potential for delivering process heat up to 200 °C in the chemical industry. Vapor compression heat pumps show clear benefits for delivering this process heat because of their potential for operating carbon free, while fully utilizing the available waste heat. Heat-driven heat pumps and heat transformers on the other hand either rely on fossil fuel combustion, utilize high-quality heat streams or poorly utilize the available waste heat.

The application potential of heat pumps in the chemical industry is discussed by further elaborating on their integration in distillation, drying and steam production. Moreover, possible integration points and heat pump configurations are presented. Steam production, however, may be of particular interest, since direct integration of heat pumps may be less favorable due to the potential reliability concerns. It also allows for convenient retrofits since steam networks are highly integrated in energy-intensive industries.

In the financial analysis it has been shown that, for a superheated steam drying process with a gross temperature lift of 81 K, vapor compression heat pumps always shows better financial appraisal than a heat transformer with auxiliary electric boiler and an electric boiler as stand alone. In countries with a low to average electricity to natural gas price ($\leq$2–2.5), it is also competitive against natural gas boilers and heat transformers with auxiliary natural gas boiler. If an emissions trading scheme is applied, the vapor compression heat pump is the most competitive option for all countries. A levelized cost of heat (0.0303–0.0424 EUR/kWh_{th}) up to 2.36 and 2.05 times as low compared to natural gas boilers and heat transformers with auxiliary natural gas boiler was found, respectively. Overall, because of the lack of a substantial amount of waste heat, heat transformers were not able to decrease the levelized cost of heat sufficiently compared to natural gas or electric boilers. For the steam production case study, similar conclusions to those for the superheated steam drying process can be made. However, heat upgrading technologies are now even more interesting because of the lower gross temperature lift and consequently higher COP. Moreover, because relatively more waste heat is available, the financial viability of heat transformers increases and almost approaches the feasibility of a vapor compression heat pumps. Furthermore, a sensitivity analysis of the levelized cost of heat on the annual operating hours, carbon pricing and waste heat availability was performed. The annual operating hours had a large, and non-linear, impact on the levelized cost of heat of the heat pumping technologies. Due to the low investment cost, the annual operating hours had less influence on the electric and natural gas boilers. As expected, the carbon price has a large impact on the levelized cost of the technologies using natural gas. The waste heat availability had a particularly large impact on the levelized cost of heat of the heat transformer. In brief, heat transformers are less interesting to be directly integrated in a process, but they can be interesting to supply steam when large amounts of waste heat are available that cannot be valorized elsewhere.

Author Contributions: Conceptualization, E.V. and C.M.; Methodology, E.V.; Writing—original draft, E.V.; Writing—review & editing, E.V., T.D., W.B., C.M., H.A., C.A., S.B., A.A., M.D.P. and S.L.; Funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

Funding: The contribution of E.V., T.D., W.B., H.A., A.A., M.D.P. and S.L. was funded by the Flemish Government and Flanders Innovation & Entrepreneurship (VLAIO) through the Moonshot project Upheat-INES (HBC.2020.2616). The contribution of C.A. and S.B. was funded by the Swiss Federal Office of Energy (SFOE) through the SWEET project DeCarbCH (DeCarbonisation of Cooling and Heating in Switzerland) (www.sweet-decarb.ch (9 May 2023)) and the project Annex 58 HTHP-CH (Contract number SI/502336-01). The APC was funded by Flemish Government and Flanders Innovation & Entrepreneurship (VLAIO) through the Moonshot project Upheat-INES (HBC.2020.2616).

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://heatpumpingtechnologies.org/annex58/task1/ (Accessed: 7 July 2022).

Acknowledgments: We gratefully acknowledge the financial support of the Flemish Government and Flanders Innovation & Entrepreneurship (VLAIO) through the Moonshot project Upheat-INES (HBC.2020.2616). In addition, the Swiss authors gratefully acknowledge the Swiss Federal Office of Energy (SFOE) for the financial support of the SWEET project DeCarbCH (DeCarbonisation of Cooling and Heating in Switzerland) (www.sweet-decarb.ch (9 May 2023)) and the project Annex 58 HTHP-CH (Contract number SI/502336-01).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Acronyms	
C	Cost (EUR)
COP	Coefficient of performance
CRF	Capital recovery factor
ETS	Emissions trading scheme
EB	Electric boiler
GWP	Global warming potential
HDHP	Heat-driven heat pump
HTF	Heat transformer
HTF + EB	Heat transformer with auxiliary electrical boiler
HTF + NGB	Heat transformer with auxiliary natural gas boiler
HTHP	High-temperature heat pump
MVR	Mechanical vapor recompression
NGB	Natural gas boiler
SGHP	Steam generating heat pump
SSD	Superheated steam drying
TRL	Technology readiness level
VCHP	Vapor compression heat pump
Parameters	
GTL	Gross temperature lift (K)
C	Cost (EUR)
h	Enthalpy (kJ/(kg · K))
i	Discount rate (%)
LCOH	Levelized cost of heat (EUR/kWh_{th})
$\dot{m}$	Mass flow rate (kg/s)
n	Lifetime (years)
p	Pressure (bar)
$\dot{Q}$	heat transfer rate (W)
T	Temperature (K)
$\dot{W}$	Power (W)
x	Quality (-)
Subscripts	
a	annual
cap	capital
el	electrical
h	high
in	inlet
l	low
m	medium
ng	natural gas
out	outlet
th	thermal

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