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# Energy efficiency improvements in Swedish construction material industry with high temperature heat pumps

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AUTOR: Monllor García, Javier

Tutores: Barceló Ruescas, Francisco; Ignatowicz, Monika; Khodabandeh, Rahmatollah

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# Energy efficiency improvements in Swedish construction material industry with High Temperature Heat Pumps

**JAVIER MONLLOR-GARCIA**

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# Energy efficiency improvements in Swedish construction material industry with High Temperature Heat Pumps

Javier Monllor Garcia

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| | Commissioner | Contact person |

# Abstact

Industries spend a significant portion of their total energy consumption on process heating, which is frequently based on fossil fuels encourage by its high temperature and power demands and accounts for a large portion of their greenhouse gas emissions. Reaching their climate goals by 2030 and beyond requires industries to electrify and reduce the carbon content of the process heating. A crucial technology for decarbonizing industrial process heating is heat pumps than can supply process heating at the highest efficiencies and based on potentially emission-free electricity. They are already a well-proven technology and are being used in industries for heating temperatures under 100 °C. Industrial heat pumps are becoming more and more advantageous as a technology, and their range of application as the preferred technology has grown to temperatures far beyond 100 °C. While several technologies are being developed, there are currently few solutions available for the significant portion of process heat requirements above 100 °C. With well-developed industries for industrial heat pumps, which are being expanded to high temperature heat pumps (HTHP), Europe and Japan are the leaders in technological advancement.

The aim of this work is to evaluate the use of HTHPs to enhance drying processes in the manufacturing of construction materials such as gypsum and polystyrene. The project focuses on critical goals such as increasing energy efficiency and lowering operating costs, which are essential for sustainable industrial operations.

Results show that HTHPs provide considerable energy efficiency improvements over more traditional systems. This efficiency lowers $CO_2$ emissions, energy consumption, and stabilizes energy costs. Nevertheless, the transition to HTHP technology faces challenges such as high initial installation costs and integration complexity, research going forward seeks to increase refrigerant with higher temperature outputs' efficiency and development.

As found, the investment payback periods are shorter in cases of electric and gas heaters. With electric heaters, the company is more exposed to price changes, while gas heaters offer a more balanced scenario. In the case of heat pumps, a $CO_2$ neutrality can be achieved and significantly lower net electricity consumption over the years, although it with the challenge of a higher initial investment.

# Keywords

High Temperature Heat Pump, Industry, Construction Materials, Waste heat, Decarbonization, Energy Transition, Drying process.

# Sammanfattning

Industrin spenderar en betydande del av sin totala energiförbrukning på processuppvärmning, som ofta är baserad på fossila bränslen som uppmuntras av dess höga temperatur- och effektbehov och står för en stor del av deras utsläpp av växthusgaser. För att nå sina klimatmål till 2030 och framåt kräver industrierna att elektrifiera och minska kolhalten i processuppvärmningen. En avgörande teknik för att avkolna industriell processvärme är värmepumpar som kan leverera processvärme med högsta verkningsgrad och baserad på potentiellt utsläppsfri el. De är redan en väl beprövad teknik och används i industrier för uppvärmning av temperaturer under 100 °C. Industriella värmepumpar blir mer och mer fördelaktiga som teknik, och deras användningsområde som den föredragna tekniken har vuxit till temperaturer långt över 100 °C. Medan flera tekniker utvecklas, finns det för närvarande få lösningar tillgängliga för den betydande delen av processvärmebehov över 100 °C. Med välutvecklade industrier för industriella värmepumpar, som utökas till högtemperaturvärmepumpar (HTHP), är Europa och Japan ledande inom tekniska framsteg.

Syftet med detta arbete är att utvärdera användningen av HTHP för att förbättra torkningsprocesser vid tillverkning av byggmaterial som gips och polystyren. Projektet fokuserar på kritiska mål som att öka energieffektiviteten och sänka driftskostnaderna, vilket är avgörande för hållbar industriverksamhet.

Resultaten visar att HTHP ger avsevärda energieffektiviseringar jämfört med mer traditionella system. Denna effektivitet sänker $CO_2$-utsläpp, energiförbrukning och stabiliserar energikostnaderna. Ändå står övergången till HTHP-teknik inför utmaningar som höga initiala installationskostnader och integrationskomplexitet, forskning framöver strävar efter att öka köldmediet med högre temperatureffekters effektivitet och utveckling.

Som konstaterats är återbetalningsperioderna för investeringen kortare i fall med el- och gasvärmare. Med elvärmare är företaget mer utsatt för prisförändringar, medan gasvärmare erbjuder ett mer balanserat scenario. När det gäller värmepumpar kan en $CO_2$-neutralitet uppnås och avsevärt lägre nettoelförbrukning över åren, även om det med utmaningen med en högre initial investering.

# Nyckelord

Högtemperaturvärmepump, industri, konstruktionsmaterial, spillvärme, avkolning, energiomställning, torkprocess.

# Nomenclature

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| COP | Coefficient of Performance [-] |
| EPS | Expanded polystyrene |
| EU | European Union |
| GHG | Greenhouse Gas |
| GWP | Global warming potential [-] |
| HPT | Heat Pumps Technologies |
| HTHP | High temperature heat pump |
| IEA | International Energy Agency |
| IED | Industrial Emissions Directive |
| IHX | Internal heat exchanger |
| ODP | Ozone depletion potential [-] |
| OECD Europe | Organisation for Economic Co-operation and Development |
| SDG | Sustainable Development Goals |
| T | Temperature [ºC] |
| VHC | Volumetric heating capacity [$J/K \cdot m^3$] |
| XPS | Extruded polystyrene |

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# 1 Introduction

The industrial contributions to global warming are significant; if uncontrolled, energy-intensive industries are expected to raise the world temperature by around 2.3ºC, directly jeopardizing the achievement of the climate targets outlined in international agreements (Climate Analytics & NewClimate Institute, 2024). By converting waste heat into usable energy, these systems reduce the thermal pollution and $CO_2$ footprint of industrial facilities.

Recognised as the main user of global energy resources, the industrial sector used over 37% of all energy used globally in 2019; around 25% of this usage directly contributed to $CO_2$ emissions (IEA, 2020). This large use emphasizes how important it is to include sustainable technology to lessen the negative effects on the environment that come with using conventional energy sources. Out of all the potential technologies, HTHP seems to be essential for improving energy recovery and industrial thermal process optimization. (Arpagaus et al., 2018).

Climate change need to be addressed given the industrial energy usage. Greenhouse gas emissions must be cut via creative methods. To comply with the ambitious goal of reducing greenhouse gas emissions by 80% by 2050 established by international accords, enterprises are forced to implement more advanced energy recovery and waste heat utilization systems (United Nations environment programe, 2023).

The attempts to keep warming to below 2 ºC are supported globally by the climate framework established by the Paris Agreement. This entails a major system and process redesign for companies (United Nations, 2015).

Policies of the European Union (EU) have a big impact on industrial energy practices and encourage the use of more environmentally friendly technology to meet sustainable futures. For instance, the (European Commission, 2010) envisages that by 2050 Europe will be the first continent to become climate neutral. This would need a dramatic change in industrial processes. Comparably, companies are required under the EU's Industrial Emissions Directive (IED) to reduce their production of pollutants, which includes HTHP adoption (European Parlament, 2023).

Environmentally friendly technology must be used, according to legislation and local requirements. For example, the IED mandates that member states uphold regulations that require sectors to reduce emissions, therefore affecting operating procedures and technological deployment plans directly (European Parlament, 2023).

In addition, the REPowerEU plan, developed in response to the energy shortages worsened by international conflicts, seeks to quickly lessen the EU's reliance on fossil fuels by diversifying energy sources and speeding up the ecological transition (European Commission, 2010).

Also, the EU must cut its energy use by 12% by 2030 compared to 2020 levels under the new Energy Efficiency Directive (Directive 2023/1791). This legislation was introduced to satisfy more stringent efficiency requirements (European Union, 2023).

Long-term sustainability cannot be maintained without sustainable industrial methods, which also help to satisfy legal obligations. Meeting the UN's Sustainable Development Goals more especially, SDG 7, which requires that everyone have access to modern, sustainable, and affordable energy (United Nations, 2023).

IEA HTP Annex 59 is a collaborative project of some countries, including Sweden, that try to work together in the study of HTHP in drying procedures. This process uses anywhere from 10 to 25% of the energy consumed in industry (Heat Pumping Technologies, 2023).

Among the many advantages of companies switching to HTHP technologies are the possibility of much reduced operating costs and increased energy efficiency. Higher temperature heat pumps used in these systems may more efficiently capture waste heat from industrial operations than can conventional systems. This capacity not only improves the general energy efficiency of industrial facilities but also greatly lowers the running costs related to energy use.(EUROBERV’ER, 2020)

As a result, the utilisation of HTHP technology in industrial applications represents a significant advancement in energy conservation and environmental preservation. These technologies bring in a new age of increased industrial efficiency and less environmental effect by being in line with international legal frameworks and sustainability objectives. This thesis attempts to investigate the possible routes and obstacles for the wider use of HTHP systems in the industry by concentrating on their technological, environmental, and regulatory components, thus guaranteeing future industrial practices are sustainable and ecologically responsible.

Putting into use a sophisticated high temperature heat pump HTHP technologies contribute to satisfy tighter emission limits, play a key part in the larger climate mitigation plan, and provide a workable way to lower the potential for global warming.

# 2 Objectives

This thesis aims to evaluate the use of HTHPs to enhance drying processes in the manufacturing of construction materials such as gypsum and polystyrene. The research focuses on critical goals such as increasing energy efficiency and lowering operating costs, which are essential for sustainable industrial operations.

The first steps will be to determine the exact energy requirements for the production process of our two cases, polystyrene and gypsum. Effective deployment of HTHP systems depends on an awareness of these energy needs. Estimating the possible reduction in emissions and energy usage will be the next stage. This work focuses on energy transition from fossil fuels to more sustainable energy sources. The objectives for industrial emission reductions set by the EU and the world will be supported by this evaluation.

Furthermore, the thesis will evaluate the long-term savings in operating expenses as well as the initial outlay of funds when using HTHP technology.

This project is a concentrated effort of the IEA HPT Annex 59, which promotes heat pumps for reducing greenhouse gas emissions and energy consumption in industrial applications. The aim is to map the industrial needs, document some case studies and propose most suitable solutions for improving energy efficiency. The goal of this thesis to evaluating the technical advantages and economic implications of HTHP technology for the building materials sector. Understanding of HTHP capabilities and encouraging their bigger use in the industry will be achieved by using insights from IEA HPT Annex 59, which will also help to guarantee that future industrial practices are sustainable and ecologically friendly.

# 3 Methodology and Limitations

The purpose of this thesis is to evaluate in detail how well HTHP technologies could improve drying procedures in the building materials industry. To guarantee a thorough and varied analysis, this work uses a mixed-methods strategy that combines quantitative and qualitative research techniques. A literature study comprising scientific articles, technical reports, and conference papers is part of the data collecting process. Moreover, the semi-structured interviews (list of questions can be found in Appendix) with important building materials industry participants are conducted to find and document some case studies. The industry's anticipation for technology improvements, operational issues, and present energy use may all be learned directly from these interviews. To evaluate the economic viability of HTHP technology adoption, cost-benefit analyses are carried out and energy consumption, emissions reduction, and cost-effectiveness related to the deployment of HTHP systems are carefully computed. Practical consequences of integrating HTHP technology into current industrial frameworks are understood more fully when empirical data from industry interviews is combined with quantitative analysis.

Apart from the fundamental approach, it is crucial to admit certain restrictions and practical difficulties experienced throughout the study. Companies were contacted only around the end of April and again in early May 2024, and while their assistance was vital and much valued, little information was given out of confidentiality concerns.

Important obstacles were also presented by practical restrictions, notably the inability to visit the Sundolitt facilities due to facility location. Assessments become more difficult when facility operators are not included in thorough conversations about the spatial and production setup needs for establishing HTHP systems.

Data collecting was further limited by the short interview time and heavy effort needed to achieve submission deadlines. The little number of interviews carried out and the possible depth of data that might have been investigated are mentioned as limitations that affected the study scope, even if the data collected are strong and provide a solid foundation for analysis.

The limitations in terms of calculations varied. Initially, only the energy expenditure for steam production and electrical consumption were provided. Not that the unit cost of diesel and electricity were important data that were assumed. The $CO_2$ emissions, however, were calculated accurately.

# 4 Energy intensives industries in EU

This chapter will present the overall energy situation in world and Europe.

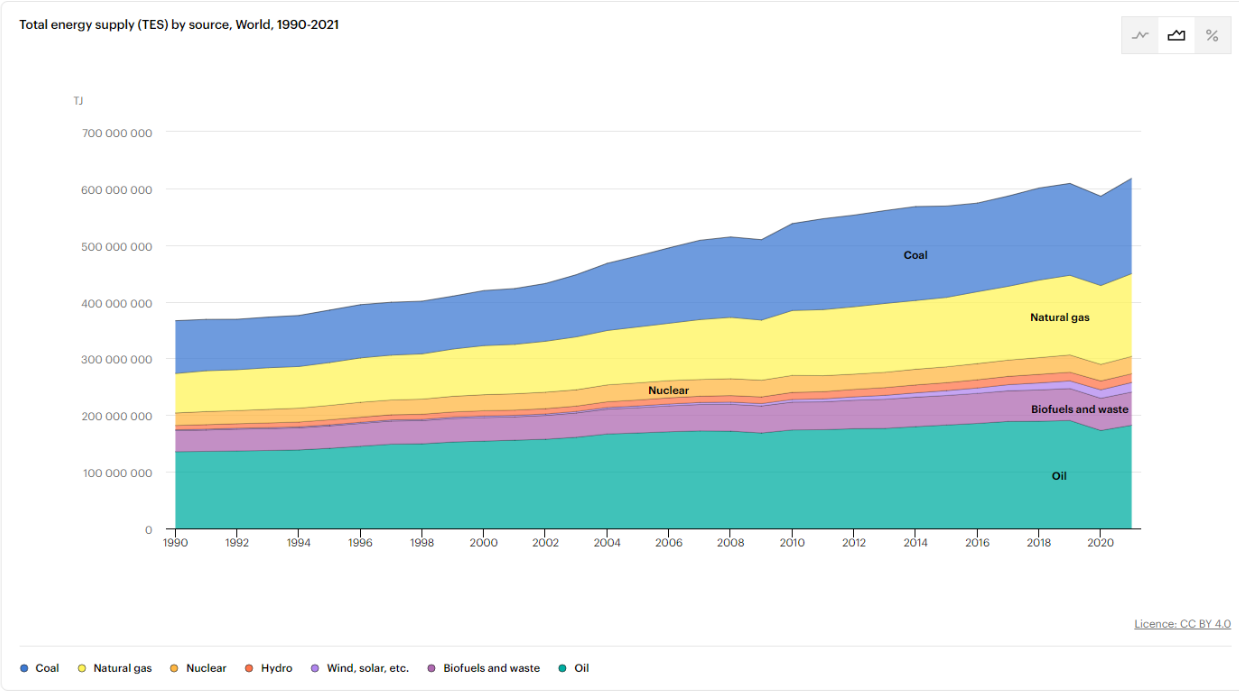


*Figure 1, Total energy supply, World* (IEA, 2024)

In the period 1990-2021 the energy consumption of the World has grown approximately by 60%, with a more significant increase in oil, coal and gas.

The figure 1 presents an overview of global energy supply trends over the past three decades. According to the figures, waste use and biofuel use climbed by 56% while oil supply jumped by 35%. Especially regarding renewable energy sources, excluding hydro, the supply of them jumped an amazing 1000%, indicating a major worldwide change toward greener fuels. Additionally, hydropower doubled with a 100% and showed a significant expansion. Natural gas use more than doubled, representing a 110% increase. Instead nuclear energy supply climbed by 40%. Though still a main energy source, coal supply grew by 81%. These patterns show a significant increase in the usage of several energy sources, therefore stressing the increasing relevance of both fossil fuels and renewable energy in the global energy scene.

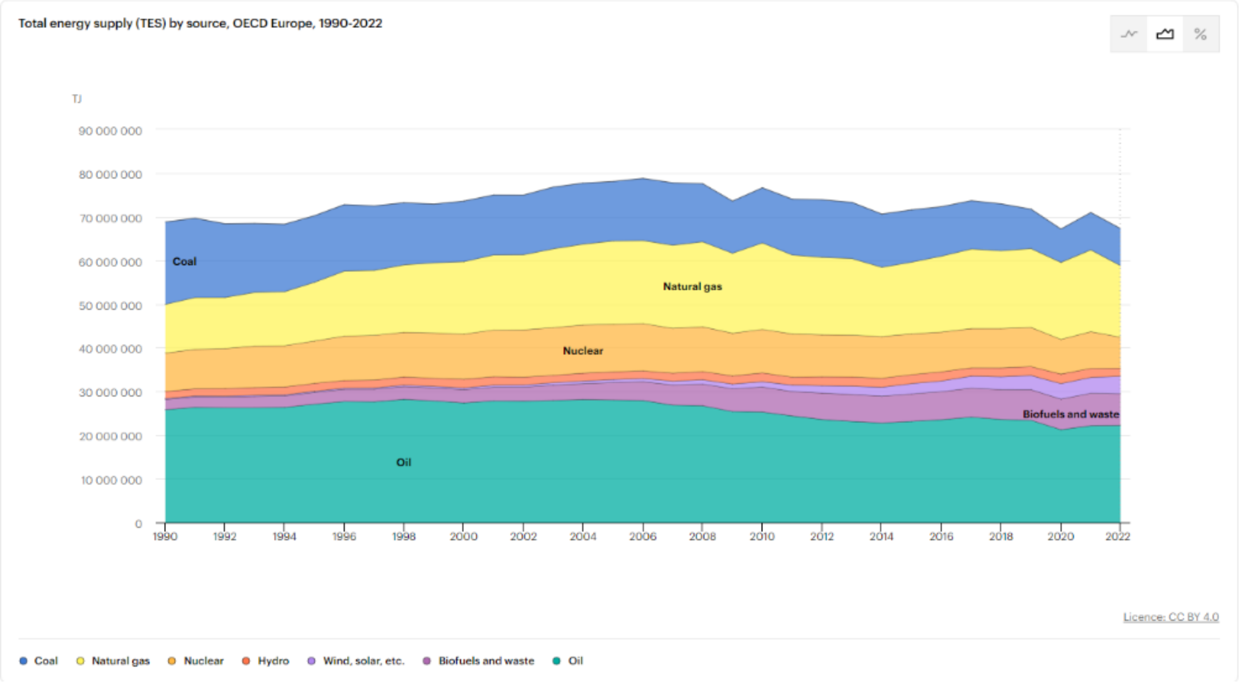


*Figure 2, Total energy supply, OECD Europe* (IEA, 2024)

The figure 2 illustrates significant changes in energy sources in OECD Europe over the past three decades. Oil supplies dropped 14% and nuclear energy fell 19% throughout this time. With a drop of 55%, coal saw the most significant decline suggesting a change away from this fossil fuel. By contrast, the usage of renewable energy sources rose dramatically. Waste use and biofuel climbed by 212%, while renewables excluding hydro jumped by about 1700%. With an 11% rise, hydropower also grew, though barely. Use of natural gas also climbed by 46%. Emphasizing the increasing relevance of renewables in the energy mix of Europe, these data clearly show a shift towards more sustainable energy sources throughout the continent.

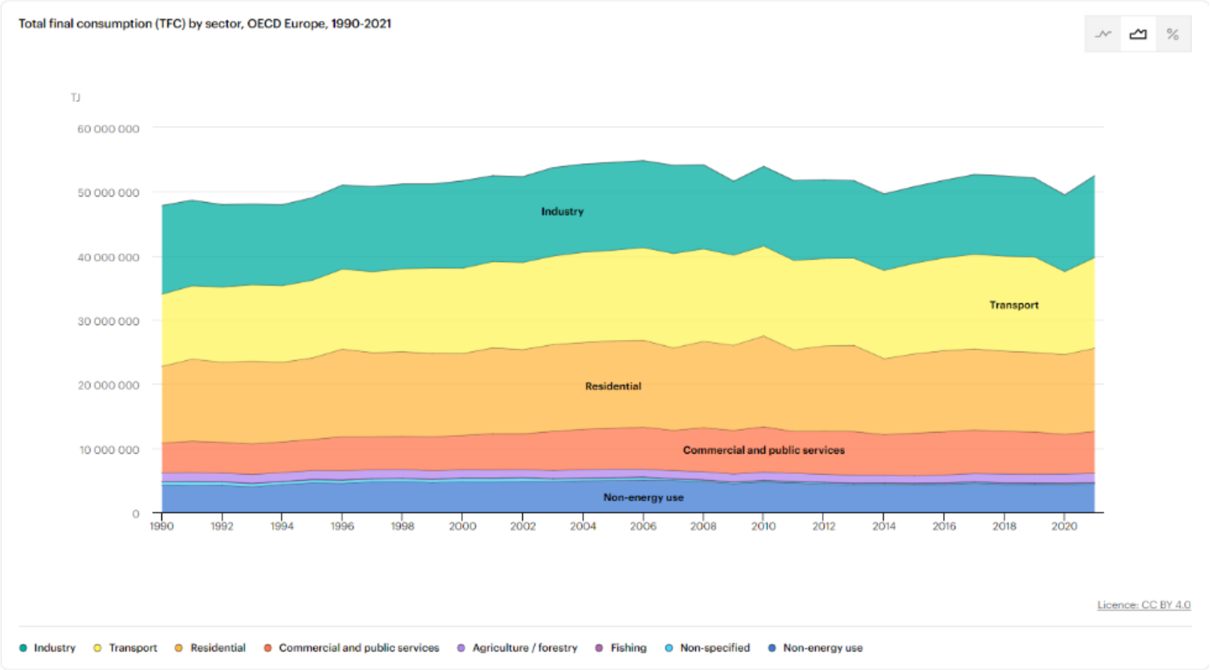


*Figure 3 Total energy consumption, OECD Europe* (IEA, 2024)

As seen, that OECD Europe has maintained its energy demand compared to global statistics, with oil and natural gas being the most significant part of energy consumption. It can be noted that coal use has been decreasing, although global coal consumption, like that of natural gas, has increased. Other cleaner energy forms, such as nuclear, which have not increased or the big increase on renewable energies.

Figure 3 presents the final consumption of energy on the OECD, by sectors. As seen, the industrial sector contributes to 25% of energy consumption, which make it perfect for introducing innovative technologies such as HTHP, to reduce primary energy use.

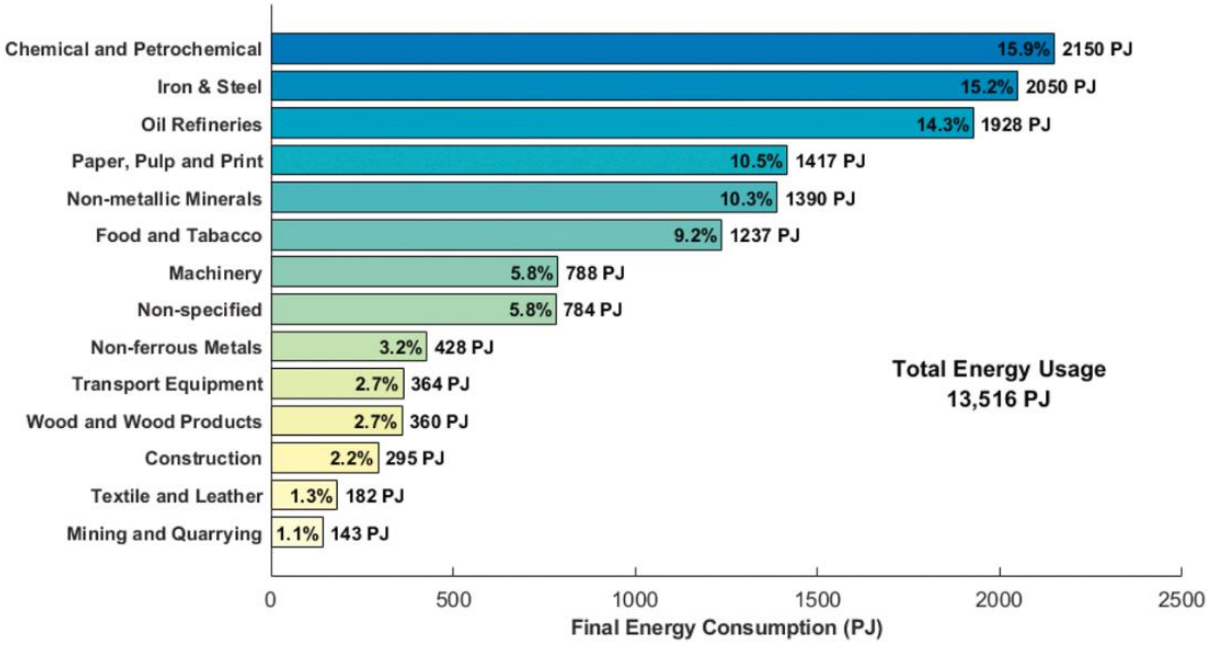


*Figure 4 Final Consumption EU* (Marina et al., 2021)

Energy-intensive industries in the EU, pivotal for both economic stability and environmental impact due to their substantial energy consumption, are under scrutiny to reduce carbon emissions significantly. Figure 4 illustrates how important these industries iron and steel, chemicals, and non-ferrous metals are as consumers of process heat both below and above 200°C, underscoring the vast thermal energy needs of many industrial processes. To evaluate the possibility of using HTHP, it is useful to pinpoint industries whose energy consumption takes place at temperatures below 200ºC.

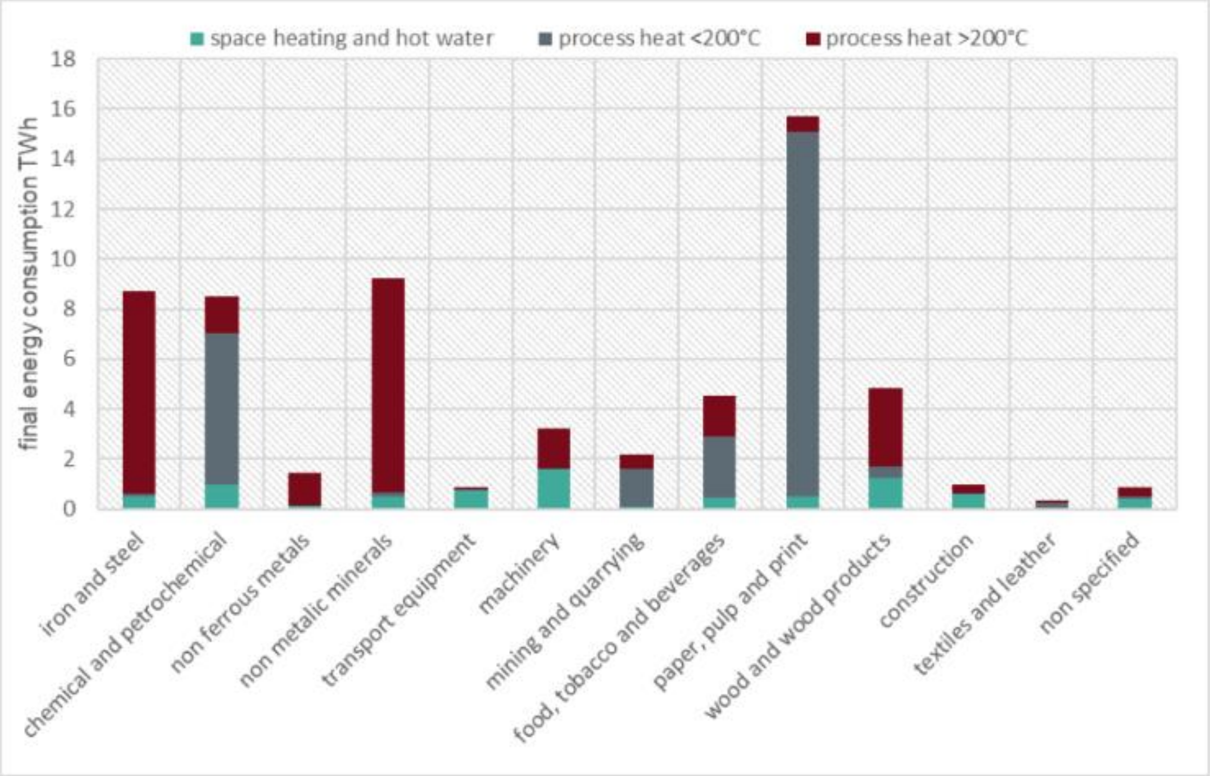


*Figure 5 Energy consumption by industries and temperatures* (Zühlsdorf, 2023)

These sectors have a big environmental effect since they not only need a lot of energy to run their operations but also mostly depend on non-renewable energy sources. The transition towards more sustainable energy sources can be observed in the increasing use of HTHPs, which are welcomed for their ability to improve energy recovery and optimise thermal processes within these industrial settings, as emphasized in (Wilk et al., 2022).

The distribution of heating capacities among different heat pump units, as shown in figure 5, demonstrates the dominance of small to medium-sized units in a variety of sectors, including refineries and the chemical industry.

This implies a slow but evident movement toward incorporating these systems into standard energy frameworks, driven by the need to meet high thermal demands effectively.

As seen in figure 5, most processes operating at temperatures below 200ºC could include HTHPs. The data derived from this bar graph is crucial because it illustrates processes below 200ºC across various industries. This is significant since only these processes can be implemented with HTHP technology. Currently, achieving higher temperature processes is not possible with this technology.

Additionally, factors such as technological obsolescence and inefficient processes highlight this consumption. There are many sectors with low power demands and temperatures below 150ºC that could already be using more modern technologies available to improve energy efficiency and reduce their carbon footprint, but instead, they continue to use old machinery that consumes an excessive amount of energy, typically fossil fuels.

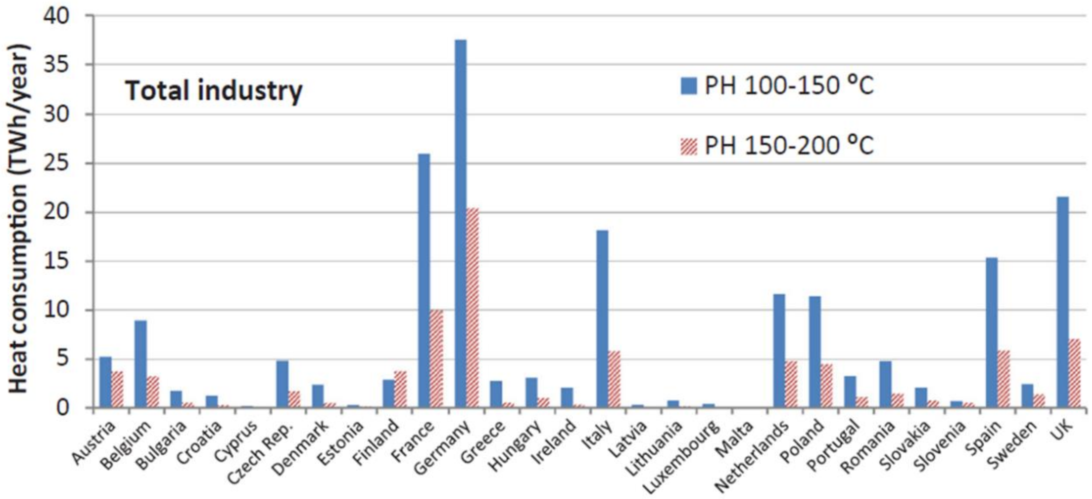


*Figure 6 heat consumption of the two temperature bans of interest per EU country,* (Kosmadakis, 2019)

The figure 6 depicts industrial heat consumption across European countries for two temperature ranges: 100-150 °C and 150-200 °C. Germany shows the highest consumption in both ranges, followed by notable levels in France, Italy, and the UK. Sweden and Spain also display significant consumption in the 100-150 °C range, indicating the potential for hightemperature heat pumps to enhance energy efficiency and reduce emissions. This variation highlights the diverse energy needs of European industries and the necessity for customized energy solutions.

## 4.1 Energy intensives industries in Sweden

Sweden has very constant energy consumption during the last 30 years due to significant energy efficiency improvements. As seen, the share of renewable energy sources raised and fossil fuel and nuclear energy usage declined, being the most important achievement in reducing the carbon emission. Swedish national energy policy is shape in large part by the usage of renewable energy sources, positively affecting industry. This energy transition is facilitated by laws promoting investment in environmentally friendly technologies and offering incentives for the energy renovation of industrial infrastructures. As show in figure 6 Sweden and Spain with high heat consumption in the 100–150 °C range, and HTHPs are ideal to stabilize energy prices and lower greenhouse gas emissions and fossil fuel consumption.

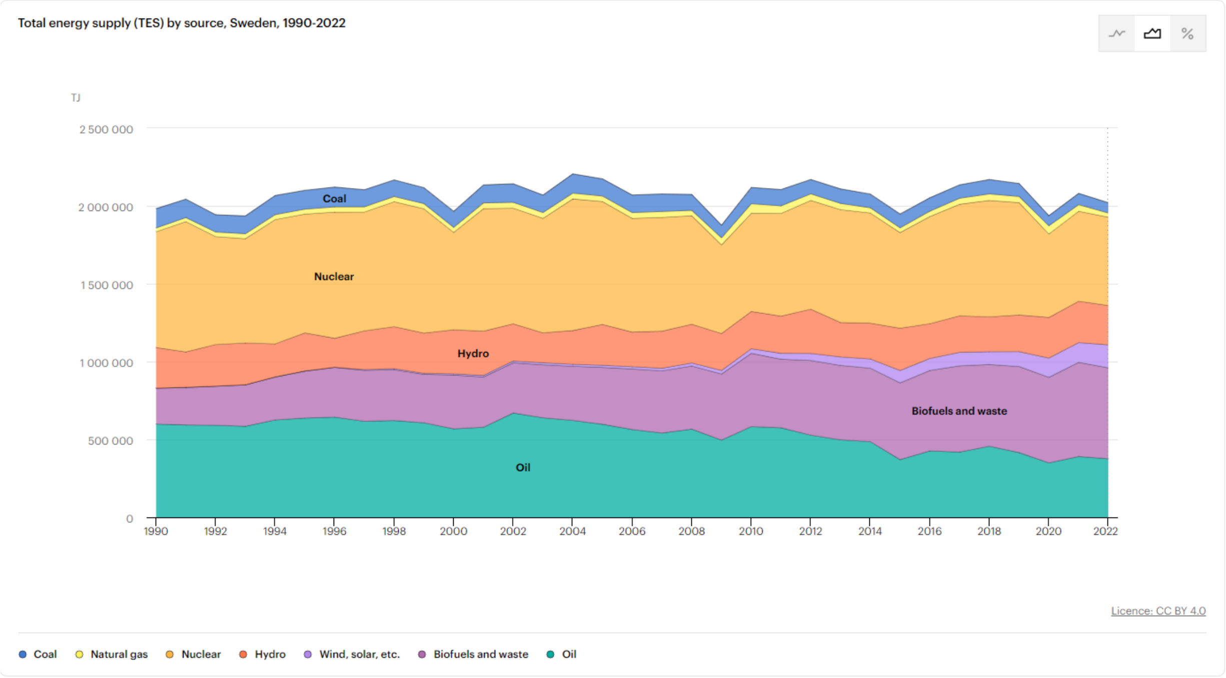


*Figure 7, Total energy supply in Sweden,* (IEA, 2024)

Figure 7 shows notable variations in the energy source composition over this time. Coal and oil use dropped significantly to 47% and 37%, respectively. Waste and biofuels, on the other hand, grew 153% in line with a change towards more environmentally friendly energy sources. Sweden's dedication to renewable energy is shown by the remarkable rise by more than 96000% in these sources excluding hydro. On the other hand, hydropower had a little loss of 3% while nuclear energy supply dropped by 24%. Natural gas use rose by 12.5% meanwhile. These patterns show a clear change in Sweden's energy scene toward less carbon-intensive sources and more renewable ones.

Sweden is archiving its targets on carbon neutrality and fossil fuel independence by 2045 and 2050 respectively, and that make significate changes on its energy landscape. (Swedish Energy Agency, 2022).

Sweden has been aggressively switching from fossil fuels to renewable energy sources including hydro, wind, solar, and biofuels in these 30 years. Their goal is to have 100% renewable electricity by 2040.

The energy consumption in Sweden is mostly determined by its industrial sector, especially by energy intensive industries like metals, chemicals, and pulp and paper. These industries will make up a sizable portion of the final energy consumption in 2020 and require large amounts of energy and at high temperatures demonstrating the difficulty of lowering emissions without sacrificing economic output. To reduce the carbon impact of these vital sectors, Sweden is implementing more renewable energy sources and improving energy efficiency.

Together with supporting Sweden's environmental objectives, this approach also complies with more general EU directives meant to lower energy consumption and boost the use of renewable energy among member states. Sweden is leading the way in progressive energy policy with significant investments in infrastructure and technology that improve energy use efficiency and sustainability in all sectors.

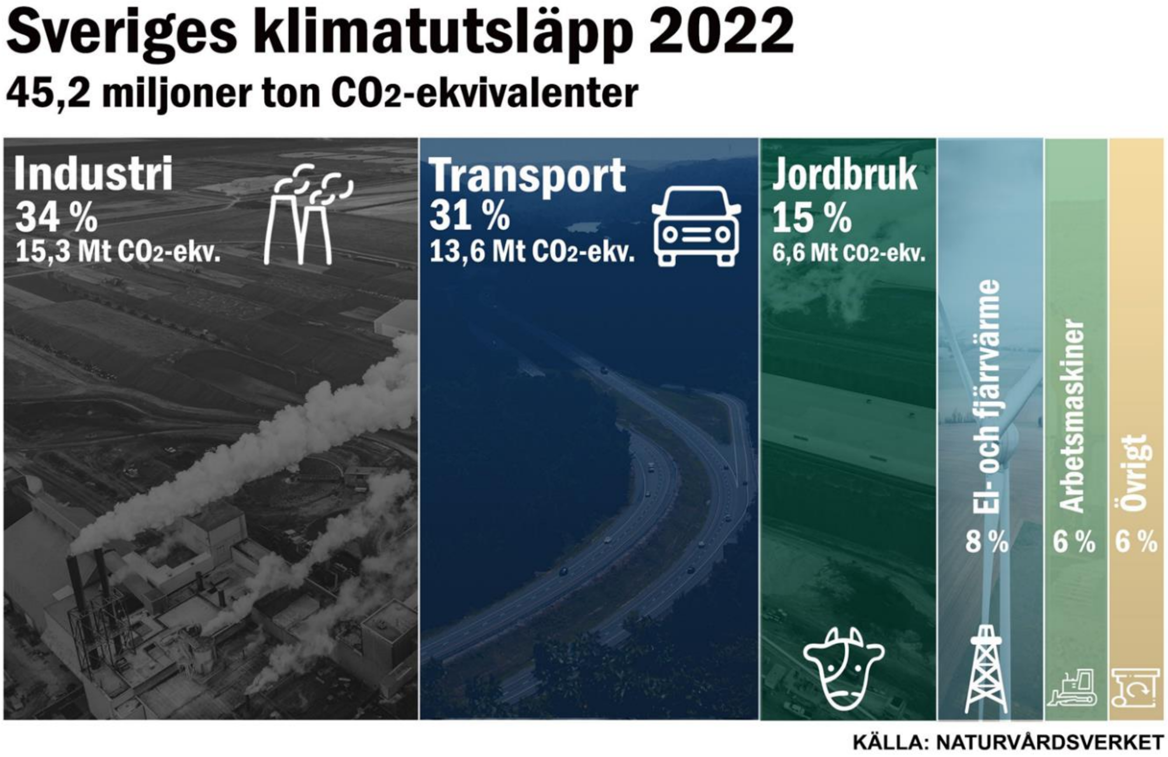


*Figure 8, Sveriges klimatutsläpp,* (naturvardsverket, 2024)

The figure 8 shows Sweden's total climate emissions at 45.2 million tons of $CO_2$ equivalents. The industry sector contributes the most, with 34% of emissions, or 15.3 million tons. High-temperature heat pumps (HTHPs) can reduce these emissions by replacing fossil fuel-based heating, improving energy efficiency and supporting Sweden's climate goals.

## 4.2 Energy intensives industries in Spain

Energy consumption in Spain has increased during the past thirty years. Usage of natural gas has essentially taken the place of coal. The nuclear generation has remained same. The energy policies and industrial consumption of Sweden and Spain are compared to show the notable differences in the application and efficacy of sustainability plans. Driven by its own regulations and the favourable climatic conditions that present significant opportunities for these technologies, Spain has been increasing its adoption of solar and wind energy. Figure 9 presents the total energy supply by diverse sources in Spain. As seen, Sweden leads with its progressive renewable energy policies compared to Spain.

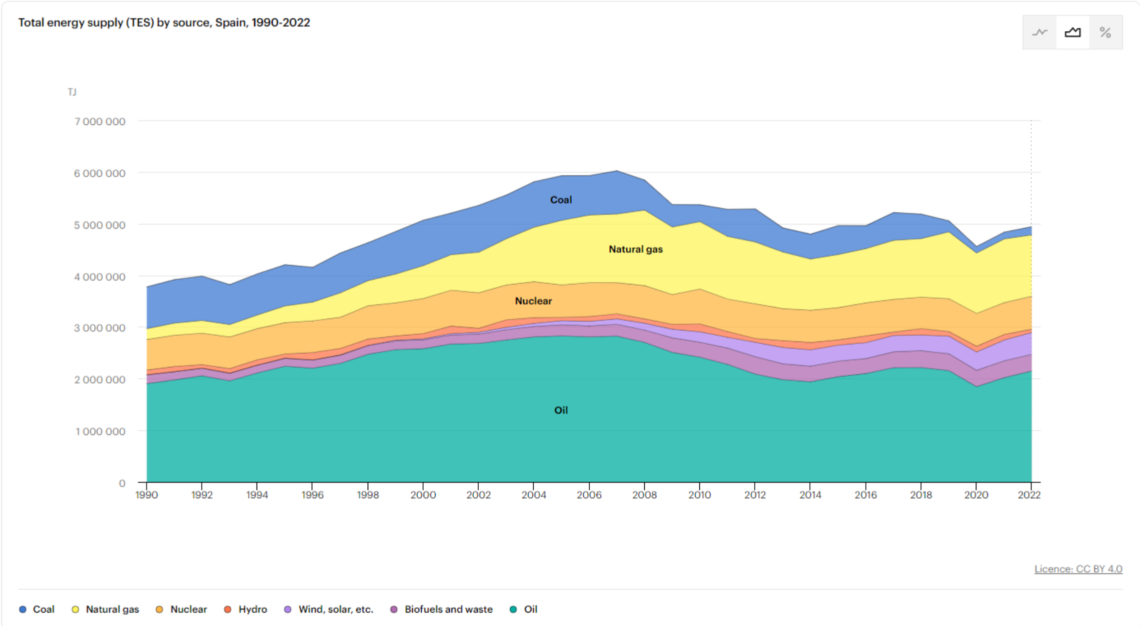


*Figure 9, Total energy supply in Spain,* (IEA, 2024)

The figure 9 illustrates the evolution of Spain's energy sources over this period. Oil usage increased by 13%, while biofuels and waste grew by 88%. There was a remarkable surge of 40000% in renewable energy sources excluding hydro, indicating a significant shift towards renewable energy. Hydropower remained stable with no change, and nuclear energy saw a modest increase of 8%. The most notable change was in natural gas, which increased by 470%, reflecting its growing importance in Spain's energy mix. Conversely, coal usage dramatically decreased by 81%, highlighting a move away from more carbon-intensive energy sources. These trends demonstrate Spain's ongoing transition to a more sustainable and diversified energy system.

In 2021, Spain's energy consumption was heavily dominated by fossil fuels, with oil and natural gas comprising 70% of its total energy supply. The comprehensive statistics shows a complex energy source balance in which renewable energy sources contributed notably with 20.3%. Nevertheless, Spain continuously works on shifting toward cleaner energy sources. This need is mostly driven by Spanish energy-intensive sectors, such chemical and non-metallic minerals sectors, which reflect larger European decarbonization trends. Currently Sweden is leading the European effort for energy efficiency and $CO_2$ neutrality thanks to its commitment to develop a sustainable energy system by 2040. These countries serve as examples of the different approaches and rates of change in Europe toward environmental sustainability and less reliance on fossil fuels and cleaner energies. (Ministerio para la transición ecologica y el reto demografico, 2023).

# 5 - High Temperature Heat Pumps

Populations, industry, and energy generation create enormous quantities of wasted heat, who cannot be immediately utilized because of its low temperature. Nevertheless, high efficiency ratio heat pumps can recover this waste heat and produce hot air or hot water for industrial processes as well as home heating. It can be sold and directed into the network of district heating as well (TRANE technologies, 2023).

A heat pump is a device that uses electricity a high-quality energy, or low heat, a very bad quality energy. As high-quality energy refers to forms of energy that have high exergy and can be converted to perform work with high efficiency, such as electricity and high temperature heat, these energy forms exhibit low entropy. Conversely, low-quality energy is characterized by high entropy and lower exergy, making it less efficient for performing work; an example is lowtemperature heat. To recover heat from one temperature and raise it to another. By varying pressure and temperature, heat pumps take use of the intrinsic thermodynamic characteristics of working fluids (refrigerants). (Zühlsdorf, 2024a).

In the field of industrial heating and cooling, HTHPs are becoming a revolutionary technology, especially for procedures that need for constant high temperatures. HTHPs are built to operate at higher temperatures than conventional heat pumps, which are typically limited to 55°C; additional study is being done to push the threshold to over 150°C. HTHP can therefore satisfy the demanding heating requirements of industrial applications where temperatures vary from 100°C to 200°C.(Arpagaus et al., 2018). Figure 10 shows the basic thermodynamic cycle of a heat pump, reverse refrigeration cycle, and its operation principle with the mass flow and heat transfer.(Jiang et al., 2022).

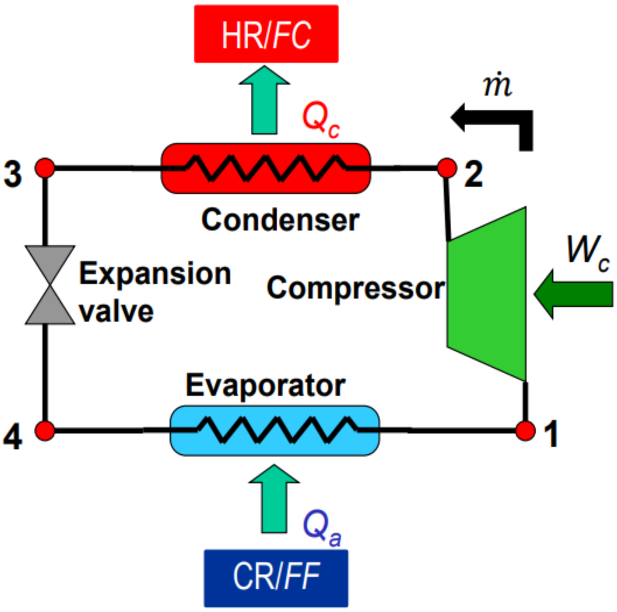


*Figure 10, Refrigeration Cycle,* (José Manuel, 1995)

The working principle of a heat pump involve a thermodynamic cycle that transfers heat from cooler to warmer environments, efficiently managing thermal energy at these elevated temperatures. The location from where heat recovered is called the heat source. Heat sources include, for instance, ambient heat, extra heat from industrial processes, solar collectors, and district heating. The reservoir that receives heat supply is called the heat sink. Heat sinks include, for instance, district heating systems, thermal energy storage charging, and process heat supply. Several heat sources and sinks at different temperatures can be connected by a heat pumping system. The temperature lift of a heat pump greatly influences its performance. Here, the difference between the entropic mean temperatures of the heat source and sink is used to compute the mean temperature lift. (Hamid et al., 2023).

An efficiency of a heat pump is expressed as the coefficient of performance (COP). It is the quantity of heating or cooling generated for each unit of energy input. COP is expressed as the heat transfer to hot reservoir ratio to the work input needed to transfer that heat. COP can be calculated as equation 1.

$$COP = \frac{Qh}{W} \quad (1)$$

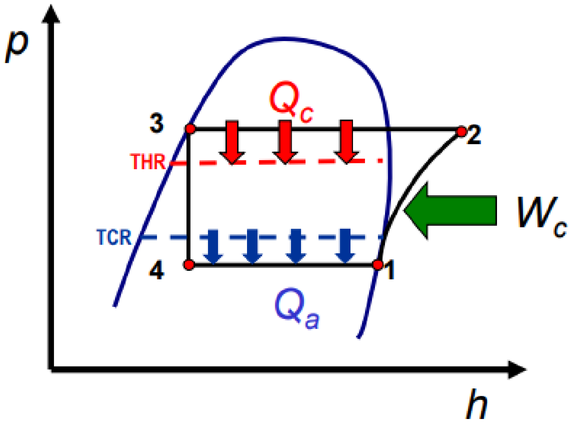
As this equation describes the definition of COP, a very important piece for understanding efficiency in heat pumps.The amount of heat transferred to a high temperature reservoir is represented by Qh, and the power input needed to transfer that heat is represented by W.

Equation 2 is directly linked to the COP, as higher temperature lift means lower COP.

$$\Delta Tlift, mean = Tsink - Tsource \quad (2)$$

The Carnot cycle is the most elementary thermodynamic cycle to represent heat pump behaviour. A Carnot cycle is an ideal cycle transferring heat from a hot reservoir to a colder reservoir while extracting work in the process. Isothermal heat absorption, isentropic compression, isothermal heat rejection and isentropic expansion are the four processes that the working fluid in the cycle goes through in succession. An example of a reverse Carnot cycle, shown in figure 3, in which work is added to move heat from a cold reservoir to a hotter reservoir is a heat pump.

*Figure 1 P-H Diagram,* (José Manuel, 2010)



The core components of heat pumps are compressor, condenser, expansion valve, and evaporators. The compressor is responsible for raising the pressure and temperature of the fluid refrigerant to the desired level, usually driven by means of an electric motor. The condenser is responsible for lowering the temperature of the refrigerant transferring useful heat at high enough temperature. In the condenser, the fluid refrigerant is condensed from vapour to liquid. The expansion valve is responsible for lowering the pressure of the fluid refrigerant by expanding it as liquid. The expansion is isenthalpic, so the liquid refrigerant evaporates and its temperature and pressure lowers. The evaporator assures the complete evaporation of the liquid refrigerant to vapour by means of absorbing heat from a warmer source. (José Manuel, 2010)

## 5.1 System types

The performance of the entire system can be maximized by arranging several single thermodynamic cycles in different ways.

### 5.1.1 Single-stage cycle (with/without IHX)

One stage cycle is the most basic system. An internal heat exchanger (IHX) can improve cycle performance, depending on the characteristics of the refrigerant. Refrigerants having a saturated vapour curve with a positive slope (dT/ds > 0) that need significant superheating to prevent wet compression benefit most from the IHX, as seen in figure 12. One can realize the compression in standard cycles or IHX cycles as a single-stage compression or as a multi-stage compression with or without interstage cooling (Zühlsdorf, 2023).

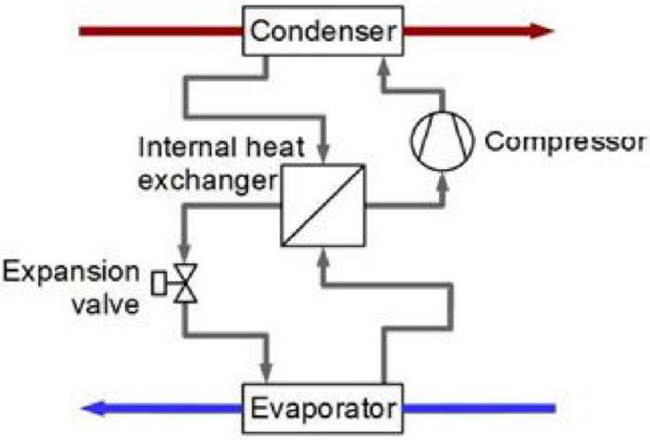


*Figure 12, Single stage,* (Zühlsdorf, 2023)

### 5.1.2 Economizer cycle

An economizer cycle (shown in Figure 13) expands a refrigerant slip stream to an intermediate pressure in an expansion valve following the condenser. In this way, this slip stream cools and partially evaporates. As so, heat is transferred from the partially evaporated (intermediate pressure) refrigerant to the liquid refrigerant (high pressure). By now the economizer heat exchanger has totally evaporated the refrigerant (intermediate pressure). The compressor is next supplied with the evaporated slip stream. Expanding, the liquid refrigerant that is left passes through the evaporator. Higher refrigerant mass flow occurs in the condenser than in the evaporator in this arrangement. Condenser and evaporator low pressure refrigerant mass flow must be compressed in part. With the remaining portion compressed only from medium to high pressure, the power consumption is reduced for the same heating capacity (Zühlsdorf, 2023).

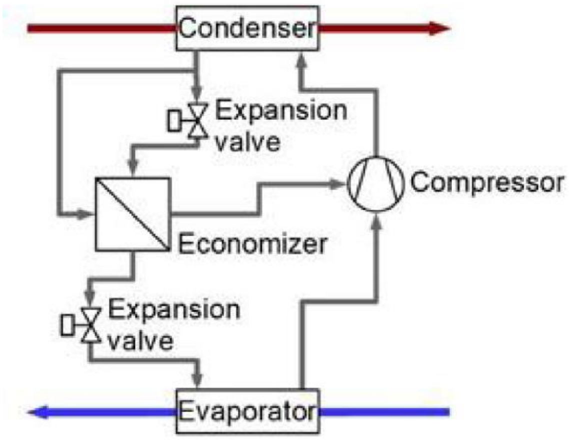


*Figure 13, Economizer cycle,*(Zühlsdorf, 2023)

### 5.1.3 Twin cycle / Multi cycle

Figure 14 illustrate this kind of cycle, which has two (twin) or more (multi) refrigeration cycles. One can connect the sources or sinks in this configuration either in series or parallel. High temperature differential between inlet and outlet is overcome by a serial connection. This arrangement produces different COPs per cycle because the operating temperatures vary throughout the cycle. The cycle with to overcome a lower temperature lift runs at a higher COP. Because not just one refrigerant cycle or compressor must supply the full heating capacity or temperature lift, the multi or twin cycle configuration offers benefits at operating conditions with larger temperature differences (between source inlet and outlet or between sink inlet and outlet) (Zühlsdorf, 2023).

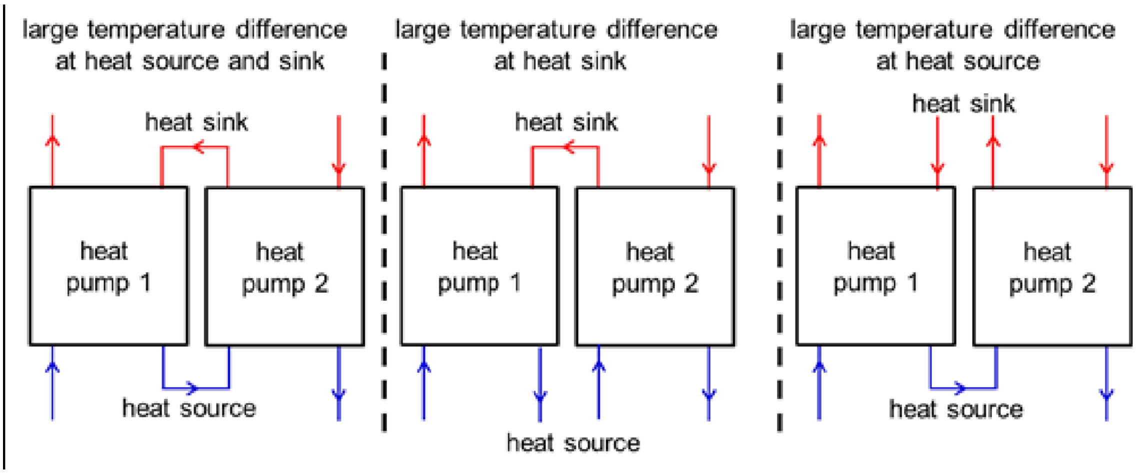


*Figure 14 Twin cycle,* (Zühlsdorf, 2023)

### 5.1.4 Cascade cycle

Two refrigeration cycles the low and high temperature refrigeration cycle that are linked by a heat exchanger, or evaporator condenser, make up the cascade cycle (Figure 15). Concurrently with the condensing of the low temperature cycle refrigerant, the high-temperature cycle refrigerant evaporates in this heat exchanger. With this arrangement, each refrigeration cycle must overcome a lower pressure ratio than with the single-stage arrangement, which, particularly at high temperature lifts, increases efficiency by 19%. Still, this arrangement produces less heat than a twin cycle because one cycle serves as the heat source for the other (Zühlsdorf, 2023)

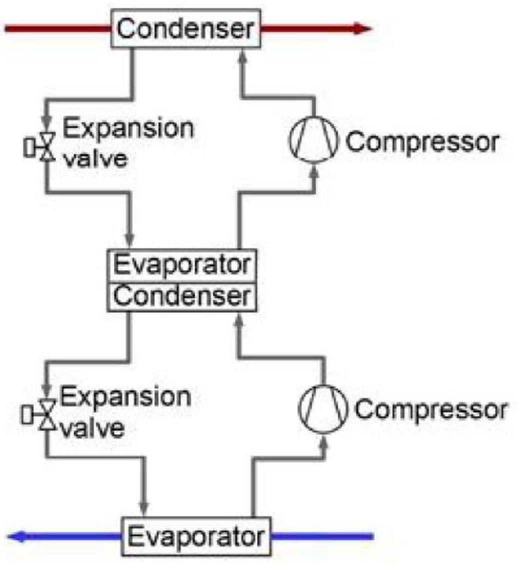
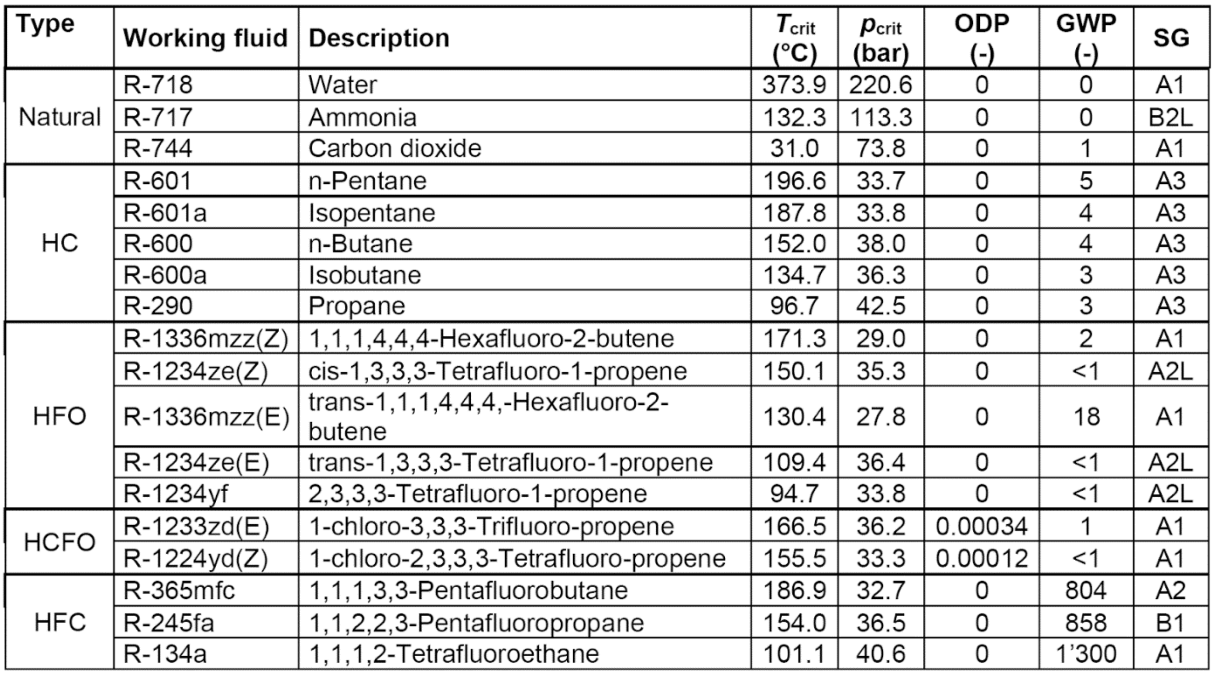


*Figure 15. Cascade cycle* (Zühlsdorf, 2023)

## 5.2 Working fluids (refrigerants)

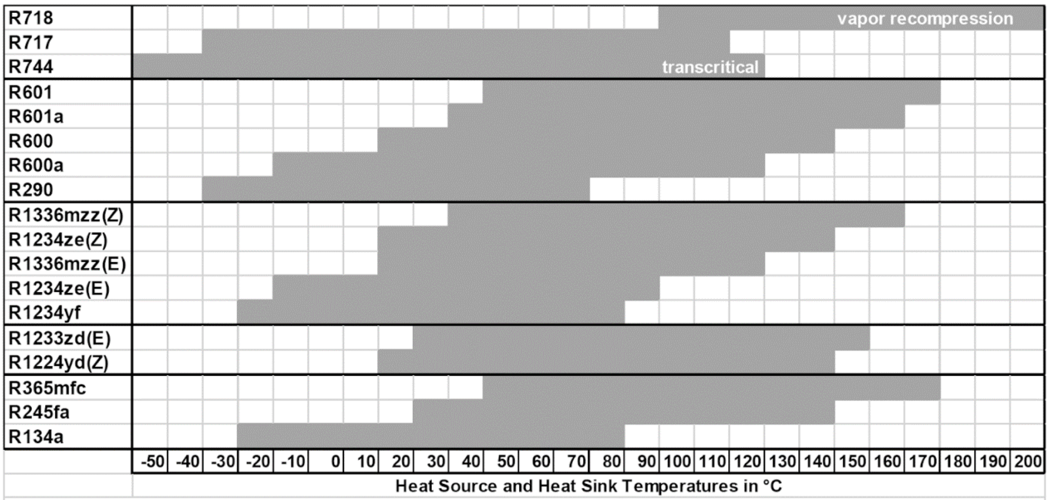
Table 1 provides a summary of the characteristics of current and potential working fluids employed in electrically powered HTHP applications (except for noble gases such as helium or argon used in Stirling and Brayton cycles). Critical temperature and pressure, the global warming potential (GWP), the ozone depletion potential (ODP), and the safety group classification are listed.(José Manuel, 1995)



| Type | Working fluid | Description | $T_{crit}$ (°C) | $p_{crit}$ (bar) | ODP (-) | GWP (-) | SG |
|---|---|---|---|---|---|---|---|
| Natural | R-718 | Water | 373.9 | 220.6 | 0 | 0 | A1 |
| | R-717 | Ammonia | 132.3 | 113.3 | 0 | 0 | B2L |
| | R-744 | Carbon dioxide | 31.0 | 73.8 | 0 | 1 | A1 |
| HC | R-601 | n-Pentane | 196.6 | 33.7 | 0 | 5 | A3 |
| | R-601a | Isopentane | 187.8 | 33.8 | 0 | 4 | A3 |
| | R-600 | n-Butane | 152.0 | 38.0 | 0 | 4 | A3 |
| | R-600a | Isobutane | 134.7 | 36.3 | 0 | 3 | A3 |
| | R-290 | Propane | 96.7 | 42.5 | 0 | 3 | A3 |
| HFO | R-1336mzz(Z) | 1,1,1,4,4,4-Hexafluoro-2-butene | 171.3 | 29.0 | 0 | 2 | A1 |
| | R-1234ze(Z) | cis-1,3,3,3-Tetrafluoro-1-propene | 150.1 | 35.3 | 0 | <1 | A2L |
| | R-1336mzz(E) | trans-1,1,1,4,4,4,-Hexafluoro-2-butene | 130.4 | 27.8 | 0 | 18 | A1 |
| | R-1234ze(E) | trans-1,3,3,3-Tetrafluoro-1-propene | 109.4 | 36.4 | 0 | <1 | A2L |
| | R-1234yf | 2,3,3,3-Tetrafluoro-1-propene | 94.7 | 33.8 | 0 | <1 | A2L |
| HCFO | R-1233zd(E) | 1-chloro-3,3,3-Trifluoro-propene | 166.5 | 36.2 | 0.00034 | 1 | A1 |
| | R-1224yd(Z) | 1-chloro-2,3,3,3-Tetrafluoro-propene | 155.5 | 33.3 | 0.00012 | <1 | A1 |
| HFC | R-365mfc | 1,1,1,3,3-Pentafluorobutane | 186.9 | 32.7 | 0 | 804 | A2 |
| | R-245fa | 1,1,2,2,3-Pentafluoropropane | 154.0 | 36.5 | 0 | 858 | B1 |
| | R-134a | 1,1,1,2-Tetrafluoroethane | 101.1 | 40.6 | 0 | 1'300 | A1 |

*Table 1. Different kinds of refrigerators.*(Zühlsdorf, 2023)

The temperature levels of the heat pump determine the refrigerant selection mostly. Consequently, to attain high efficiency, the refrigerant characteristics should best match the process needs. The temperature ranges for the several refrigerants are displayed in the figure 8 below. With condensation, the critical temperature determines the upper application limit for subcritical cycles. Effective operation of the heat pump should be ensured by a condensation temperature of roughly 15 K below the critical temperature (Zühlsdorf, 2023).



Note: The lower limit is defined by the boiling temperature at 1 bar and the upper limit is 15 K below the critical temperature for subcritical condensation. Exceptions are R744 (transcritical up to 120 °C) and R718 (vapor recompression).

*Figure 16. Temperature range and refrigerators* (Zühlsdorf, 2023).

HFCs like R-245fa and R-365mfc are widely used as working fluids in HTHPs this day. Their GWP is rather high, though, and these working fluids will be limited for some time to come to prevent global warming (F-gas regulations). Therefore, only low GWP synthetic refrigerants and natural refrigerants will be used in future. (José Manuel, 2010)

### 5.2.1 Natural refrigerants

Natural refrigerants suitable for HTHP applications are water (R-718), $CO_2$ (R-744), ammonia (R-717), and hydrocarbons (e.g., R-600, R-601).

#### 5.2.1.1 Water

When using water (R-718) in a subcritical cycle, a major part of the heat pump cycle may be below atmospheric pressure because of the high normal boiling point of 100 °C. In addition, the latent heat of water is large, which makes water very attractive for temperatures above 150 °C. However, the required swept volume and pressure ratio are very high due to the low water vapour density. Therefore, several compression stages are required with intermediate cooling (e.g., water injection) to keep the discharge temperature to a tolerable level (Zühlsdorf, 2023).

#### 5.2.1.2 Carbon dioxide

Carbon dioxide (R-744) has a critical temperature of 31 °C and high critical pressure of 73.6 bar. $CO_2$ heat pumps achieve heat sink temperatures of about 90 to 120 °C in transcritical cycles. R-744 is feasible as an HTHP working fluid if the return temperature of the heat sink is low and not too far above the critical temperature. The high temperature difference in the gas cooler makes R-744 particularly suitable for hot water or air heating processes (Zühlsdorf, 2023)

#### 5.2.1.3 Ammonia

Ammonia (R-717) as refrigerant is widely used in refrigeration and industrial heat pumps up to about 90 °C heat sink temperature. Beneficial is its high volumetric heating capacity (VHC) compared to other working fluids due to its low molecular weight resulting in high vaporization latent heat. However, for higher temperatures, existing compressor technology is limited by the high discharge pressures. With special cast steel construction, ammonia compressors can withstand pressures of up to about 76 bar and 110 °C. However, certain safety precautions must be implemented due to the toxicity of ammonia (B2L). For a 1 MW 2-stage heat pump, the ammonia charge is approximately 350 kg.(José Ramón et al., 2020)

#### 5.2.1.4 Hydrocarbons (HC)

The hydrocarbons are refrigerants without ODP and very low GWP having high critical temperatures up to 196.6 °C at 38.0 bar. Butane R-600 and isobutane R-600a are considered a suitable medium in HTHPs with condensation temperatures up to about 120 °C. These temperatures can be achieved in standard compressors. On the other hand, special safety measures must be implemented due to the high flammability (A3).(José Ramón et al., 2020)

### 5.2.2 Alternative synthetic working fluids

#### 5.2.2.1 Chlorofluorocarbons CFCs

Chlorofluorocarbons (CFCs) high GDP, harmful for the environment. They are very stables on the atmosphere, for that reason they are been eliminating its use. Classification of A1, not explosives or toxics.(José Ramón et al., 2020)

#### 5.2.2.2 Hydrochlorofluorocarbons HCFCs

Hydrochlorofluorocarbons (HCFC) affects to the ozone layer, but less than the CFCs. They are also in an eliminating faze. Classification of A1, not explosives or toxics. (José Ramón et al., 2020)

#### 5.2.2.3 Hydrofluorocarbons HFCs

Hydrofluorocarbons (HFC) good substitute of CFCs or HCFCs, with an ODP of 0 but a hight GDP they are classified as A1, more probable of causing leaks because lower molecular size.

They require 5-30% less refrigerant than the CFC. (José Ramón et al., 2020)

#### 5.2.2.4 Hydrofluoroolefins HFOs

Hydrofluoroolefins (HFOs) are refrigerants of 4º generation, with a low GDP, are considered environmentally friendly but it is sometimes flammable.

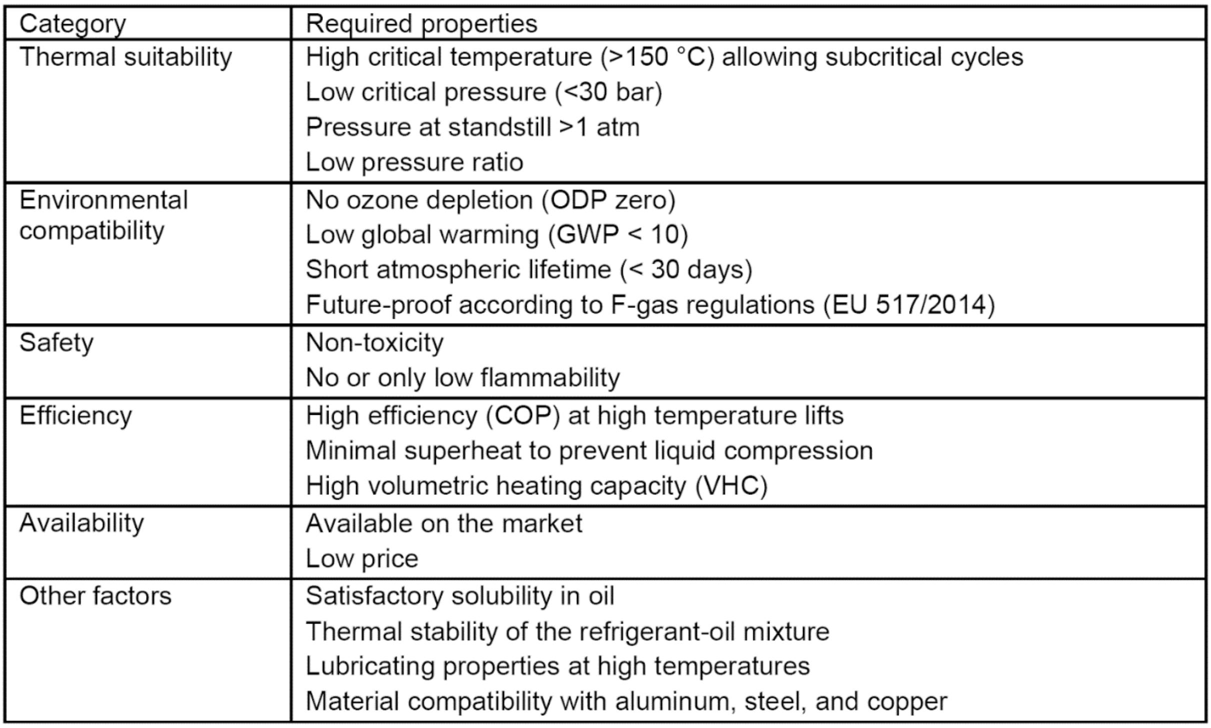
Hydrofluoroolefins (HFOs) have a major TFA issue mostly related to their possibility for contaminants, especially during manufacture. These contaminants, which can be byproducts or unreacted source materials, can compromise the HFO refrigerant's performance, safety, and environmental profile. (José Manuel, 2010)

### 5.2.2.5 Hydrochlorofluoroolefins HCFOs

Promising class of refrigerants with lower environmental impact than their predecessors include hydrochlorofluoroolefins (HCFOs). Even if HCFOs still have a fraction of ODP as compared to hydrochlorofluorocarbons (HCFCs), they are progressively being replaced with even more environmentally friendly substitutes. Classed as A1, HCFOs pose very low danger to human health and safety since they are non-toxic and non-flammable.(José Manuel, 2010)

### Working fluid aspects

One of the most important aspects of HTHP design is choosing the working fluid, or refrigerant. Thermal suitability, environment compatibility, safety, efficiency, availability, and other aspects can be grouped as the fundamental evaluation criteria for the application in HTHPs. Table 2 presents some required properties of the refrigerants use in heat pumps. (José Manuel, 2010)



| Category | Required properties |
|---|---|
| Thermal suitability | High critical temperature (>150 °C) allowing subcritical cycles<br>Low critical pressure (<30 bar)<br>Pressure at standstill >1 atm<br>Low pressure ratio |
| Environmental compatibility | No ozone depletion (ODP zero)<br>Low global warming (GWP < 10)<br>Short atmospheric lifetime (< 30 days)<br>Future-proof according to F-gas regulations (EU 517/2014) |
| Safety | Non-toxicity<br>No or only low flammability |
| Efficiency | High efficiency (COP) at high temperature lifts<br>Minimal superheat to prevent liquid compression<br>High volumetric heating capacity (VHC) |
| Availability | Available on the market<br>Low price |
| Other factors | Satisfactory solubility in oil<br>Thermal stability of the refrigerant-oil mixture<br>Lubricating properties at high temperatures<br>Material compatibility with aluminum, steel, and copper |

*Table 2. Category and Required properties of Refrigerants,* (Zühlsdorf, 2023)

Since trained staff can guarantee maintenance, in industry environmental analysis is given greater weight than hazard potential. The risks categorization is based on the current standard and ranked according to flammable (A3) to non-flammable (A1) and toxic (B) to non-toxic (A). Important for environmental analysis are the ODP and GWP. The permissions are listed in the EU 517/2014 F-Gas Regulation. The ODP for industrial heat pumps has to be 0, but GWP values over 1 are also accepted.

## 5.3 Compressors

A compression heat pump is mostly made up of the compressor. From a lower to a higher pressure, it compresses the gaseous refrigerant. The efficiency of the HP system is therefore greatly impacted by the compressor. There exist several compressor types.

The efficiency of these systems has been much increased by developments in compressor technology. The higher pressures and temperatures at which modern compressors can now function are necessary to produce the thermal outputs needed in industrial environments.

Piston, scroll, screw, and turbo compressors (including centrifugal compressors) are the principal compressor types now used in HTHPs. Electric motors power these compressor types most of the time.(Zühlsdorf, 2024c)

### 5.3.1 Piston compressor

It draws in gaseous refrigerant at lower pressure through a valve as the piston descends. Higher pressure compression of the gas results from the piston moving upward. The pulsating volume flows and potential liquid hammer are the drawbacks of this kind of compressor. .(Zühlsdorf, 2024c)

### 5.3.2 Screw compressor

Two rotors shaped like screws rotating counter to one another do the compression in this kind of compressor. For instance, the small size and achievable high speeds are benefits of screw compressors. An issue is the oil injection required for sealing. Furthermore, it calls for oil management systems, and high-temperature oil degradation could be a problem restricting its use. .(Zühlsdorf, 2024c)

### 5.3.3 Scroll compressor

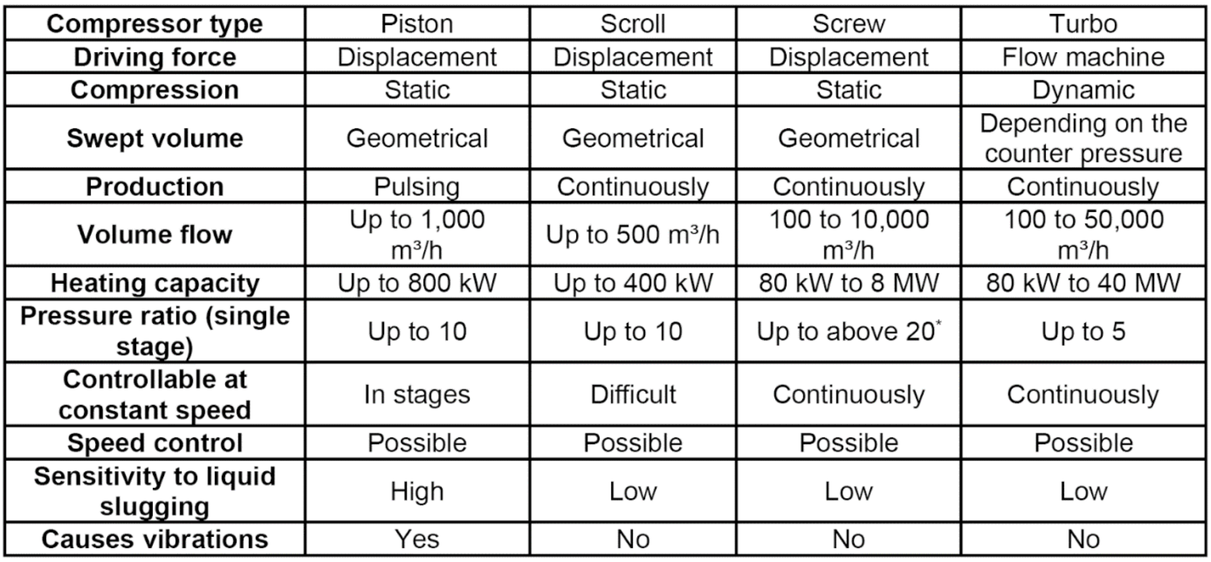
It compresses gaseous refrigerant by means of two spirals that slide into one another. This kind has low vibration, low noise, and is not sensitive to liquid hammer. Still, the compressor type's capacity range is rather small. .(Zühlsdorf, 2024c)

### 5.3.4 Turbo compressor

The turbo compressor is not a displacement principal compressor; rather, it is a fluid-flow machine. Rotating impellers in this kind of compressor transfer the energy to the medium. Diffuser is used to increase the pressure. The low abrasion, excellent speed control, big flow rates, and little space need are the advantages of this kind. Still, the practical pressure ratios are modest for each stage.

The low density of the water vapour is usually compensated for by large compressors or high-speed oil-free turbo compressors with high flow rate and low-pressure ratio. .(Zühlsdorf, 2024c)

Table 3 summarizes the main characteristics of the above-described compressor types.



| **Compressor type** | Piston | Scroll | Screw | Turbo |
|---|---|---|---|---|
| **Driving force** | Displacement | Displacement | Displacement | Flow machine |
| **Compression** | Static | Static | Static | Dynamic |
| **Swept volume** | Geometrical | Geometrical | Geometrical | Depending on the counter pressure |
| **Production** | Pulsing | Continuously | Continuously | Continuously |
| **Volume flow** | Up to 1,000 m³/h | Up to 500 m³/h | 100 to 10,000 m³/h | 100 to 50,000 m³/h |
| **Heating capacity** | Up to 800 kW | Up to 400 kW | 80 kW to 8 MW | 80 kW to 40 MW |
| **Pressure ratio (single stage)** | Up to 10 | Up to 10 | Up to above 20* | Up to 5 |
| **Controllable at constant speed** | In stages | Difficult | Continuously | Continuously |
| **Speed control** | Possible | Possible | Possible | Possible |
| **Sensitivity to liquid slugging** | High | Low | Low | Low |
| **Causes vibrations** | Yes | No | No | No |

*Table 3. Characteristics of compressors,* (Zühlsdorf, 2023)

Moreover, compressors vary not only in their working principles but also in their designs, particularly in the case design. Fully hermetic, semi-hermetic, and open compressors are distinguished generally. Within a hermetically welded housing are the compressor and motor in fully hermetic compressors. These compressors have the high tightness as one benefit. An drawback is that this kind of compressor cannot be serviced. The open compressor has a separated motor and compressor, unlike the totally hermetic compressor. This kind has a drawback of possible leaks, albeit repairable. A housing encircling the compressor and motor in a semi-hermetic compressor is not welded. Tighter than an open compressor, this kind also allows for maintenance. (Serrano Cruz)

### 5.3.5 Rotational compression

Instead of the compressors indicated above, the rotation heat pump, which is based on the Joule process, increases pressure by use of the centrifugal potential. A rotation heat pump is made up of two heat exchangers mounted on a rotor together with their piping. Gaseous heat transfer medium is circulated by use of a fan. (Serrano Cruz)

# 6 Drying Processes in industry

Commercial laundries as well as the food, paper, chemical, and ceramics industries all extensively use drying techniques. The Handbook of Industrial Drying lists over 20 industrial drying sectors and describes at least 15 different dryer types.

At 10 to 25% of industrial energy use, drying processes are major contributors. Drying is one of the primary methods used in industrial preservation for many products even now. The fundamental idea of drying has not changed thousands of years, and convective dryers are still the most popular kind of dryer.(Zühlsdorf, 2024b)

A product in a convective dryer loses moisture by evaporation. The modifications in the air state are depicted in Figure 9 (a). To this end, the product is heated to evaporation temperature and the required enthalpy of evaporation is transferred by a hot and comparatively dry air flow (state 2).

Mainly, product waste and fossil fuels are burned in industrial convective drying plants. Most of the time, the moisture taken out of the material to be dried is discharged into the surroundings. High energy content in this exhaust air is frequently only partly used by heat recovery. (GEA, 2023)

The possibility to use a heat source at low temperatures (at the evaporator) and supply a heat sink at higher temperatures (condenser) is presented by heat pumps. With a closed loop drying system, drying energy basically, the latent heat from water evaporation is recovered by using the combined heating and cooling load and returned to the drying process as dehumidified and re-heated drying air. (DEDERT, 2023)

One way to include a heat pump into the convective drying process is shown in Figure 17 (b). The evaporator is supplied with heat by the humid exhaust air that leaves the dryer (3). To this end, portions of the sensible heat and evaporation enthalpy are recovered by cooling (3→4) and dehumidifying (4→5) the humid exhaust air. Before the dryer starts drying, the incoming supply air can be (1–2) pre-heated after compression to the drying temperature level.

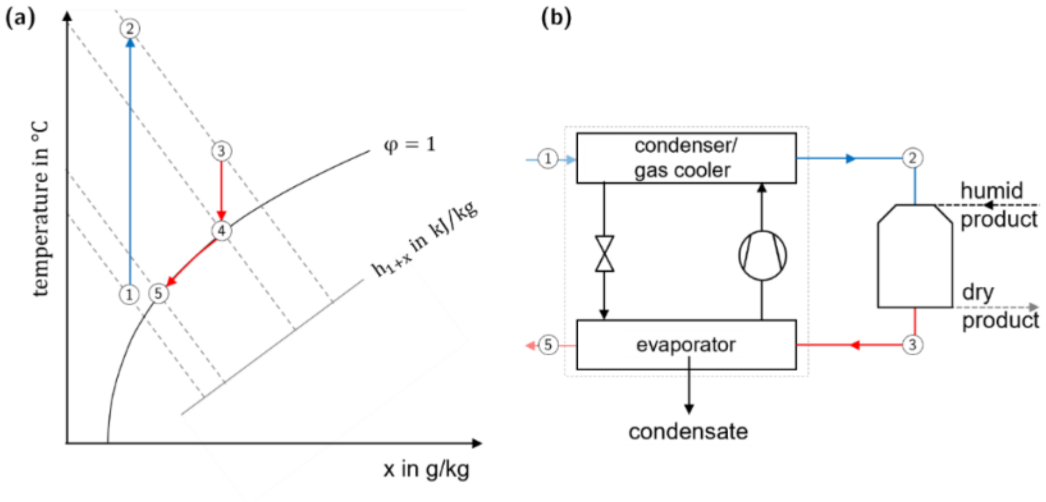


*Figure 17 (a) Changes of state of convective drying process in the Mollier-h-x diagramand (b)in the schematic of an integrated heat pump.* (Sun et al., 2023)

One of the key success elements of the drying application is the requirement of heat sources and heat sinks, which allows effective process integration without storages. Because the exhaust air is so moist, a significant waste heat source exists at the dew point temperature. Heat pumps are the better choice on the sink side because of their higher efficiency at high temperature changes. The integration of HTHPs is favoured by low supply air temperatures, high extract air humidities and air mass flows. Conversely, air has a lower density and heat capacity when used as a heat transfer media. High temperature lifts are possible when these characteristics cause big temperature changes with little enthalpy flow changes during drying.

## 6.1 Brick drying

As Figure 18 illustrates, brick manufacture is broken down into six stages from raw material to finished good. Process of the raw materials and creation of the so-called "green bricks" make up the first three stages. Drying comes in at step four. Bricks are fired in step five, then allowed to cool before being packed in the final stage.

Drying is the energy-intensive process, but both drying and firing need thermal energy.

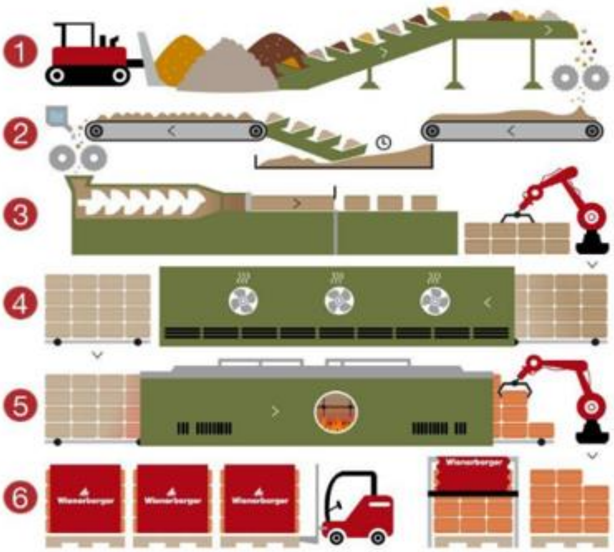


*Figure 18 Brick Drying* (Zühlsdorf, 2024a)

Brick drying has historically been done mostly with fossil-fired convective air dryers, where the evaporated water from the product is released into the exhaust air and frequently not used for additional energy recovery. Dew points of the moist exhaust air from convective drying range from 30 to 65 °C. Figure 18 combines tunnel dryer and tunnel kiln. The drying agent, air, moves counter-currently to the bricks. The tunnel dryer is run on hot air from the kiln and, if needed, hot air from burning natural gas. Over the length of the tunnel dryer, the temperature drops. Note that the tunnel dryer runs nonstop. Bricks dry down to 2% moisture content after entering the dryer at 28%.

Thus, the moist exhaust air can be used as a heat source and the energy for drying recovered by integrating a heat pump. (Zühlsdorf, 2024a).

## 6.2 Molded fiber dryers

Particularly (latent) waste heat, which stays at too low a temperature for reuse in the drying process, has a significant unrealized potential.Combining this potential with energy conservation could greatly lower $CO_2$ emissions.

In many sectors of the economy, drying is an essential procedure to meet particular quality requirements. Convective and contact drying are the two categories into which drying processes fall according to their heat transfer mechanism. By convective drying, moisture is removed from a product by use of a hot gas, typically air. The idea behind this technique is heat transfer, in which moisture evaporates and is carried away by the gas flow when heated gas contacts wet material. A convective drying process is best illustrated by the manufacture of molded fiber.

Molded fiber, produced by using a pulp molding machine to shape pulp fibers into various forms for packaging materials. The product's starting moisture content when it enters the dryer after molding usually falls between 35 and 40 wt %. Egg trays, for example, are dried to a final moisture content of about 6% and egg cartons to about 4%. The product comes into direct contact with a moving hot air stream while it is drying. This air and natural gas burn together in a chamber, and the heated combustion products that are produced combine with cooled, recirculated air. Hot drying air is blasted from the top of convective dryers through the first layer of perforated plates. A portion of the air typically 10–20% is released into the atmosphere to keep moisture levels constant, and some heat is taken out of this stream to heat process water.

Extra air drawn into the combustion chamber makes up for other losses or the volume lost to the atmosphere or for heating other operations. (Zühlsdorf, 2024a)

## 6.3 Steam generation in Industry

Often produced with steam boilers by burning natural gas, steam is one of the most crucial heat transfer and process media used in industrial processes.

Smaller sized heat exchangers allow the advantageous heat transfer characteristics of steam during condensation. When steam is injected into a product directly, it is also used as a reactant. Steam drying might be found, for instance, in the paper, food, or textile industries.

Either the production process condensate is evaporated again in the boiler or fresh water of the required purity is evaporated in the boiler, depending on the steam quality requirements and the plant arrangement. Usually, in closed loop systems, the condensate enters the boiler subcooled and evaporates once more. One can accomplish the subcooling by targeted cooling, as in the case of heat recovery, or by using the steam and condensation, respectively. Though vacuum designs are also present, as in distillation columns and paper machines, most steam applications are run above atmospheric pressures.

Unlike steam generation based on fossil fuels, heat pumps require a heat source. This can be ambient heat (fresh air, groundwater, geothermal energy) or waste heat from a process that may also need cooling. Should the waste heat flow require cooling, the heat pump can perform both cooling and steam production duties. Steam generation requires heat pumps in a broad power range of about 300 kW to more than 10 MW.

Steam is usually supplied at the highest necessary pressure level and then expanded to the other necessary pressure levels in steam generators based on fossil fuels. Heat pump COP is highly influenced by temperature lift, thus the heat pump has a higher COP for lower the temperature lift. Thus, it is crucial to supply the steam at the necessary pressure level when using a heat pump system. Steam compression is a remedy to be considered if steam at higher pressure is required.

Furthermore, for heat pump integration, a storage device can be installed on the source side as well as the steam side. When the waste heat source is not available and the steam demand is not matching, this becomes very crucial. Use of so-called steam accumulators is appropriate on the steam side. But these need either extremely big volumes or show a sharp drop in pressure when steam is released. All the same, adding a storage device to the heat pump system can make the steam production process more flexible and enable the heat pump to run more continuously.(Zühlsdorf, 2024a)

# 7 Case Study

Sundolitt Sweden is a subsidiary of Sunde Group, European leader in the manufacture of expanded polystyrene (EPS) and extruded polystyrene (XPS). Sundolit Sweden manufactures and supplies expanded polystyrene insulation, packaging and civil engineering products and insulation boards.

Sundolit Sweden products play a crucial role in many industries from insulation boards for construction, lightweight void formers in civil engineering, fish boxes and protective package for food, pharmaceuticals and electronics. (Sundolitt, 2024)

## 7.1 Manufacturing process

EPS (Expanded Polystyrene) is obtained from the transformation of expandable polystyrene. This raw material is a styrene polymer containing a blowing agent, pentane. Like all plastic materials, polystyrene foam is ultimately derived from petroleum, although it should be noted that only 6% of petroleum is used for the manufacture of chemicals and plastics, compared to 94% for transport and heating fuels.(MAN Energy Solutions, 2023a), (MAN Energy Solutions, 2023b).

The process of transforming the raw material (expandable polystyrene) into finished articles made of expanded polystyrene basically consists of three stages

**First stage: pre-expansion**

Devices known as pre-expanders, the raw material is heated by steam to a temperature of between 80 and 110°C. The bulk density of the material falls from about 630 kg/m$^3$ to densities in the range of 10 - 30 kg/m$^3$ depending on the temperature and exposure time. The light cellular plastic beads with tiny, closed cells containing air inside are created during the pre-expansion process from the compact beads of the raw material.(Anape eps, 2023)

**Second stage: stabilisation and intermediate storage**

In the second stage an internal vacuum is produced when the recently expanded particles cool down; this vacuum must be filled by diffusion of air. For the following processing stage, this increases the beads' expandability and mechanical stability. This procedure occurs while the pre-expanded material is being intermediately stored in ventilated silos. The beads are drying at the same moment.

### Third stage: expansion and final moulding

At this point, the stabilized and pre-expanded beads are moved to moulds, where they are welded together after being filled with steam again.This method allows one to obtain big blocks (which are then machined into the desired shapes, such slabs, vaults, cylinders, etc.) or shaped products with their final finish.

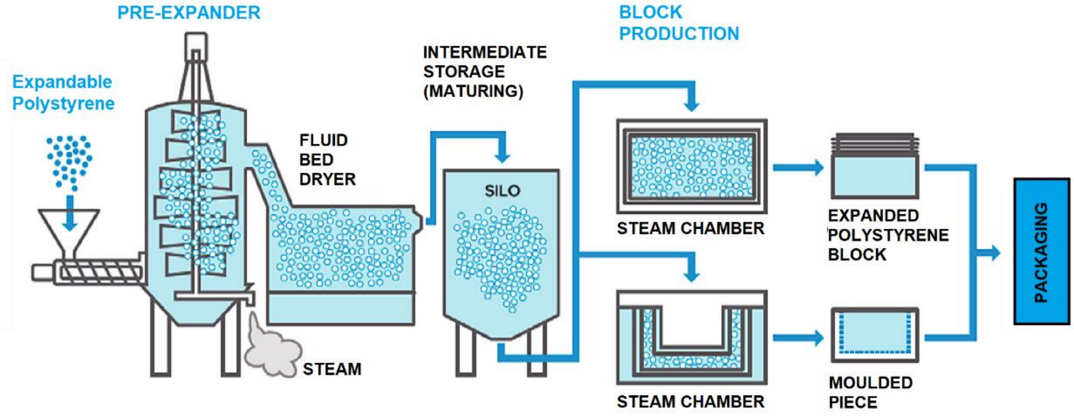


*Figure 19. EPS manufacturing process* (AGICO CEMENT, 2023)

Figure 19 presents a typical EPS manufacturing process.As mentioned before only the operational energy costs have been shared. The main energy demands in the manufacturing process are electricity and steam, that accounts for approximately 4 million sek per year, 25% of total energy cost is due to electricity expenses and 75% is due to steam generation. Note that the current and 2023 prices for both diesel and electricity have been compared and given assumptions in this calculation study have been done ().

Although the company has not shared the annual energy consumption, following assumptions allow estimating it:

- Cost of diesel: 3 000 000 sek/year
- Cost of industrial diesel without VAT: 9,5 sek/l
- Specific heat for diesel: 10 kWh/l (energyfaculty, 2024)
- Boiler efficiency: 0,9 (greenmatch, 2024)

Estimated steam energy consumption 2 700 000 kWh/year

- Cost of electricity: 1 000 000 sek/year
- Unit cost of electricity without VAT: 0,3 sek/kWh

Estimated electricity consumption 3 000 000 kWh/year

Steam is generated in a diesel boiler, at a pressure of 1.8 bar (130ºC). Steam consumption is around 2500 kg/h with peaks of 5 kg/s.

Assuming a specific enthalpy of 2700 kJ/kg (energyfaculty, 2024) for steam at 130ºC, a mass flow of 2500 kg/h corresponds to a power of 1875 kW.

## 7.2 Viability study: Diesel vs HTTP

As far as steam is generated at 130ºC, it is reasonable to consider a high temperature heat pump as a steam generator instead of a diesel boiler.

No cooling process has been identified where energy can be harnessed in a cost-effective way, thus, a HTHP will have as cold source ambient air.

Assuming that the part of the heat wasted by the machinery and steam released when opening the moulds, now contained in the manufacturing building is used in part as a cold source.

In this scenario a cold source temperature of approximately 15ºC and a hot sink temperature about 130ºC is considered.

As seen in on figure 20 with a Tlift (GTL) of 130 K, we have a COP of 2.3.

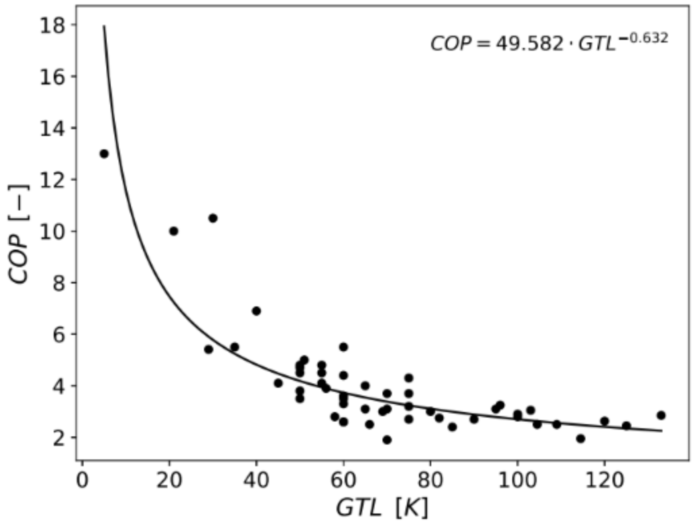
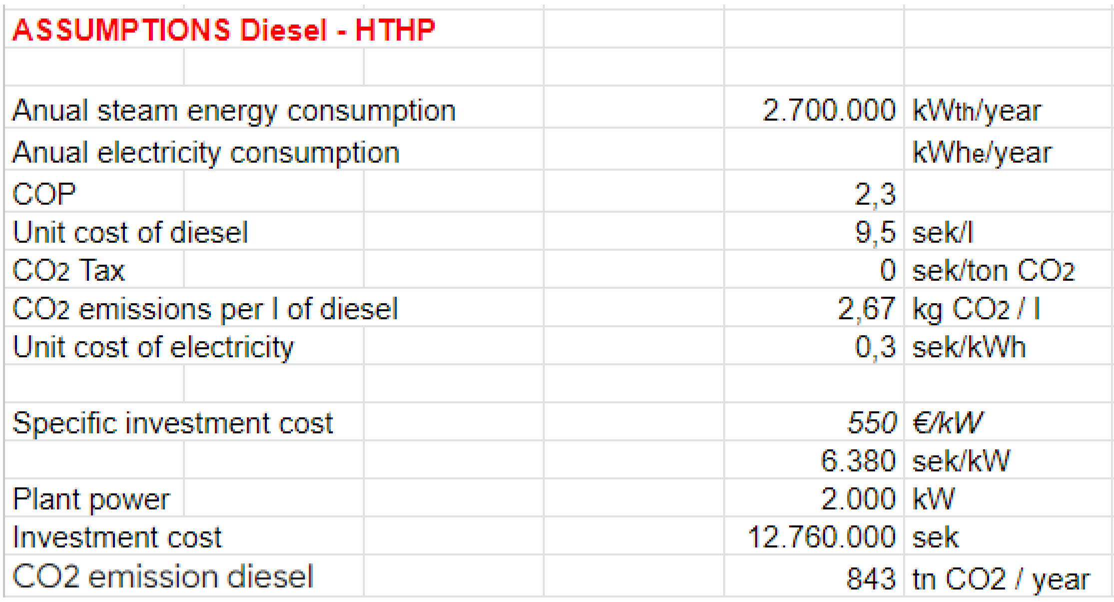


*Figure 20 COP of HTHP as function of Temperature lift* (Vieren et al., 2023)

Therefore, taking into account the estimated steam and electricity consumption, and with the assumptions stated below, the cost of producing steam with HTHP and diesel boiler can be compared. Note that the specific investment costs and maintanace costs are taken from (Vieren et al., 2023)

- Annual steam energy consumption: 2 700 000 kWh
- COP: 2,3
- Cost of electricity without VAT: 0,3 sek/kWh
- Cost of diesel without VAT: 9,5 sek/l (Elbruk, 2024)
- HTHP Plant power: 2 000 kW
- Specific investment cost: 550 €/kWh (Vieren et al., 2023)
  6 380 sek/kWh
- Maintenance cost: 4% of investment (Vieren et al., 2023)



| ASSUMPTIONS Diesel - HTHP | | |
|---|---|---|
| | | |
| Anual steam energy consumption | 2.700.000 | $\text{kW}_{\text{th}}$/year |
| Anual electricity consumption | | $\text{kW}_{\text{he}}$/year |
| COP | 2,3 | |
| Unit cost of diesel | 9,5 | sek/l |
| $CO_2$ Tax | 0 | sek/ton $CO_2$ |
| $CO_2$ emissions per l of diesel | 2,67 | kg $CO_2$ / l |
| Unit cost of electricity | 0,3 | sek/kWh |
| | | |
| Specific investment cost | *550* | *€/kW* |
| | 6.380 | sek/kW |
| Plant power | 2.000 | kW |
| Investment cost | 12.760.000 | sek |
| CO2 emission diesel | 843 | tn CO2 / year |

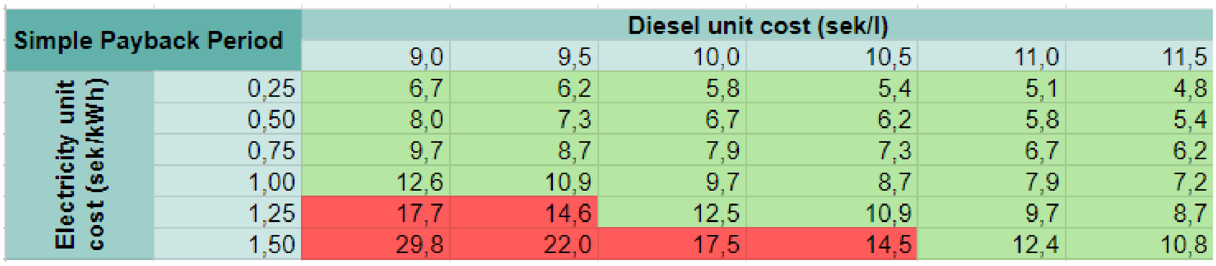
*Table 4, Assumptions forcalculations.*

Sensitivity analysis of payback period is presented un tables 5 and 6 below:

| **Annual savings** | | **Diesel unit cost (sek/l)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **9** | **9.5** | **10** | **10.5** | **11** | **11.5** |
| Electricity unit cost (sek/kWh) | **0,25** | 1.896.122 | 2.046.122 | 2.196.122 | 2.346.122 | 2.496.122 | 2.646.122 |
| | **0,50** | 1.602.643 | 1.752.643 | 1.902.643 | 2.052.643 | 2.202.643 | 2.352.643 |
| | **0,75** | 1.309.165 | 1.459.165 | 1.609.165 | 1.759.165 | 1.909.165 | 2.059.165 |
| | **1,00** | 1.015.687 | 1.165.687 | 1.315.687 | 1.465.687 | 1.615.687 | 1.765.687 |
| | **1,25** | 722.209 | 872.209 | 1.022.209 | 1.172.209 | 1.322.209 | 1.472.209 |
| | **1,50** | 428.730 | 578.730 | 728.730 | 878.730 | 1.028.730 | 1.178.730 |

*Table 5, Annual savings.*

As seen in table 6, an implementation of a HTHP in this case would have a payback period of around 10 years with current energy prices.



| **Simple Payback Period** | | **Diesel unit cost (sek/l)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | 9,0 | 9,5 | 10,0 | 10,5 | 11,0 | 11,5 |
| **Electricity unit cost (sek/kWh)** | 0,25 | 6,7 | 6,2 | 5,8 | 5,4 | 5,1 | 4,8 |
| | 0,50 | 8,0 | 7,3 | 6,7 | 6,2 | 5,8 | 5,4 |
| | 0,75 | 9,7 | 8,7 | 7,9 | 7,3 | 6,7 | 6,2 |
| | 1,00 | 12,6 | 10,9 | 9,7 | 8,7 | 7,9 | 7,2 |
| | 1,25 | 17,7 | 14,6 | 12,5 | 10,9 | 9,7 | 8,7 |
| | 1,50 | 29,8 | 22,0 | 17,5 | 14,5 | 12,4 | 10,8 |

*Table 6, Simple payback period.*

Although the project's profitability is not good, perhaps with the help of grants, the project could be considered.In addition to having the problem of implementation itself, the space to put an HTHP in that company is limited and a more exhaustive study would be needed.

This case is quite interesting since a relatively long return on investment assuming constant prices is expected. However, considering environmental concerns and the increasing significance of $CO_2$ taxes, gradually phasing out the use of diesel burners could be beneficial. While it may initially involve a significant investment, it might be prudent to wait and see if this technology becomes more affordable over time.

## 7.3 Viability study: Diesel vs Natural Gas Boiler

Another potential solution worth considering is switching fuel from diesel to natural gas. Initially, we can consider that the current boiler would be suitable, and the only change required would be replacing the diesel burner with a natural gas one. Additionally, it would be necessary to dismantle the existing diesel fuel supply system and install a Natural Gas Regulation and Measurement Station in its place.

Considering the following hypotheses:

- Annual steam energy consumption: 2 700 000 kWh
- Cost of diesel: 9,5 sek/l (Elbruk, 2024)
- Specific heat for diesel without VAT: 10 kWh/l (energyfaculty, 2024)
- Cost of natural gas without VAT: 0,6 sek/kWh (energyfaculty, 2024)
- Boiler efficiency 0,9 for diesel and natural gas

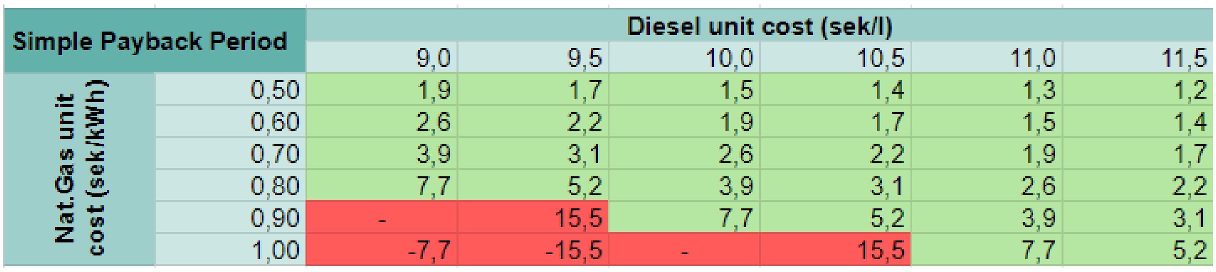
  (greenmatch, 2024)
- Specific investment cost: 100 €/kWh

  1 160 sek/kWh
- Maintenance cost: The same as with diesel burner

Tables 7 and 8 presents the sensitivity analysis of payback period:

| **Annual savings** | | **Diesel unit cost (sek/l)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **9** | **9.5** | **10** | **10.5** | **11** | **11.5** |
| Nat.Gas unit cost (sek/kWh) | **0.5** | 1 200 000 | 1 350 000 | 1 500 000 | 1 650 000 | 1 800 000 | 1 950 000 |
| | **0.6** | 900 000 | 1 050 000 | 1 200 000 | 1 350 000 | 1 500 000 | 1 650 000 |
| | **0.7** | 600 000 | 750 000 | 900 000 | 1 050 000 | 1 200 000 | 1 350 000 |
| | **0.8** | 300 000 | 450 000 | 600 000 | 750 000 | 900 000 | 1 050 000 |
| | **0.9** | 0 | 150 000 | 300 000 | 450 000 | 600 000 | 750 000 |
| | **1.0** | -300 000 | -150 000 | 0 | 150 000 | 300 000 | 450 000 |

*Table 7, Annual savings.*



| Simple Payback Period | | Diesel unit cost (sek/l) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 9,0 | 9,5 | 10,0 | 10,5 | 11,0 | 11,5 |
| Nat.Gas unit cost (sek/kWh) | 0,50 | 1,9 | 1,7 | 1,5 | 1,4 | 1,3 | 1,2 |
| | 0,60 | 2,6 | 2,2 | 1,9 | 1,7 | 1,5 | 1,4 |
| | 0,70 | 3,9 | 3,1 | 2,6 | 2,2 | 1,9 | 1,7 |
| | 0,80 | 7,7 | 5,2 | 3,9 | 3,1 | 2,6 | 2,2 |
| | 0,90 | - | 15,5 | 7,7 | 5,2 | 3,9 | 3,1 |
| | 1,00 | -7,7 | -15,5 | - | 15,5 | 7,7 | 5,2 |

*Table 8, Simple payback period.*

In this case, we can observe that the investment payback periods are much shorter than in the case of the heat pump. Therefore, the company would start saving money within a few years. It's also worth noting that the prices of diesel and natural gas are often closely related, so we couldn't expect one to decrease while the other increases. Additionally, using natural gas instead of diesel would be more beneficial for the environment, as each kW generated from gas releases much less $CO_2$ than diesel.

## 7.4 Viability study: Diesel vs Electric Boiler

Finally, a third possibility would be to replace the current steam boiler with a diesel burner with a new electric boiler for steam production. Although the efficiency of an electric boiler is much lower than that of a HTHP (a COP of around 0,9 is considered), the investment is much lower than in the case of the heat pump. If the electricity consumed in the industrial plant were 100% from renewable sources, the same objectives as those of the HTHP would be achieved, although with higher electricity consumption.

Moreover, the company will be less exposed to price volatility in recovering the investment.

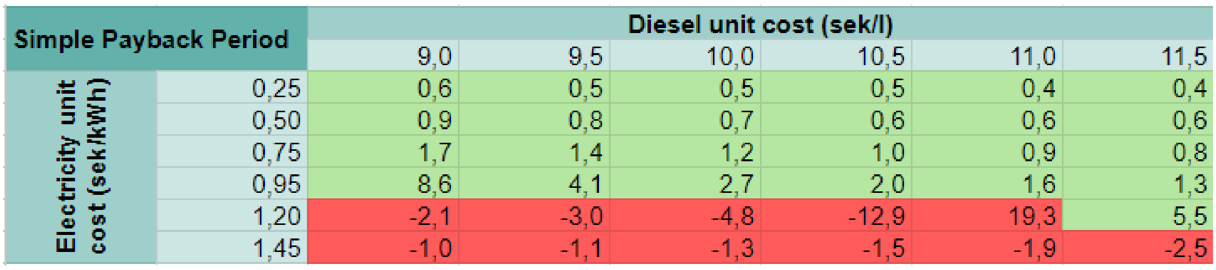
Considering

- Annual steam energy consumption: 2 700 000 kWh
- Cost of electricity: 0,3 sek/kWh
- Electric boiler efficiency without VAT; 1
- Cost of diesel: 9,5 sek/l
- Specific heat for diesel without VAT: 10 kWh/l
- Diesel boiler efficiency: 0,9
- Specific investment cost: 50 €/kWh (Vieren et al., 2023)
  580 sek/kWh
- Maintenance cost: The same as for diesel boiler

Tables 9 and 10 show the sensitivity analysis of payback period:

| **Annual savings** | | **Diesel unit cost (sek/l)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **9** | **9.5** | **10** | **10.5** | **11** | **11.5** |
| Electricity unit cost (sek/kWh) | **0,25** | 2.025.000 | 2.175.000 | 2.325.000 | 2.475.000 | 2.625.000 | 2.775.000 |
| | **0,50** | 1.350.000 | 1.500.000 | 1.650.000 | 1.800.000 | 1.950.000 | 2.100.000 |
| | **0,75** | 675.000 | 825.000 | 975.000 | 1.125.000 | 1.275.000 | 1.425.000 |
| | **0,95** | 135.000 | 285.000 | 435.000 | 585.000 | 735.000 | 885.000 |
| | **1,20** | -540.000 | -390.000 | -240.000 | -90.000 | 60.000 | 210.000 |
| | **1,45** | -1.215.000 | -1.065.000 | -915.000 | -765.000 | -615.000 | -465.000 |

*Table 9, Annual savnings.*



| **Simple Payback Period** | | **Diesel unit cost (sek/l)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | 9,0 | 9,5 | 10,0 | 10,5 | 11,0 | 11,5 |
| **Electricity unit cost (sek/kWh)** | 0,25 | 0,6 | 0,5 | 0,5 | 0,5 | 0,4 | 0,4 |
| | 0,50 | 0,9 | 0,8 | 0,7 | 0,6 | 0,6 | 0,6 |
| | 0,75 | 1,7 | 1,4 | 1,2 | 1,0 | 0,9 | 0,8 |
| | 0,95 | 8,6 | 4,1 | 2,7 | 2,0 | 1,6 | 1,3 |
| | 1,20 | -2,1 | -3,0 | -4,8 | -12,9 | 19,3 | 5,5 |
| | 1,45 | -1,0 | -1,1 | -1,3 | -1,5 | -1,9 | -2,5 |

*Table 10, Simple payback period.*

As seen, in this case the company will be more exposed to electricity price volatility in recovering the investment, although it remains much lower than that of the heat pump. However, if electricity prices were to rise, it would cost more money. Moreover, it is also important to underline that this scenario is neutral $CO_2$ emission scenario since electricity is used. Although Sweden's present electricity generation is not entirely renewable, but still the majority comes from renewables and can be considered green electricity.

Therefore, replacing the diesel boilers could be considered as an easy way to move forward $CO_2$ neutrality with a low investment.

The several difficulties in implementing biomass have ruled out the possibility of producing heat from it, including the major space it consumes, the large installation cost needed, and the processing of combustion emissions.

# 8 Conclusion

Comparing HTHPs to conventional heating systems, one of their main advantages is their remarkable energy efficiency. When an HTHP is included into a cogeneration system, for example, where a 100 kW gas burner would normally generate 85 kW of heat that can be used, an HTHP with a Coefficient of Performance (COP) of 2,3 can produce up to 200 kW of heat. With less dependence on volatile fossil fuel prices, this efficiency not only lowers energy consumption but also offers industrial operations a more steady and predictable energy cost scenario. Nevertheless, HTHP technology is not without difficulties, though. The first installation costs can be high, and different industries have quite different levels of difficulty when integrating these systems into their current industrial infrastructures. Improved compressor efficiency and the development of better refrigerants with higher temperature outputs are the main goals of current research and development to address these issues.

The acceptance of HTHPs also depends critically on market trends and public opinion. Wider adoption of HTHPs depends on raising knowledge and comprehension of their operational and environmental advantages. Furthermore, regulatory systems that encourage the use of sustainable technologies by means of strict energy efficiency and emissions reduction targets, such those set by the EU, have a significant impact on market dynamics. These rules promote technological innovation in addition to supporting environmental goals, so promoting the creation of more effective and efficient HTHP solutions for a range of industrial applications. HTHP installation needs meticulous preparation and modification. Many times, new systems created to handle the cutting-edge technology need to be installed or existing facilities must be retrofitted. Often, this procedure requires major modifications to the current electrical and mechanical systems to make them compatible with the high-power needs of HTHPs. In addition, the installation of sophisticated control systems that maximize their performance often determines how well these systems integrate. These systems are essential for dynamically modifying HTHP performance in reaction to changing environmental conditions and energy demands, so optimizing operational efficiency and reducing energy waste.

In conclusion, even if HTHPs have a lot to offer in terms of environmental impact and energy efficiency, their use is dependent on overcoming financial and technological obstacles. In this case study we can observe an average return of the investment for the Diesel vs. HTHP of 7 years being in some cases optimistic, we could try to implement the technology but with some risk. Furthermore, the investment payback periods are shorter in cases of electric and gas heaters. With electric heaters, the company is more exposed to price changes, while gas heaters offer a more balanced scenario. In the case of heat pumps, a $CO_2$ neutrality can be achieved and significantly lower net electricity consumption over the years, abeling with the challenge of a higher initial investment. The electric boiler would be a good option for changing diesel for electricity, in a short period of time, with not much risk. Due to the legislation about contamination, we need to act quickly, and this one is a good option before an HTHP technology implementation, that could be seeing on future days.

# 9 Sustainable Development Goals

**SDG 7: Affordable and Clean Energy** - The importance of ensuring access to modern, sustainable, and affordable energy for all. Through High Temperature Heat Pumps (HTHPs), the research helps the shift to greener energy sources and advances sustainability in industrial processes by raising energy efficiency and lowering running costs.

**SDG 8: Decent Work and Economic Growth** - By improving energy efficiency and reducing operating costs, the adoption of High Temperature Heat Pumps (HTHPs) contributes to sustainable economic growth and creates opportunities for decent work. By reducing energy costs, the application of new technology in industrial processes can result in job creation in the green energy industry and improve the competitiveness of sectors.

**SDG 9: Industry, Innovation, and Infrastructure** - The thesis discusses the implementation of High Temperature Heat Pumps (HTHP) in the industrial sector to enhance energy efficiency and innovation in manufacturing processes. Particularly in the manufacturing processes of gypsum and polystyrene, the thesis encourages the development of sustainable industrial infrastructure and stimulates invention in the building material sector by including HTHP technology.

**SDG 11: Sustainable Cities and Communities** - The emphasis on environmentally friendly industrial methods helps to indirectly assist the building of more sustainable towns and communities. The thesis helps to create better and healthier metropolitan surroundings by lowering greenhouse gas emissions and raising energy efficiency in industrial activities. (United Nations, 2023)

**SDG 12: Responsible Consumption and Production** - The focus on energy efficiency and reduction of greenhouse gas emissions aligns with the goal of ensuring sustainable consumption and production patterns. The thesis seeks to maximize industrial processes to reduce waste and enhance resource usage, therefore enabling more ethical manufacturing techniques.

**SDG 13: Climate Action** - The focus on reducing greenhouse gas emissions and mitigating climate change is central to the thesis. Based on international agreements, it addresses the need of reducing greenhouse gas emissions by 80% by 2025 and emphasizes how HTHPs can be very important in reaching this goal by enhancing energy recovery and maximizing industrial thermal processes.

# 10 Future work

Future work will be to investigate other possible implementations of HTHP technology in other processes. The fact that this implementation is not viable in a specific industry does not mean that the technology is not viable. It is important to continue studying these technologies to improve global energy consumption. Companies around the world should start considering investments that benefit climate mitigation and the world. As researchers, engineers and academic institutions, we have to promote the use of clean and sustainable technologies, without forgetting the economic aspects.

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# Appendix

## Questions for enterprise.

General Information on Manufacturing Process

1. Could you describe the overall manufacturing process for gypsum and PVC insulation at your facility?

2. What are the key temperature, humidity levels and power requirements for manufacturing these materials? (for the process and after the process) All the parameters for all the steps

Duration about all process for one piece.

3. What types of machinery and equipment are currently used in your drying processes?

4. Can you outline the current layout and space availability in your factory for new equipment

5. What is the initial temperature and water content? And the final temperature and water content?

Energy Use and Efficiency

6. What is the current primary energy source for your drying processes?

7. Could you provide a detailed energy balance of your current operations?

8. What are the typical energy losses observed during the gypsum and PVC drying processes, and how are they currently managed?

9. Are there any other processes within your facility that generate significant amounts of heat that could potentially be recovered?

10. Do you have any boilers?

11. How many hours the facility is on operation?

12. Any shutdowns? How longs they are?

14. Size of the system?

15. Differences between winter and summer?

16. Pinpoint spots for improve systems in energy efficiency.

17. Do you plan something on the next 5 years?

18. Could they provide the sketch or scheme of the dry process?

19. What type of dry process do you have?

20. Approximate energy values annually?

21. How the cost of gas is about of electricity?

22. And what plan do you have for that problem? (cost of gas)

23. What are the average monthly and annual costs associated with your current drying operations, specifically related to gas consumption?

24. How is the gas purchased (e.g., via long-term contracts, spot market purchases) and what are the typical pricing structures?

25. What does maintenance entail for your current drying systems and what are the typical costs associated?

26. How was in the energy crisis?

27. How you would do for not being so dependant to fluctuations

28. Gas or biomass?

29. What is the age of the installation?

30. Energy performance installation

### Environmental and Operational Parameters (With energy)

31. What humidity levels and drying times are required to achieve optimal quality in your products?

32. Are there any specific environmental regulations or compliance issues that impact your drying operations?

33. How do seasonal variations affect your production process, particularly in terms of temperature and humidity control?

34. What plan do you have for the future?

35. Political landscape

### Feasibility of Integrating HTHP

36. Have you considered using high-temperature heat pumps in your drying processes before?

37. What are your primary considerations or concerns about integrating an HTHP system?

38. Would there be potential logistical challenges in installing an HTHP system in your existing setup?

39. What are the potential benefits you see in integrating an HTHP system in terms of energy savings and operational efficiency?

## Decision-Making Factors

40. What criteria will determine whether you opt for a full replacement of gas burners with an HTHP system or a hybrid system that also uses some gas?

41. What financial or operational thresholds must be met for the integration of an HTHP system to be considered successful?

42. Who are the decision-makers in your company regarding these types of infrastructure investments, and what is typically their main concern?

## Additional Technical Considerations

43. What technical support and warranties are you looking for when considering new equipment like an HTHP?

44. How do you evaluate new technologies for compatibility with existing operations?

45. Is there a pilot phase typically involved when implementing new technology in your processes?

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