# Assessment of life cycle impacts of sustainable technologies in industrial environments

A Thesis Submitted for the Degree of Doctor of Philosophy

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# Abstract

This thesis focuses on the analysis and assessment of the life cycle impacts of heat pipe-based heat exchangers (HPHE) in energy-intensive industries (EIIs), namely the steel, aluminium, and ceramics industries. These industries, vital to the European economy, are responsible for substantial greenhouse gas emissions, which renders their decarbonisation a key priority. Waste heat recovery (WHR) innovations, such as the HPHE, offer an attractive solution by capturing and reusing waste heat to improve energy efficiency and reduce emissions. This is the premise of the ETEKINA project, that has served as the starting point for this study.

The research investigates the economic and environmental implications of HPHEs, through a life cycle assessment (LCA). The LCA involves the quantification of the environmental impacts through the calculation of indicators, such as global warming potential and human carcinogenic toxicity. To perform the calculations, the goal, scope, functional unit, boundary conditions and inventories of the LCA are created. The LCA is thus carried out for the three industrial demonstrations of the ETEKINA project, the ceramics, aluminium and steel industries.

Additionally, the thesis explores business modelling to assess the market viability of HPHE technologies, considering economic benefits such as reduced operational costs and enhanced competitiveness in global markets.

Key findings highlight the energy-saving potential of HPHEs, translating it to environmental indicators, identifying hotspots for further design and production improvement, and aligning the development work with the decarbonisation targets outlined in the European Green Deal and the Paris Agreement.

# Declaration

No part of this thesis has been submitted in support of an application for any degree or qualification of Brunel University London or any other University or Institute of learning.

# Acknowledgments

I would like to express my gratitude to my supervisor, Professor Hussam Jouhara, for his indispensable guidance and support throughout the duration of this research.

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I would also like to acknowledge my wife Vassiliki and my daughters Iliana and Dimitra for their patience and encouragement. Last but not least, my parents and wider family for their continued support and faith in me.

# Publications

1. **A. Vlasopoulos**, J. Malinauskaite, A. Żabnieńska-Góra, H. Jouhara, "Life cycle assessment of plastic waste and energy recovery",
   **Energy, vol. 277, 15 August 2023, 127576**,
   https://doi.org/10.1016/j.energy.2023.127576

2. H. Jouhara, N. Nieto, B. Egilegor, J. Zuazua, E. Gonz´alez, I. Yebra, A. Igesias, B. Delpech, S. Almahmoud, D. Brough, J. Malinauskaite, **A. Vlasopoulos**, M. Hill, B. Axcell, "Waste heat recovery solution based on a heat pipe heat exchanger for the aluminium die casting industry", **Energy, vol. 266, 1 March 2023, 126459**,
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3. **A. Vlasopoulos**, H. Jouhara "Life cycle analysis of a heat recovery system in the ceramics industry", presentation at 16th Sustainable Energy and Environmental Protection conference – SEEP 2024, 9-12 September 2024, Vienna, Austria

4. **A. Vlasopoulos**, H. Jouhara, "Assessment of heat pipe technology for challenging industrial scenarios", presentation at 10th Materials Science and Smart Materials conference, MSSM 2024, 15-17 May 2024, Athens, Greece

5. **A. Vlasopoulos**, A. Żabnieńska-Góra, H. Jouhara, „LCA practices in the end of life stage of waste plastics", presentation at 9th Materials Science and Smart Materials conference, MSSM 2023, Modena, Italy

# Glossary

HPHE – Heat Pipe Heat Exchanger

EII – Energy-Intensive Industries

GHG – Greenhouse Gas

LCA – Life Cycle Assessment

EU – European Union

UNFCCC – United Nations Framework Convention on Climate Change

FEC – Final Energy Consumption

IPCC – Intergovernmental Panel on Climate Change

SOx – Sulfur Oxides

NOx – Nitrogen Oxides

PM2.5 – Fine Particulate Matter (particles with diameters less than 2.5 micrometers)

CO2-eq – Carbon Dioxide Equivalent

DCB – Dichlorobenzene (used in toxicity assessments)

PDF – Potentially Disappeared Fraction (of species)

ROI – Return on Investment

AP – Acidification Potential

GWP – Global Warming Potential

BAHX – Brazed Aluminium Heat Exchanger

ACHE – Air-Cooled Heat Exchanger

MCHS – Microchannel Heat Sink

IP – Intellectual Property

EMS – Energy Management System

SCADA – Supervisory Control and Data Acquisition

BI – Business Intelligence

PEF – Product Environmental Footprint

OEF – Organisational Environmental Footprint

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# Introduction: Research Gap, Aims and Objectives

Energy Intensive Industries (EIIs) are industrial sectors that consume large amounts of energy by employing high-temperature processes for production. These industries include the processing stages located upstream in the value chain, such as refining raw ores and producing feedstock materials that are subsequently utilised by the manufacturing sector, but also the direct manufacturing of products through high temperature processes. Examples include the steel, aluminium, and ceramic sectors, as well as the mineral, chemicals and cement industries. The reliance of modern civilisation on EIIs is massive, and their importance in regional and national economies is equally crucial. With approximately 8.5 million direct and 20 million indirect jobs in Europe, and an annual turnover of €2 trillion, these industries are critical to the economy and prosperity of Europe. The same however applies to their role in the global decarbonisation endeavour, as EIIs are currently responsible for 20% of total greenhouse gas emissions in Europe and 25% of Final Energy Consumption (FEC). The largest share of industrial energy usage is for heating purposes, accounting for over 80% of the total energy demand, with over 50% of process heating applied to very high temperature processes (over 500ºC), and over 75% of process heating is generated by fossil fuels and natural gas. Considering that the largest share in operating expenditure is related to energy costs, it is evident that energy efficiency is a key consideration in industrial process engineering.

Energy efficiency has however increased sharply in priority since the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, subsequent Kyoto Protocol in 1997 and ultimately the Paris Agreement of 2016. The Intergovernmental Panel on Climate Change (IPCC), the scientific body tasked with supporting the implementation of the Paris Agreement in accordance with the UNFCCC, emphasizes the critical mission of improving energy efficiency across all sectors and economic activities, including, and highlighting industries, as a key component in the effort of reducing greenhouse gas emissions and mitigating climate change. In the European landscape, the European Green Deal reflects the global endeavour to mitigate climate change, through an ambitious strategy for climate neutrality by 2050. In this strategy, industrial decarbonisation is central and expressed in multiple policy packages and initiatives.

Finally, recent geopolitical developments, centred on the Russian invasion of Ukraine, have violently introduced, and underscored the importance of energy security and resilience. The concurrent shocks reverberating through the production value chains were triggered by the reduction of low-cost energy supply, further highlighting the role of energy efficiency.

Industrial waste heat recovery (WHR) and reutilisation is a key contributor to energy efficiency. WHR involves capturing excess heat that would otherwise be lost to the environment and reusing it for other processes within the plant. Waste heat is routinely used for industrial process heating (e.g., pre-heating or drying, often in the same process or sub-process), water or space heating, and can also provide sustainable energy to district heating networks or generate electricity. Recuperating lost energy also synergises naturally with renewable energy technologies, comprising integrated energy management techniques, that are highly coveted by EIIs. Among the technologies employed in WHR, heat exchangers are commonly used for the absorption and transfer of waste heat from gaseous exhausts. In industrial research, heat exchangers remain a topic of interest due to the inherent challenges in system design, material and working fluid development, the optimisation of operational and maintenance cycles, and other areas that directly impact the viability of the investment. Among other types of heat exchangers, heat pipe heat exchangers (HPHE) have received relatively limited attention. This is due to the challenges with the simulation and design of the system, and the intrinsic requirements of HPHEs for customisation, or tailoring to specific industrial processes.

This thesis focuses on the heat pipe heat exchanger (HPHE), aiming to provide a methodology for the streamlined quantification of the value proposition of the technology, considering both the economic, and environmental impacts, specified within the context of decarbonisation and related policy objectives.

The thesis is based on the work carried out in the ETEKINA project[1], funded by the EC as part of the EE-17-2016-2017 - Valorisation of waste heat in industrial systems call. The project concluded on 2022, was funded with €5,539,610 and comprised a partnership of 10 organisations. What sets apart ETEKINA from other projects, is the singular focus on the HPHE technology. Industrial energy efficiency is a key, strategic priority for Europe, and there are tens of projects funded each year on the topic. Nonetheless, only a few focus on WHR, and so far only ETEKINA focused on the HPHEs. Still, one of the gaps in the project was identified as the lack of an LCA study on the HPHEs themselves, a gap that this thesis was built to address.

# Organisation and Structure of the Thesis

In the first chapter, the thesis analyses the state of the art in the following domains: firstly, the energy consumption in energy intensive industries and how sustainable energy and energy efficiency affects climate policy objectives. Moreover, the challenge of industrial waste heat is analysed from an economic and technological perspective, and state of the art solutions are presented in the domain of heat exchangers, considering the aluminium, ceramic, steel and waste management industries. Secondly, existing policy and policy trends are analysed, centred on the heat exchanger perspective, considering both the EU and UK policy landscapes. The policy analysis will be used in the elaboration of the results in the final chapter. Next, an analysis of the heat-pipe-based heat exchanger (HPHE) technology is presented, focusing on the comparative advantages compared to conventional heat exchangers, as well as a review of the barriers and limitations of the technology. Finaly, the chapter concludes with a review of the LCA domain, focusing on the work carried out in the target industries, especially with regards to heat exchangers.

The second chapter comprises the methodology section of the thesis, describing the design of the research and the methods employed. The methodology is focused in two areas: the first is the LCA of the HPHE cycle, and the second is centred on the business modelling. Through this study, the advantages of recovering and reutilising thermal energy in this sector will be quantified, complemented by a brief analysis on the potential applications of the recovered heat.

The third chapter presents the results, elaborating through a comparative assessment with the applied HPHE in the ceramic, steel and aluminium industries, focusing primarily on the energy savings. The results will be positioned in the policy and market analysis, elaborated from the business perspective, addressing the viability of the market, the business model and the financial perspective.

The fourth chapter summarises the key findings and their implications on the EU industrial research ecosystem. Finally, research questions that arise from the work conducted are highlighted, providing a roadmap for future studies.

# Chapter 1: State of the art

## 1.1 Sustainable energy and energy efficiency importance in achieving climate policy objectives, the role of LCA

In 2023, global $CO_2$ emissions amounted to 37.4 billion tonnes (Gt), an increase of 1.1% (410 million tonnes (Mt)). This is slightly lower compared to an increase of 490 Mt in 2022 (1.3%). In 2023, 65% of this was coal emissions [2]. Following Net Zero Roadmap [3] by 2035, emissions must be reduced by 60% in emerging market and developing economies and 80% in advanced economies compared with 2022 levels. Figure 1 shows the variability of global energy-related $CO_2$ emissions between 1900 and 2023.

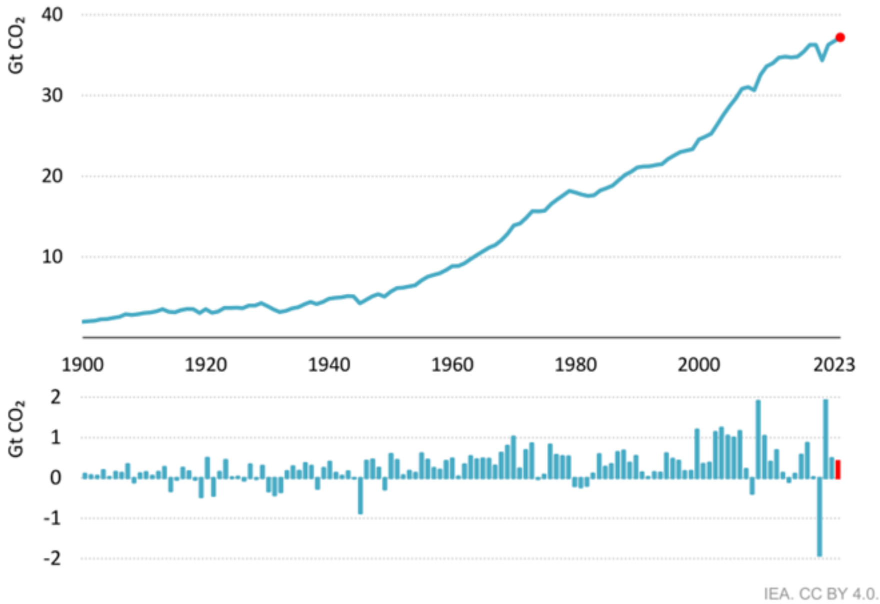



*Figure 1. Global energy-related CO2 emissions and their annual change, 1900-2023 [1]*

With this in mind, and in order to achieve climate neutrality by 2050, the EU must reduce its energy consumption and increase its energy efficiency [4]. The transition to clean energy with zero net emissions requires a radical change in both the direction and scale of energy innovation. Reducing energy waste and energy consumption throughout the energy system is necessary in all sectors of the economy. Energy efficiency is crucial to moving towards clean energy system such as renewable energy as it accounts for more than 40% of the emission reductions needed by 2040, according to the IEA's Sustainable Development Scenario [5]. EU policy in this area aims to reduce the amount of energy required for the same process without reducing growth prospects [6]. Energy efficiency encourages the improvements of energy security by promoting the reduction of energy consumption, reduction of emissions, reducing energy costs to enhance competitiveness and to contribute to the overall energy and climate goals. The key here is innovation because it supports new technologies and the development of existing ones. Innovation processes are most often not linear. They go through many modifications from the initial idea to market. Therefore, reducing global $CO_2$ emissions will require a broad range of different technologies working across all sectors of the economy in various applications and combinations. As the IEA notes [7] a combination of regulation, provision of information and incentives is the best approach to bolster energy efficiency and accelerate decarbonisation in the industrial sector.

Another concept that brings us closer to reducing $CO_2$ emissions is circular carbon economy. It is based on a closed-loop system and includes the 4Rs: reduce (increase energy efficiency and minimise combustion), reuse (innovative technologies to capture $CO_2$), recycle (chemically converted $CO_2$ into new products) and remove (using technology to capture and store $CO_2$) [8]. This contributes to a circular economy where waste is kept to a minimum, thereby creating further value [9].

Indeed, the circular economy perspective is crucial in addressing the critical challenge of decarbonising EIIs. The circular economy framework emphasises closing material and energy loops, extending product lifecycles, and decoupling economic growth from environmental degradation—aspects that are highlighted in the thesis analysis of HPHE implementation in EII. Thus, HPHEs not only contribute to energy efficiency, but also promote the creative use of effectively free energy, that can have an enabling effect on circular economy approaches.

For this approach to be effective, quantification tools are necessary. LCA can therefore serve as a tool quantifying the environmental, and potentially economic, and social impacts of resource flows across interconnected systems, where societal- (S-LCA) and Lifecycle Cost Analysis (LCC) are implemented. Through mapping material and energy flows, LCA provides data to be interpreted and enables opportunities to be identified. These opportunities enable the closing of loops, optimising waste resource valorisation, and fosters cross-sector collaborations— all of which are core tenets of symbiosis frameworks. For instance, in industrial symbiosis, where byproducts from one process become inputs for another, LCA can not only validate the net environmental benefits of such exchanges, but also supports the design process, ensuring that avoided burdens (e.g., reduced virgin material extraction or emissions) outweigh logistical or operational trade-offs [10].

These novel strategies also possess significant economic potential, as symbiosis can unlock €1.8 trillion in annual resource savings globally by 2030, particularly in energy-intensive sectors such as steel and cement [11]. While in 2025 these initiatives are yet to achieve critical mass, the potential is clear. Urban symbiosis extends this logic to cities, where LCA informs integrated waste-to-energy systems, district heating networks, and circular construction practices, where industrial waste heat is a valuable resource. The European Union’s Circular Economy Action Plan highlights LCA as a critical enabler for transitioning cities to “zero-waste” models, citing case studies where urban-industrial partnerships reduced landfill dependency by 30% through co-processing initiatives [12]. Furthermore, a study by Kalundborg Symbiosis Institute[13] illustrates how LCA-guided planning in Denmark's industrial park averted 635,000 tonnes of $CO_2$ annually by repurposing waste heat and byproducts across over 20 facilities. These are only a few examples of embedding LCA into policy and corporate strategies, enabling stakeholders in scaling symbiosis from pilot projects to systemic transitions.

## 1.2 Economic and technological challenges of industrial waste heat

Decarbonising the industrial sector is a big challenge. According to the IEA, low-carbon technologies for many processes are too expensive or are still under development [14]. Many industrial processes use heat characterised by high temperatures and, in addition, the industrial equipment used has a long service life and is not frequently replaced.

More than half (50.9%) of the industry's final energy consumption in 2021 consisted of natural gas, oil and petroleum products, solid fossil fuels and non-renewable mixed waste (Figure 2). However, the EU industry's dependence on fossil fuels was even higher when considering that more than a third of the EU's electricity and more than half of its heat was generated from fossil fuels [15].

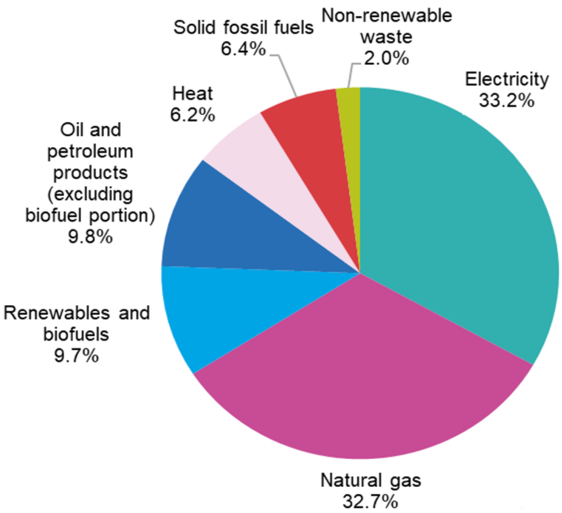



*Figure 2. Energy products used in the EU industrial sector in 2021 [10]*

Currently, researchers are conducting a lot of studies to determine the potential for waste heat energy recovery. Bianchi et al. [16] estimated a theoretical potential based on technical process analysis and Carnot's potential for industrial waste heat recovery in the European Union based on EU statistical energy databases. They focused on identifying an assessment of primary energy consumption in 18 industrial sectors and associated temperature levels for waste streams, it was noted that more than half of total primary energy consumption in industry is dissipated to the environment. The analysis carried out showed that the theoretical potential is 920 TWh (29% of industrial consumption is waste energy from exhaust or effluents) and the Carnot potential is 279 TWh. In the first case, the greatest energy waste occurs at temperatures below 100 °C (marked as low temperature (LT), Figure 3, 51% compared to 23% for Carnot potential). However, the Carnot potential indicates whether waste heat can be used further for technical work or for heat exchange.

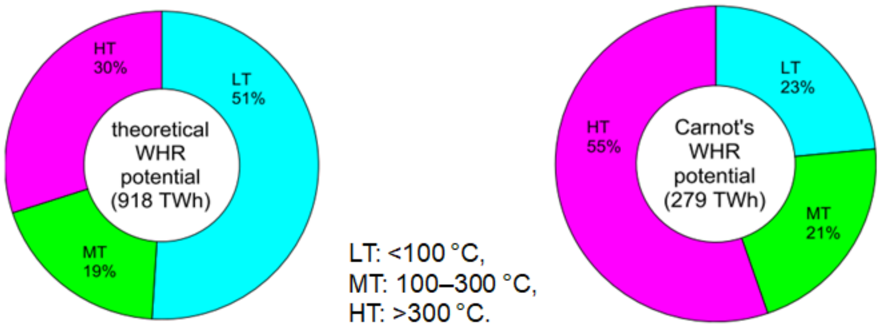



*Figure 3. Waste heat recovery potential in EU divided into low temperature (LT), medium temperature (MT) and high temperature (HT)[11]*

Kosmadakis [17] focuses on assessing the industrial potential of waste heat in EU countries and UK using data from 2015 to 2021, for each country, temperature level and industrial sector. It was estimated that the total waste heat potential of EU and UK industries in 2021 compared to 2015 is lower at 221.32 TWh/year. Figure 4 presents the waste heat per industrial sector. ‘Other’ refer to the sector with low heat demand. The non-metallic minerals industry and the iron and steel industry generate the biggest amounts of waste heat (approximately 85 TWh/year and 50 TWh/year).

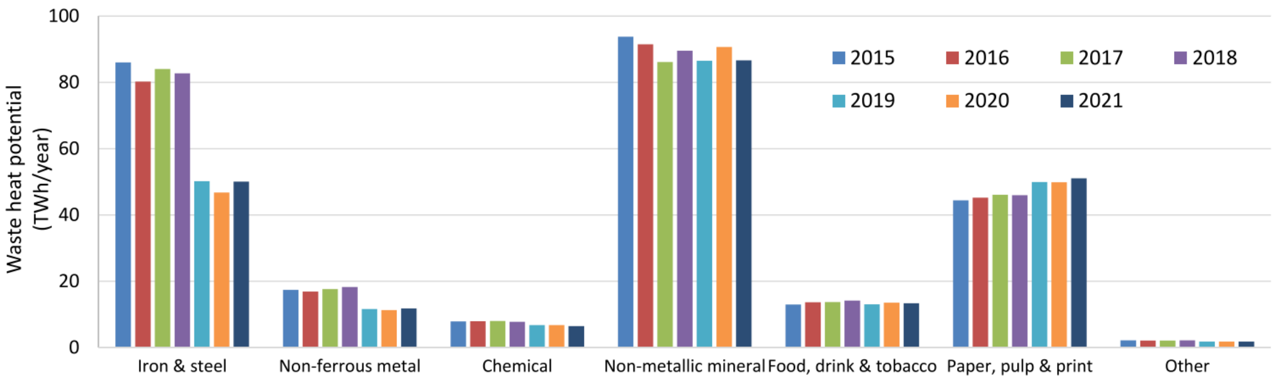



*Figure 4. Waste heat potential per EU industrial branch between 2015 and 2021 [12]*

As can be seen from the Figure 5, the potential for waste heat is very low for temperatures below 100°C. The total waste heat potential for the industrial sector is greatest at temperatures 100-200°C as most industrial sectors operate at these temperatures. This does not change the fact that other industries with higher process temperatures can also generate significant amounts of waste heat.

In the case of the iron and steel industry, the waste heat temperature exceeds 200°C.

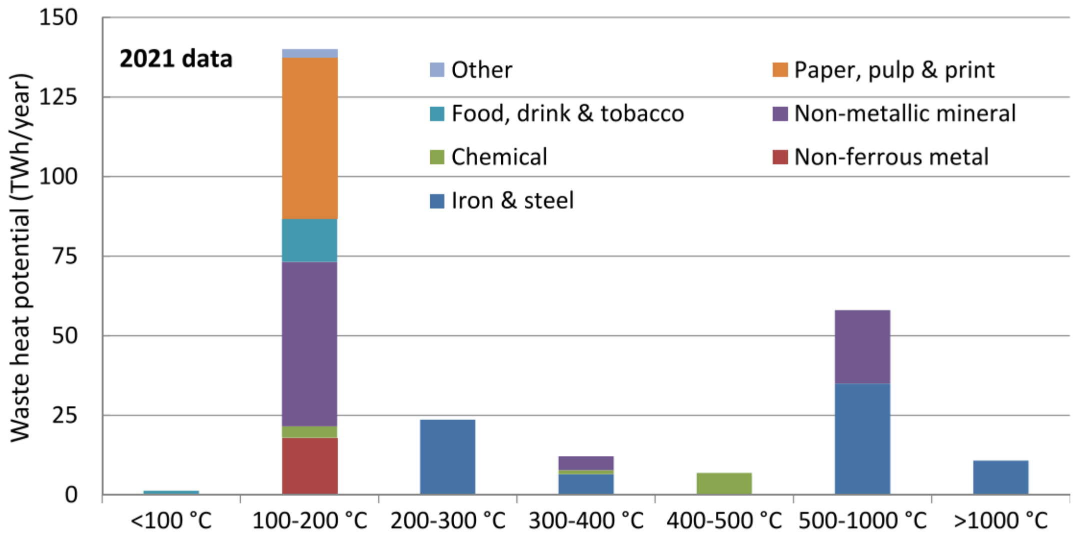



*Figure 5. Waste heat potential per industrial sector and temperature range in 2021[12]*

The authors identified three possible solutions used for waste heat recovery: direct heat recovery (with heat recovery efficiency of 90 %), waste heat upgrading and waste heat to power. It was estimated that 129 TWh/year is the total potential for direct heat recovery. In the respective temperature ranges:

- 100-150°C :53.5TWh/year which represents approximately 40%
- 200–500°C:24TWh/year (17,9%)
- 500–1000°C: 22TWh/year (16,4%).

Direct heat recovery potential in each EU country and UK per industrial branch in 2021 is shown in Figure 6.

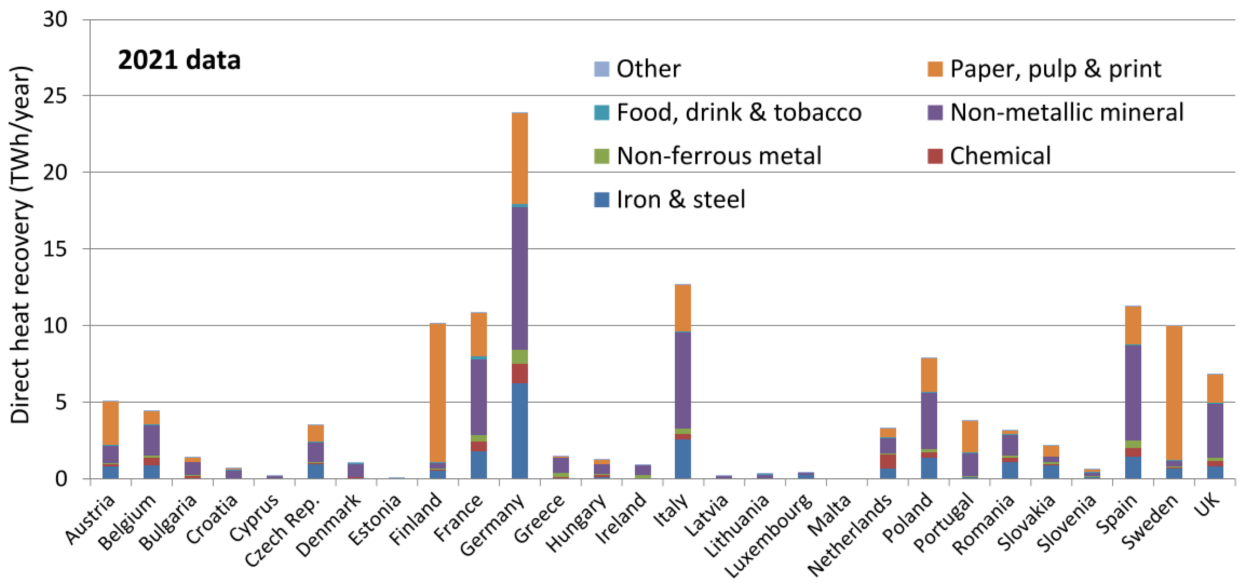



*Figure 6. Direct heat recovery potential in each EU country and UK per industrial branch in 2021[12]*

## 1.3 Literature review of state-of-the-art solutions in heat exchangers

### 1.3.1 Aluminium industry

The aluminium industry is a significant source of $CO_2$, emitting almost 270 Mt of direct $CO_2$ emissions in 2022, which is about 3% of direct industrial $CO_2$ emissions worldwide [18]. According to the IEA, in primary aluminium smelting, improvements in energy efficiency have been negligible in recent years due to the use of the best available technology at the time for more than a decade.. However global demand for primary aluminium is projected to increase by up to 40% by 2050, with post-consumer scrap recycled aluminium more than tripling [19]. This is due to the development of economies and urbanisation. In the report "Aluminium Sector Greenhouse Gas Pathways to 2050" the International Aluminium Institute [20] identified three domains to reduce greenhouse gas emissions in the aluminium industry: electricity decarbonisation, direct emissions and recycling and resource efficiency. The first area involves the implementation of carbon capture utilisation and storage (CCUS) and decarbonised power generation. The second, addresses emissions from fuel combustion, process emissions, transport emissions and raw materials. The solution could be CCUS, a transition to green hydrogen or electrification. The last includes advances in resource efficiency and increasing collection rates. The first two areas would reduce greenhouse gas emissions by 50% and 35% respectively through the use of CCUS. Although global aluminium collection rates are high, currently around 75% for end-of-life scrap and over 95% for production scrap respectively, the IEA notes that maximising scrap collection availability will remain insufficient to meet demand through recycled production alone [18].

A significant amount of electricity is consumed in the aluminium subsector. Decarbonising this energy source would make it possible to reduce indirect and direct emissions [18]. As Figure 7 shows, in the short term, increasing the share of aluminium production from low-carbon electricity represents a significant source of potential emissions reductions. By analysing the type of energy powering aluminium production since 2010, the share of coal has increased and the share of hydropower has decreased. This is due to China's increased share of aluminium production. In that market, coal is used to supply electricity for more than 80% of production. In other markets in Europe, South America and North America, hydropower provides more than 80% of production.

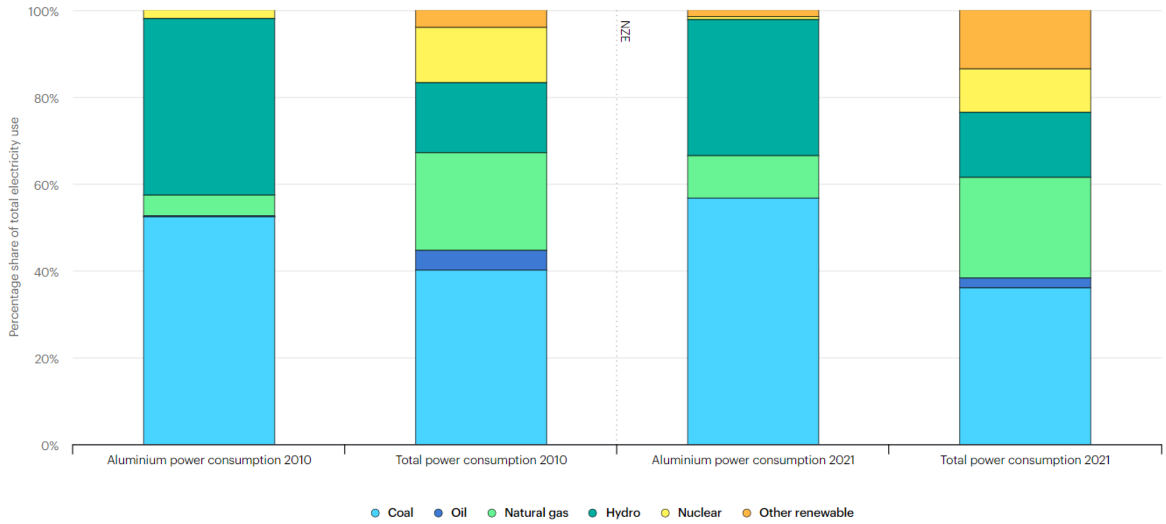



*Figure 7. Electricity used in aluminium production compared with total electricity consumption, 2010 and 2021 [13]*

To meet the expectations of the Net Zero Emissions (NZE) by 2050 target, the aluminium sector needs to both develop and implement near-zero emission technologies. Policy makers, international collaboration and private sector strategies are increasingly coordinating to address the challenges facing the decarbonisation of the aluminium industry. As is well known, the European Union runs the EU Emissions Trading System in 2017 to reduce greenhouse gas emissions cost-effectively. In addition, the EU has agreed a carbon border adjustment mechanism which will also cover aluminium. The permanent scheme involving the purchase of certificates will start in January 2026 [18]. In 2021 and 2022 the United States issued three separate statements on steel and aluminium along with the UK, European Union and Japan on actions to reduce the carbon content of steel and aluminium. In turn, major aluminium producers engage in multi-stakeholder initiatives across the value chain and concentrate on setting the baseline in the sector and potential technology tracks, developing demand for low-carbon products and investments, identifying policy and financial levers and finally aligning business performance with net zero emissions.

**The ETEKINA project**

ETEKINA was an EU funded research project aiming to recover 57-70 % of the waste heat stream in energy intensive industries. ETEKINA stands for "heat pipE TECHnologies for INdustrial Applications" and officially started October 2017, concluding in September 2022. Ten companies and institutes from across Europe joined forces to improve the energy performance of energy intensive processes. Their solution is based on heat exchanger technology (HPHE) using heat pipes for thermal recovery. As part of the project, three HPHE prototypes will be built and tested for three different production plants in the aluminium, steel and ceramics sectors. The different industrial environments produced different exhaust streams with different waste heat quantity and quality (chemical composition, different particles coming out along with the gases, temperature and pressure of the flue gases), and provided different processes where the recovered heat might be utilized. The challenge: the recovery solution should be adapted increasing the overall efficiency and being cost-effective. The Heat Pipes Heat Exchanger units were designed by experts from Brunel University London (United Kingdom). Waste heat technology specialist Econotherm (United Kingdom) manufactured the heat pipe heat exchangers and installed them at the following demonstration sites:

**Aluminium Production**: Fagor Ederlan (Arrasate, Spain)

**Steel Production**: SIJ Metal Ravne (Ravne na Koroškem, Slovenia)

**Ceramic Production**: Atlas Concorde (Modena, Italy)

All activities relating to the practicability and efficiency of the aluminium parts production were supported by Ikerlan (Spain), a non-profit technological research centre and ETEKINA's project coordinator as well as by Insertec (Spain), a manufacturer of furnaces.

The Jožef Stefan Institute (Slovenia), a scientific research institute, analysed the practicability and efficiency of the steel production. The same was done for the ceramic production by the University of Modena and Reggio Emilia (Italy).

The European Science Communication Institute (ESCI) based in Germany was the projects' media partner and lead of the communication and dissemination activities.

The aluminium industry was investigated as part of the ETEKINA project in search of opportunities to reduce energy consumption. This was followed by proposals to reduce energy costs by increasing overall energy efficiency and ensuring compliance with the EED.. More specifically, industry stakeholders were found to be interested in using a customised tool to manage recovered waste heat and verify the energy savings from the technology. For this purpose, the focus was on a passive system for recovering waste heat from industrial flue gas streams in industrial processes. The framework of the ETEKINA project concerned the non-ferrous metal industrial sector, represented by a low pressure die casting facility of Fagor Ederlan S. Coop. The exhaust waste heat fluxes discharged to the environment and occurring at the analysed facility are summarised in Table 1.

*Table 1. . Exhaust waste heat streams discharged to the environment [17]*

| Sub-process (SP) | WH source | SP WH vs. total WH |
|---|---|---|
| Melting furnace | Fumes at 170 °C rejected to the atmosphere | 18% (single stream) |

| | | |
|---|---|---|
| Casting | Water at 40 °C dissipated in a cooling tower. | 22% (7 streams) |
| Parts cooling | Water at 40 °C dissipated in a cooling tower. | 9% (7 streams) |
| Solution treatment | Fumes at >400 °C rejected to the atmosphere | 26% (2 streams) |
| Quenching treatment | Water at 40 °C dissipated in a cooling tower | 20% (2 streams) |
| Ageing treatment | Fumes at 135 °C rejected to the atmosphere. | 5% (2 streams) |

Although the flue gases from the melting furnace are from a single waste heat stream and have the highest energy content, the limited repeatability of the recovery technology used, the location of process or moderate temperatures are not the most appropriate choices. Most reasonable solution is to use streams at temperature levels between 520 °C and 540 °C from the second sub-proces: solution treatment. Low variation during the working period (nominal mass flow rate 1580 kg/h) and low levels of corrosiveness are perfectly in line with the heat recovery objectives. The aging heat treatment furnace uses around 15% of the total thermal heat treatment process energy consumption.

In order to safely fulfil their function of connecting key automotive components, the aluminium steering knuckles produced by the plant require specific metallurgical properties through progressive heat treatment. Three heat treatment processes can be distinguished, Figure 8. The first involves heating the parts to 540 °C in a solution heat treatment furnace (SHTF). Next, they are rapidly cooled to 40 °C by being immersed in a quench tank (QT) and subsequently, the parts are reheated to 160 °C in an ageing furnace (AHTF). The purpose of the passive heat recovery system used is to capture the thermal energy of the exhaust gas from the solution furnace exhaust fumes and use it in the ageing furnace. Both furnaces are heated with natural gas fired and are a roller-hearth continuous type.

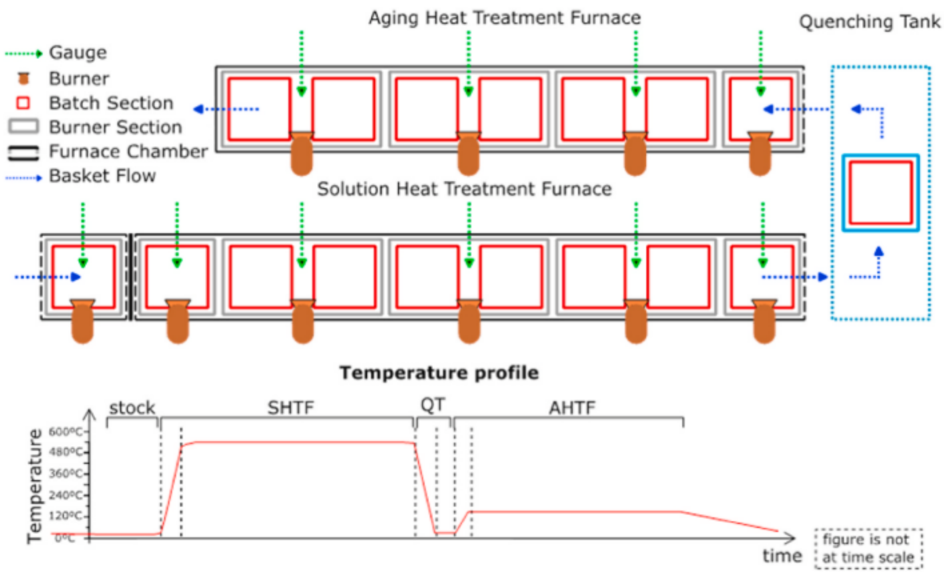



*Figure 8. Scheme of heat treatment process in aluminium industry [18]*

The heat recovery technology used in the ETEKINA project for aluminium industry is discussed in section 1.4.

### 1.3.2 Ceramic industry

Ceramic material describes inorganic, non-metallic mineral materials. They are characterised by their brittleness, are hard and are formed using heat. Furszyfer Del Rio et al. [21] specified two categories of the ceramics industry: traditional ceramics (ceramic goods, tiles, domestic articles) and advanced ceramics (bio- ceramics, electronic and electrical ceramics, and ceramic coatings). The European Ceramics Industry Association details this division into: construction and housing, consumer goods, industrial applications and high-tech and innovation [22]. Figure 9 presents value of EU ceramics production in 2007-2020. Ceramics companies are mostly classed as small- or medium-sized businesses [23]. This makes it difficult to access government funding for demonstrations of greener technologies and pilot projects.

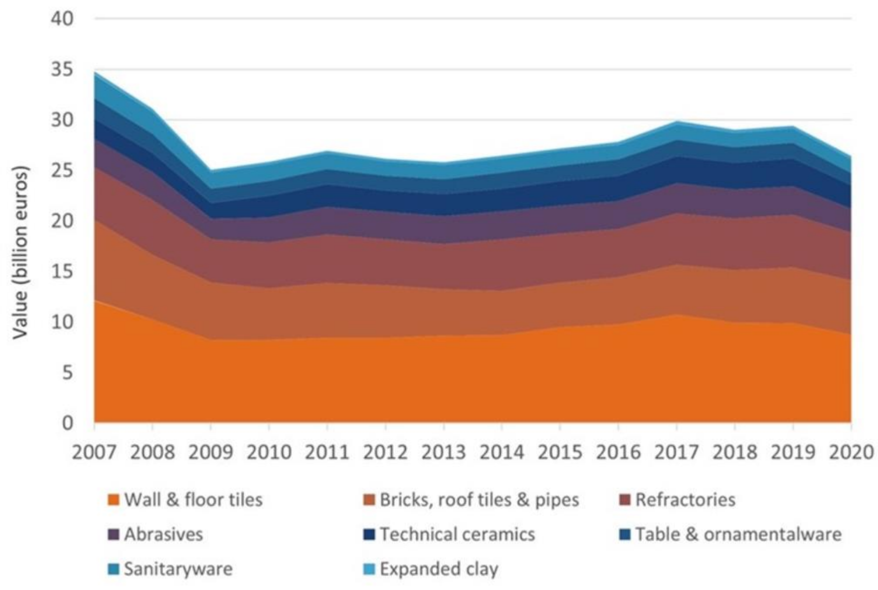



*Figure 9. Production value in EU ceramics between 2007-2020 [22]*

Statista [24] predict that the value of the ceramics market worldwide will grow to almost 360 billion US dollars by 2030. According to data on the world's leading ceramic tile producer in 2022 [25], China was the world's leading producer of ceramic tiles, producing around 7.31 billion square metres of ceramic tiles. In Europe, Spain and Italy lead the way, producing 500 and 431 million square metres respectively. According to Confindustria Ceramica [26] in 2021, the Italian ceramics industry recorded strong growth in sales, exports and production. At the end of that year, it was +12% compared to 2019 (458 million square metres).

All ceramic sectors are energy-intensive. 30% of the total production costs are related to the energy used. Total emissions from the european ceramic industry are 19 million tonnes of $CO_2$ annually [27]. In 2020 share of emission in the ceramic industry was 64% from fuel combustion for drying and heating process, 19% from indirect emissions, mainly from electricity production and 17% from process emissions generated by mineralogical transformation of the clay. The European ceramics sector has reduced total emissions by more than 45% since 2000 but there are still pathways to achieve carbon neutrality by 2050. These include: a switch to renewable energy, reduction in process emissions, in the manufacturing process innovation and increased efficiency, $CO_2$ capture and carbon removal technologies and offsetting measures. Measures contributing to the reduction of emissions from fossil fuel combustion and from process related emission are shown in Figure 10 and Figure 11 respectively.

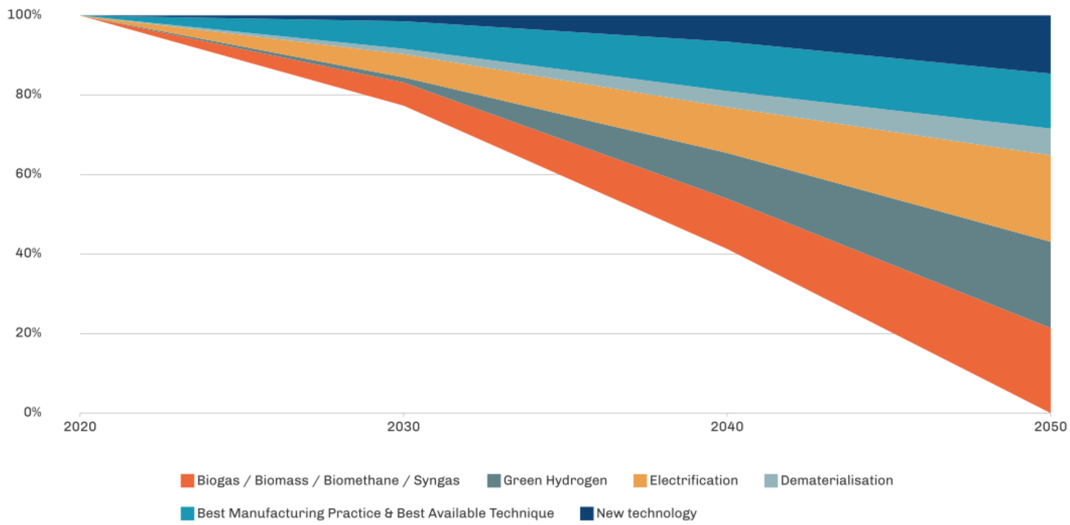



*Figure 10. Measures contributing to the reduction of emissions from fossil fuel combustion [26]*

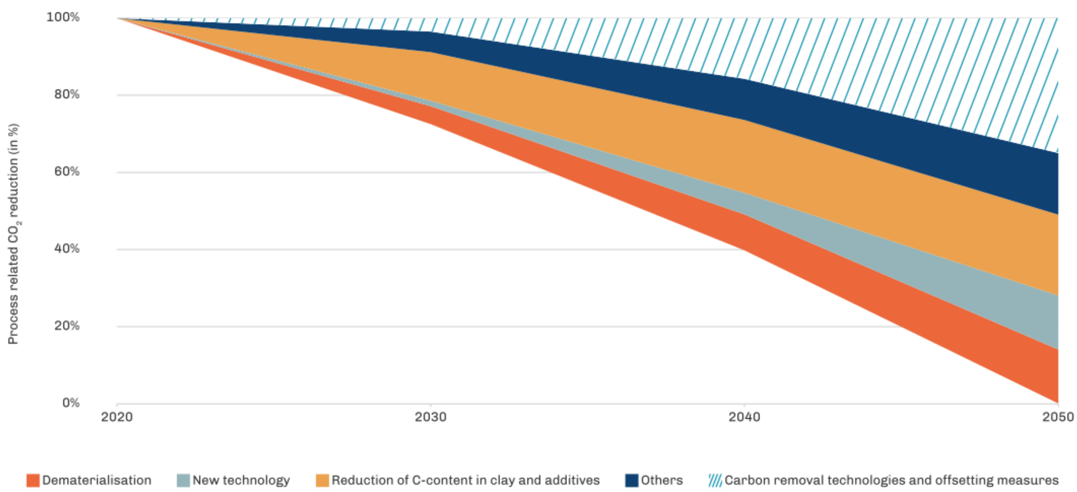



*Figure 11. Measures contributing to the reduction of process related emission [26]*

Ding et al. [28] analysed 14 green technologies leading to the decarbonisation of the ceramics industry producing of sanitary ware in China, focusing on energy efficiency improvement, energy substitution, process improvement and material consumption reduction. Additionally, they assessed the economic feasibility of the proposed solutions. They showed that electrification and clean energy are the most beneficial in a long-term decarbonisation pathway. Furszyfer Del Rio et al [21] compiled a table of 32 new technologies that reduce emissions from the ceramics industry's production processes and have developed a decarbonisation roadmap. Their work included a categorisation of technologies into current technologies, pilot only, that need to be significantly developed and breakthrough technology. This division is shown in Figure 12.

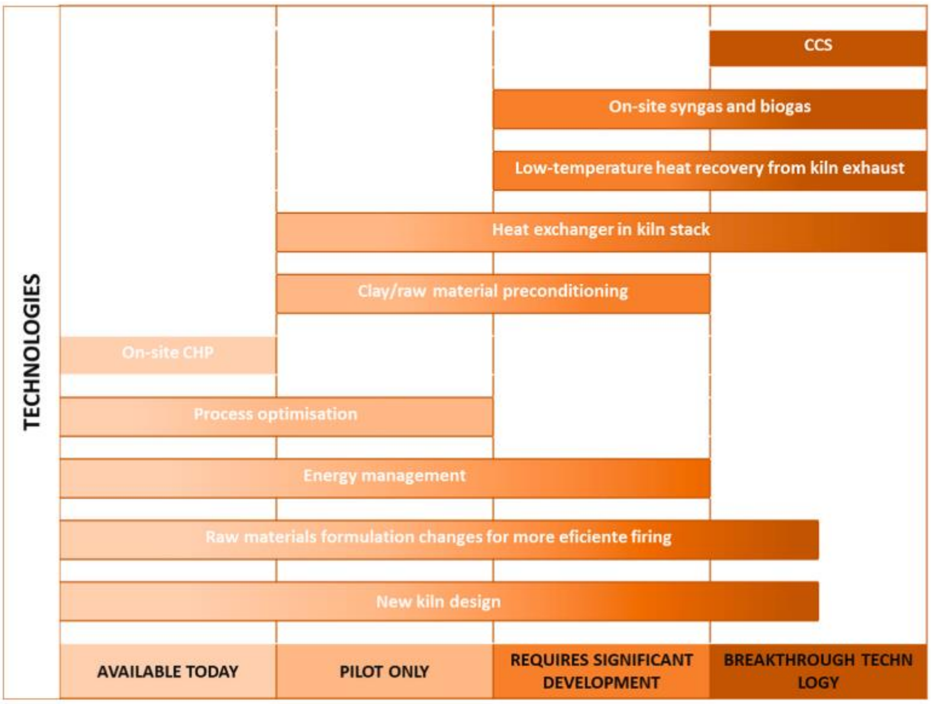



*Figure 12. Action plan for decarbonisation of the ceramics industry [19]*

Besier [29] indicated that the most cost-beneficial decarbonisation options for Dutch ceramic plants in the perspective 2030 timeframe are a combination of industrial heat pumps, green gas from on-site digestion and CCS. As noted in [27] recovery of excess heat by capturing kiln gases to preheat the combustion or dryer is an important way to reduce fuel consumption, reduce $CO_2$ and improve efficiency.

As part of the ETEKINA project, the energy intensity of aceramic tile production plant located in a ceramic district in the Emilia-Romagna region of Italy was carried out. In terms of thermal energy consumption for the industry was analysed, the firing stage accounts for 53% of thermal consumption, spray drying for 35% and drying for 10%. Several stages of production can be identified: selection of the raw materials which are then ground in continuous mills with the addition of a mixture of water, hydraulic paste compression, tile drying, decorating and firing in ceramic kilns at approximately 1250 °C. For this installation all exhaust waste heat streams being released to the environment are presented in Table 2.

*Table 2. Exhaust waste heat streams discharged to the environment [17]*

| Sub-process (SP) | WH source | SP WH vs. total WH |
|---|---|---|
| Spray dryer | High-wet air at 100 °C rejected to the atmosphere | 50% |
| Dryer | Low-wet air at 130 °C rejected to the atmosphere | 12% |

| | | |
|---|---|---|
| Kiln - exhaust gases | Fumes at 250 °C rejected to the atmosphere | 21% |
| Kiln - cooling | Air at 70 °C rejected to the atmosphere. | 17% |

All stages of the process are shown in Figure 13. The process of making ceramics begins in continuous mills where raw materials such as clays, sands, feldspars and kaolin are ground together with water . This is followed by the shaping of products using hydraulic presses to achieve the desired geometry. The final stages are drying, decorating and firing in ceramic kilns at a temperature of approximately 1250°C. Passive heat recovery from the flue gases from the tile firing process in the ceramic kilns was used to reduce fuel consumption by approximately 40% compared to the installation in the current system.

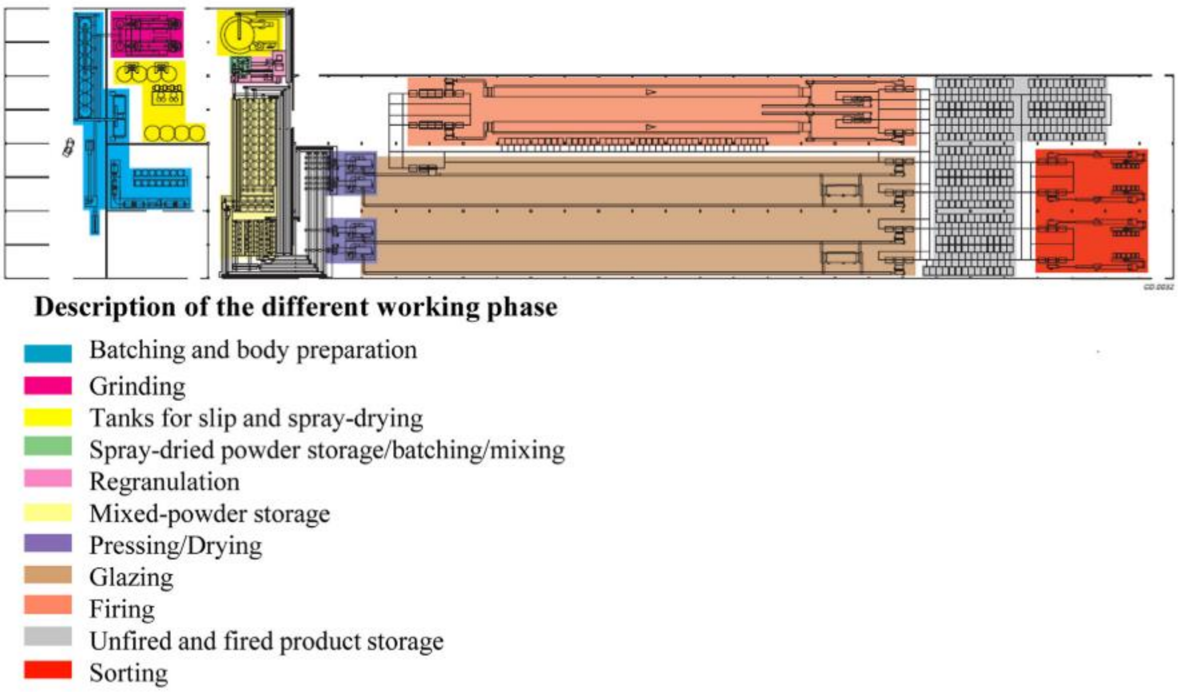


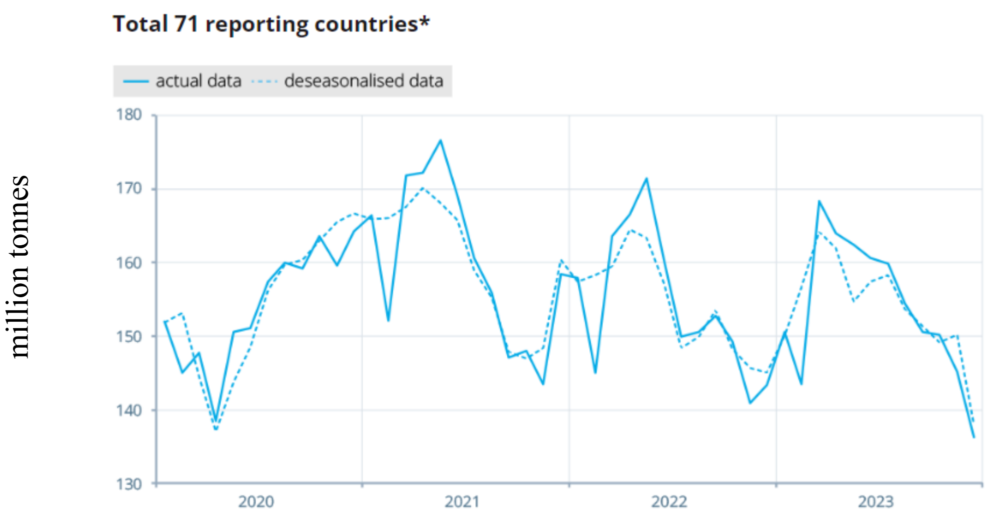

*Figure 13. Stages of the ceramic tile manufacturing process* [30]

The heat recovery technology used in the ETEKINA project for ceramic industry is presented in section 1.4. The benefits gained from the technology used have improved energy efficiency and reduced the environmental impact of the ceramic process.

### 1.3.3 Steel industry

Demand for steel has been growing steadily for the past 70 years and is forecast to continue to increase as a result of the economic expansion of India, Africa and the ASEAN countries [31]. Growth in the EU is expected to be around 0.5% per year [32]. Currently, the sector using steel the most is building and infrastructure (52%) followed by mechanical equipment (16%,), automotive (12%), metal products (10%), other transport (5%), electrical equipment (3%) and domestic appliances (2%) [33].

Steel production is one of the most energy-intensive industries. In 2022, it accounted for approximately 7-9% of global $CO_2$ emissions [33]. Per tonne of crude steel, 1.91 tonnes of $CO_2$ was emitted and 20.99 GJ of energy were consumed. These calculations were based on production weighted averages of scrap-based electric arc furnace (EAF), blast furnace-basic oxygen furnace (BF-BOF) and direct reduced iron (DRI)-based EAF steel production. Looking at the sustainability indicators associated with material efficiency the conversion into steel products or co-products of raw material is 97.65%. Additionally, the steel industry invested 6.29% of its revenues in new processes and products. Steel production in the EU, as elsewhere in the world, is not constant throughout the year. Figure 14 shows its variability from 2020 to 2023, based on data from 71 countries that account for 98% of world crude steel production.



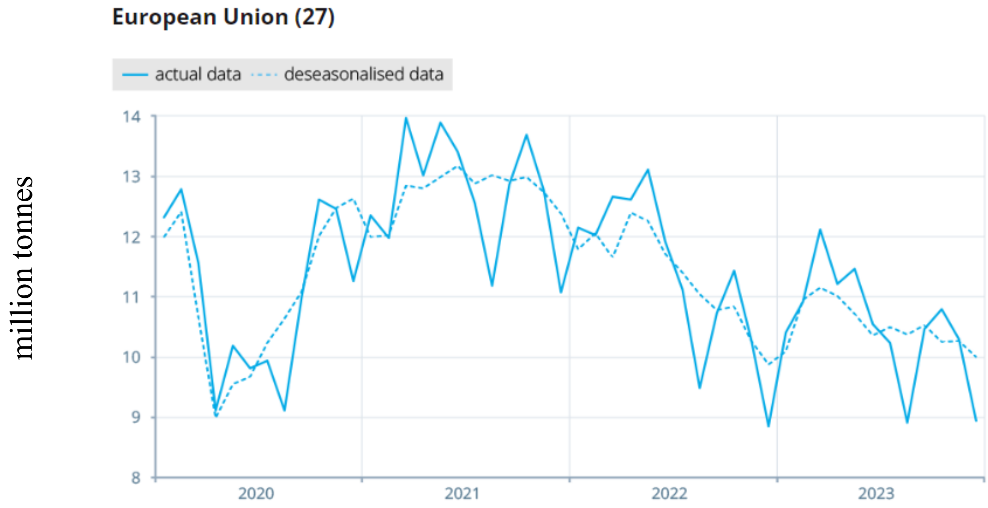



*Figure 14. Monthly variability in crude steel production from 2020 to 2023; *71 countries that account for 98% of world crude steel production [32]*

It is evident that the direct $CO_2$ intensity of crude steel production has declined slightly over the past few years, but in order to achieve the net zero emission targets by 2050, it is still necessary to look for ways to reduce $CO_2$ emissions as steel production is highly reliant on coal [31].

In 2023, a total of 1892 million tonnes was produced globally. China and India are the main contributors with 1,019.1 and 140.8 million tonnes respectively. Crude steel production and use by geography in 2023 is presented in Figure 15. Others included: Africa 1.3%, South America 2.2%, Middle East 2.9% and Australia and New Zealand 0.3%.

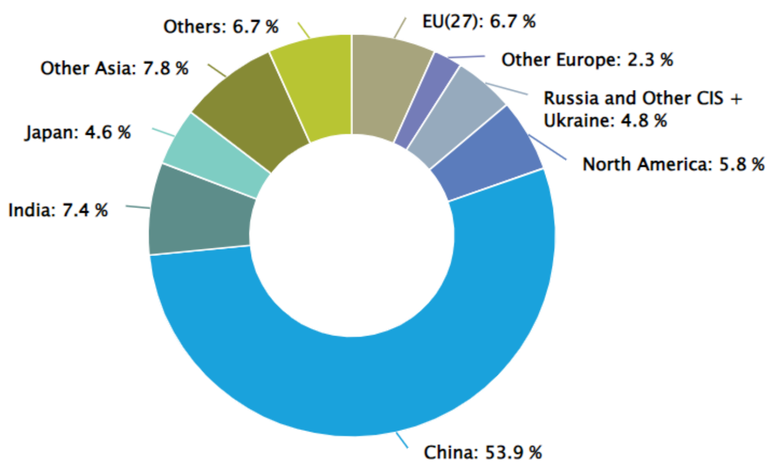



*Figure 15. Crude steel production and use in 2023 [32]*

The blast furnace method using coal as the raw material produces 57% of steel in Europe and the remaining by the electric-arc furnaces route using scrap as the raw material [34]. S&P Global Commodity Insights interactive map presents major low-carbon projects already scheduled by leading steelmakers (26 projects). Although, as the author notes, there are at least 60 projects aimed at reducing $CO_2$ emissions in the steel industry in Europe by 81.5 million mt/year by 2030. The data presented shows that, where possible, companies are mainly switching to electric arc furnaces using hydrogen. However, the difficulty remains in the easily sourced and economically viable hydrogen and green energy. Above and beyond this, problems with sourcing sufficient scrap metal are predicted, according to a report published by UK Steel. This does not apply to structural steel as in a circular economy the scrap network allows 99% of all UK structural sections to be recovered; 86% for recycling and 13% for reuse [35]. As Aaskov notes [34], no steel company or steel sector in the world has yet successfully decarbonised and the UK has the opportunity to become the first steel sector to achieve net zero emissions. A number of decarbonisation methods are needed to achieve this: electrified steel production, carbon capture and storage, and hydrogen [36]. It is therefore necessary to develop and apply new technologies that have not yet been implemented on a large scale elsewhere in the world and for the UK facing high electricity prices for industry [37].

Following the "UK structural steelwork: 2050 decarbonisation roadmap" [35], direct emission reduction technologies used in many UK and EU steel plants, which will reduce $CO_2$ by 28% include: waste heat recovery, coke dry quenching, top pressure recovery turbines, injection of natural gas or process gases, increased use of scrap in the BOF and EAF processes, use of biomass and biowaste. Carbon capture use and storage will enable a 25% reduction in $CO_2$. The circular economy, steel transport fabrication and erection and decarbonisation of the electricity grid will reduce $CO_2$ by 15%, 8%, and 6.5% respectively.

In the report [38], the IEA summarised the progress on the state of transformation achieved by 2023 and made recommendations for the next years in five areas: standards and definitions, demand creation, research and innovation, trade conditions, finance and investment. Only in the first area was good progress observed. The others were assessed as modest.

As part of the ETEKINA project, it was estimated that there are more than 60 sources of wasted heat in SIJ Metal Raven [39][40]. The technology that has the greatest potential for replicability in a steel processing company was selected: billet-heating furnace (Allino). Natural gas-fired furnace heats the steel billets in the selected process. The furnace has several gas burners arranged along the furnace in 4 heating zones. In addition, a recuperator is used there to raise the combustion air temperature. As shown in Figure 16, the excess heat from the flue gas after the recuperator was selected for passive heat recovery.

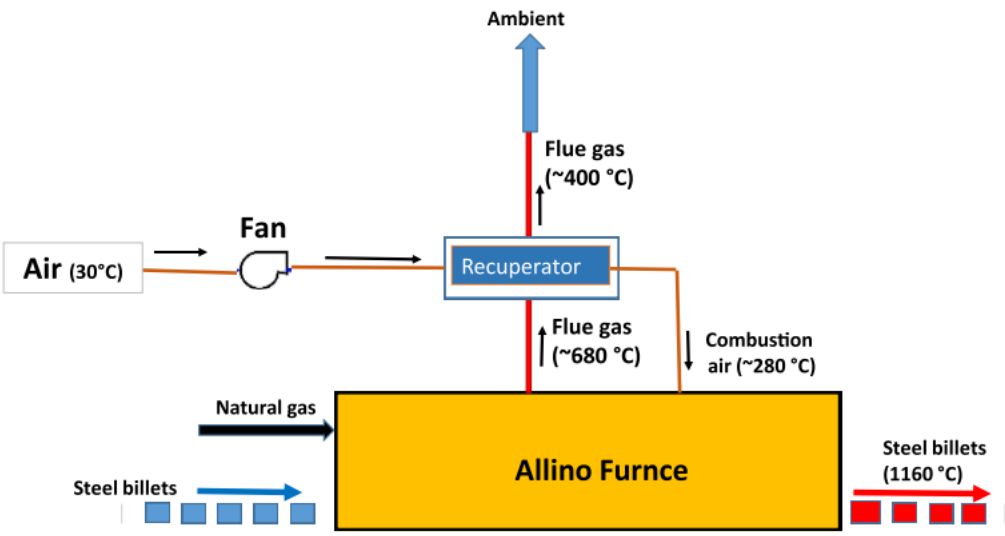



*Figure 16. Schematic of the billet heating furnace in steel processing industry [17]*

The chosen process was a big challenge. The average temperature value of the selected heat flux was approximately 360 °C (200-400 °C) and mass flow rate varied between 1000 kg/h and 8000 kg/h [41]. The advantage of the chosen heat flux was the low level of corrosivity (natural combustion fumes with excess air).

## 1.4 Comparative advantages and limitations of heat-pipe-based heat exchanger technology

Waste heat can come from, among other things, direct combustion processes, flue gases, components, products and equipment from process plants. There are many methods for recovering waste heat. The basic division includes active and passive methods, as shown in Figure 17. The most important aspect is to determine how much heat can be recovered from a particular process and to ensure that this recovery operates at maximum efficiency. This chapter discusses passive heat recovery methods in industry, focusing on heat exchangers with particular attention on the innovative HTHP solution.

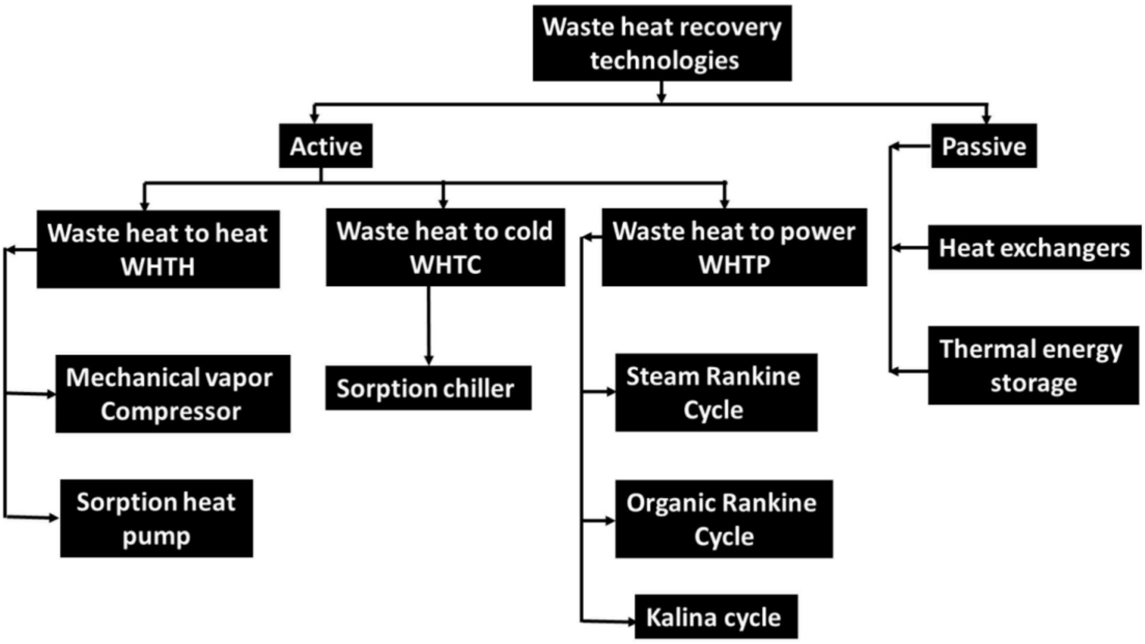



*Figure 17. Categorization of waste heat recovery technologies [39]*

### 1.4.1 Heat exchanger technology, a brief review of available types

A heat exchanger is a device that facilitates the process of heat exchange between two fluids that are at different temperatures. Heat exchangers are used in many engineering applications, such as refrigeration, heating and air-conditioning systems, power plants, chemical processing systems, food processing systems, automobile radiators, and waste heat recovery units. Air preheaters, recuperators, economizers, evaporators, superheaters, condensers, and cooling towers used in a power plant are a few examples of heat exchangers [42].

The domain of heat exchangers is a diverse field yielding many different types of heat exchangers already commercialised and established in industrial application:

**Shell and Tube Heat Exchangers (STHE)**[43]: Shell and Tube Heat Exchangers are widely used in oil refining, preheating, oil cooling, steam generation, boiler blowdown heat recovery, vapor recovery systems, and industrial paint systems. They are designed to transfer heat between two or more fluids, such as liquids, vapours, or gases, of different temperatures. The heat exchanger is comprised of a tubular tank and an integrated tubing section. Shell and tube heat exchangers are used as evaporators and condensers, either in vertical or horizontal position [44]. The main risk to shell and tube heat exchangers is corrosion, thus the selection of material and system design need to be precise in assessing the application environment. As the heat exchanger tubes are inaccessible, corrosion is thus unmanageable outside of chemical cleaning [45]. The corrosion issue is exacerbated by the vulnerability of the outer part of the tube, that is fabricated through electric welding [46]. Moreover, shell and tube heat Exchangers are volume-intensive systems with significant weight, that may be unsuitable for compact applications. To counterbalance these disadvantages, shell and tube heat exchangers show good resistance to scale formation and can achieve substantial lengths of service life if the corrosion threat is managed. The efficiency is only 70% [47]. Figure 18 presents a typical layout of a shell-and-tube heat exchanger. However, other configurations are also possible: U-tube heat exchanger, fixed tube sheet exchanger or floating head exchanger [48].

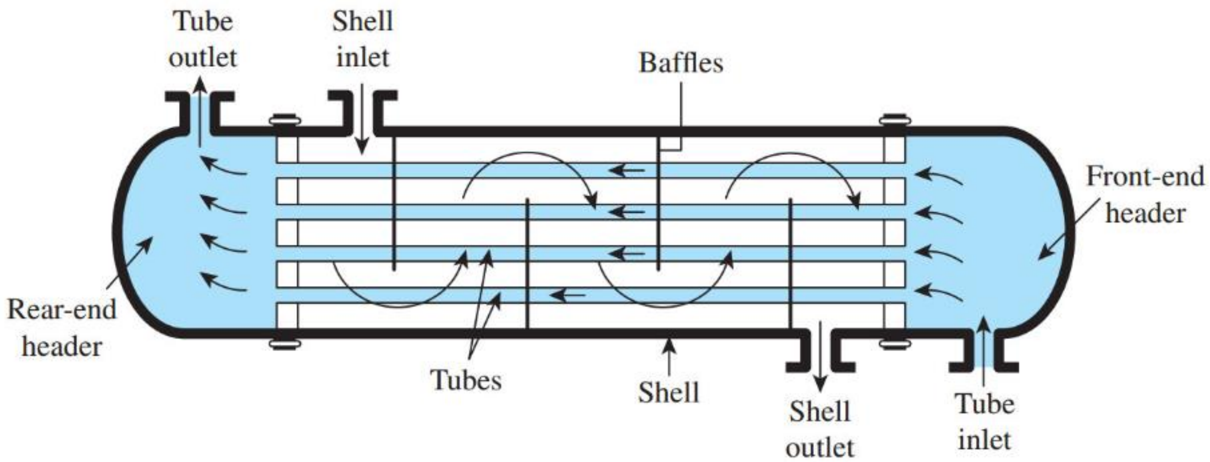



*Figure 18. Diagram of shell and tube heat exchangers [46]*

**Double Pipe Heat Exchangers (DPHE)**: Double pipe, or pipe-in-pipe heat exchangers consist of two pipes with different diameters inserted one into the other. The assembly process is facilitated by clutch couplings, enabling the joining of various sections of the piping into a coil, delineating the required spatial configuration for heating and cooling media. These sections are superimposed, ensuring that the flows of the heating and cooling media are directed counter-currently. The cooling medium is introduced from the lower part of the system and rises after being heated. Steam accumulates in the upper region and moves downwards after condensation. Double pipe heat exchangers are commonly used within the food industry and in any application where high heat transfer coefficient is required, and high-pressure operations need to be managed. Maintenance and cleaning is carried out on level areas [47]. Double pipe heat exchangers possess several advantages such as: high flow rate of the coolant, ease of maintenance and versatility in applications. On the other hand, the spatial requirements of the system are significant, excluding applications where compact dimensions are necessary. Moreover, the cost of the system is substantial. Finally, the complex multi-material and multi-phase interactions necessitate expert knowledge that is not commonly found within the industry.

**Plate Heat Exchangers (**PHE**)** [49]: Plate heat exchangers are commonly used in the metal industry due to their high efficiency in heat exchange. The design of PHEs allows for a large surface area contact between the two fluids, facilitating efficient heat transfer, as shown in Figure 19. They consist of many corrugated plates of stainless steel, separated by seals installed without adhesives through precise machining, preventing the mixing of media. In the metal industry, plate heat exchangers are used to control fluid temperatures using other fluids that may already be part of the industrial process [50]. Plate heat exchangers are compact and easy to maintain, making them ideal for use in industries where space is a constraint. They can be easily modified by adding or removing plates to meet changing heat transfer requirements. For instance, in steel production, they can be used to cool down hot steel or preheat cold steel, improving the efficiency of the production process. Plate heat exchangers are also quite compact, and multifunctional, presenting excellent versatility due to the customisation of plate numbers. Moreover, this level of modularity is also very beneficial with regards to maintenance, as worn plates can be easily replaced. On the other hand, Plate heat exchangers are very susceptible to clogging due to particulate loading, necessitating frequent cleaning and notorious for their short service life.

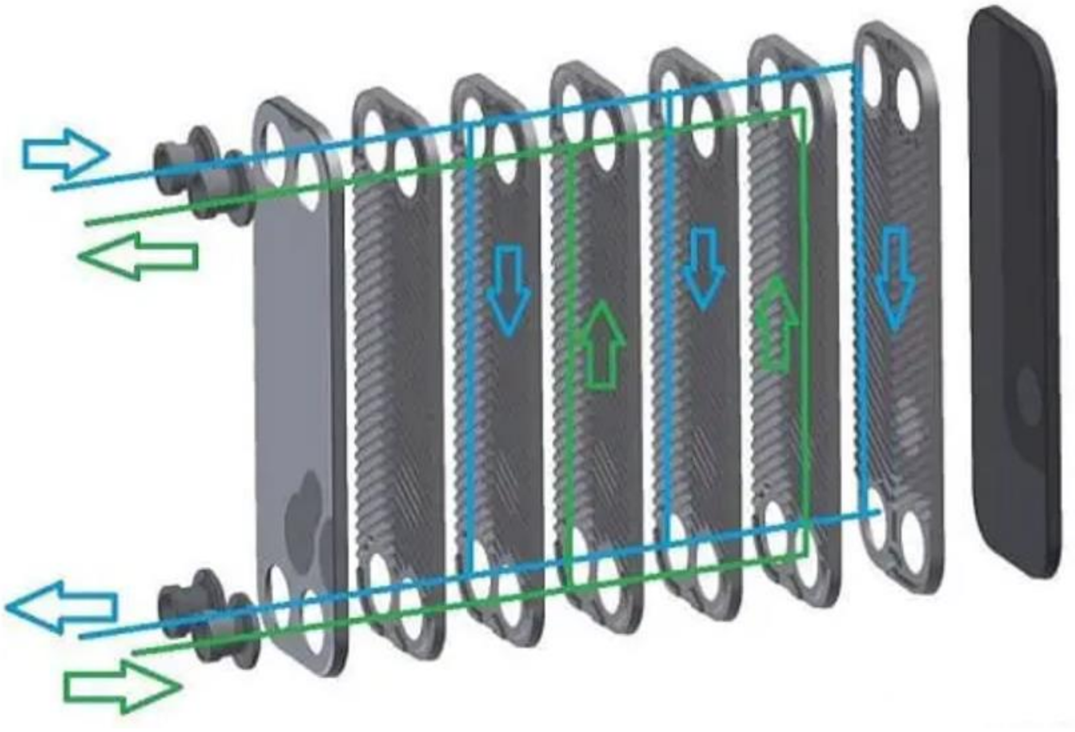
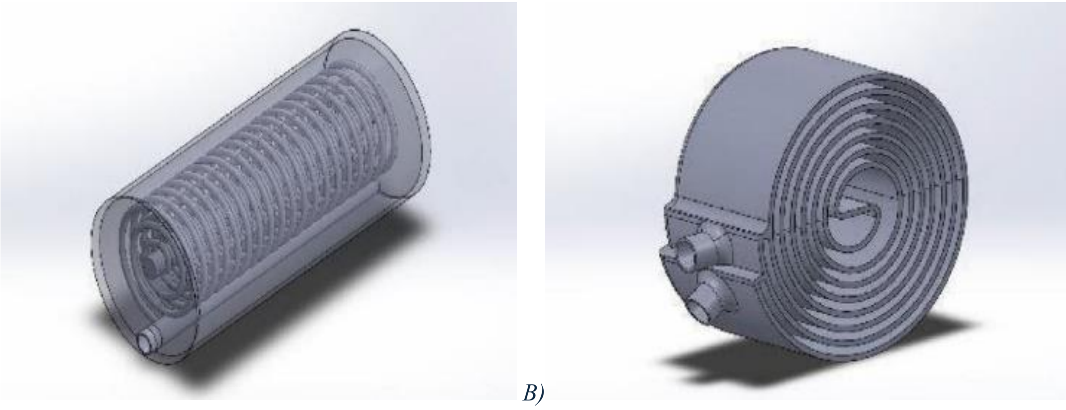


*Figure 19. Plate Heat Exchanger [49]*

**Spiral plate and spiral tube heat exchangers** [51][52]: Spiral plate heat exchangers are made of two metal plates that are wound on each other. One stream of process fluid enters the heat exchanger through the centre and flows from the outside, while the second stream enters from the outside and flows inward. Their advantages include versatility in terms of material, counterflow operation, low pressure drop and lack of dead zones that prevent the accumulation of solid particles. On the other hand, they are quite costly, and the IP is held by a handful of companies making availability limited. Spiral tube heat exchangers are made of spiral pipes, and mainly used for small capacity systems, sharing the advantages and disadvantages of their spiral plate counterparts. The differences in heat exchanger design are shown in Figure 20.



A) B)

*Figure 20. Spiral heat exchanger: A) Spiral tube B) spiral plate [52]*

**Printed Circuit Heat Exchangers (PCHEs)** [53]: PCHEs are ultra-compact and highly efficient, making them suitable for a wide range of applications. They are constructed by brazing together corrugated sheets, which form the channels for the hot and cold fluids. The combined result is maximum efficiency and minimum footprint, ensuring the lowest total lifecycle cost. PCHEs operate with two or more media on opposite sides of a diffusion welded plate. It is possible to have high-pressure flows on both sides, and a 2D/3D plate pattern can be optimized to provide the required thermal length and pressure drop. They are used across the energy industry, in oil and gas, power generation, marine, and clean technology systems. An example of a heat exchanger is shown in Figure 21.

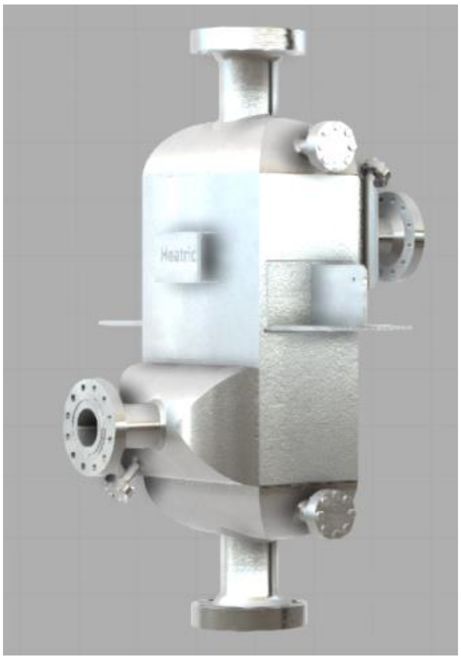



*Figure 21. Heatric Printed Circuit Heat Exchanger [53]*

**Air-Cooled Heat Exchangers (ACHEs)** [54]: ACHEs are used when water is scarce or its use is restricted. They are commonly used in power plants and large chemical processes. The main function of the ACHE is the direct cooling of various process mediums by atmospheric air. They do not require an auxiliary water supply because of the lost water due to drift and evaporation. The construction of an ACHE is simple. Typically, air-cooled exchangers consist of a finned tube bundle with rectangular box headers on both ends of the tubes. Cooling air is provided by one or more fans. The fans can be either forced or induced draft depending on whether the air is pushed or pulled through the tube bundle [55]. The space between the fans and the tube bundle is enclosed by a plenum chamber that directs the air. The main advantage of ACHEs is that they do not use water, but the trade-offs are significant: the systems are volume intensive, manufacturing is expensive, the ribs become easily clogged and the fans generate substantial noise [56].

**Brazed Aluminium Heat Exchangers (BAHXs)** [57] efficiently transfer heat in cryogenic applications, boasting high reliability and low energy consumption, Figure 22. Used in LNG and gas processing, BAHXs are compact, lightweight, and exceed conventional exchangers in surface area per volume. Operating at low temperatures, they reduce energy use and environmental impact. Crafted from aluminium, they offer superior thermal conductivity and corrosion resistance. With minimal downtime (less than 0.01%), BAHXs enhance availability and productivity for diverse industries. BAHXs are primarily employed in the aluminium process industry, particularly for heat recovery applications in smelters and refining plants.

*Figure 22. Brazed Aluminium Heat Exchangers [57]*

**Ceramic Heat Exchangers** [58] find extensive application in the ceramics industry, leveraging their commendable attributes of high corrosion resistance and thermal efficiency. Within the ceramics sector, there exists a notable opportunity for harnessing waste heat from industrial processes. Furthermore, ongoing research has led to the development of ceramic lattice structures, predominantly composed of alumina ($Al_2O_3$), zirconia ($ZrO_2$), and silicon carbide (SiC), renowned for their resilience in high-temperature environments and resistance to oxidation. The integration of additive manufacturing technologies has further refined the precision in crafting unit cells from these materials, marking a significant advance in high-temperature heat exchanger design and functionality [59]. Ceramic heat exchangers are primarily employed in the ceramics industry, particularly for high-temperature applications where their excellent heat resistance and chemical inertness are crucial.

## Innovations in the heat exchanger technology

As shown in the previous section, heat exchangers are an established technological field with many resulting products. Nonetheless, research continues to improve all aspects of heat exchangers, aiming to address their limitations. Notable research and product development work is being carried out in the following areas:

**Novel Cast Aluminium - Cerium Heat Exchanger** [60]: This heat exchanger is the first to be cast in one piece, including the headers, eliminating the need for brazing or welding. It was developed by the Oak Ridge National Laboratory and is part of a project funded by the U.S. Department of Energy.

The heat exchanger is made using an Al-Ce alloy, which was invented by ORNL under the Critical Material Institute.

**Microchannel Heat Sinks** [61]: Microchannel heatsinks (MCHS) are modern heat exchangers with fluid flowing channels of size in microscale. These are very compact heat exchangers with higher ratios of heat transfer area to the volume. Huge research work has been going on to improve the hydraulic and thermal performance of the MCHS.

**Phase-change Cooling Technology** [62]: Phase-change technology is one of the most impactful advances that have helped make heat exchangers possible. By utilizing a cooling fluid's latent heat of vaporization, heat exchangers can transfer large amounts of waste heat very efficiently.

### 1.4.2 The role of the heat-pipe based heat exchanger

As described, heat exchangers play a crucial role in Energy Intensive Industries (EIIs). As industrial heat exchangers are largely bespoke systems, the availability of many types of systems (detailed in the previous section) is highly important. One of the limitations of conventional HX is fouling and corrosion, which can be mitigated by the design of an appropriate geometry of the system, and improved material surface properties, or addition of a medium between the evaporator and the heat source creating thermal resistances, both challenging propositions: Design space is restricted due to materials processability properties (also limiting heat exchanger performance) and, mostly, manufacturability-imposed limitations. State-of-the art models and simulation-based solutions do not consider sustainability, safety or circularity criteria for product design and manufacturing path selection. The development of designs for heat exchangers in challenging applications requires extensive knowledge in areas such as simulating multi-phase and multi-component systems, advanced materials and coatings or component functionalisation as well as engineering design. The intradisciplinary knowledge is limited to few experts, which in turn increases the cost and limits availability. Thus, most industrial heat recovery applications prefer clean, high-temperature waste heat sources in large capacity systems, which necessitates dilution, solid removal via filters or cyclones and restricts heat recovery to sensible heat, leaving a substantial share of waste heat unexploited.

It is thus evident that access to robust heat exchangers at reasonable unit and maintenance costs is a key enabler for EIIs to achieve impactful decarbonisation steps, bolstering flexibility, resilience and competitiveness. These needs can be addressed by the HPHE. The HPHE has multiple benefits such as an isothermal surface which eliminates any hot or cold spots, increasing the lifetime of the system for applications where the exhaust is corrosive. HPHEs are passive devices without need for pumping or mechanical components and a higher reaction time than other heat transfer systems.

## Description of the HPHE technology

Waste heat can be effectively and efficiently recovered with the use of Heat Pipe Heat Exchanger (HPHE) technology. A heat pipe is a technology that uses two phase heat transfer phenomena to transfer waste heat from one location to another. Figure 23 presents a heat pipe design which consists of a vacuumed sealed container which may include a wick structure and a working fluid such as acetone, water, ammonia methanol or sodium. When heat is applied from a heat source to one end of the heat pipe, the working fluid boils at this end (which is called an evaporator) where it is in equilibrium state with its own vapour and flows from the evaporator via the adiabatic section to the other end (condenser). The working fluid vapour rejects the latent heat at the condenser to a heat sink condensing the vapour to liquid. The condensate flows back to the evaporator section by flowing through the wick structure which provides a capillary action in wicked heat pipes. In wickless heat pipes which are also called thermosyphons, the liquid flows back by the assistance of gravity [63]. When the liquid working fluid reaches the evaporator section, it evaporates, and the two-phase cycle is repeated.

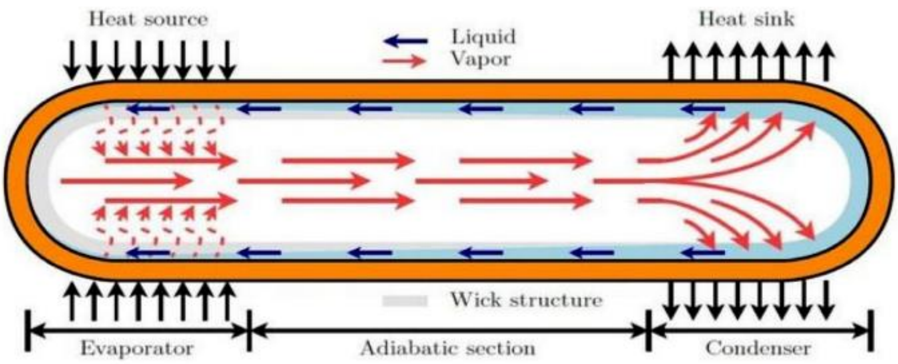



*Figure 23. Schematic of a heat pipe [18]*

Within a heat exchanger unit many heat pipes work together in parallel in a container where the hot production stream passes by at the lower side to heat the liquid inside the tubes. At the upper section of the heat exchanger, a cool stream flows along, absorbing the heat of the condensate. This heated stream can now be transported to parts of the production line where it can be re-used.

Heat pipe heat exchangers with unique features of automatic fouling management avoid acid condensation, high temperature operation and multi-sink capability. The HPHE system is a combination of multiple heat pipes that work independently, a separation plate that isolates the two fluid streams (hot and cold streams) and the external casing (Figure 23). This ensures that there is no risk of contamination of the streams, heat pipes require minimal maintenance and failure of few heat pipes does not considerably influence the overall performance of the heat pipe heat exchanger [64].

HPHE architecture design and the mathematical models for designing heat pipe-based heat exchangers for waste heat valorisation in industrial processes have been developed as a pre-step to manufacturing of the HPHE [30].

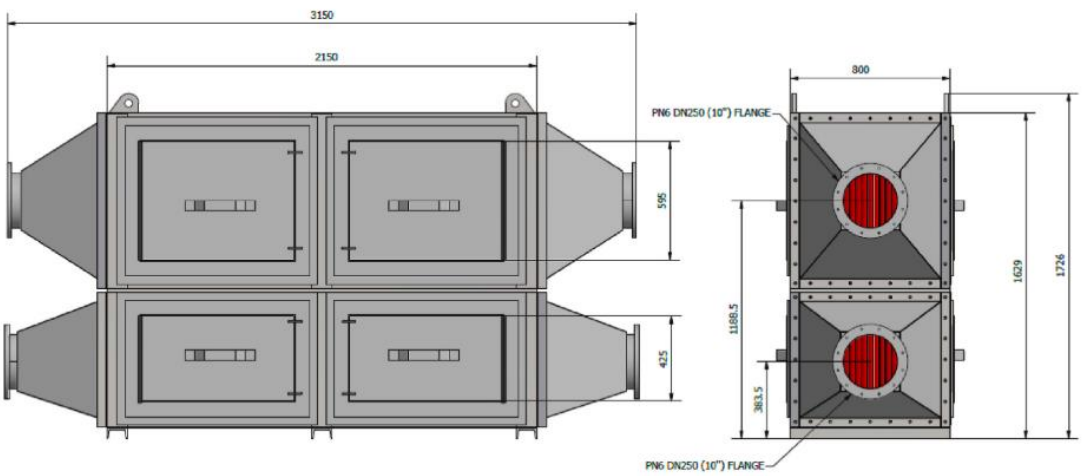
### 1.4.3 The role of the ETEKINA HPHE

ETEKINA HPHE addresses both the technical difficulties for recovering and re-using energy losses within the process industries, as well as the economic barriers which is represented by the cost associated to the heat pipe system installation and maintenance.

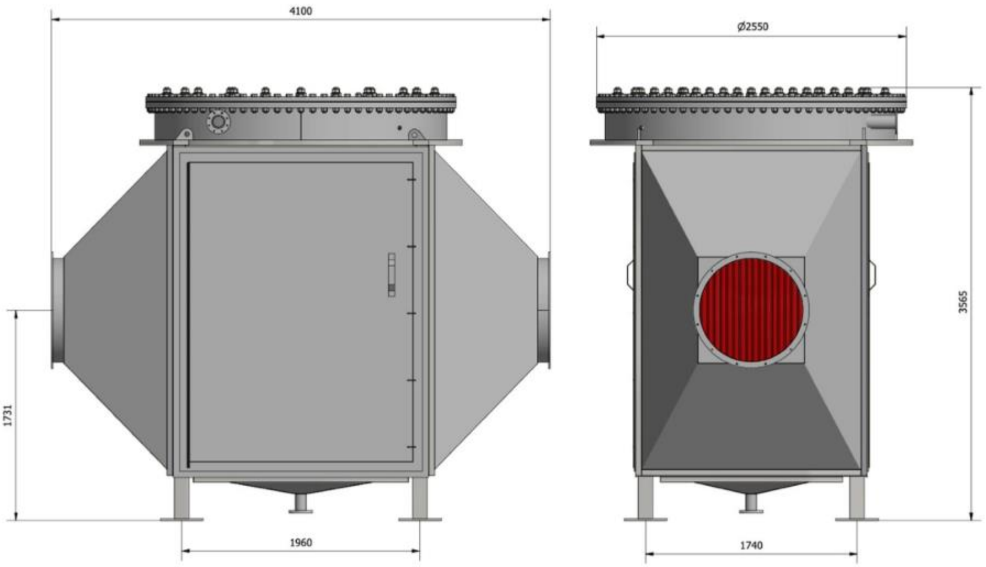
Technological barriers are related to the conservative approach of these industries, for which any additional element which is not related to the achievement of the production goal is seen as a potential for failure. The positive demonstration of the results from the ETEKINA project provides a relevant impact in terms of the future applicability in the industrial context of a technology capable of transforming the waste heat into useful thermal energy. It is a turnkey solution, modular and applicable to a wide types of industrial production lines and, capable to follow, in a flexible way, the performance of the host industry.

A dedicated HPHE has been designed for each type of industry: aluminium, ceramic, steel as presented in Figure 24.

A) Aluminium industry




B) Ceramic industry




C) Steel industry

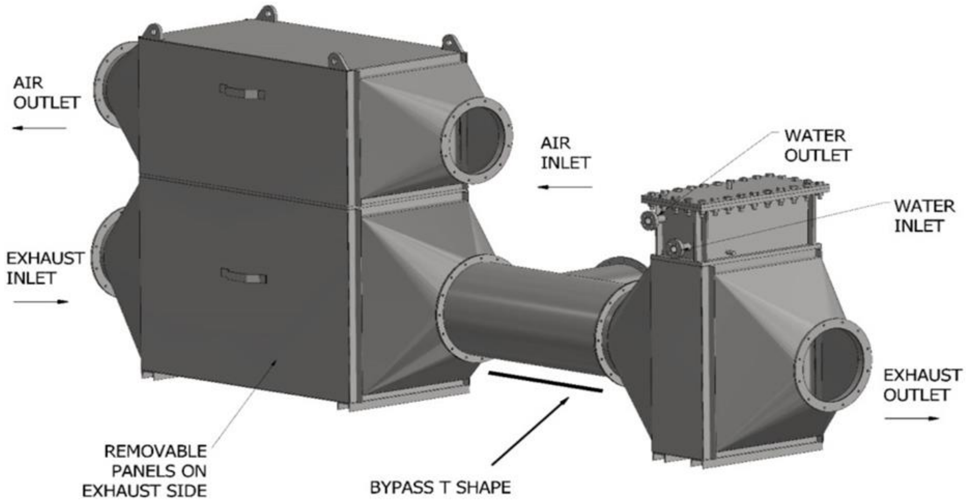



*Figure 24. Visualisation of HPHE used for aluminium, ceramic and steel industry [18][29]*

As the principle of the heat pipe is fixed, a theoretical heat exchanger model for the aluminium case is presented as follows. Through heat pipes, the heat from the hot flue gas stream is transferred to the cold air stream in the HPHE exchanger. Each heat pipe transfers heat independently, operating as an individual heat exchanger. The temperature difference between the flue gas stream and the heat sink stream is crucial for heat exchange to take place. The heat transfer process can be described as a series of thermal resistances, analogous to electrical resistances, Figure 25. The total thermal resistance of a single heat pipe ($R_{th}$, $(\mathrm{K \cdot W^{-1}})$) is described as follows:

$$R_{th} = R_{eo} + R_{cond\_e} + R_{ei} + R_{ci} + R_{cond\_c} + R_{co} \quad (1)$$

where forced convection heat transfer resistances are defined by $R_{eo}$ and $R_{co}$ at the evaporator and condenser; wall radial conduction by $R_{cond\_e}$ and $R_{cond\_c}$ at the evaporator and condenser and $R_{ei}$ *and* $R_{ci}$ show the boiling and condensation resistances, which can be calculated from formula (2) describing the relationship between thermal resistance (R, $(\mathrm{K.W^{-1}})$), heat transfer coefficient (h, $(\mathrm{W.m^{-2}.K^{-1}})$) and heat transfer surface area (A, $(\mathrm{m^2})$):

$$R = \frac{1}{hA} \tag{2}$$

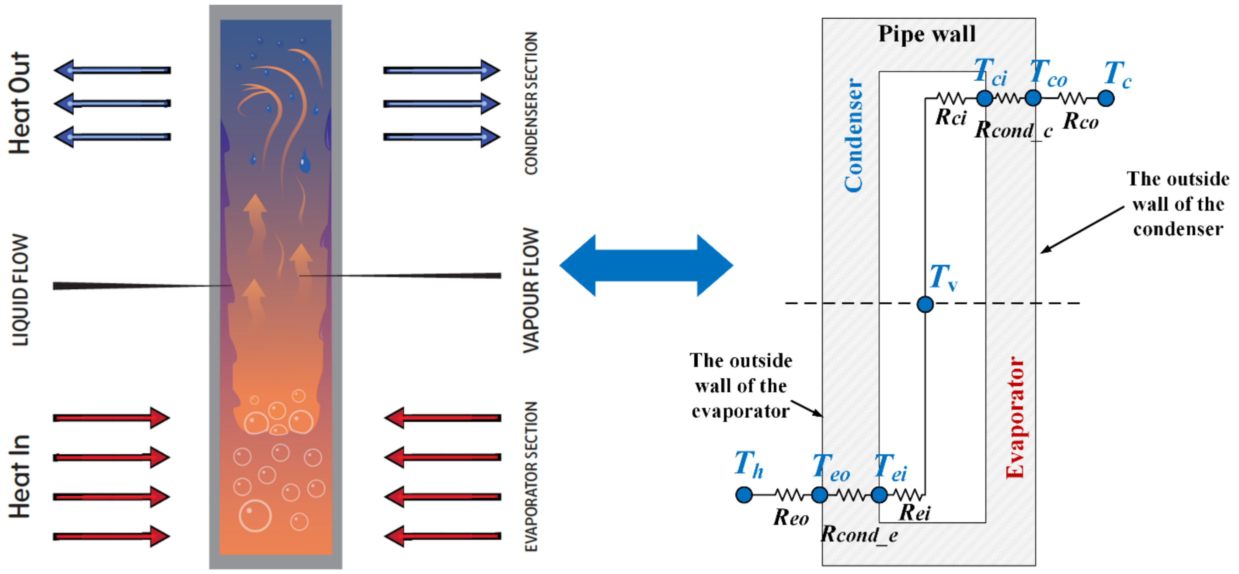



*Figure 25. Thermal resistance model of two-phase working cycle of a heat pipe*

For boiling and condensation, the heat transfer coefficient is determined based on the correlation provided by Rohsenow [65] and Nusselt correlation[66][67], respectively. The radial conduction resistances of the evaporator and condenser walls $\left(R_{cond_{e(c)}}\right)$ are given by the following:

$$R_{cond\_e(c)} = \ln(D_o/D_i)\,/(2\pi L_{e(c)}K_{e(c)}) \tag{3}$$

where the external and internal diameters of the heat pipe are described by $D_o$ and $D_i$ (m), the wall thermal conductivity at the evaporator and condenser by $K_e$ or $K_c$ $(\mathrm{W.m^{-1}K^{-1}})$ respectively and lengths of the evaporator and condenser by $L_e$ and $L_c$ (m).

$R_{eo}$ and $R_{co}$ can be determined from the forced convection heat transfer coefficient of each pipe formula, Zukauskas [68][69][70] and corresponding heat transfer area (Eq 2).

The total thermal resistance $R_{HPHE}$ $(\mathrm{K.W^{-1}})$, based on the electrical analogy in Figure 26, can be determined from the following equation:

$$\frac{1}{R_{HPHE}} = \frac{1}{R_{hp,1}} + \frac{1}{R_{hp,2}} + \cdots + \frac{1}{R_{hp,n-1}} + \frac{1}{R_{hp,n}} \tag{4}$$

where the subscript hp applies to heat pipe, and number of heat pipes in the heat exchanger is n. The total thermal resistance $R_{HPHE}$ of a tube heat exchanger can be expressed by Eq. 5 on the assumption that the resistance of the heat pipe is equal for all heat pipes.

$$R_{HPHE} = \frac{R_{hp}}{n_{total}} \tag{5}$$

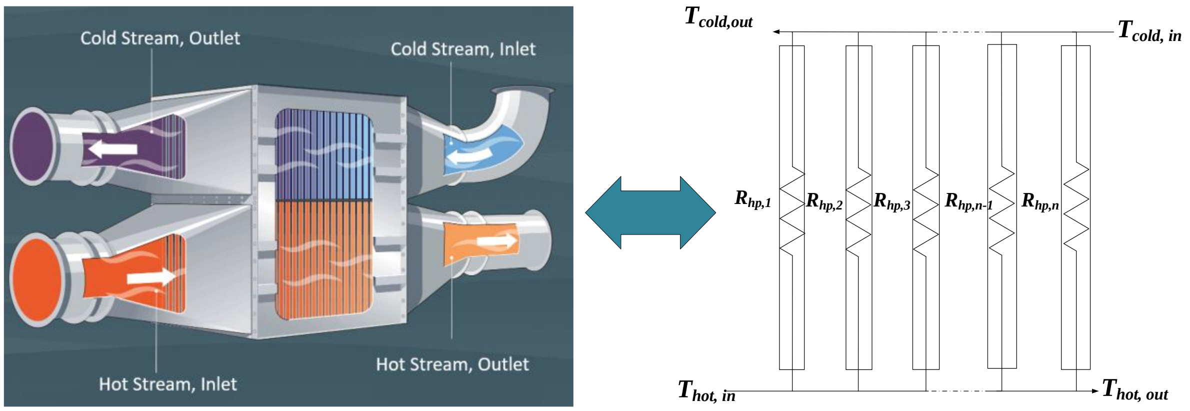



*Figure 26. Thermal electrical analogy of a HPHE*

The ETEKINA HPHEs address both the technical difficulties for recovering and reusing energy losses within the process, as well as the economic barriers. Technical difficulties include:

1. Material constraints and costs. As it is, the case of waste heat streams with high chemical activity requires more advanced recovery equipment materials to withstand corrosive environments.
2. Energy re-use in processes at relatively high temperatures, which require an efficient heat transfer at small temperature differences between source and sink streams.
3. Physical location of the unit processes due to difficulties to transport the heat between those locations.
4. Particulates in exhaust: a specific design and assessment is needed to make sure that particulates don't stick to heat exchanger elements.

## 1.5 Review of life cycle assessment work in target industries with a focus on heat exchangers

Life Cycle Assessment (LCA) is a comprehensive method for evaluating the environmental impacts associated with all stages of a product's life from cradle to grave. The International Organization for Standardization (ISO) provides guidelines for LCA in ISO 14040 and ISO 14044 standards, which delineate four stages: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and

Interpretation. An LCA comprises four main stages: (1) Define the goal and scope of the study, (2) Inventory analysis, (3) Impact assessment and (4) Interpretation of results, Figure 27.

The above method can be implemented in various fields, such as: comparing two systems in terms of energy usage, GHG emissions, or a total life cycle cost [71]; role in achieving the United Nations Sustainable Development Goals [72] and two products and their environmental impact [73].

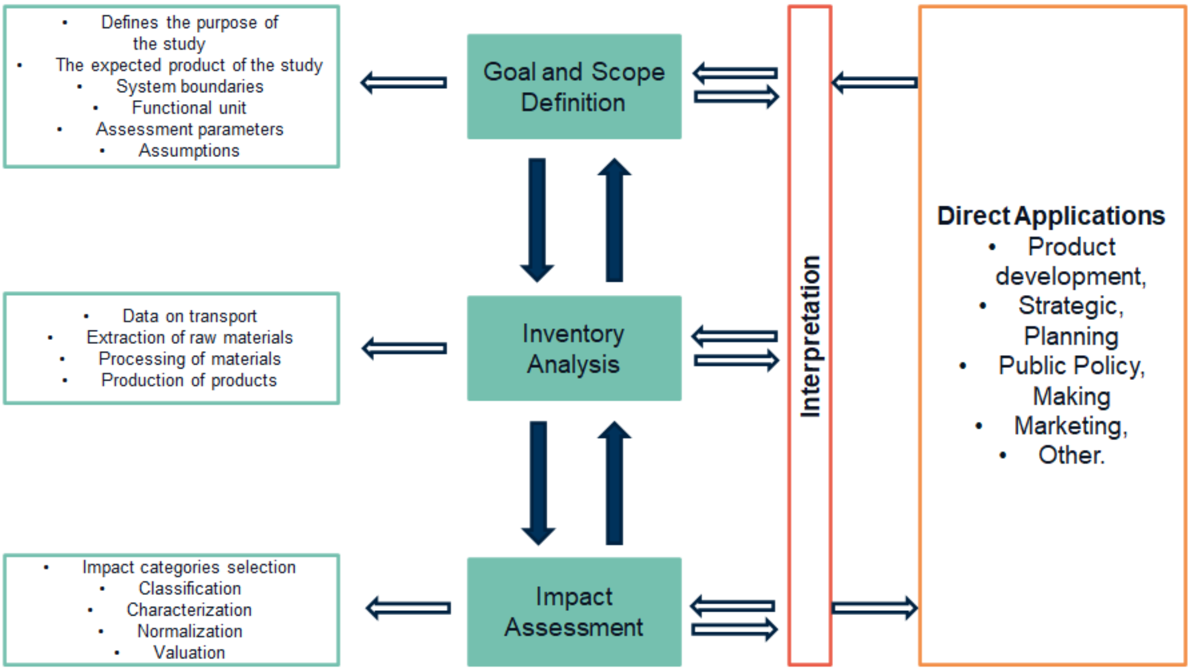



*Figure 27. LCA Assessment Framework (per ISO 97-06)*

Ros-Dosdá et al. [74] focused their analysis on the reduction of greenhouse gas emissions for 2020 and 2050 by the European ceramic tile industry. They used GaBi software to analyse different technological options. The results showed that the 2020 targets were not a problem, however, the 2050 targets require the introduction of innovative technological solutions covering endogenous and exogenous aspects. This involves reducing dependence on non-renewable fuels, applying innovations in product eco-design and implementing highly efficient energy measures. The authors noted a relationship between increasing the scope of LCA analysis and the environmental innovations needed. The main environmental benefits arise during the use and end of life phase. Precise target setting is therefore necessary to be able to compare solutions objectively. Mano et al. [75] used life cycle assessment eco-costs to optimise the heat exchanger network. The eco-cost is derived from the Ecoinvent database. Research has shown that fuel choice is crucial. An air-cooled heat exchanger using encapsulated phase change material (EPCM) was used for dry cooling of the power plant. The LCA and techno-economic analysis for this case was carried out by Zhang et al. [76] in GaBi by comparison with commercial dry and wet cooling technologies as a base system. Ghasemi et al. [77] studied, among other things, the environmental impact of pillow plate heat exchangers with different concentrations of microencapsulated phase change material slurry (from 0 to 15%) in Simapro 9.3 software by utilizing TRACI 2.1 V1.02/US Canadian 2008 method (the Chemical and Environmental Impacts Reduction and Assessment Tool). The results showed a slight increase of 2.5% in emissions to the environment, taking into account that it is the material phase of the system that has the greatest impact on the environment. The literature review performed confirms the lack of an existing life cycle analysis for the heat pipe heat exchanger. Therefore, the main motivation of this research is to assess the environmental benefits of HPHEs in order to expand their potential applications.

Life Cycle Assessment is a method for evaluating the environmental impacts of a product or service from the extraction of its resources to disposal, commonly referred to as "cradle to grave". This approach examines the energy and material flows throughout all stages, including raw material extraction, production, usage, and end-of-life disposal. Section 2.2 provides a general overview of the LCA methodology, both in general and in terms of application in the HPHE technology. LCA is a widely recognised tool that provides transparent environmental communication. Moreover recently, life cycle thinking has been quite prominent in the shaping of environmental policy. A notable example is the European Union's Integrated Product Policy (IPP), as well as similar initiatives globally, such as China’s Circular Economy.

## Stages of an LCA

### Step 1: Define the goal and scope

The Life Cycle Assessment (LCA) process begins with defining the goal and scope, establishing the context and determining how the results will be communicated. In the first step, the objectives of the assessment are formulated, and the products or services are defined. This phase includes key details such as the functional unit, system boundaries, impact categories, assumptions, and limitations, Figure 28

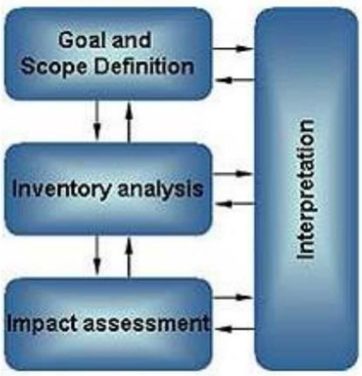



*Figure 28 LCA outline with the four steps that is required for a LCA (UNEP, 2015*

## Step 2: Inventory analysis

The inventory analysis entails the collection and calculation of data to quantify the inputs and outputs that are related to the product system(s) under examination. This includes resource consumption as well as emissions to air, water, and land. The methods for collecting and calculating data follow the goal and scope of the study. In general, two types of data are used. Primary data are the type of data directly extracted or collected from the actual process. For example, the values for the operation of the installed HPHE system were provided directly from Atlas Concorde in the ETEKINA project. On the other hand, secondary data are data that is collected from literature, published in statistic reports etc. The values for the $CO_2$ footprint and other indicators are secondary data and delineated as such.

The findings from the inventory analysis can serve as inputs both for the life cycle assessment and the interpretation phase. Yet, inventory analysis is, by nature, an iterative process. As more data are gathered and the system becomes clearer, new data requirements or constraints may arise. This could necessitate the collection of more accurate data or adjustments to the system boundaries. Consider for instance the integration of renewable energy in an industrial process, other changes in the energy mix, a change in raw material procurement, mode of transport and other factors. This is an issue with most published LCA works, as by definition these are static analyses that are unreliable to use for long term predictions. In the case of this study for instance, there is no way to predict if a firing kiln will be electrified, reducing the amount of waste heat, or if other changes take place, thus a short prediction horizon is employed in the impact estimates, up to 5 years.

## Step 3: Impact Assessment

The life cycle of a product is connected to a very large number of substance emissions and resource extractions, which can substantially vary in their environmental relevance. Life cycle impact assessment (LCIA) helps the interpretation of LCA studies by translating these emissions and resource extractions into a limited number of environmental impact scores [78].

As each input and output, including emissions, has varying environmental impacts, some may have no significant effect, whilst others contribute across multiple impact categories. The impact assessment stage allows highlighting the importance of the most important contributors The impact assessment process is divided into several steps such as classification of the inventory data into distinct impact categories, characterisation or aggregation of said data, normalisation, which entails assessing the relative magnitude of impacts in relation to an individual's effect over a specific period of time, and finally optionally assigning indicator weightings to the different impact categories.

The foundation of impact assessment is characterisation, that is enabled by characterisation factors. Characterisation factors indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released). There are two mainstream ways of deriving characterization factors: (a) at midpoint or (b) at endpoint.

(a) Characterisation factors at the **midpoint** level are located somewhere along the impact pathway, typically at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category (Goedkoop et al. 2009).
(b) Characterisation factors at the **endpoint** level correspond to three areas of protection, i.e. human health, ecosystem quality and resource scarcity.

The two approaches are complementary in that the midpoint characterization has a stronger relation to the environmental flows and a relatively low uncertainty, while the endpoint characterization provides better information on the environmental relevance of the environmental flows, but is also more uncertain than the midpoint characterization factors[78].

The life cycle impact assessment method called ReCiPe2016 used in this thesis is an updated version of the ReCiPe2008 that provides harmonized characterisation factors at midpoint and endpoint levels [79].

Human health, ecosystem quality and resource scarcity are the three areas of protection where DALYs (disability adjusted life years), with relevance to human health, representing the years that are lost or that a person is disabled due to a disease or accident.

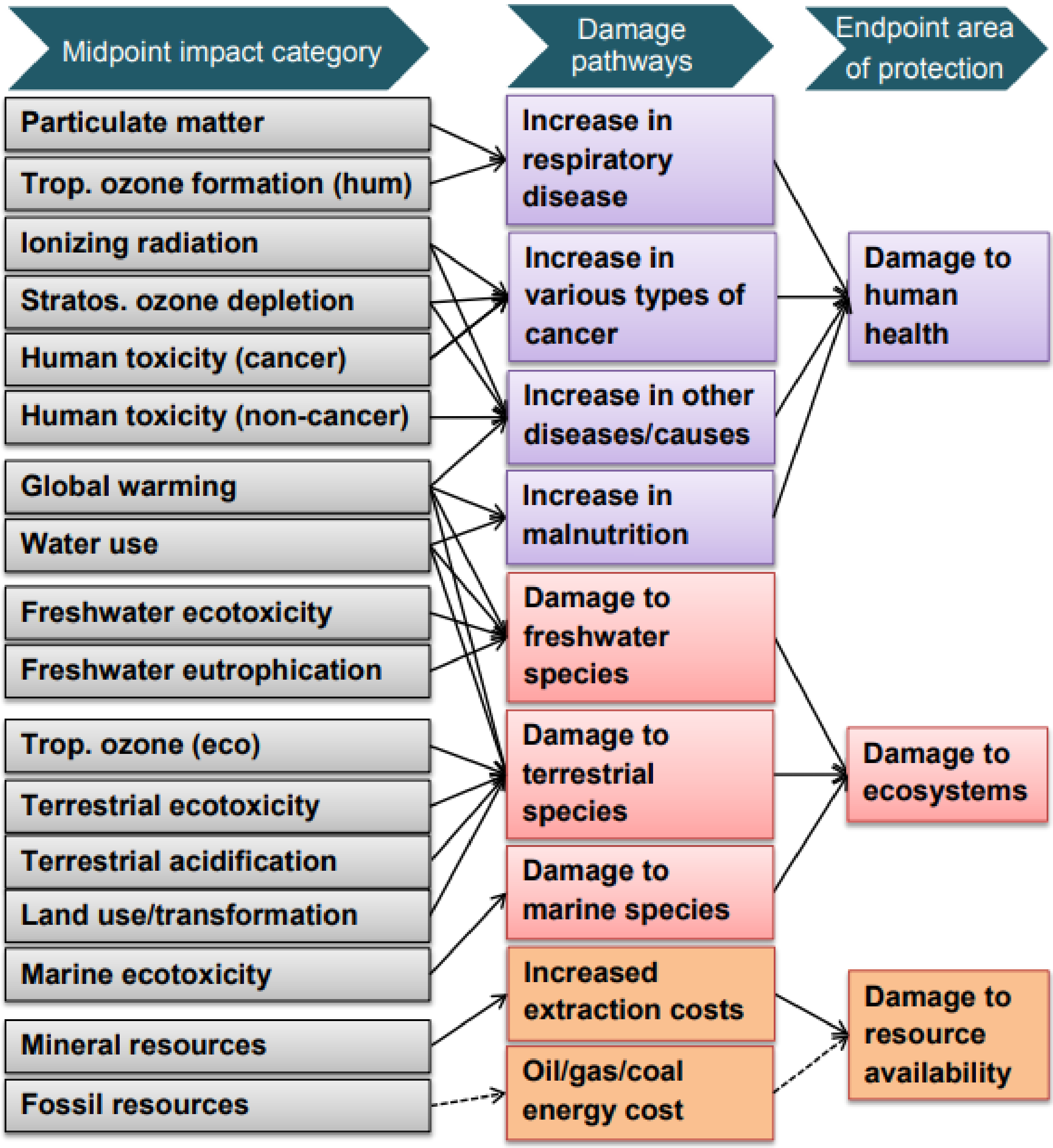



*Figure 29 Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection.*

The overview of the link between the environmental mechanisms, i.e. the midpoints, and the three areas of protection is shown in Figure 29.

The unit for ecosystem quality is expressed as local relative species loss in terrestrial, freshwater and marine ecosystems, respectively, integrated over space and time (potentially disappeared fraction of species·$m^2$·year or potentially disappeared fraction of species·$m^3$·year). To combine the impacts on terrestrial, freshwater, and marine ecosystems into a single unit (species.year), species densities for these three ecosystems were incorporated in the same manner as suggested by Goedkoop et al.[80]. The unit for resource scarcity is dollars ($), representing the additional costs associated with future mineral and fossil resource extraction. Endpoint characterisation factors (CFe) are obtained from midpoint characterisation factors (CFm) using a constant mid-to-endpoint factor specific to each impact category [81]:

$$CFe_{x,a} = CFm_x \times F_{M\rightarrow,E,a}$$

where:

**a** denotes the area of protection, i.e. human health, (terrestrial, freshwater and marine) ecosystems or resource scarcity,

**x** denotes the stressor of concern and

**FM→E,a** is the midpoint-to-endpoint conversion factor for area of protection a.

These mid-to-endpoint factors remain constant for each impact category, as the environmental mechanisms are assumed to be the same for all stressors after the midpoint impact point along the cause-effect pathway.

## Midpoint indicators

ISO/TR 14047:2012 outlines the evaluation of seven key impact categories: Climate Change, Acidification, Eutrophication, Human Toxicity, Photochemical Ozone Creation, Ecotoxicity, and Ozone Layer Depletion. However, in practice, many reviewed studies diverge from this approach, often incorporating additional indicators to enhance the assessment. A detailed list of these indicators, alongside their respective conversion factors, is provided to offer clarity and context.

### Climate change

For the assessment of climate change impacts, the selected midpoint characterization factor is the widely accepted Global Warming Potential (GWP), which quantifies the cumulative increase in infrared radiative forcing caused by greenhouse gases (GHG), expressed in kg $CO_2$-equivalent[82][83]. In relation to human health effects, the methodology proposed by De Schryver et al.[84] was employed to estimate the heightened risks of diseases such as malnutrition, malaria, diarrhoea, and increased flooding. For terrestrial ecosystems, the increase in the potentially disappeared fraction of species due to rising global temperatures was assessed based on Urban's 2015 review [85]. Additionally, the impact of global temperature rise on river discharge and subsequent changes in fish species distribution was evaluated following the framework provided by Hanafiah et al.[86].

**Stratospheric ozone depletion**

For stratospheric ozone depletion, the ozone depletion potential (ODP) was used as the midpoint characterization factor, expressed in kg CFC-11 equivalents. ODP represents the time-integrated reduction in stratospheric ozone concentration over an infinite time horizon[87]. The human health impacts of reduced stratospheric ozone were modelled using a midpoint-to-endpoint approach, following Hayashi et al. [88]. This method proceeds in two stages: first, it links ozone depletion to an increase in UVB radiation, and second, it associates this UVB rise with an elevated disease burden. The estimation of human health damage included the increased incidence and corresponding loss of DALYs due to three types of skin cancer (malignant melanoma, basal cell carcinoma, and squamous cell carcinoma) as well as cataracts caused by UVB exposure.

**Ionising radiation**

The midpoint characterization factor for ionising radiation is based on the collective dose resulting from radionuclide emissions. This midpoint factor, referred to as the Ionising Radiation Potential (IRP), is expressed in Cobalt-60 equivalents to air. In the mid-to-endpoint analysis, the human health impacts of the collective dose were evaluated by estimating the incidence of various cancer types. This approach used fatal and non-fatal cancer incidence rates per cancer type, as reported by Frischknecht et al.[89]. These data were then combined with the disability weight for each cancer type (**Error! Bookmark not defined.**)[84] to estimate the health burden.

**Fine particulate matter formation**

For the midpoint characterization of fine particulate matter formation, the human intake of PM2.5 was considered. The particulate matter formation potentials (PMFP) are expressed in kg of primary PM2.5-equivalents. The change in ambient PM2.5 concentrations following the emission of precursors, such as $NH_3$, NOx, $SO_2$, and primary PM2.5, was estimated using emission-concentration sensitivity matrices from the global source-receptor model TM5-FASST[90]. The intake fraction served as the basis for calculating human health impacts, specifically cardiopulmonary and lung cancer mortality resulting from exposure to fine particulate matter, as outlined by Van Zelm et al. [91].

**Photochemical ozone formation**

For the midpoint characterisation factors of photochemical ozone formation concerning human exposure, the intake of ozone by the human population was used. The human health ozone formation potential (HOFP) is expressed in kg NOx-equivalents. The change in ozone concentration after precursor emissions (NOx or non-methane volatile organic compounds (NMVOC)) was predicted using emission-concentration matrices from the TM5-FASST model [91]. The ecosystem ozone formation potential (EOFP), also in kg NOx-equivalents, relates to the cumulative difference between hourly mean ozone concentrations and 40 ppb during daylight hours across the growing season in ppm·h (AOT40) [91]. Effect and damage factors for respiratory mortality linked to ozone exposure were determined by Van Zelm et al.[91], using intake fractions. For damage to terrestrial ecosystems, the effect factor reflects the change in the PDF of forest and grassland species due to changes in ground-level ozone exposure.

**Terrestrial acidification**

The midpoint characterisation factors for acidifying emissions were based on the pollutant's atmospheric and soil fate, as calculated by Roy et al. [92]. Acidification potentials (AP) are expressed in kg SO2-equivalents. The GEOS-Chem model [93] was used to estimate changes in acid deposition following emissions of NOx, NH3, and $SO_2$. The resulting changes in soil acidity were then derived using the PROFILE geochemical steady-state model [94]. An effect factor was added to the endpoint calculations to account for species loss due to soil acidity[92]. This factor measures the change in the PDF of vascular plant species with varying H+ concentrations across biomes such as temperate forests, tundra, and (sub)tropical forests [95].

**Freshwater eutrophication**

For freshwater eutrophication, midpoint characterization factors focus on the fate of phosphorus, with freshwater eutrophication potentials (FEP) expressed in kg P equivalents to freshwater. Phosphorus fate factors for freshwater emissions were derived from Helmes et al.[96], and for emissions to agricultural soils, it was assumed that 10% of phosphorus is typically transported to surface waters [97]. The effect factor for freshwater eutrophication, which captures species loss due to phosphorus concentrations, was incorporated into the midpoint calculations based on Azevedo et al.[98]. This factor measures changes in the potentially disappeared fraction (PDF) of species, depending on the type of freshwater body, species group, and climate zone.

**Toxicity**

For toxicity, the midpoint characterization factors for human toxicity, freshwater ecotoxicity, marine ecotoxicity, and terrestrial ecotoxicity are expressed in kg 1,4-dichlorobenzene-equivalents (1,4DCB-eq), derived from the fate and effects of chemical emissions. These calculations were performed using the global multimedia fate, exposure, and effects model USES-LCA 2.0[Error! Bookmark not defined.], updated for dissociating chemicals[Error! Bookmark not defined.] and incorporating data from the USEtox database [99]. The ecotoxicological effect factor evaluates changes in species richness due to altered environmental concentrations of chemicals. Ecotoxicological damage factors use acute toxicity data as an approximation for real-world conditions[100].

The human toxicity category is selected to assess the impact of emissions from substances used throughout the product's lifecycle on human health. The human toxicity potential is determined by the fate, exposure, and effects of toxic substances over an infinite time horizon and is measured in the reference unit of kg 1,4-dichlorobenzene (DCB) equivalent (vi). This impact category is included to highlight that, although a product may not pose direct harm to humans during its use phase, its manufacturing processes can involve harmful substances that negatively affect human health. Moreover, human toxicity factors distinguish between carcinogenic and non-carcinogenic effects, reflecting changes in disease incidence from substance intake.

**Water use**

In terms of water use, the midpoint characterization factor is expressed in cubic meters of water consumed per cubic meter extracted. Water consumption for agriculture was estimated using water requirement ratios from[101], while estimates for industrial and domestic use were based on assumptions from [102]. The impact on human health is measured in DALYs, reflecting malnutrition caused by water shortages in low-development regions[103]. Impacts on terrestrial ecosystems were assessed using net primary productivity (NPP) as a proxy for damage to vascular plant species **Error! Bookmark not defined.**, and impacts on freshwater ecosystems were quantified by estimating fish species loss from reduced water discharge [86].

**Land use**

For land use, midpoint characterization factors are expressed in $m^2 \cdot yr$ annual crop equivalents, reflecting species loss due to different land use types, such as annual crops, forestry, and urban areas. Species loss was estimated by comparing species richness in natural and altered land covers [104]. Land conversion midpoint factors also considered recovery toward semi-natural habitats, based on average recovery times [105].As these midpoint characterization factors already capture local species loss, no additional steps were applied in the mid-to-endpoint pathway.

**Mineral resource scarcity**

For mineral resource scarcity, the midpoint characterization factor is Surplus Ore Potential (SOP), expressed in kg Cu-equivalents. This factor accounts for the decline in ore grade due to current mineral extraction, leading to an increased amount of ore required per kilogram of extracted mineral. SOP measures the additional ore produced in the future due to present-day extraction activities [106].

The midpoint-to-endpoint factor for mineral resource scarcity converts surplus ore to surplus costs, using cumulative tonnage relationships for 12 metals[107].

**Fossil resource scarcity**

Lastly, for fossil resource scarcity, the midpoint characterization factor is Fossil Fuel Potential (FFP), expressed in kg oil-equivalents. This is calculated as the ratio between the higher heating value of the fossil resource and the energy content of crude oil [108]. Endpoint characterization factors for fossil resource extraction—covering crude oil, natural gas, and coal—are expressed as Surplus Cost Potential (SCP), derived from cumulative cost-tonnage relationships for these resources.

Table 3 presents midpoint indicates and their units.

*Table 3Midpoint indicators and their units*

| | |
|---|---|
| Climate change | kg $CO_2$-eq |
| Particulate matter | kg PM2.5-eq |
| Human carcinogenic toxicity | kg 1,4DCB-eq |
| Ozone formation | kg NOx eq |
| Terrestrial acidification | kg SO2 eq |
| Fossil resource scarcity | kg oil eq |
| Mineral resource scarcity | kg Cu-eq |
| Ozone formation, Human health | kg NOx eq |

## Step 4: Interpretation of Results

The results from the impact assessment are then interpreted to provide insights and recommendations. This involves:

**Results Analysis**: Analysing the results to identify significant impact contributors and lifecycle stages with the highest environmental burdens.

**Sensitivity Analysis**: Performing sensitivity analysis to understand the influence of key assumptions and data uncertainties.

**Reporting**: Compiling the findings into a comprehensive report that includes graphical representations of the results, key impact areas, and suggested improvements.

Example Application: 100kW Heat Exchanger

### 1.5.1 Literature review of LCA studies on heat exchangers in industrial applications

There are almost 50,000 results on ScienceDirect alone related to heat exchanger applications in energy intensive industries. Likewise, there are over 10,000 results on LCA in energy intensive industries. Conversely, there is a distinct gap in the assessment of heat exchanger lifecycle impacts in energy intensive industries.

While there are studies highlighting energy and emissions performance improvements, these do not go into the depth required to assess environmental impacts on the level that is enabled through LCA. For instance, Bianchi et al. compared plate heat exchangers (PHEs) and shell-and-tube configurations in steel billet reheating furnaces, identifying a 17% lower global warming potential (GWP) for PHEs due to reduced material intensity and fouling resistance. In the ceramics sector, Furszyfer Del Rio et al. emphasized the importance of LCA in validating the circularity of kiln exhaust heat reuse, showing that spray dryer preheating via HPHEs lowered fossil fuel dependence by 35% while aligning with EU Product Environmental Footprint (PEF) criteria [109]. A thesis from 2016 assessed the LCA and Life Cycle Costing of heat exchangers in the Port of Gothenburg [110].

As there are no other relevant studies as of this date, the ambition of this thesis is to develop a benchmark for the assessment of the lifecycle impacts of heat exchangers in the target industries.

### 1.5.2 Available tools for LCA

There are many software tools for LCA analysis. The most commonly used are presented below.

- **OpenLCA**

OpenLCA is a tool for modelling and assessing life cycles, performing Life Cycle Assessments (LCAs). This covers modelling the life cycle in a narrow sense, by connecting processes visually or via tables, assessing them, regarding environmental, economic or social impacts, and analysing these results for the identification of hotspots. Also, comparisons of products are possible, and also assessments and comparisons of organisations. This requires the importing of the external databases and methods, which can be either for free use or commercial [111].

- **SimaPro**

SimaPro [112] allows users to customize the modelling of their LCA by adjusting parameters and inputs to reflect specific industry or regional factors. SimaPro is LCA software chosen by product designers, LCA experts, consultants and research institutes. SimaPro, through life cycle assessment (LCA), supports sustainability efforts. By analysing data and sustainability reports, the environmental performance of services and products can be compared and measured, thereby influencing decision-making. In addition, the software can be used for: environmental, carbon, water and social footprints, sustainable product design, biodiversity assessment. It enables the impact of any substance or process to be studied. Several databases are integrated into the LCI databases such as ecoinvent, industry data or agri-footprint and additional ones can be downloaded directly from the website. By changing the parameters in the LCA model, it is possible to carry out extensive scenario analysis to reflect specific industry or regional factors. In this thesis, SimaPro was selected due to the availability of resources and training material, the reasonable learning curve, the acceptance of the tool in the research ecosystem, as well as the availability of an academic license.

- **Sphera (GaBi)** [113]

Sphera's LCA for Experts (formerly GaBi) similarly to the previously mentioned software allows LCA modelling and reporting based on reliable and consistent environmental data (more than 20 sector databases).

- **One Click LCA**

One Click LCA [114] is a tool to calculate the environmental impact of construction, infrastructure and renovation projects, in addition to publishing third-party verified environmental production declarations (EPDs). The manufacturer's website states that One Click LCA is supporting more than 80 international standards as well as certifications, including LEED, GRESB, BREEAM, and others. Furthermore, it integrates seamlessly with BIM software tools such as: Autodesk Revit®, Bentley iTwin®, Tekla Structures® and many others. It enables the efficient assessment of life-cycle cost, and biodiversity and circularity assessment.

- **EcoChain (Mobius)**

Ecochain Mobius [115] is a popular tool widely used by organizations and businesses to carry out Life Cycle Assessments. It features a user-friendly interface and functions to facilitate data collection and analysis.

- **Umberto**

Umberto [116] enables the environmental impact of companies or products to be analysed (PCF, CCF, LCA, EPD). It is software for sustainability analyses, life cycle assessments (LCA) or material flow analyses (MFA) while pointing out areas for improvement.

### Software selection: SimaPro

SimaPro is often chosen over other LCA software due to its comprehensive features and flexibility, which are particularly valuable for complex assessments. The software is suitable for academic research due to its adaptability, that is highly valuable for the less explored application of heat exchangers. Simapro is also compatible with the most prevalent databases (eg ecoinvent) and environmental impact assessment methods, such as ReCiPe, CML, and ILCD. Simapro is relatively user-friendly, features extensive documentation, and thus is more accessible for LCA beginners despite a somewhat steep learning curve, that is the trade-off for the flexibility. Simapro is also extensively used in academia meaning that results are easier to compare with other studies, improving the aspects of credibility and acceptance in the research community. Therefore, SimaPro was chosen to perform the LCA analysis of HPHE.

# Chapter 2: Methodology

## 2.1 Design of the research

The current thesis is built upon the ETEKINA project as a foundation and is intended to advance the research and innovation work carried out, addressing specific research gaps with regards to the wider energy efficiency domain, and focused on the HPHE technology and its application in EIIs. The ETEKINA project was focused on thermal energy recovery with a clear technological scope, demonstrating new technologies. The mission statement of ETEKINA was based on the premise that although resource and energy efficiency have already been improved in EIIs and continue to do so, energy and fuels still represent a significant part of the operating costs. For instance, in the Aluminium industry, the average primary energy costs are estimated over 22% of total operating costs [62]. In the steel industry these costs represent up to 40% of total operational costs [63]. Finally, in the ceramics production processes, the energy consumption accounts for over 30% [64] of production costs. These figures make them suffer from a lack of competitiveness on the world stage since energy in Europe is expensive, which was true in 2016 when the proposal was being prepared, but even more so in 2024.

Thus, the strategic goal of the ETEKINA project was to achieve substantial energy savings coupled with significant greenhouse gas emission reductions by use of waste heat recovery systems. Namely, the goals of the project were:

- The design and development of an innovative heat recovery technology based on the HPHE, capable of recovering 57-70% of the waste heat, and reducing the primary energy consumption of the process by 15-50%, while reducing emissions by over 160t$CO_2$/y.
- The demonstration of cost-effective waste heat recovery in industrial applications and operational working conditions in the three sectors.
- The support for market penetration of new heat exchanger technology applications, focusing primarily in the non-ferrous, steel and ceramic sectors.

The ETEKINA Heat pipe heat exchanger is an innovative product intended to be used in challenging waste heat streams; it has special features of automatic fouling management, avoiding acid condensation, high temperature operation and multi-sink capability.

Energy efficiency is the current market trend which encourages the improvements of energy security by promoting the reduction of emissions, reduction of energy consumption, reducing energy costs to enhance competitiveness and to contribute to the overall energy and climate goals. Effectively these trends are all fulfilled by the use of the innovative ETEKINA HPHE to recover 40% to70% of waste heat energy in process/ energy intensive industries, reducing emissions and costs of energy consumption due to reducing the use of raw energy. In turn this helps the customer to fulfil their obligation to their social corporate responsibility and legal requirements, as well as enhance their competitive advantage.

| | |
|---|---|
| | **Title**: HEAT PIPE TECHNOLOGY FOR THERMAL ENERGY RECOVERY IN INDUSTRIAL APPLICATIONS<br>**Call**: EE-17-2016-2017 - Valorisation of waste heat in industrial systems<br>**Details**: Horizon 2020, Budget: €5,539,610, Duration: 2017-2022 |

*Figure 30 Information about the ETEKINA project*

ETEKINA was submitted to the Horizon 2020 (FP8, running from 2013 to 2020) call for proposals titled EE-17-2016-2017 - Valorisation of waste heat in industrial systems. There are several calls for proposals each year that focus on industrial energy systems and overall sustainability, Figure 30. The focus is mainly on collaborative industrial research projects that usually have budget allocations exceeding €5 million and range in the Technology Readiness Level between 5 and 7, Figure 31. This means that each project features between 10 and 30 organisations working together to achieve specific objectives related to decarbonisation of industrial processes, integration of renewables, reduction of the carbon and energy footprint of products etc. What sets the ETEKINA project apart is that it is specifically focused on waste heat recovery, which is a rare occurrence. In fact, while waste heat recovery is a valuable technology and falls within the scope of a very wide range of research projects (e.g., geothermal, district heating, process intensification etc), it is rarely the singular focus of a call for proposals.

| Level | Description |
|---|---|
| TRL 1 | Basic principles observed, the start of scientific research |
| TRL 2 | Technology concept formulated, no to very little experimental proof of concept |
| TRL 3 | Experimental proof of concept conducted |
| TRL 4 | Technology validated in the laboratory |
| TRL 5 | Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies) |
| TRL 6 | Technology demonstrated as a fully functional prototype in a relevant environment (industrially relevant environment in the case of key enabling technologies) |
| TRL 7 | System prototype demonstration in operational environment |

*Figure 31 EU Horizon 2020 technology readiness levels*

This meant that ETEKINA featured 10 partners focusing on the HPHE technology as a unit and delivering high value results such as research work on shell materials, working fluids, simulations, prototyping and testing, Figure 32.

*Figure 32 ETEKINA Consortium*

There are however, notable gaps in the assessment of environmental impacts for heat recovery solutions.

Firstly, there are few studies assessing heat exchangers from an environmental perspective, focusing instead on energy and economic benefits. The environmental benefits are mainly accumulated in the operation stage and stem from energy savings; thus the lack of studies can be attributed to this effect. This however leads to the lack of visibility of the environmental advantages of waste heat recovery.

Secondly, industrial heat recovery systems are largely bespoke and differ significantly from one-another, even in the same industries. This customization leads to variability in performance, material use, and environmental impacts, complicating the assessment process. Also, long-term performance and degradation diverge, and are difficult to estimate in systems with long lifespans. Accurately capturing the long-term environmental benefits, such as energy savings and reduced emissions, requires detailed operational data, which may not always be available or reliable, complicating the LCA process.

These issues are addressed in this study, taking advantage of the ETEKINA project and its focus on heat exchangers, providing a wealth of information for the technologies and enabling the LCA.

Through the LCA I have strived to quantify the environmental benefits of HPHE technology in reducing greenhouse gas emissions and improving energy efficiency in EIIs. I have paired the LCA with the evaluation of exploitation potential, such as return on investment, by assessing energy savings and cost reductions from implementing HPHEs. The findings from the LCA were aligned with EU policy objectives, such as those outlined in the European Green Deal, relevant to industrial decarbonization. Finally, I have compared HPHEs to other technologies with decarbonisation potential, using the LCA to highlight the advantages and limitations of HPHEs, supporting industries and other stakeholders to make informed decisions about which technology best suits their needs in terms of both environmental and economic performance.

## 2.2 Life Cycle Assessment of HPHE technology

## 2.3 LCA model construction for the HPHE technology

The LCA model for the HPHE in the target industries (ceramic, aluminium, steel) was designed to evaluate the environmental impacts of the implementation of the HPHE technology for waste heat recovery in the process lines, as addressed in the ETEKINA project. The LCA model data were collected, and the model structure was consolidated in an excel sheet prior to the generation of the model in the LCA software. The methodological approach was defined. There are three primary methodological approaches for conducting a life cycle assessment:

The **Cradle to Gate** approach begins with raw material extraction and concludes at product manufacturing, excluding use, recycling, and disposal phases. As we are focusing on the use phase, this approach is not considered.

The **Cradle to Cradle** approach offers the most comprehensive analysis, including recycling and all other relevant processes from raw material extraction to final disposal. Despite being a holistic approach, end-of-life management of heat exchangers is complex as the total lifetime is difficult to predict. Moreover, accumulation of corrosion and fouling can lead to asset failure and while this is not the case for the HPHE, it is one of the reasons that there is limited life cycle related literature available. Thus, the only data source for C2C approach would be primary data that is scarce and not characteristic as heat exchangers are largely bespoke systems.

The **Cradle to Grave** method extends from raw material extraction to product disposal but omits recycling, thus being the most suitable for this study.

The material selection is based on the properties of thermal conductivity, corrosion resistance, and mechanical strength, **Error! Not a valid bookmark self-reference.**.

*Table 4 Structural material for each HPHE unit in the study*

| Unit | Weight (kg) | Material |
|---|---|---|
| Italy (ceramics) | 12,050 kg | Stainless steel |
| Slovenia (steel) | 2,950 kg | Carbon steel |

| | | |
|---|---|---|
| Spain (aluminium) | 2,100 kg | Carbon steel |

For the working fluid, water, ammonia or commercial fluids are usually used. The working fluid can be recycled as there is no physical connection between the heat pipe exterior and interior. The energy required to manufacture the HPHE is omitted, as it accounts for a very low share of the steel production at 1.4%.

The scope of the study is more complex, and includes establishing system boundaries, the functional unit (industrial processes in each case), and specifying the lifecycle stages to be included (e.g., raw material extraction, manufacturing, use phase, end-of-life). An analysis of the work done for each of the demo cases is provided in the next sections.

### 2.3.1 Demo case #1 ceramic processing

#### Introduction

The ceramic industry is widely recognized as a high-energy intensive sector. According to a report by Confindustria Ceramica [117], the Italian ceramic tile and refractory materials industry consumes approximately 1.5 billion cubic meters of natural gas annually, along with an electricity demand of 1,800 GWh per year. Given the significant levels of waste heat generated, the industry is well-suited for the implementation of industrial waste heat recovery systems, which aim to reduce greenhouse gas emissions, lower energy costs, and enhance overall process efficiency. The “Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry” (2007)[118] reviews numerous methods for improving industrial performance, with particular emphasis on waste heat recovery from the kiln. This excess heat, particularly from the cooling zones of roller kilns, can be repurposed to preheat air for the drying phase or utilized in cogeneration systems such as CHP or ORC to produce both heat and electricity for the plant [119].

The use of cogeneration units is especially advantageous due to the ceramic manufacturing process's simultaneous demand for heat and electricity. Mezquita et al.[120] introduced a theoretical approach to quantify energy savings from the recovery of cooling gases in the exhaust chamber, achieving potential savings of up to 17% in the case study analysed. Similarly[121] demonstrated that an organic Rankine cycle is an efficient method for heat recovery from the indirect cooling air of ceramic furnaces, with thermal power recovery ranging from 128 kW to 180 kW, and maximum electrical power outputs between 18.5 kW and 21 kW. Additionally, Beltran [122] proposed a cogeneration system where heat from the cogeneration plant is mixed with hot air from the kiln's cooling section. If the temperature remains insufficient, a gas burner is employed to meet the required level.

## End user: Atlas Concorde

Atlas Concorde, a leading player in the global ceramic industry, has over 50 years of history since its founding in 1969. The company has experienced faster-than-average revenue growth in the last 15 years, thanks to more than 4,000 customers across 130 countries. With sales reaching €360 million in 2022 and over 800 employees, Atlas Concorde is known for its commitment to quality and sustainability. The company operates four production facilities on five continents and maintains a strong international presence with 16 commercial offices and 7 showrooms. The Fiorano Modenese plant is recognized as one of the most advanced in Italy, while the Finale Emilia plant is undergoing significant expansion to boost its capacity, focusing on large slabs and wall tiles. The company has long prioritized responsibility and partnership, reinforcing its global leadership in the tile market.

Ceramiche Atlas Concorde is a prominent player in the ceramic tile sector, offering high-performance and aesthetically driven ceramic solutions across various applications. With over four decades of operation, the company has established a reputation for strength, ethical practices, and reliability, reflected in its consistently positive financial performance. Serving more than 2,700 customers in over 100 countries, Atlas Concorde has earned a high level of trust within the industry. Recognizing that the ceramic industry is highly energy-intensive—where energy costs, primarily from natural gas and electricity, represent the third-largest expense—Atlas Concorde is actively addressing the rising energy prices and competition from producers utilizing cheaper energy sources. The Italian ceramic industry, including Atlas Concorde, is increasingly focused on improving energy efficiency.

In recent years, the company has implemented several energy efficiency initiatives, including the modernization of ceramic machinery, installation of new cogeneration plants, and the enhancement of waste recovery systems. A key area of exploration involves the reuse of waste heat streams, which have significant temperature recovery potential. Atlas Concorde is currently investigating the possibility of directing this recovered energy to the dryers, which would result in substantial energy savings.

In collaboration with the ETEKINA project partners, Atlas Concorde seeks to address the challenges of corrosion and dust associated with kiln exhaust gases and to identify the optimal thermal medium, whether oil, superheated water, or another solution. Any necessary modifications to existing equipment will be closely monitored to ensure the effective recovery and utilization of waste heat.

## Case study

The ceramics industry is the second largest energy consuming sector in Europe. The main energy used in the ceramics industry is heat generated through burners using natural gas. The main area can be identified in three stages, the drying stage and the firing stage, and the cooling stage. The firing stage represents about 75% of the total energy cost. The roller hearth kiln technology is considered to be the most cost-effective solution for ceramic tile manufacturing. The kiln is separated into two sections, the firing stage and the cooling stage. The cooling stage generates large amounts of waste heat as the exhaust of the kiln is composed of a challenging flue gas for heat recovery. The recovery of this heat in an efficient way with no cross contamination has been achieved with a heat pipe heat exchanger (HPHE) system, which was designed, manufactured and installed on a roller hearth kiln and is presented in Figure 33.

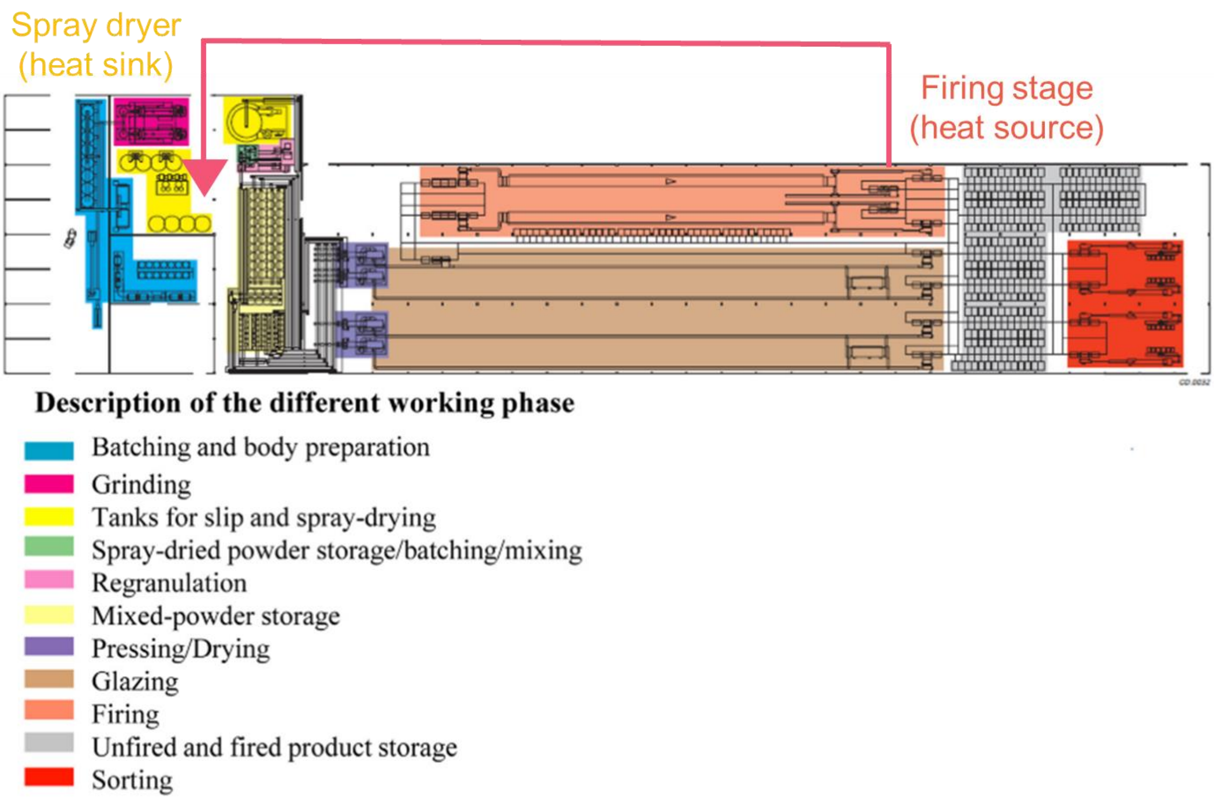



*Figure 33 Concept of the waste heat recovery implementation in the ceramics demonstration*

The tile ceramic industry is the largest sector within the traditional ceramics sector. Tile manufacture represents a market of 14 billion Euros and 75% of the total energy consumption regarding the other traditional ceramics sector. Ceramic tiles consume large amounts of natural gas, and the emissions related to the natural gas consumption are evaluated at about 265 kg of $CO_2$ per tonne of fired tile. The energy used in the manufacturing of tiles is around 28 kWh/m$^2$[123].

By reducing the energy consumption, the emissions will also be reduced. In ceramics manufacturing, some gaseous pollutants are also produced, such as $SO_X$, $NO_X$, HF, and HCL.

The manufacturing process of the tiles depends on the type of tiles produced. In this study the process investigated is based on the roller hearth kiln technology of the Atlas Concorde process line. The tile can be unglazed, single glazed or double glazed. Five main steps can be distinguished in the process: the raw material and body preparation (the composition of the tile influences its mechanical, durability and visual properties.), the shaping (by using impact toggle presses, screw presses or hydraulic presses with a pressure of about 35 MPa), the drying (the drying temperature depends on the drying technology used: roller dryers, tunnel dryers or vertical dryers), the firing (increase the mechanical properties and guarantee a good integrity; the tunnel kiln or the roller hearth kiln) and the final product shipping[123]. A schematic representing the manufacturing process of tiles can be seen in **Error! Reference source not found.**.

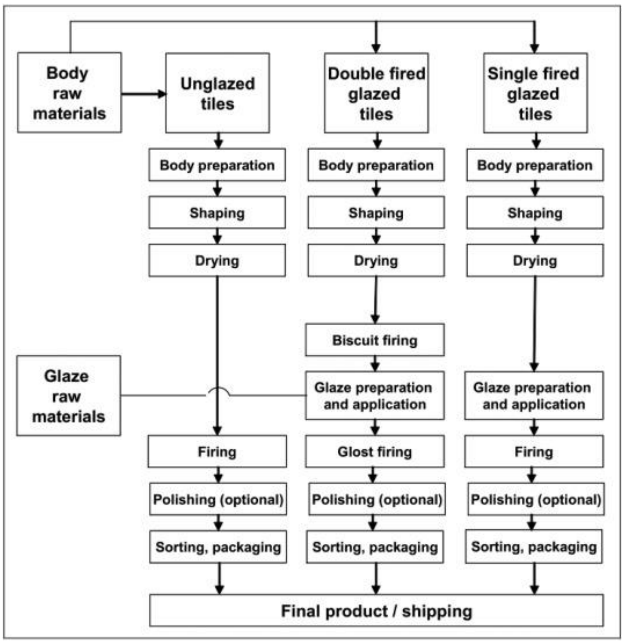



*Figure 34 Schematic of the tiles manufacturing process* [123]

The composition of ceramic tiles includes a blend of natural materials, such as aluminium silicate-based clays and metal oxides, along with synthetic additives like pigments and colorants. The raw materials are mixed in a controlled environment, with water acting as a bonding agent (approximately 35%). This mixture is then dried through a spray drying process at temperatures ranging from 350°C to 450°C, reducing the moisture content to 5%–9%. The resulting product is a powder with a moisture level of 5%, which is then shaped using various pressing techniques, such as impact toggle, screw, or hydraulic presses, at a pressure of around 35 MPa.

Once shaped, the tiles are subjected to a drying process, with the technology used depending on production requirements—tunnel, roller, or vertical dryers. Drying temperatures range from 200°C to 220°C for vertical dryers and 300°C to 350°C for tunnel dryers, and the process lasts between one and four hours, depending on the moisture content. The heat required for drying is either recovered from the kiln's waste heat or generated through the combustion of natural gas. A key challenge in utilizing kiln waste heat lies in the composition of the exhaust gases, which may affect the quality of the final product.

The primary objective of the firing stage is to strengthen the tile by binding its molecular structure, enhancing its mechanical properties and ensuring durability. Two main kiln technologies are employed in the ceramics process: the tunnel kiln and the roller hearth kiln. The roller hearth kiln is the dominant technology in tile production today, though certain heat recovery techniques developed for tunnel kilns can also be applied to roller kilns, particularly in terms of capturing waste heat from exhaust gases. The firing process involves four stages: heating the tile to approximately 1300°C, followed by direct cooling using air streams (1300°C–700°C), indirect cooling through radiative processes (700°C–300°C), and finally slow cooling, bringing the tile down to 30°C.

The ceramics industry predominantly relies on natural gas and other fossil fuel burners for firing porcelain tiles, resulting in significant $CO_2$ emissions and inefficient heat usage. Ceramic tiles consume large amounts of natural gas, and the emissions related to the natural gas consumption are evaluated at about 265 kg of $CO_2$ per tonne of fired tile. The energy used in the manufacturing of tiles is around 28 kWh/$m^2$[124].

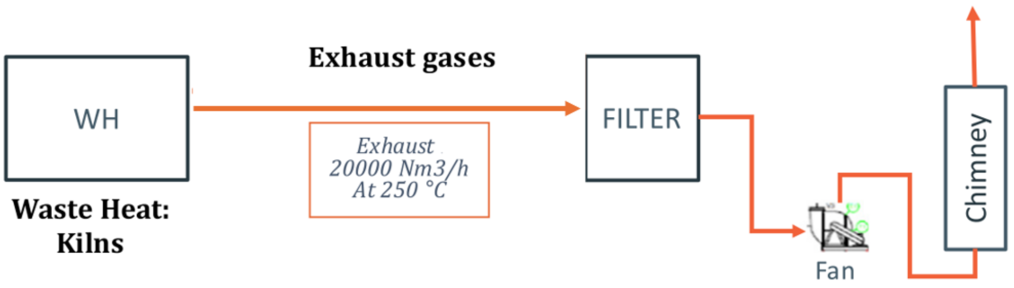
With the European ceramics sector emitting around 19 million tonnes of $CO_2$ annually—roughly 1% of total industrial emissions—decarbonizing the firing process is critical to achieving industrial sustainability. Conventional roller kilns, commonly used in tile production, operate with an efficiency as low as 13%, with most heat lost through the emission of hot gases. This inefficiency makes the process highly energy-intensive, raising production costs and the price of the final product. Additionally, the industry's reliance on natural gas, a finite resource, makes manufacturers susceptible to price fluctuations and potential supply disruptions.

In this case, heat recovery takes place directly from the flue gases of the ceramic furnaces (whose temperature is 245-250°C) and the recovered heat will be used in the spray dryer. Figure 35 shows the mass flows in the ceramic industry without and with HPHE. The main flows are represented by the blue and red lines:

- Red circuit: represents the heat source, the flue gases from the kilns.
- Blue circuit: the secondary flow. Water is the heat transfer fluid.
- Purple circuit: it represents the working fluid (air) of the spray drier process.

The most suitable working fluid proved to be distilled water and the selected compatible shell material is stainless steel.

A) Without HPHE




B) With HPHE

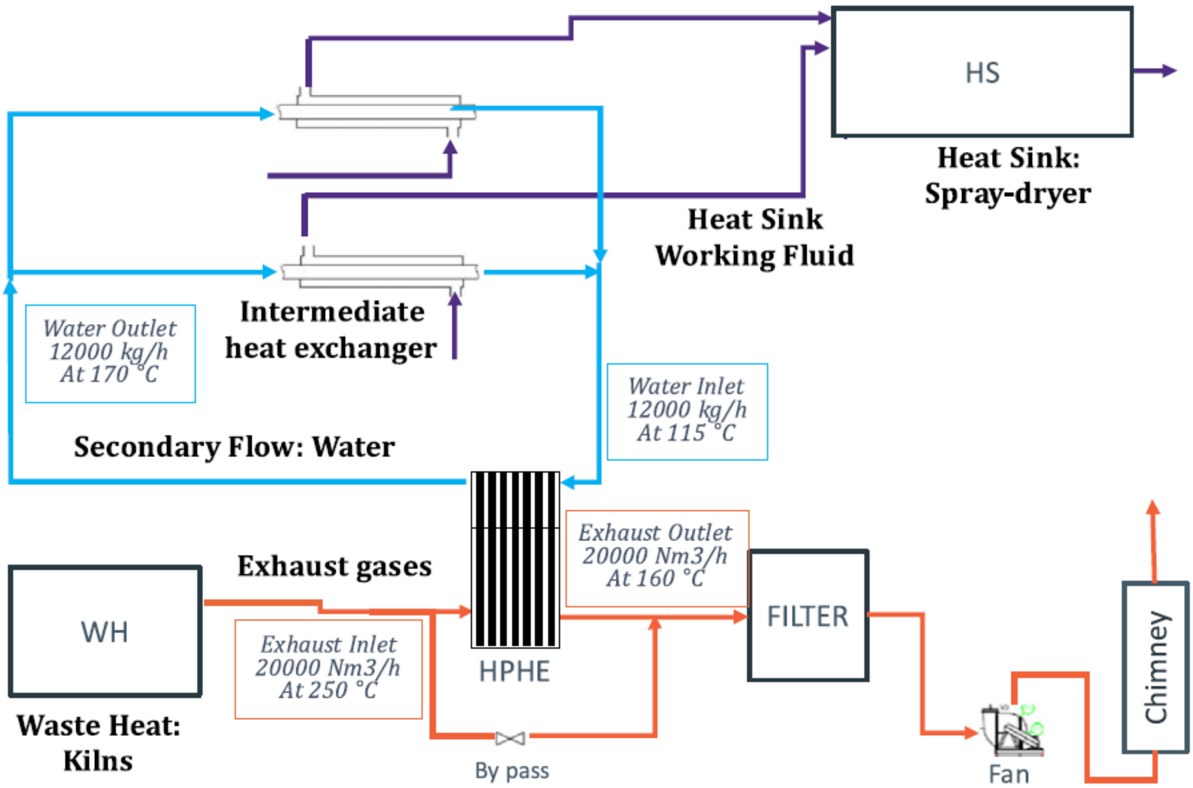



*Figure 35 Scheme of the HPHE waste heat recovery in the ceramic plant* [41]

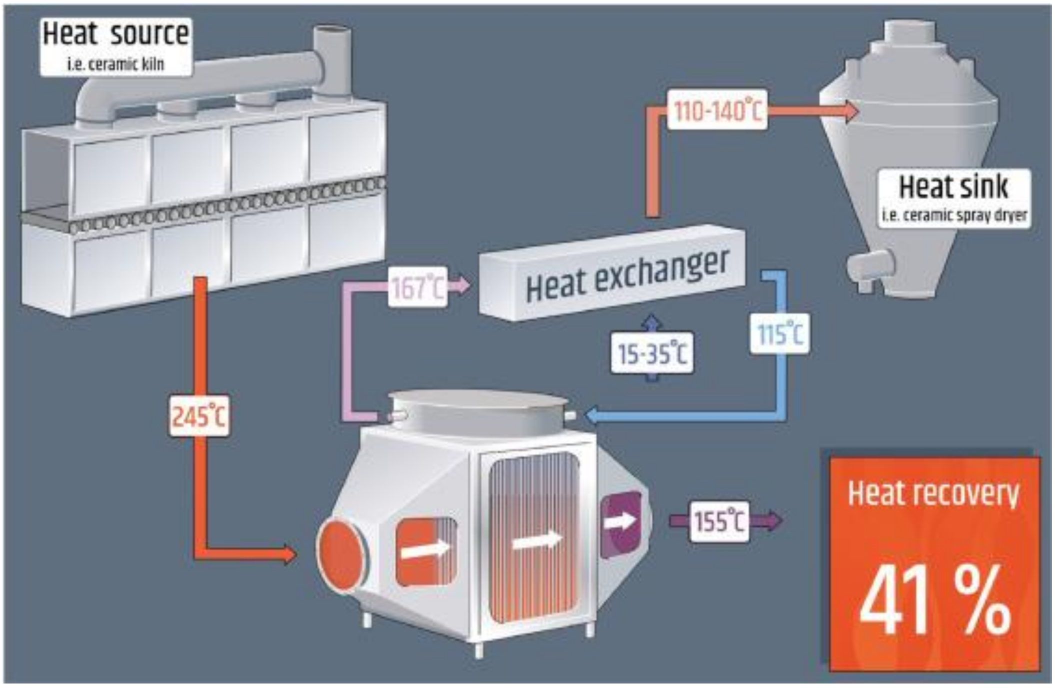



*Figure 36 Schematic of the designed heat recovery system*

The HPHE has been installed in the ceramic tile production facility upstream of the main chimney to transfer the recovered heat from the exhaust gases by means of an intermediate fluid, water, to two parallel intermediate heat exchangers of the spray dryer in which the heat recovered by the water will be transferred to the air used in the spray dryer as shown in the Figure 36. The system is also equipped here with additional measuring sensors to identify temperature, pressure and flow rates. The temperature difference between the inlet and outlet temperatures of the heat exchanger on the evaporator side is 90°C, on the condenser side about 50°C. In addition, a thermal-hydraulic centrifugal pump with an inverter is integrated into the heat transfer fluid circuit to vary the flow rate and temperature of the water stream. Rotational speed in the range 1800-3000 rpm also allows the exhaust gas temperature at the outlet of the system to be regulated and prevents the formation of acidic condensate in the exhaust gas. With the assumed temperatures of exhaust gas and water in the system, it was determined that a heat recovery of 700kW is possible.

## Lifecycle assessment methodology

### *Goal and scope definition*

This LCA study aims to measure the environmental impacts of implementing an HPHE waste heat recovery system in the drying and sintering processes of ceramic tile manufacturing. To do so, the environmental impact of the process with the HPHE integrated (scenario B) is compared to the baseline process (scenario A in Figure 35).

### *Functional unit*

The functional unit is a fundamental element of the LCA study, and is employed to describe the function of the system that is investigated. In this study, the functional unit is set as 1 process of the industry, or the capacity of the process under consideration, multiplied by the time of operation in hours for 5 years of operation. The main process is the spray drying process, as the beneficiary of the recovered heat. This way, the CO2 burden of the HPHE manufacturing and transport, and the natural gas consumption for fossil-based heating, as well as the recovered heat are allocated to 1 process unit (i.e. spray drying process). This functional unit provides the analysis with the flexibility to address both short term and long-term horizons.

## *System boundaries*

The boundaries of the system are shown in Figure 37.

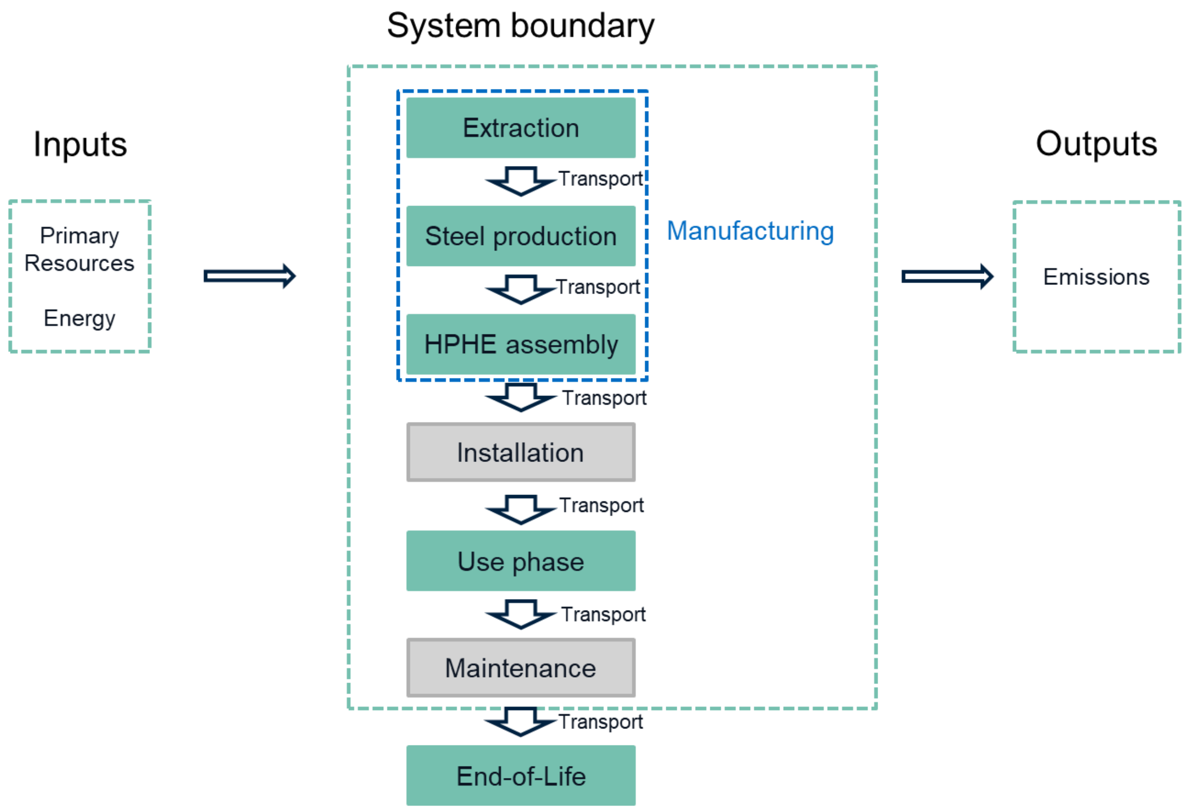



*Figure 37 System boundaries of the LCA for the ceramics case study*

**Manufacturing stage**: The upstream stages of the HPHE lifecycle consist of the raw material extraction and processing, transportation and energy supply components. This includes the extraction of raw materials like steel, copper, aluminium and other materials and additives used in the HPHE manufacturing. Moreover, it includes the transportation fuel for the materials to the manufacturing site. In this study, these stages have been consolidated in the Manufacturing stage. This is done for confidentiality reasons, as a detailed description of the manufacturing process cannot be provided. Thus, the main material by weight used in the HPHE was selected as reference, producing a "worst-case” scenario for the manufacturing footprint, that would still be close to reality. Therefore, it is assumed that stainless steel comprises 100% of the 12,05-ton mass of the HPHE, and the manufacturing contribution is estimated based on the impacts of extracting and processing this amount of stainless steel.

The first stage in an LCA is the extraction stage, which comprises all the flows relating to the extraction of raw materials, namely material and energy needed to produce the HPHE system. For this study, the materials considered are stainless steel and carbon steel.

**Transportation stage**: For the transport stage, once the HPHE is assembled, three sections of transport are calculated: (a) from the Econotherm manufacturing facilities to London by land (approximate location as specific airport is not known) (b) from London to Bologna airport by air and (c) from there to Atlas Concorde facilities where the HPHE was installed. Segment (a) is 158km by lorry (transport, freight, lorry 7.5-16 metric ton), with the same mode of transportation calculated for the 45km of segment (c) from Bologna airport to Atlas Concorde facilities. Segment (b) is conducted by air. For each of the segments, the corresponding ton.km are calculated.

**Installation stage**: As the HPHE unit arrives in an assembled state, the installation stage is not included in the calculations due to the lack of observable data. One of the assumptions employed in this study is that the installation impact of the HPHE system is a fraction of the manufacturing process. Subsequent research will try to collect primary data from the installation process of new systems.

**Use phase**: The core processes of the HPHE lifecycle are where the assessment has focused and comprise the operation stage. The most energy-intensive stage where tiles are fired in a kiln (roller hearth kiln), involving high energy use and emissions, and it serves as the heat source.

Within the operation process, only the spray dryer stage needs to be analysed, as it is the stage where the benefits of the HPHE will be incurred. Other stages of ceramic material production (preparation, shaping etc) that do not feature thermal energy flows are beyond the scope of the work. The firing stage and cooling stages interaction provides the heat source for the HPHE, as the heat exchangers will harvest the heat that would otherwise be wasted during the cooling process. The firing stage is the most energy-intensive stage where tiles are fired in a kiln (roller hearth kiln), involving high energy use, usually from fossil fuels. Due to the high temperatures required (usually over 1200°C), it is also a process that is expensive to electrify.

HPHEs are passive devices that do not require any energy (e.g., fans, pumps) or any other resource to function, simplifying the creation of the model.

**Maintenance**: For the first 5 years, maintenance is required twice per year (1/6 months). Maintenance consists of cleaning the HPHEs with water. For ceramics, 453 lt per maintenance cycle (per 6 months) are expended. As there is a lack of data on maintenance beyond 5 years, this will be the time limit for this study. Nonetheless, previous instances of HPHE installations have demonstrated vastly superior cost-effectiveness and robustness compared to conventional (plated, shell & tube) heat exchangers, and the figures will be revised as part of follow-up work.

**End-of-life stage**: This stage is not included in the study. As the ETEKINA systems have not yet reached five years of operation, there is no data on their total lifetime. This will be the work of follow-up research.

## *Life Cycle Inventory*

Data collection was carried out using primary data and the Ecoinvent database to build the inventory. The inventory of primary data was collected by the input of the technology provider and industrial process manager through the ETEKINA project. The inventory is presented in Table 5.

*Table 5 Life Cycle Inventory of ceramic processing*

| Technology | Input | Unit | Amount | Data type | Output | Unit | Amount |
|---|---|---|---|---|---|---|---|
| Manufacturing | | | | | | | |
| HPHE manufacturing | Steel, chromium steel 18/8 (Stainless steel) | kg | 12050 | Secondary | HPHE system | P | 1 |
| Transportation | | | | | | | |
| HPHE transportation | Transport, freight, lorry 16-32 metric ton | ton.km | 1903.9 | Secondary | | | |
| | Transport, freight, aircraft, unspecified | ton.km | 14038.25 | Secondary | | | |
| | Transport, freight, lorry 16-32 metric ton | ton.km | 542.25 | Secondary | | | |
| Operation | | | | | | | |
| Heat recovery | HPHE system | P | 1 | Primary | Recovered Heat | kW | 700 |
| | Water | Lt/y | 906 | Primary | | | |
| Spray drier | Recovered Heat | kW | 700 | Primary | Spray drier | Process | 1 |
| | Heat - Natural gas | kW | 1007 | Primary | | | |

### 2.3.2 Demo case #2 aluminium production

#### Introduction

In the aluminium industry, approximately 70% of total energy consumption occurs due to thermal processes, presenting a substantial opportunity for waste heat recovery technologies. Specifically, within aluminium die casting, the production process involves casting, forming, cooling, and additional thermal processing, including the sub-processes of solubilising, quenching, and ageing. Aluminium die casting is particularly noteworthy due to its high energy demands, requiring significant heat input across nearly all stages of the production process. The energy-intensive nature of this sector poses a challenge to the competitiveness of European companies, as energy costs in Europe are generally higher compared to other regions where aluminium die casting is prevalent [125] [126][127]. This underscores the importance of implementing heat recovery technologies, especially between processes in the same plant.

While direct comparisons of energy use—particularly electricity and natural gas—can be made between various countries, it's important to recognize that China's non-ferrous metal production sector relies more heavily on coal as a primary energy source, making cost comparisons more difficult. These are further exacerbated by the current state of EU energy security as part of decoupling from Russian gas. According to Yanjia and Chandler [128], oil and natural gas account for only 5% of China's total energy consumption, with coal (52%) and electricity (43%) dominating energy use in aluminium production.

The potential for waste heat recovery as an energy efficiency solution in the wider aluminium sector has been investigated by many researchers, but there is much less focus on the HPHEs [129].

#### End User: Fagor Ederlan

The case study concerns the low pressure die casting plant of Fagor Ederlan. S. Coop [130], Figure 38. Fagor Ederlan is a global leader in Chassis and Powertrain components for the Automotive sector. Fagor Ederlan, and has a turnover of €565 million, produces 45 million components annually and is ranked first in its field. It employs 3,500 people, 72% of whom are cooperative members, indicating a strong employee ownership model. In terms of environmental commitment, Fagor Ederlan has invested €2.4 million in sustainability initiatives worldwide. Fagor owns 16 plants globally, with 11 in Europe, Figure 39.


*Figure 38 Fagor Ederlan plant in the Basque country*


*Figure 39 Location of Fagor plants globally*

## Case study

In this case study, thermal processes are the second most energy-intensive operation in the facility, with the ageing heat treatment furnace alone accounting for 15% of the thermal energy use. Significant waste heat is generated during thermal treatment, and its recovery, with minimal risk of cross-contamination between streams and reduced equipment failure, has been successfully achieved using a HPHE-based system.

The HPHE system, designed, manufactured, and installed in the solution furnace exhaust stack, is capable of recovering up to 88.6 kW under steady-state conditions at 400°C. The return on investment for this solution has been estimated at 35 months, with an anticipated reduction in $CO_2$ emissions of 86 $tCO_2$/year when optimal engineering practices are followed. Furthermore, a theoretical model for predicting the thermal performance of the HPHE was developed and validated, achieving a deviation within ±20% of the experimental results. Three processes can be distinguished in the heat treatment of aluminium:

1. initial high-temperature process (temperature 540°C -> solution heat treatment furnace)
2. cooling unit process (temperature 40 °C -> quenching heat treatment pool)

3. low temperature unit process (temperature160 °C -> artificial ageing heat treatment furnace).

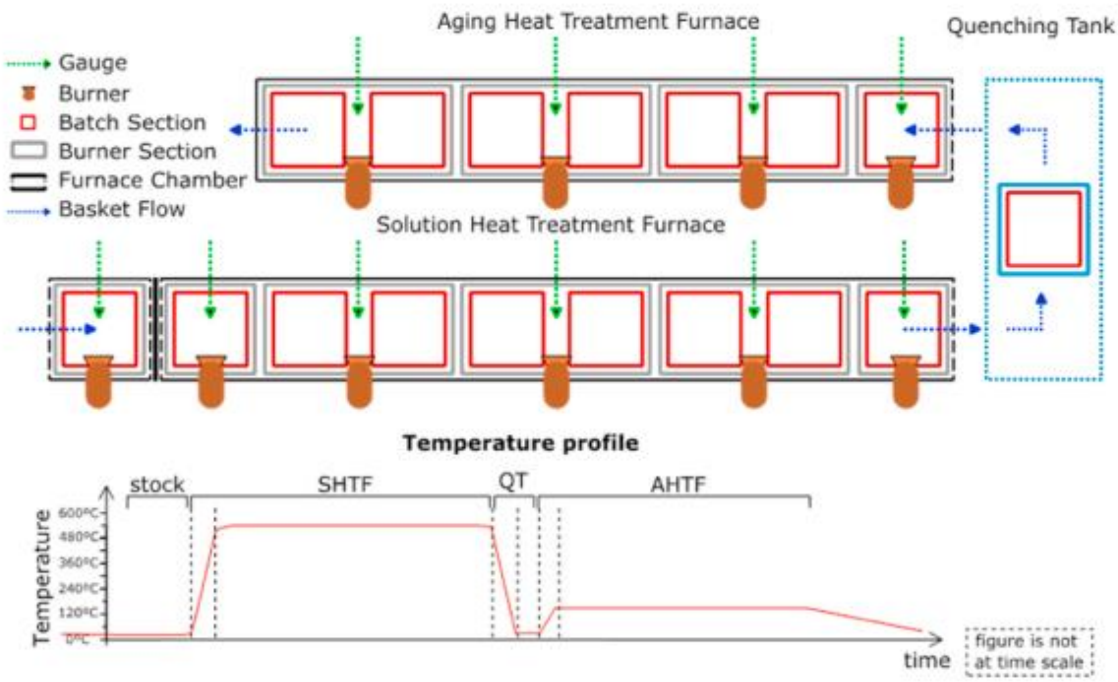



*Figure 40 Scheme of heat treatment process in Fagor Ederlan**Error! Bookmark not defined.***

Waste heat accounts for almost 40% of the heat input to the first process. Due to the high temperature of this stream, it can be used as a thermal charge for an artificial ageing furnace. Figure 40 presents the diagram of the waste heat recovery in thermal treatment furnaces of aluminium automotive parts. The designed air to air crossflow HPHE (consisting of 310 heat pipes installed in a staggered arrangement) allows 89 kW recovery based on 1791 kg $h^{-1}$ of flue gas at 400°C and a secondary stream flow rate of 1802 kg $h^{-1}$ at 145°C. The heat exchanger bundles incorporate two working fluids: distilled water and Dowtherm™ (with higher maximum operating temperature). This division into two sections allows a much higher output temperature to be achieved.

A) Without HPHE

B) With HPHE

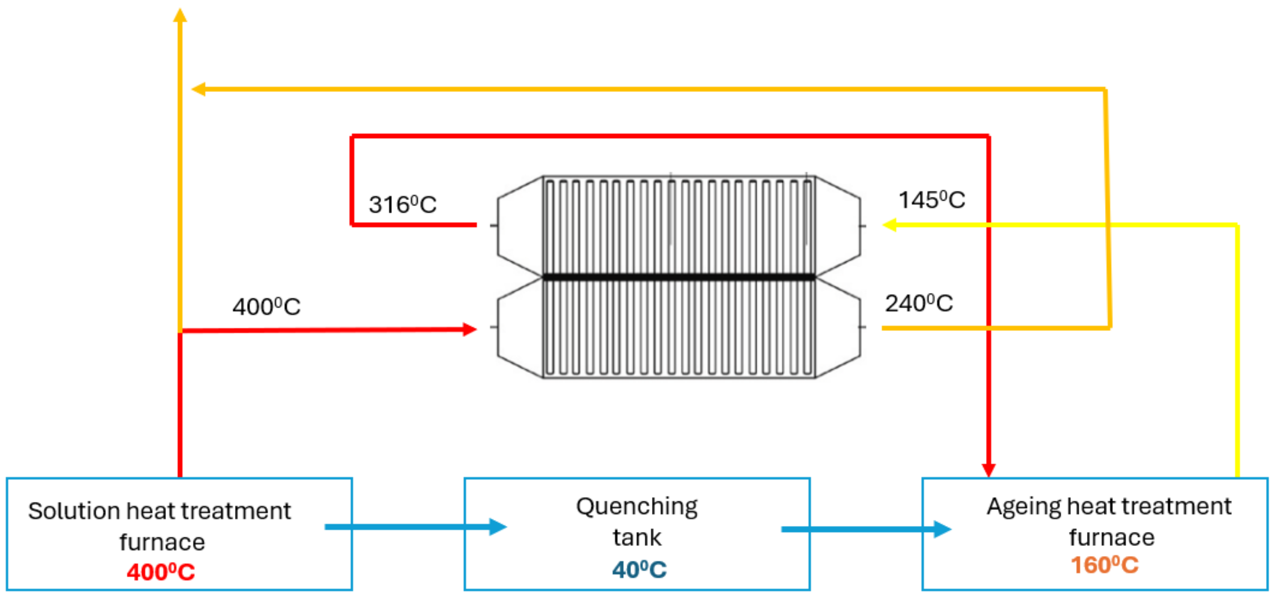



*Figure 41 Scheme of the HPHE waste heat recovery in thermal treatment furnaces of aluminium automotive parts [57]*

In the low pressure die casting plant of Fagor Ederlan. S. Coop the designed HPHE was installed on the platform between the two furnaces in question: solution and ageing treatment furnaces, Figure 41 and Figure 42. On the evaporator side, the exhaust gas is extracted from the solution furnace through a bypass system. Subsequently, in order to control the temperature of the exhaust gas, it passes through the air dilution valve.

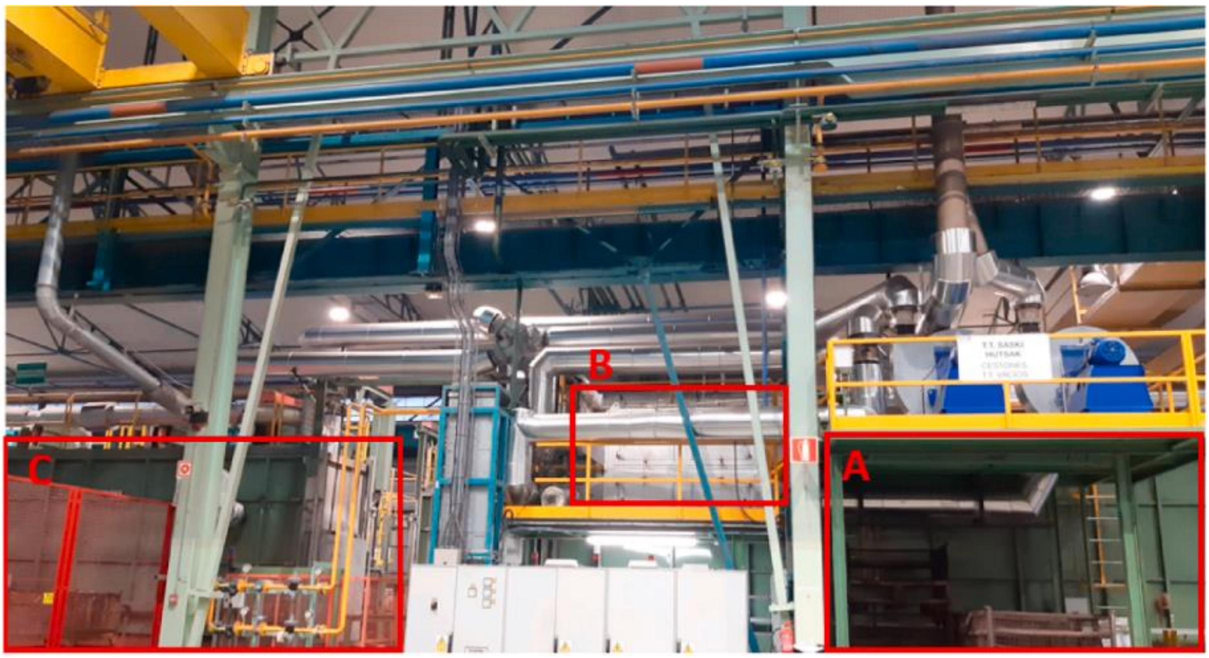



*Figure 42 WHR- HPHE system installed at Fagor Ederlan: a) solution heat treatment furnace, b) the HPHE unit, c) the ageing heat treatment furnace* ***Error! Bookmark not defined.***

After passing through the HPHE, the cooled flue gases are directed to the stack. Air drawn from the last section of the ageing furnace passes through the condenser side of the HPHE. After heating, the air is reinjected into the first section of the ageing furnace. All necessary safety systems including temperature control and an additional bypass (to start the HPHE cold) were included. The system is equipped with additional measuring devices, such as K type thermocouples, pitot probe sensors, pressure and temperature sensors. This allowed the identification of: HPHE heat loss to the ambient, mean efficiency of heat recovery and total thermal energy recovery. Jouhara et al.[63] presented a detailed analysis of HPHE operating for 1893h. The main results are presented in the Table 6 below. The application of best engineering practice is also included in the Table 6. It applies to: insulation of the ducting and HPHE, improved control of flue gas and hot gas leaks and optimised valve size. The installation of the HPHE allowed 97 kW to be recovered from the furnace flue gas stream and transferred 61 kW to the secondary stream.

*Table 6 Main outcomes of the waste heat recovery system*

| | Data extrapolated from real measurements | Expected results for Best Engineering Practices |
|---|---|---|
| Exhaust fumes power referred to 25 °C, MW | 0.203 | 0.203 |
| Available energy in the exhaust, MWh | 180 (885 h) | 1035 (per year) |
| HPHE primary efficiency, % | 48 | 48 |
| Thermal energy recovered by primary stream, MWh | 86 (885 h) | 496 (per year) |
| HPHE secondary efficiency, % | 63 | 96 |
| Thermal energy transferred to secondary stream, MWh | 54 (885 h) | 476 (per year) |
| Facility efficiency, % | 62 | 90 |
| Thermal energy transferred to furnace, MWh | 34 | |
| Operating hours during monitored period, h | 885 | |
| Expected annual working hours, $h.year^{-1}$ | 5100 | 5100 |
| Annual thermal energy transferred to furnace, $MWh.year^{-1}$ | 196 | 428 |

| | | |
|---|---|---|
| Annual primary energy savings from Natural Gas, MWh.year−1 | 218 | 476 |
| Annual $CO_2$ emission reduction, $TnCO_2$.year−1 | 39.5 | 86 |
| Annual electricity consumption, MWh.year−1 | 50.85 | 33.66 |

Lifecycle assessment methodology

### *Goal and scope definition*

This LCA study aims to measure the environmental impacts of implementing an HPHE waste heat recovery system in the interface between the two furnaces in question: solution and ageing treatment furnaces. The solution furnace operating as the heat source, and the ageing treatment furnace as the heat sink. To do so, the environmental impact of the process with the HPHE integrated (scenario B) is compared to the baseline process (scenario A).

### *Functional unit*

The functional unit in the aluminium case is the same as in the ceramics case: 1 process of the industry, or the capacity of the process under consideration, multiplied by the time of operation in hours. The main process is the ageing treatment, as the beneficiary of the recovered heat.

### *System boundaries*

The system boundaries are the same as in the ceramics case:

**Manufacturing stage**: The same approach and restrictions to the ceramic industry apply. The main material by weight used in the HPHE was selected as reference, producing a "worst-case" scenario for the manufacturing footprint, that would still be close to reality. Therefore, it is assumed that carbon steel comprises 100% of the 2.1-ton mass of the HPHE, and the manufacturing contribution is estimated based on the impacts of extracting and processing this amount of carbon steel.

**Transportation stage**: For the transport stage, once the HPHE is assembled, three sections of transport are calculated: (a) from the Econotherm manufacturing facilities to London by land (approximate location as specific airport is not known) (b) from London to Bilbao airport by air and (c) from there to Fagor Ederlan facilities where the HPHE was installed. Segment (a) is 158km by lorry (transport, freight, lorry 7.5-16 metric ton), with the same mode of transportation calculate for the 60km of segment (c) from Bilbao airport to Fagor Ederlan facilities. Segment (b) is conducted by air. For each of the segments, the corresponding ton.km are calculated.

**Installation stage**: As the HPHE unit arrives in an assembled state, the installation stage is not included in the calculations due to the lack of observable data. One of the assumptions employed in this study is that the installation impacts of the HPHE system are a fraction of the manufacturing process.

**Use phase**: The HPHE utilized in this application is configured as an air-to-air crossflow system, Figure 43. Positioned in the lower section, the evaporator facilitates the extraction of thermal energy from the exhaust stream. In the upper section, air from the ageing furnace is recirculated through the inlet, allowing further energy integration. The thermal energy recovered by the evaporator is then transferred to the heat sink medium through the condenser section, optimizing the overall heat recovery process.

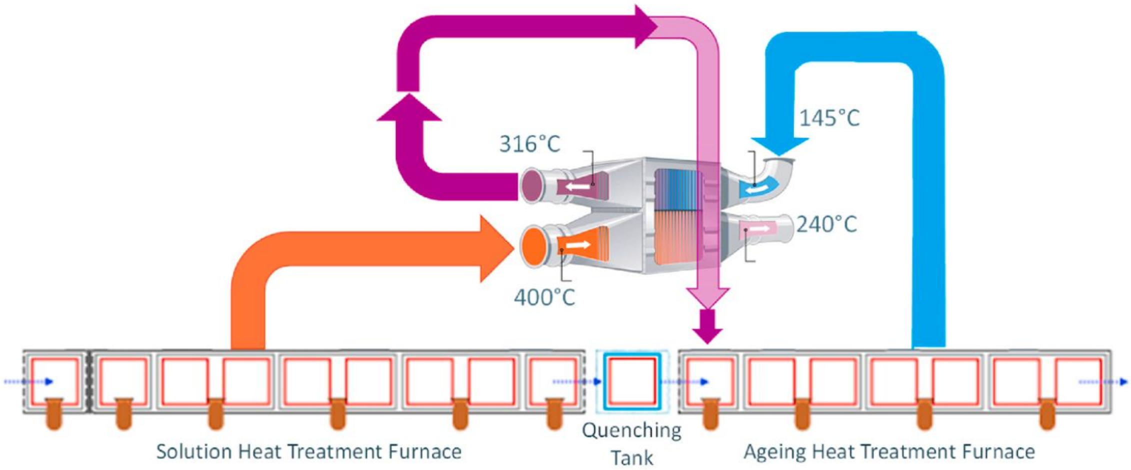



*Figure 43 Layout of the HPHE based WHR system implemented in ETEKINA* [63]

The HPHE is composed of 310 heat pipes arranged in a staggered configuration. The system employs two distinct working fluids within the heat exchanger bundles: distilled water and Dowtherm™, as illustrated in Figure 44. By dividing the HPHE into two sections, it achieves a significantly higher temperature output, as the maximum operating temperature of the Dowtherm™ bundle exceeds that of the water-based heat pipe bundle.

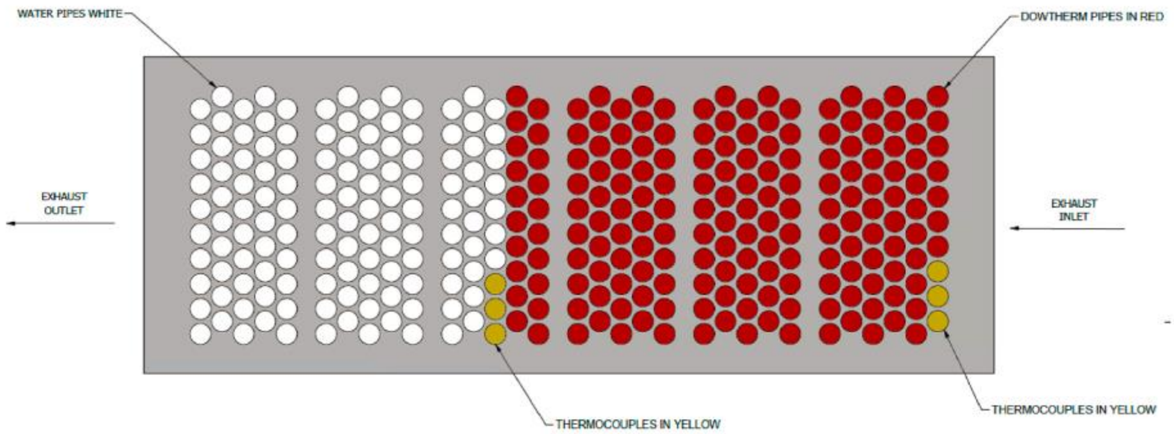



*Figure 44 Diagram of separation plate showing heat pipe arrangement.* ***Error! Bookmark not defined.***

The influence of the waste heat recovery system on the natural gas consumption of the ageing furnace is substantial and shown in Figure 45. The fluctuations between the green data points are attributed to variations in production, as the number of parts treated daily differs in terms of geometry and weight. Consequently, the thermal energy required for treatment also varies. Nonetheless, two distinct levels of natural gas consumption are observable in the figure. During the periods of reduced gas consumption, the HPHE system was functioning optimally. Conversely, during the period of elevated consumption, a valve failure in the waste heat recovery system resulted in its temporary shutdown. The figure demonstrates that the HPHE system, when operational, contributes to nearly a 50% reduction in the ageing furnace's natural gas consumption.

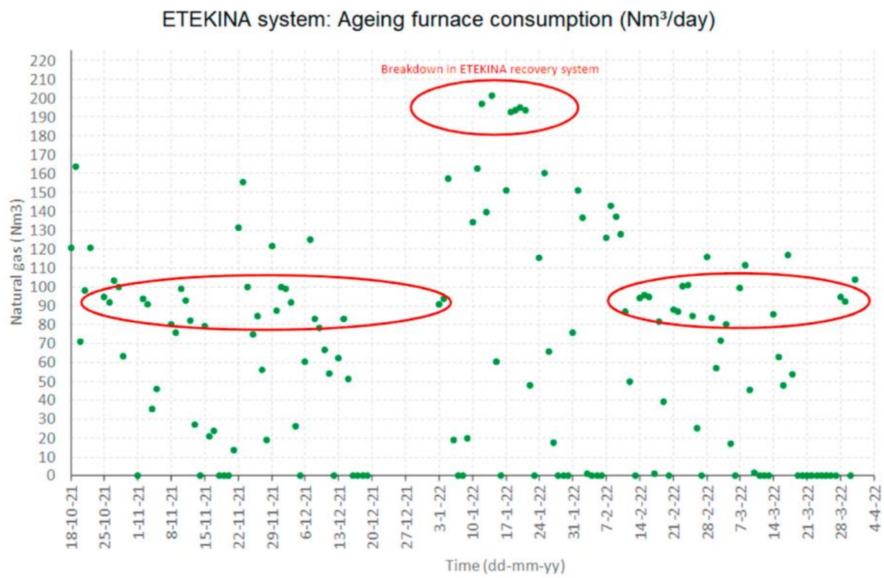



*Figure 45 Ageing furnace gas consumption (Nm3. day− 1)****Error! Bookmark not defined.***

**Maintenance**: For the first 5 years, maintenance is required twice per year (1/6 months). Maintenance consists of cleaning the HPHEs with water. For ceramics, 79 lt per maintenance cycle (per 6 months) are expended.

## *Life Cycle Inventory*

Data collection was carried out using primary data and the Ecoinvent database to build the inventory. The inventory of primary data was collected by the input of the technology provider and industrial process manager through the ETEKINA project. The inventory is presented in Table 7.

*Table 7 Life Cycle Inventory of aluminium manufacturing*

| Technology | Input | Unit | Amount | Data type | Output | Unit | Amount |
|---|---|---|---|---|---|---|---|
| Manufacturing | | | | | | | |
| HPHE manufacturing | Steel, unalloyed (carbon steel) | kg | 2100 | Secondary | HPHE system | P | 1 |
| Transportation | | | | | | | |
| HPHE transportation | Transport, freight, lorry 3.5-7.5 metric ton | ton.km | 331.8 | Secondary | | | |
| | Transport, freight, aircraft, unspecified | ton.km | 1946.7 | Secondary | | | |
| | Transport, freight, lorry 3.5-7.5 metric ton | ton.km | 127 | Secondary | | | |
| Operation | | | | | | | |
| Heat recovery | HPHE system | P | 1 | Primary | Recovered Heat | kW | 88.6 |
| | Water | Lt/y | 220 | Primary | | | |
| Ageing furnace | Recovered Heat | kW | 88.6 | Primary | Spray drier | Process | 1 |
| | Heat - Natural gas | kW | 117 | Primary kW | | | |

### 2.3.3 Demo case #3 steel production

## Introduction

The steel industry has been at the forefront of decarbonisation, but still is extremely active in researching solutions for improving its energy demand profile. The EU steel industry, for instance, faces the need to reduce greenhouse gas emissions in line with climate policy objectives, such as the European Green Deal, and the need to maintain competitiveness amid rising energy costs, especially as energy costs represent up to 40% of total operational expenses, extreme competition from China and regulatory constraints. As such, waste heat recovery is essential, as the steel sector is intrinsically one of the most energy-intensive sectors globally. The production of steel involves high-temperature processes, such as smelting in blast furnaces and steelmaking in basic oxygen furnaces, which generate significant quantities of waste heat, that are ideal targets for recovery and valorisation. HPHEs are capable of recovering heat from exhaust gases in high-temperature processes and are well-suited to the harsh environments typical of steel production, where issues like corrosion and particulate matter can hinder the performance of conventional heat exchangers.

### End user: SIJ Metal Ravne

SIJ (Slovenian Steel Group) is one of the leading producers of stainless steel and special steels in Europe. SIJ are Slovenia's largest vertically integrated metallurgy group, with Ravne operating as part of a group with 33 companies. Specializing in tool steels and stainless steel quarto plates, the company ranks among the top three EU producers in this field. It serves more than 70 markets globally, with 85% of its production dedicated to exports. Employing over 3,500 people, SIJ Metal Ravne is deeply committed to sustainability, with nearly 80% of its materials coming from recycled sources. The company has been at the forefront of the circular economy for 40 years, contributing to resource efficiency and environmental responsibility.

### Case study

The steel case study represents the third analysis within this thesis, focusing on the Metal Ravne plant in Slovenia. Key sections of interest include the Steel Plant, where raw steel is produced; the Forging Shop, where billets, rods, and other forms are created; the Rolling Mill, where these products are further processed; and various heat treatment and machining processes for finalizing special steels. The primary process examined involves the enhanced recovery of waste heat from the billet-heating furnaces, specifically during heat treatment. The Allino billet-heating furnace was selected due to its high replicability potential within steel processing industries. This process heats steel billets using a natural gas-fed furnace, with strict internal conditions requiring a complex air introduction system for pressure regulation. The furnace operates with several gas burners distributed across four heating zones, and an integrated recuperator partially elevates the combustion air temperature. Heat extraction from the flue gases occurs post-recovery from the recuperator, as illustrated in Figure 46. One significant challenge for this system lies in the high variability of the heat stream. Temperatures fluctuate between 200°C and 450°C, with peaks surpassing 500°C, resulting in an average temperature of approximately 360°C. Flue gas mass flow rates range from 1,000 kg/h to 8,000 kg/h, further complicating the design. However, the potential for heat recovery remains substantial, reaching up to 620 kW. Fortunately, the composition of the excess heat stream—natural combustion fumes with excess air—ensures relatively low corrosivity, minimizing risks related to material degradation.

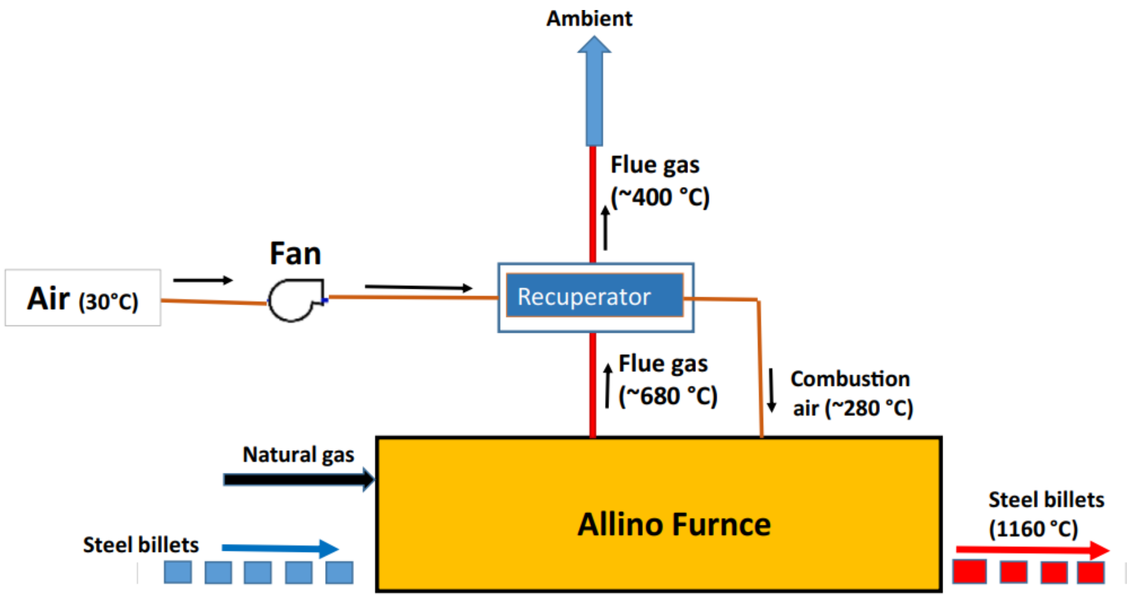
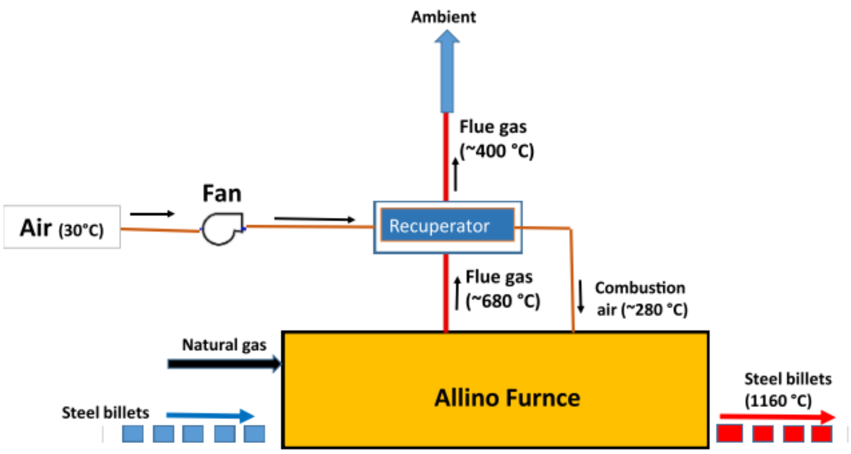



*Figure 46 Schematic representation of the billet heating furnace in steel processing industry* [41]

In order to achieve a certain material structure, it is necessary to pre-heat steel billets to high temperatures with full temperature control before further processing. It is estimated that the available waste heat potential is more than 12% of the input heat (more than 2600 MWh/year) and the identified excess heat stream of the flue gas is estimated at about 20% of energy input to the furnace (or more than 4200 MWh/year). The use of HPHEs will contribute to reusing more than 40% of the main waste heat potential of flue gases. Heat exchange takes place in two HPHE exchangers, Figure 47. In the first, preheated combustion air from the first HPHE stage (HPHE_air) is fed into the recuperator for further heating. The flue gases, after leaving the first heat recovery stage, enter the second HPHE stage (HPHE_water) to heat water in the company's heating system during the winter period.

A) Without HPHE




B) With HPHE

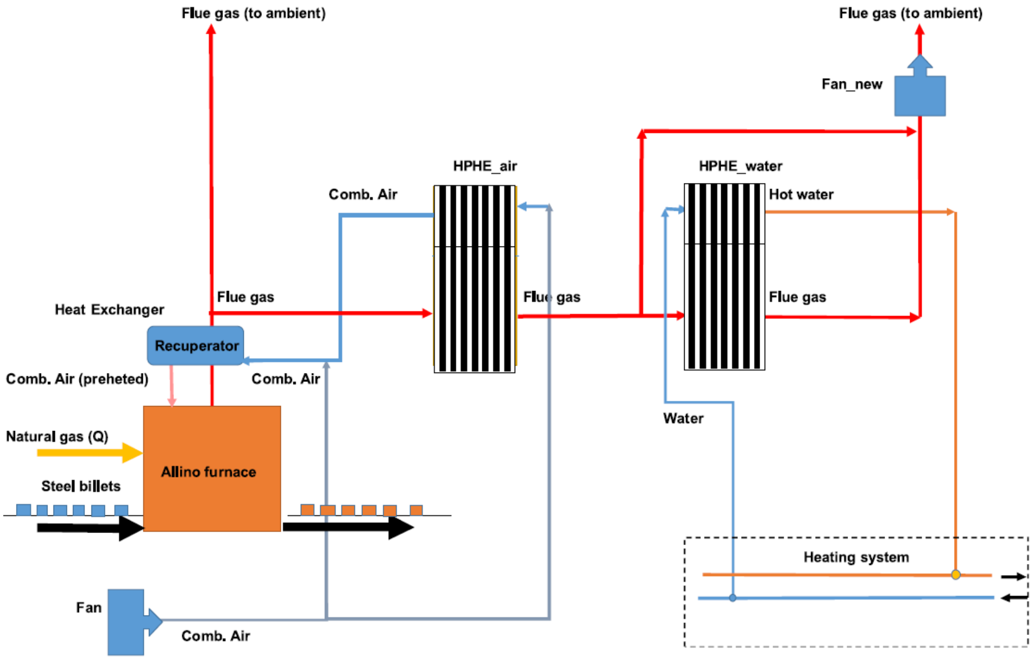



*Figure 47 Scheme of the waste heat recovery in metal steel industry A) without HPHE B) with HPHE [35]*

Table 8 summarises the main parameters of the dual unit HPHE with exhaust to air and exhaust to water, implemented in the steel industry.

*Table 8 Main parameters of the HPHE applied in steel industry*

| **Parameter** | **Units** |
|---|---|
| Exhaust inlet temperature | 360°C |
| Exhaust outlet temperature (to the ambient) | 178.5°C |
| Exhaust mass flow rate | 6,150 kg.h-*1* |
| Combustion air inlet temperature | 30°C |
| Combustion air outlet temperature | 180°C |
| Combustion air mass flow rate | 6,590 kg.h-*1* |
| Water inlet temperature | 70°C |
| Water outlet temperature | 90°C |
| Water mass flow rate | 3,000 kg.h-*1* |
| Thermal power recovered | 349,989 W |

## Lifecycle assessment methodology

### *Goal and scope definition*

This LCA study aims to quantify the benefits of implementing an HPHE waste heat recovery system in the steel industry, between the heat source, the allino-furnace and two heat sinks: preheating combustion air, and transferring the remaining heat to the facility heating system. To do so, the process with the HPHEs integrated (scenario B) is compared to the baseline process (scenario A).

### *Functional unit*

The functional unit in the steel case is the same as in the ceramics case: 1 process of the industry, or the capacity of the process under consideration, multiplied by the time of operation in hours. The main process are the dual heat sinks, addressed as a single process, as the beneficiary of the recovered heat.

### *System boundaries*

The system boundaries are the same as in the ceramics case:

**Manufacturing stage**: The same approach and restrictions to the ceramic industry apply. The main material by weight used in the HPHE was selected as reference, producing a "worst-case" scenario for the manufacturing footprint, that would still be close to reality. Therefore, it is assumed that carbon steel comprises 100% of the 2.1-ton mass of the HPHE, and the manufacturing contribution is estimated based on the impacts of extracting and processing this amount of carbon steel.

**Transportation stage**: For the transport stage, once the HPHE is assembled, three sections of transport are calculated: (a) from the Econotherm manufacturing facilities to London by land (approximate location as specific airport is not known) (b) from London to Graz airport by air and (c) from there to Metal Ravne facilities where the HPHE was installed. Segment (a) is 158km by lorry (transport, freight, lorry 7.5-16 metric ton), with the same mode of transportation calculated for the 120km of segment (c) from Graz airport to Metal Ravne facilities. Segment (b) is conducted by air. For each of the segments, the corresponding ton.km are calculated.

**Use phase**: The steel manufacturing process requires billets to be preheated to elevated temperatures prior to further processing, with precise temperature control essential to ensure the desired material structure. The identified waste heat from the flue gases accounts for approximately 20% of the furnace's energy input, equivalent to over 4,200 MWh per year, while the recoverable waste heat potential exceeds 12% of the heat input, representing more than 2,600 MWh annually. One of the key objectives of the ETEKINA project is to recover more than 40% of this waste heat potential by employing a Heat Pipe Heat Exchanger (HPHE). In the first stage, preheated air from the HPHE (HPHE_air) is directed into the recuperator, where it is further heated to temperatures exceeding 400°C. Subsequently, the flue gases exiting HPHE_air enter the second stage (HPHE_water), where they are used to heat water for the company's heating system during the winter months. The overall waste heat recovery strategy, utilizing HPHE technology for both combustion air preheating and space heating, as applied in the steel industry, is depicted in Figure 47.

The design of the two-stage HPHE system must account for the distinct working conditions at each stage. This includes the exhaust stream temperatures at the inlets of both HPHE stages and the required temperature levels for the heat sinks, such as the combustion air and heating water. Based on these operational parameters, the working fluid's temperature within the heat pipes can be calculated, allowing for the appropriate selection of the fluid. This process follows a similar approach as outlined in the case of the aluminium plant sector.

**Maintenance**: For the first 5 years, maintenance is required twice per year (1/6 months). Maintenance consists of cleaning the HPHEs with water. For ceramics the steel demo case, 79 lt per maintenance cycle (per 6 months) are expended.

## *Life Cycle Inventory*

Data collection was performed with the Ecoinvent database. The inventory of primary data was collected by the input of the technology provider and industrial process manager through the ETEKINA project. The inventory is presented in **Error! Not a valid bookmark self-reference.**

*Table 9 Life Cycle Inventory of aluminium manufacturing*

| Technology | Input | Unit | Amount | Data type | Output | Unit | Amount |
|---|---|---|---|---|---|---|---|
| Manufacturing | | | | | | | |
| HPHE manufacturing | Steel, unalloyed (carbon steel) | kg | 2950 | Secondary | HPHE system | P | 1 |
| Transportation | | | | | | | |
| HPHE transportation | Transport, freight, lorry 3.5-7.5 metric ton | ton.km | 466.1 | Secondary | | | |
| | Transport, freight, aircraft, unspecified | ton.km | 3708.15 | Secondary | | | |
| | Transport, freight, lorry 3.5-7.5 metric ton | ton.km | 354 | Secondary | | | |
| Operation | | | | | | | |
| Heat recovery | HPHE system | P | 1 | Primary | Recovered Heat | kW | 350 |
| | Water | Lt/y | 158 | Primary | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Ageing furnace | Recovered Heat | kW | 350 | Primary | Spray drier | Process | 1 |
| | Heat - Natural gas | kW | 394.6 | Primary | | | |

# Chapter 3: Business plan for the exploitation of HPHE technology

In this section, a business plan is carried out for the innovative product: HPHE. The business plan is structured in the following stages. The first step is the market analysis consisting of defining the market, the analysis of existing and potential needs, relevant challenges and desirable characteristics of the new products that will hit the market. Market research is conducted to define the size of the market, and a competitor analysis is developed to identify potential customers and analyse the legal environment. The second phase uses the tools developed to describe the results and introduce the business model. The work then focuses on financial forecasts, and, in the final stage, a roadmap is developed for the market entry strategy.

## 3.1 Market analysis

Market analysis is an integral part of effective business management. It enables companies to gain a deep understanding of customer needs, identify new opportunities and assess the competition. This enables companies to make informed strategic decisions, minimise risk and optimise their operations, resulting in long-term success and growth in a dynamically changing marketplace. Market analysis is the process of systematically collecting, processing and interpreting data on the market in which a product, in this case HPHE, is planned to be implemented. Before launching a new product on the market, it is necessary to understand the needs and preferences of potential customers and to analyse the activities of competitors. There are many benefits of market analysis, such as: understanding the competitive environment, recognising trends, discovering opportunities for diversification or growth, reducing the risks or costs associated with introducing new products and/or services as well as boosting marketing efforts.

This market analysis is oriented towards the heat exchanger market in general. Therefore, the following steps were carried out, adapted to the context of industrial energy systems, including sectors like heat exchangers, heat pipes, and various process industries (e.g., steel, ceramics, chemicals, plastics, waste processing).

### 3.1.1 Market need definition

Energy intensive industries in Europe currently face a number of challenges. The main challenges are related to the economics of operation, as EIIs strive for climate neutrality and enhanced resource efficiency by 2050, as per the EU ambitions. The European process industries are a catalyst for achieving the climate neutrality goals by 2050. With approximately 8.5 million direct and 20 million indirect jobs in Europe, and an annual turnover of €2 trillion, these industries are critical to the EU economy and prosperity. Yet, industrial processes are currently responsible for 20% of total greenhouse gas emissions in Europe and 25% of Final Energy Consumption (FEC). It is not just a matter of achieving medium-long term sustainability goals but ensuring EU industries (and society) enjoy resilience and sovereignty against global energy markets risks and disruptions (e.g. Ukraine war). The majority (66 %) of industrial energy use is for process heating purposes [131], Figure 48. The bulk of the energy consumption is driven by the demand for thermal energy, responsible for 2390 TWh/a or 81 % [132] of the total energy demand, with 37% for heating up to 200°C.

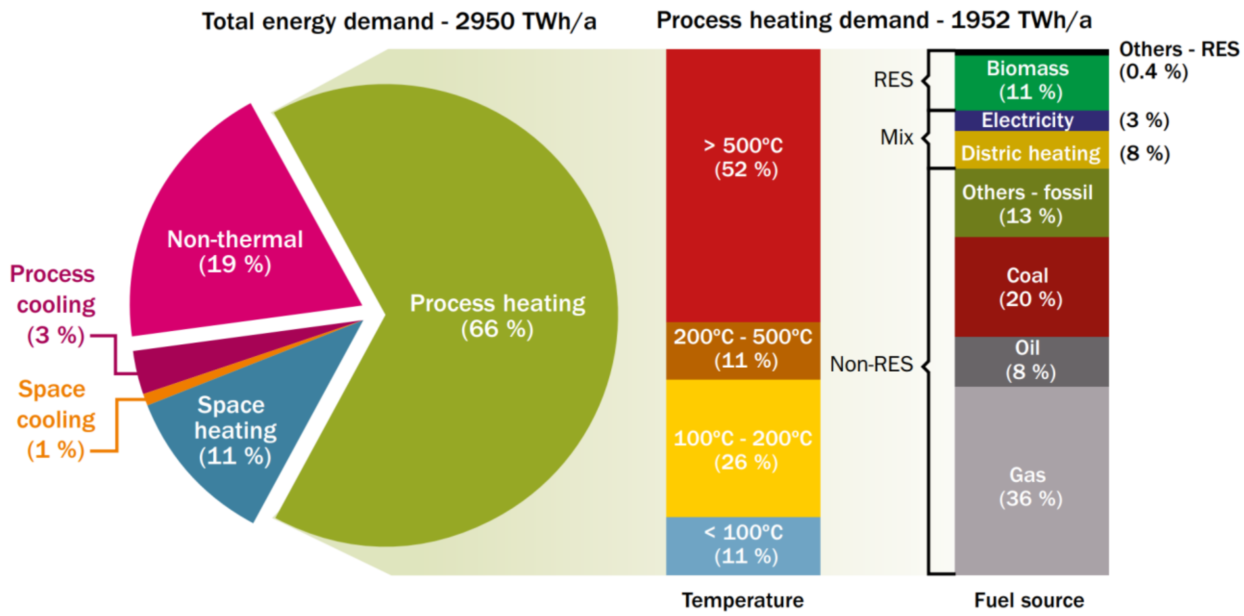



*Figure 48. Process heating demand [1]*

The current industrial process heat demand is primarily (78%) covered by fossil fuel sources. Gas is the largest fuel source (36%), with still large shares of coal (20%) and oil (8%) being used. The $CO_2$ emissions resulting from the use of these fossil fuels for process heating by industry is estimated to be 552 Mt/a. Decarbonisation strategies for heating energy in the range of up to 200°C (corresponding to 37% of total process heating demand) have the potential of reducing energy demand by 722TWh/and emissions by over 200Mt $CO_2$/a.

There is, therefore, substantial emphasis on the energy dimension, and in particular thermal energy. To define the market need regarding new heat exchanger products, information available from the ETEKINA project, as well as the Processes4Planet partnership was used, and an analysis and grouping of the market needs was carried out, considering both technological and non-technical challenges.

Key issues include high energy consumption and inefficiencies in existing processes, which lead to excessive waste. Additionally, integrating renewable energy sources and advanced heat recovery systems remains complex, while the transition to electrified thermal processes presents both technological and economic hurdles. The need for effective carbon capture technologies and compliance with stringent environmental regulations further complicates thermal energy management. From the perspective of the ETEKINA project, the following challenges have been identified:

### *Technological challenges*

**T1** Lack of effective available solutions for waste heat recovery from challenging waste heat streams.

**T2** Need to further improve waste heat recovery in extreme conditions from production processes to beat the benchmark.

**T3** Lack of available space to integrate energy saving solutions in existing plants.

**T4** Condensation of gases leading to corrosion at cold spots that damage the metallic structure of the heat exchangers.

**T5** Thermal stress cracking due to differential expansion between heat transfer surface and casing.

**T6** Complex, fragile structures, vulnerable to catastrophic single point failures of conventional heat exchangers.

**T7** Thin metal surfaces required for effective heat transfer, vulnerable to erosion, corrosion and fouling.

### *Non-technological challenges*

**N1** Need for reduction in emissions within energy intensive industries adhering to the Industrial Emissions Directive and the EU Emissions Trading System Directive (EU ETS).

**N2** Need to improve energy efficiency and the set targets under the EU Energy Efficiency Directive and national regulatory frameworks.

**N3** High energy costs for intensive industries preventing competitive advantage in comparison to international markets.

**N4** Conventional heat exchanger maintenance can be costly and time consuming.

### *Desired features of a new heat exchanger product based on market needs*

Thus, the features of a new heat exchanger product would enable more effective recovery and reuse of waste heat from industrial processes, significantly improving overall energy efficiency, but also improving the technoeconomic of the solution. Key features include:

- Advanced materials and designs for enhanced heat transfer and durability, especially in corrosive environments (dust, acid condensation etc).
- Modular and scalable configurations to accommodate varying process conditions and heat loads, in order to be suitable for bespoke design and manufacturing
- Capacity to recover low-grade heat, that may be used for space heating, hot water or other low-temperature applications
- Capacity to manage high temperature streams for industrial heating re-utilisation
- Reduced maintenance requirements and ease of installation

Nice-to-have features will be:

- Integrated heat storage capabilities to provide flexibility
- Intelligent monitoring and control systems to optimize performance but also maintenance and repair cycles

### *Unique selling points of the ETEKINA HPHE*

A conventional heat exchanger (such as a shell and tube heat exchanger) is a potential competitor to the ETEKINA HPHE. However, when comparing the two solutions, HPHE is second to none.

The traditional solution is characterised by a complex, fragile structure, prone to catastrophic failure at single points. It has many typical failure modes. There is stress cracking caused by the difference in expansion between the surface and the enclosure, cold spot induced condensation leading to corrosion. Thin metal surface required for effective heat transfer, vulnerable to erosion and corrosion. Failure is always catastrophic and difficult to manage. Maintenance is costly and time consuming. Finally, these exchangers have a much shorter lifespan given the demanding waste heat fluxes.

The main competitive advantages that can guarantees the successful commercialization of the ETEKINA HPHE solution are as follows:

capability to recover waste heat even with several challenging aspects present in the heat streams, such as:

- ➢ Fouling management (presence of particles)
- ➢ High operating temperature
- ➢ Acidic condensation
- ➢ Multi-sink capability

  - Heat is transferred to a secondary fluid in a safe and passive manner, without contamination, and is effectively ready to be used.
  - Recovery of 40% to 70% of the available waste heat energy.

- The ETEKINA HPHE can fit within the existing process (in the factory/ plant) with minor to no modification needed in the factory.
- An average annual reduction in cost of energy due to lower consumption varies depending on the unit size and characteristic and will range from approx. €18,000 to €155,000 per year.
- An average reduction of GHG emissions will also range from approx. 110 to 850 $T_{CO2e}$/year.
- Short payback period of less than 4 years, high ROI in excess of 160%.
- Simple, robust structures with multiple redundancies built in.
- Failure modes eliminated.
- Pipes free to expand and contract without applying stress to casing.
- Isothermal operation eliminates cold spots and condensation.
- Heat transfer not affected by wall thickness hence thicker walls possible, typically 2.5mm or 3.5mm pipe, with higher corrosion allowance.
- Consequence of failure is minimised and manageable.
- System can be maintained in situ.
- Long life of the heat exchanger typically 10 to 20 years.

The HPHE heat recovery systems can significantly reduce energy consumption, thus lowering operational costs in the production of heat exchangers and enhancing overall competitiveness. Adoption of the technology also enhances compliance with environmental regulations for end users. Heat recovery systems help companies meet stringent environmental regulations by reducing greenhouse gas emissions, which is increasingly important for maintaining good ESG metrics.

Market differentiation also plays a role here: Companies that offer heat exchangers with integrated functions, such as self-cleaning, or integrated sensors, can differentiate themselves in a crowded market. Finally, businesses that invest in developing innovative heat recovery technologies can establish themselves as leaders in the market, thereby reducing the threat of substitutes and new entrants by continuously raising the industry standard. Here, the considerable advantages of the ETEKINA HPHE can provide a substantial competitive advantage.

### 3.1.2 Market research (size and growth)

Having carried out the market need definition, the next step is to conduct thorough market research to gather data on the current market size, potential growth, competitors, and customer segments. It is also important to look at regulatory environments, as these can significantly impact market viability and can function as drivers for innovation, especially in the EU.

## *Market size definition*

The implementation of the ETEKINA HPHE solution is in line with market and climate trends. A potential market is EIIs of significant size segments that are looking to reduce energy consumption and subsequently reduce energy costs in their facilities, increasing overall energy efficiency and EED compliance. Above this, process industries and equipment manufacturers (systems with a high percentage of waste heat streams through flue gases and any other waste heat streams - latent or sensible waste heat) should be considered, Figure 49.


*Figure 49. Potential Market for ETEKINA HPHE*

Looking at the size of the European market (EU-27), all companies that are classified in the energy-intensive industry sector together account for more than 450000. However, focusing on the three industries under consideration, the following should be taken into account: the non-ferrous industry comprises 296 enterprises, while the steel 231, and the ceramic sector 241.

## *Industry growth*

In an expanding industry, competition is usually less dramatic because the market is growing so fast that competitors have little need to fight for customers—think of the automobile industry of the early 20th century and the dot-com boom of the late 1990s. However, in a stagnant or declining industry, competition can be ferocious as firms fight for a larger piece of a shrinking pie, such as in the global coal mining or print media industries of today. The market is expected to grow, but the competition remains fierce as companies vie for market share, Table 10.

*Table 10. Industry growth forecast*

| Industry size | Industry growth | Projection | Source |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 16 B$ (2021) | 5.3% | 25.5 B$ by 2030 | [133] |
| 23.2 B$ (2024) | 7% | 32.2 B$ | [134] |
| 18.1 B$ (2023) | 5.4% | 26.26 B$ | [135] |
| 17.6 B$ (2023) | 8.26% | 35.4 B$ | [136] |
| 18.08 B$ (2024) | 9.34% | 28.26 B$ | [137] |
| 19.08 B$ (2023) | 4.34% | 27.96 B$ by 2032 | [138] |
| 16.64 B$ (2023) | 6.25% | 24.41 B$ by 2031 | [139] |
| 18.04 B$ (2021) | 6% | 34.24 B$ by 2031 | [140] |

The heat exchanger market in Europe as valued at €5b in 2022 and is projected to reach €8bn by 2031, expanding at a CAGR of 4.8% during the forecast period 2023 - 2031[141], Figure 50. For these projections to materialise, however, and for the European manufacturing and user industry to benefit from these developments, further technological breakthroughs are still needed aimed at improving the energy efficiency of heat recovery equipment and reducing installed costs.

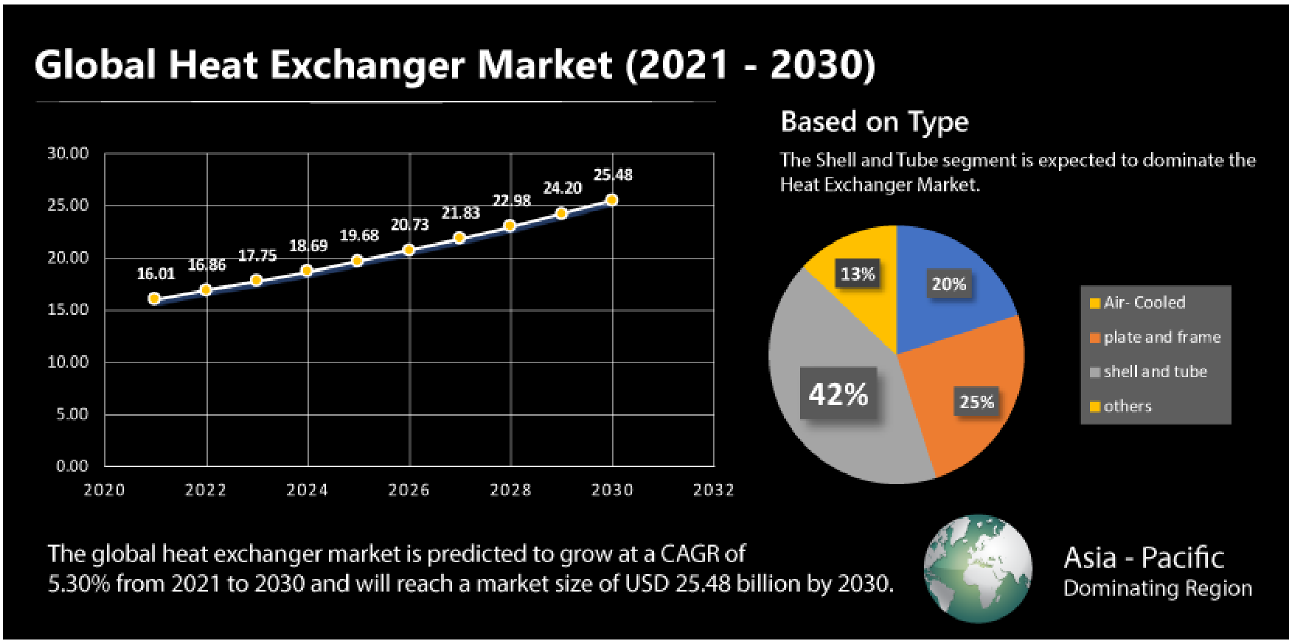



*Figure 50. Global heat exchanger market 2021-2030 [11]*

## *Cement*

Global cement production has consistently increased since 1950, with developing countries, especially in Asia, contributing significantly to the majority of the growth during the 1990s [142]. In the EU's economy cement and lime production plays a vital role. Cement is essential for construction and civil engineering, while lime is crucial for the steel industry and the production of materials such as building supplies, plastics, paints and rubber. Environmental concerns are becoming increasingly important in these industries, prompting innovations like using waste materials as substitute fuels and raw materials.

The EU produced about 22 million tonnes of lime, contributing approximately €2 billion to the EU's GDP in 2011. The cement industry, in 2006, produced 267.5 million tonnes, valued at €9 billion from 356 facilities, accounting for 10.5% of global production. However, this share dropped to 5.6% by 2011, with production falling to 195.5 million tonnes. Around 4,000 tonnes of cement per day are produced in typical cement plants. The EU's net trade in cement is projected to decrease from 13.0 Mt/a in 2021 to 11.0 Mt/a by 2030, with cement capacity shrinking from 274.8 Mt/a in 2021 to 269.1 Mt/a by 2030, resulting in a lower capacity utilization rate of 63.7% by 2030.

The lime industry directly employs over 11,000 people, while the cement sector provides approximately 61,000 direct jobs and up to 365,000 indirect positions. Moreover, over 305,000 people work in concrete production. Cement plays a crucial role in the construction industry, with a production value of €1,640 billion and an added value of €505 billion in 2010. Therefore, the sector makes a major contribution to the economy, supporting some 20 million jobs [143].

The challenges in the sector are mainly linked to energy and investment. The production processes are extremely energy-intensive, with energy costs making up as much as 40% of total costs in cement production and 50% in lime production. The theoretical thermal energy requirement for the mineralogical and chemical reactions during clinker production (excluding drying and preheating) is around 1700 MJ per tonne of clinker. However, the actual thermal energy demand for various kiln sizes and systems ranges from approximately 3,000 to 6,500 MJ per tonne of clinker [144]. Additionally, kilns, which require substantial long-term investment, create challenges for producers when adjusting to changes in demand or meeting new energy and emissions regulations.

To tackle these issues, the sector is advancing the use of alternative bioenergy and incorporating renewable heat. After 2030, electrical heating for cement kilns may serve as an alternative to bioenergy, with electrochemical solutions expected to emerge closer to 2050 (SRIA).

### *Ceramics*

The EU ceramics industry, which spans across 30 member countries, is predominantly composed of small and medium-sized enterprises (SMEs), making up 80% of the sector. This industry generates a production value of €26 billion and maintains a positive trade balance of €5.1 billion, underscoring its status as a leading export sector, Figure 51. However, with energy costs comprising up to 30% of production expenses, the industry is highly sensitive to fluctuations in energy prices. The sector is also a significant employer, providing 200,000 direct jobs across the EU. Italy, Germany, Spain, France, the UK, Portugal, and Austria are among the major producers, with robust ceramic industries also emerging in the Czech Republic, Poland, and Hungary—countries that traditionally export their ceramic products to other EU nations[145].

Export orientation is a defining characteristic of the EU ceramic industry, with 30% of its production sold outside the EU market. Despite its strong competitive position both domestically and internationally, the market landscape has shifted significantly over the past decade. The rise of low-cost products from new competitors in emerging and developing countries, coupled with persistent trade barriers, has made access to crucial new markets more challenging[146]. The value of ceramics production in the EU27 is shown in Figure 51.

The EU Ceramic Industry faces substantial challenges[147]:

**Competition**: The influx of mass-produced, low-cost products, particularly in tableware, from emerging economies.

**Energy and Raw Material Costs**: High energy prices and reliance on non-EU sources for raw materials.

**Trade Barriers**: Obstacles such as tariffs and stringent testing and certification schemes that limit market access.

**Market Dynamics**: Changes in consumer lifestyles and the substitution of ceramics by other materials.

**Workforce Issues**: The ongoing challenge of attracting and retaining a skilled workforce.

**Regulatory pressure**: As one of the EII sectors, ceramic companies are under pressure to reduce their energy and material footprints.

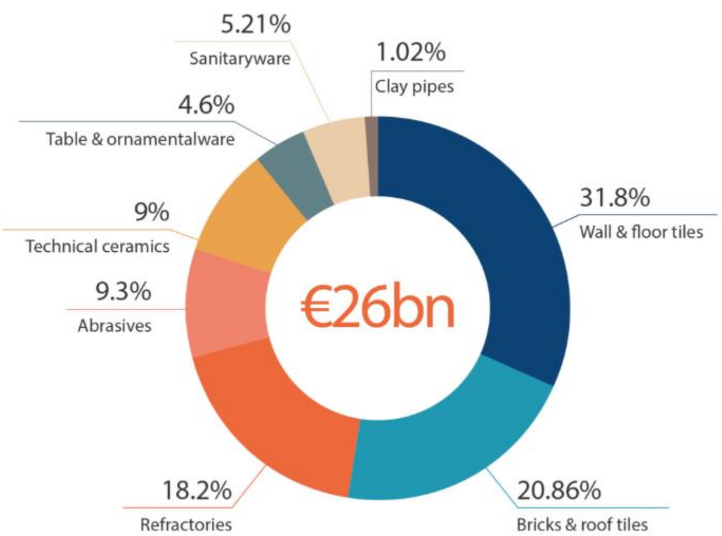


*Figure 51. Production value in EU27 ceramics* [14]

To achieve this goal, by 2030, the industry is expected to deploy technologies aimed at eliminating energy-related emissions, estimated at 16 $MtCO_2$, through enhanced process efficiency, including the digitalization of energy management and process optimization. The recovery of excess heat, particularly through heat exchangers in kiln stacks, as well as the integration of biogas and solar heat, will play key roles. Post-2030, the adoption of hydrogen as a GHG emission-free fuel and the electrification of kilns for certain applications will further advance the industry's decarbonization efforts, with full electrification anticipated by 2040. Integrated renewable heat will be utilized for drying processes. Additionally, process emissions, which account for 4 $MtCO_2$, are characterized by dispersed $CO_2$ sources with varying concentrations and volumes. By 2030, the industry will have access to flexible $CO_2$ capture and purification technologies to mitigate these emissions (SRIA).

## *Chemicals*

The chemicals industry is one of Europe's largest and most vital manufacturing sectors. As an "enabling industry," it plays a critical role in providing innovative materials and technological solutions that bolster Europe's industrial competitiveness. The sector encompasses the production of petrochemicals, polymers, basic inorganics, specialties, and consumer chemicals. Currently, the industry is undergoing rapid structural changes, facing significant challenges such as heightened competition from other countries and rising operational costs. Despite these pressures, the chemicals industry has demonstrated resilience, recovering swiftly from economic downturns and maintaining stability in overall sales. During the pre-COVID era (2018), the EU chemicals industry represented approximately 7.5% of EU manufacturing turnover, generating sales of €565 billion and accounting for around 17% of global chemical sales. The sector provided 1.2 million direct, highly skilled jobs in 2015 and supported an estimated 3.6 million indirect jobs, impacting roughly 19 million jobs across all supply chains. The labour productivity in the sector was 77% higher than the average for manufacturing, and a trade surplus of €45 billion was generated[148].

As an energy-intensive industry, the chemicals sector is heavily influenced by climate change and energy policies. The industry is also subject to extensive regulation to ensure worker safety, consumer health, and environmental protection, which compounds the cumulative cost effects more so than in other sectors. Faced with severe competitive pressures, the EU chemicals industry must navigate challenges including increased international competition, rising energy and feedstock prices, the need to enhance resource efficiency, and the push for continuous innovation[149].

The sector faces substantial challenges, namely:

**Access to Raw Materials and Energy**: To unlock the full potential of sustainable chemicals, the industry requires fair and non-discriminatory access to biomass at competitive prices, alongside a favourable legal and regulatory framework.

**Investment in Capacity**: Although the chemicals industry contributes to economic growth, Europe's share of global production is declining, and investment in new capacity is low. To attract investment, the industry needs access to critical inputs, especially energy and raw materials, at prices that reflect international cost conditions.

**Policy Coordination**: Effective coordination between EU industrial, climate, environmental, and energy policies is essential, along with a comprehensive understanding of the cumulative cost effects arising from these policies.

**Regulatory Environment**: The sector is heavily regulated, particularly in areas concerning health, safety, environmental protection, climate change, and energy issues. A stable and predictable regulatory environment is crucial for the future competitiveness of the chemicals industry.

The industry is currently grappling with the repercussions of the Russian war against Ukraine, weak demand, high energy costs, rising interest rates, and inflation. These challenges have been compounded by the US Inflation Reduction Act, which poses further competitive threats. In 2023, the EU27 chemical industry experienced a 10.6% decline in production, the third-largest drop reported from January to September. Capacity utilization fell to 74.1% in the third quarter of 2023. This downturn comes at a critical time when the industry is undergoing its most significant transformation—moving towards climate neutrality, circularity, and digitalization, while transitioning to safe and sustainable chemicals, all by 2050.

Chemical production volumes in Europe decreased by 6.6% in 2023, reversing a 5.1% growth in 2022. The outlook for 2024 is modest, with a predicted growth of only 1.9%. The EU's competitiveness on global markets continues to be eroded by high energy and feedstock costs, and confidence in the sector remains low, with no signs of a strong recovery[150].

There is a clear trend towards increased demand for more sustainable chemicals. However, with Europe's overall demand growth being low, this shift may largely result in a zero-sum transition, where demand for fossil-fuel-based or high-emission chemicals decreases as demand for sustainable alternatives rises. By 2030, the chemicals sector can significantly reduce direct emissions through various strategies. Indirect emissions can be mitigated by integrating renewable electricity, potentially reducing GHG emissions by 54 $MtCO_2$. The sector can replace natural gas with biomethane for thermal processes and utilize electricity to generate lower-temperature heat through heat pumps, displacing gas boilers and reducing emissions by an additional 1 $MtCO_2$ by 2030. Further emissions reductions can be achieved through energy efficiency improvements driven by new catalysts, process intensification, and digitalization, along with the adoption of hybrid burners. Additionally, advances in chemical recycling technologies, capable of recycling waste back into the chemical sector (e.g., plastics, used oils, and solvents), are on the horizon, although their full impact is yet to be determined. An in-depth assessment is planned before 2024 to better understand the potential of these waste streams.

## *Non-ferrous metals*

Non-ferrous metals, including aluminium, copper, and zinc, are crucial to the EU's manufacturing industries, sustainability initiatives, and overall economic growth. These metals are indispensable for various products in the automotive, aerospace, mechanical engineering, and construction sectors, owing to their unique thermal, electrical, and insulating properties, coupled with their endless recyclability and low weight. These attributes make them essential for achieving the EU's energy and resource efficiency objectives. The sector contributes 1.25% (€19.91 billion) to EU manufacturing, with a turnover of €116.09 billion (1.8%) recorded in 2010. The EU ranks among the world's largest consumers of non-ferrous metals, with aluminium representing the largest share in this sector, however, the EU has been losing its share of the global market, and its reliance on imported raw materials for metal production is rapidly increasing. Still, the sector employs over 300,000 people, with the majority of these jobs located in downstream industries[151].

Non-ferrous metals are integral to Europe's leading manufacturing sectors, with their use distributed across six main sectors[152], Figure 52.

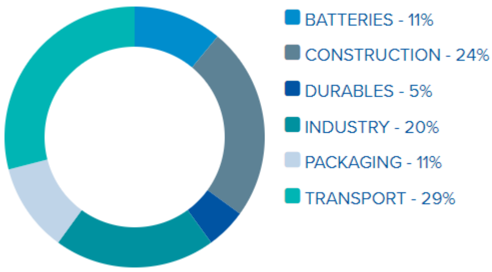



*Figure 52. Six main sectors of non-ferrous metals [21]*

**Energy prices**, particularly electricity, represent the main challenge and comprise a significant portion of production costs. In the primary production of aluminium and zinc, electricity costs account for nearly 40% of total production expenses. Given that the sector has already undergone substantial electrification (58% of the energy mix), countries within the EU Emissions Trading System (ETS) face indirect costs up to seven times higher than direct costs. Operating in a global market where prices are consolidated (largely through the London Metal Exchange), these additional costs cannot be passed on to customers, leading to a high risk of carbon leakage for the European non-ferrous metals sector. To remain competitive and secure jobs in Europe, there is an urgent need for solutions to address the challenges faced by energy-intensive industries, as emphasized by trade unions advocating for the sector's sustainable future in Europe[153].

Transitioning to GHG emission-free electricity could significantly reduce emissions by 20 $MtCO_2$ by 2030. Remaining direct emissions, which primarily stem from the use of carbon electrodes, carbon reduction agents, and fuel for heating, can be mitigated by adopting inert cathodes or bio-coal cathodes to address process $CO_2$ emissions (5 $MtCO_2$). Fossil fuel emissions (10 $MtCO_2$) can be further reduced through energy efficiency improvements and the use of biomethane. These innovations are expected to take place before 2030. After 2030, GHG emission-free hydrogen can be introduced to replace natural gas, with the electrification of heaters anticipated post-2040. Additionally, design for recycling is crucial to enhance the recovery rate of non-ferrous metals, particularly from composites. P4Planet aims to foster efficient and climate-friendly recovery and recycling processes, digitalize the value chain, incorporate inherent recycling of materials, and establish new recycling value chains where none currently exist, with full implementation expected by 2040.

### *Minerals and ores*

The EU metallic minerals sector produces a diverse range of ores, which yield metals or metallic substances. The EU is a significant producer of chromium, copper, lead, silver, and zinc. However, the majority of metallic ores that supply the European metallic industry are imported, with only a few EU countries—Austria, Finland, Greece, Ireland, Poland, Portugal, and Sweden—having active mines. In these countries, metal mining contributes more than 1% to the global production of certain metallic minerals. The sector is of strategic importance to the EU, especially as the challenges faced are difficult to address locally. For instance, certain "high tech" or "minor" metals, such as Rare Earth Elements (REEs) and Platinum Group Minerals (PGMs), which are essential for future environmental technologies, are currently produced in significant quantities only outside the EU. Moreover, Metal mining operations require substantial investment due to the large scale or complexity of the operations, the processing needs to concentrate ores, and, in many cases, the requirement to operate underground[154].

Direct emissions from the minerals sector are primarily generated by lime kilns. By 2030, all direct fuel-related emissions (6 $MtCO_2$) can be eliminated by switching to bioenergy, and after 2030, through the integration of renewable electricity or heat. Process emissions (14 $MtCO_2$) can be reduced by employing carbon capture technology, with oxyfuel processes creating a pure $CO_2$ stream that requires less purification. Post-2030, electrical heating of kilns can serve as an alternative to bioenergy. Near 2050, electrochemical options that also produce hydrogen will become available and will need to be integrated, allowing for a comprehensive reduction of $CO_2$ emissions by 2050. The indirect emissions (3 $MtCO_2$) from electricity consumption, primarily from mining industrial minerals, will also decrease as GHG emission-free electricity becomes more widely available. The direct integration of renewable electricity for heat and energy flexibility will further support the transition of the power system [155][156], Figure 53 and Figure 54.

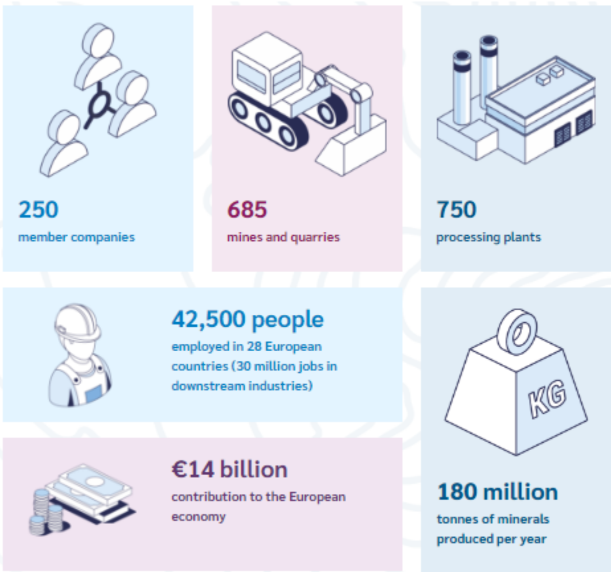



*Figure 53. Key facts and figures [24]*

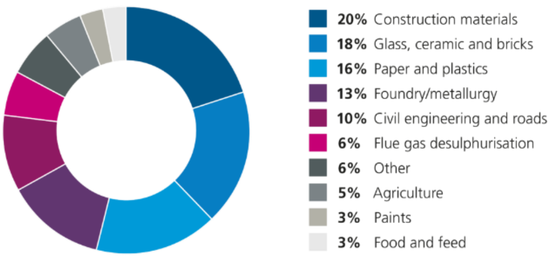



*Figure 54. Main markets for industrial minerals in Europe [24]Steel*

The steel industry has long been a cornerstone of the EU economy, driving innovation, economic growth, and employment. In response to the downturn in steel demand following the economic crisis, the European Commission has focused on revitalizing the sector to secure its future. Steel is intricately connected to numerous industrial sectors, including automotive, construction, electronics, and renewable industries. The EU is the second-largest producer of steel globally, following China, with an annual output exceeding 177 million tonnes, accounting for 11% of the world's steel production. Steelmaking is closely intertwined with many downstream industries, such as automotive, construction, electronics, and both mechanical and electrical engineering. It plays a vital role in the

EU's objective to increase the industrial sector's share of GDP to 20% by 2020. The EU steel industry operates across 500 production sites spread over 23 EU countries.

Despite a recovery in demand and a surge in steel prices towards the end of 2020 and early 2021—with hot rolled coil prices rising by 46% from September 2020 to January 2021—the COVID-19 pandemic exacerbated the structural challenges facing the European steel industry. The price surge was driven by a temporary supply shortage as demand in sectors like automotive and construction rebounded faster than EU steelmaking capacity. In 2020, capacity utilization in the European steel industry fell to about 63%. Over the next three years, capacity utilization is expected to recover to between 70% and 75%, with anticipated demand stabilizing at approximately 140 million to 150 million tonnes per year, setting the stage for a "new normal" in the industry. To achieve a sustainable capacity utilization rate of around 85%, a reduction of 25 million to 30 million tonnes of surplus capacity would be necessary[157].

The primary challenges facing the EU steel industry include the cost and availability of raw materials and energy, compliance with environmental and climate change regulations, and intense competition from producers outside the EU. These challenges were highlighted in the EU's steel action plan. Establishing the right regulatory environment is crucial for the sustainable development and efficient functioning of the internal market. Such a framework ensures investor certainty and predictability, providing a level playing field for the steel industry.

Non-EU steel-producing countries often employ trade restrictions to advantage their domestic industries. These restrictions include tariff barriers, non-tariff measures such as technical regulations, conformity assessment procedures, export incentives, and limitations on raw material exports for steelmaking. The EU addresses these barriers through its market access strategy, enforcing international commitments and ensuring a level playing field for the EU steel sector.

Like other EIIs, energy costs are a major factor in the competitiveness of the EU steel sector, accounting for up to 40% of total operational costs. European steel producers face higher energy prices compared to most international competitors, a disparity that has worsened with recent price developments[158].

By 2030, bio-coal and hydrogen can partially replace fossil coal in existing integrated steel production, potentially reducing emissions by 30% in the BF/BOF route. If 10% of steel plants adopt this technology between 2024 and 2030, it could reduce emissions by 5 $MtCO_2$ in 2030, not accounting for economic factors. The digitalization of plants could further enhance process efficiency, for example, by minimizing the number of cooling and heating cycles needed for finished products. Secondary steelmaking emissions could be eliminated by using GHG emission-free electricity for indirect emissions and bio-coal for the anodes. Additionally, blast furnace gases (CO and $H_2$) could be utilized in the chemical industry to produce chemical products or synthetic fuels by 2030. After 2030, hydrogen-based Direct Reduced Iron (DRI) technology could enable GHG emission-free steelmaking, potentially eliminating up to 190 $MtCO_2$ of direct emissions by 2050 when combined with biogas. Alternatively, new iron-making technologies, such as iron bath smelting, could produce pure $CO_2$ streams suitable for use as secondary resources or in combination with Carbon Capture and Storage (CCS). Renewable energy sources, including biogas and electricity, could power finishing processes and other smaller operations. The shift from coal will also eliminate the need for coke-making and sintering, significantly reducing onsite waste production and the associated handling requirements. However, emissions from downstream steel processing will still need to be addressed through sector-specific innovations. By 2040, advanced recycling technologies are expected to be developed, capable of cleaning scrap from non-ferrous metals. These metals can be recycled and used as secondary resources, while the resulting high-purity steel scrap can be melted in an electric arc furnace, Figure 55.


*Figure 55. The European steel industry in numbers [28]*

## *Summary*

Table 11 summarises and compiles the current challenges and potential value of HPHE.

*Table 11. Summary of current challenges and potential value of HPHE*

| EII Sectors | Current challenges | Potential HPHE value |
|---|---|---|
| Cement and Lime Industry | • **High energy consumption**: Production processes are highly energy-intensive.<br>• **Investment requirements**: Kilns require significant, long-term investment, making it difficult to adapt to demand fluctuations or new energy/emissions regulations.<br>• **Decreasing market share**: Global competition is increasing, particularly from emerging economies. | **Heat recovery** : Utilizing waste heat recovery systems can significantly reduce energy consumption, cutting costs and emissions.<br><br>**Reduced operating expenses**: Compared to other waste heat recovery systems, HPHEs have reduced costs throughout their lifecycle. |
| Ceramics Industry | • **Competition**: Increased competition from low-cost producers in emerging economies.<br>• **Energy costs**: High energy prices impact production costs.<br>• **Raw material dependence**: Reliance on non-EU produced raw materials, especially from Russia and China.<br>• **Workforce issues**: Difficulty in attracting and retaining skilled labour.<br>• **Market access**: Trade barriers limiting access to new markets. | **Heat recovery**: Implementing heat exchangers in kiln stacks to recover excess heat, thereby reducing energy costs, as well as emissions and associated secondary costs<br>**Material recovery**: Subsequent innovations in HPHE technology enables material and water recovery.<br>**No dependence on critical raw materials**: HPHEs are fabricated mainly with carbon and stainless steel. |
| Chemicals Industry | • **Energy and feedstock costs**: Rising prices for energy and raw materials. | **Chemical recycling**: Developing chemical recycling technologies to reduce the need for virgin materials |

| | | |
|---|---|---|
| | • **Regulatory pressures**: Stringent regulations related to safety, environmental protection, and climate change.<br>• **Global competition**: Increased competition from non-EU producers, with declining global market share.<br>• **Investment needs**: Low investment in new capacity due to high costs and regulatory uncertainty. | and lower energy use, made more accessible by leveraging HPHE technology.<br>**Process intensification**: Enhancing energy efficiency through heat recovery and reutilisation within the process or in other processes.<br>**Heat recovery**: The chemical industry features attractive heat fluxes for recovery and reutilisation. |
| Non-Ferrous Metals Industry | • **High energy costs**: Electricity costs represent a significant portion of production expenses.<br>• **Carbon leakage risk**: High risk of carbon leakage due to global competition and inability to pass on energy costs.<br>• **Resource dependency**: Dependence on imported raw materials and limited EU resources. | **Heat recovery**: Implementing energy recovery systems to lower operational costs and enhance competitiveness, reducing also emissions related costs. |
| Metallic Minerals Industry | • **Energy-intensive operations**: Underground mining requires significant energy, contributing to high operational costs.<br>• **High investment needs**: Metal mining operations demand substantial investment due to the complexity and scale of operations. | **Heat Recovery in Ventilation Systems**: Utilizing heat recovery in ventilation systems to reduce energy consumption in underground mining operations.<br>**Process Electrification**: Integration of renewable electricity to support mining processes and reduce reliance on fossil fuels.<br>**Heat recovery**: Implementing energy recovery systems to lower operational |

| | | |
|---|---|---|
| | • **Limited EU resources**: Heavy reliance on imported ores with limited active mines in the EU. | costs and enhance competitiveness, reducing also emissions related costs. |
| Steel Industry | • **High energy costs**: Energy costs are a significant component of steelmaking expenses. <br>• **Global competition**: Intense competition from non-EU producers, often benefiting from trade protections in their home countries. <br>• **Regulatory environment**: Need for a stable regulatory framework to ensure sustainability and competitiveness. <br>• **Structural overcapacity**: Excess production capacity and underutilization in the industry. | **Heat recovery**: Implementing heat exchangers in high temperature processes to recover excess heat, thereby reducing energy costs, as well as emissions and associated secondary costs. |

### 3.1.3 Competitive Analysis

Competitor analysis is performed to assess the strengths, weaknesses, market positioning, and product portfolio. This aids in defining the unique value proposition and gaining a competitive advantage. In the industrial energy systems sector, it's important to evaluate both direct competitors with similar technologies and indirect competitors offering alternative solutions to the same challenge. The characteristics of the main competitors in the market are outlined below.

**Alfa Laval AB:** Founded in 1883 by Gustaf de Laval and Oscar Lamm, Alfa Laval AB is a Swedish company that has grown into a global leader in the provision of specialized products for heavy industry. The company's extensive product range includes equipment designed for heating, cooling, separating, and transporting fluids such as oil, water, chemicals, and other industrial substances. With its headquarters in Lund, Sweden, Alfa Laval operates through subsidiaries in over 100 countries, including key markets like South Africa, Denmark, Italy, India, Japan, China, the Netherlands, and the United States. The company employs more than 18,000 people worldwide and, as of 2021, reported an impressive revenue of approximately €4.05 billion. Alfa Laval's long-standing commitment to innovation and sustainability continues to drive its success in the global market[159][160].

**API Heat Transfer Inc.**

API Heat Transfer Inc. has positioned itself as a market leader in the development of innovative and energy-efficient heat transfer equipment. With a heritage spanning over 130 years, API serves a broad range of industries, providing tailored heat transfer solutions. The company's global workforce of more than 1,600 employees supports its operations across various manufacturing facilities worldwide, delivering top-tier sales, service, and customer support. In 2024, API reported a revenue of approximately €1.08 billion, further solidifying its market position with the strategic acquisition of Basco Engineered Products. This acquisition has strengthened API's presence in the chemical, petrochemical, and oil and gas sectors, expanding its product offerings and enhancing its competitive edge.

**Danfoss A/S**

Founded in 1933 by engineer Mads Clausen, Danfoss A/S is a Danish multinational company with a significant impact on global markets, particularly in the sectors of cooling, air conditioning, heating, and variable-frequency drives. With its headquarters in Nordborg, Denmark, Danfoss employs nearly 42,000 people worldwide. The company is known for its robust commitment to sustainability, innovation, and technological advancement, which has allowed it to maintain a leading position in its industries[161]. Danfoss has been a participant in the United Nations Global Compact since 2002, adhering to principles of social and environmental responsibility, which are integral to its business strategy and operations.

**Exchanger Industries Limited**

Exchanger Industries was found in 1961, and since then it has built a reputation as a leading Alberta-based and globally recognized designer and manufacturer of shell & tube and air-cooled heat exchangers within the natural gas, oil and petrochemical industries.

Exchanger Industries continues to implement the cutting-edge enterprise systems to maximize value for their customers. Offering customized 3-D CAD, Enterprise Resource Planning (ERP), Material Resource Planning (MRP), and proprietary activity cost-based estimate programs build the foundation for efficient scalability that allows us to further improve cost competitiveness while maintaining the integrity and quality that our customers demand. EIL's upgraded competitive capabilities resulting from these operational effectiveness initiatives have driven increases in relative market share in rapidly growing natural gas midstream, natural gas power generation, liquefied natural gas, petrochemical and renewable powers storage end use segments.

**Mersen**

Mersen is a global expert in electrical specialties and advanced materials for high-tech industries. With more than 50 industrial sites and 18 R&D centres in 33 countries around the world, Mersen develops custom-built solutions and delivers key products to its clients to meet the new technological challenges, and has designed and manufactured a comprehensive portfolio of heat exchangers using various technologies (blocs, tubes) and the materials (graphite, SiC, tantalum, zirconium, titanium). These heat exchangers can be installed as condensers, heaters, coolers...in the corrosive chemical processes with more than 450 mechanical designs completed each year. The highly experienced engineering staff provides drawing and mechanical design support using various software tools to produce the calculations required by the current pressure vessel design codes (ASME, EN 13445, CODAP, AD 2000 Merckblatt) and ANSYS for the specific Finite Element Analysis.

**Hieta exchangers**

HiETA Technologies is a product development and production company specialised in the use of Manufacturing (metal 3-D printing) of Compact Heat Exchangers, Turbo Machinery, Combustion & Fuel Delivery, Design Engineering, Materials Development, CFD, 1D Sizing, Build to Print, Lightweight Structures, End-to-end design and manufacture, Thermal Management, Waste Heat Recovery, Aerospace, Motorsport, Energy, and Automotive. This enables manufacturing more effective geometries and heat transfer surfaces of heat exchangers and other heat and mass transfer components.

**Thermex Heat Exchangers**

Thermex are UK based manufacturers of heat exchangers, providing reliable and cost effective cooling products since 1979. A heat exchanger is an important part of any equipment that produces waste heat such as engines, generators and hydraulic power packs, therefore it is essential that the best heat exchanger design is selected to ensure reliability and longevity of your equipment. Over the years, Thermex has developed into one of the world's leading heat exchanger manufacturers, with ISO 9001:2015 certification and a UK manufacturing plant.

Thermex have been manufacturing Shell and Tube Heat Exchangers since 1979, but in more recent years they have added Air Cooled and Brazed Plate Heat Exchangers to their portfolio.

**Tranter Inc.**

Tranter Inc. is a global engineering and manufacturing group specializing in thermal management solutions across a variety of industries, including the process industries, district heating, and building services. Tranter has established a strong presence in multiple countries, driven by its focus on research and development. This commitment to innovation is evident in the company's efforts to expand its global footprint and enhance its product offerings. Tranter's expertise in plate heat exchangers, combined with its solution-driven approach, positions it as a key player in the heat transfer market. Tranter's revenue is $35.6 Million Employees, 548 (373 on RocketReach) ;

**Kelvion Holding GmbH (formerly GEA Group)**

With origins dating back to 1920, Kelvion Holding GmbH has evolved into a global leader in heat exchanger technology. The company, originally part of the GEA Group, now operates independently, focusing on serving industries such as chemical, petrochemical, and energy. Kelvion's product portfolio includes advanced heat exchangers designed to improve efficiency, flexibility, and durability in demanding industrial environments. The company's rich history and ongoing commitment to technological innovation ensure its continued leadership in thermal engineering. Kelvion employs more than 18,000 professionals. In 1999, GEA was acquired by mg technologies AG (the successor of Metallgesellschaft), which was renamed to GEA Group AG in 2005. In 2010, GEA bundled all of its heat exchanger activities in one segment ("HX"). In 2014, GEA Heat Exchangers was acquired by Triton fund. With a new name, the core business of the former GEA Heat Exchangers Segment has been formally split from the GEA Group AG and is writing its own history as Kelvion. The other segments of the Heat Exchanger Division are now operating under their own names: DencoHappel (former Air Treatment Business) and Enexio (former Power Cooling Solutions Business).

**HRS Heat Exchangers Ltd.**

Specializing in the design and manufacture of a wide range of heat exchangers, HRS Heat Exchangers Ltd. has carved out a niche in energy recovery, particularly in wastewater treatment. The company's expertise extends to tubular, scraped surface, and plate heat exchangers, as well as complete turnkey systems for applications such as heating, cooling, sterilization, and pasteurization. With a revenue of approximately €19.6 million and a dedicated team of 110 employees, HRS is recognized for its innovative approaches to improving energy efficiency and sustainability.

**Koch Heat Transfer Company, L.P**.

Part of the larger Koch Industries conglomerate, Koch Heat Transfer Company, L.P. is renowned for providing specialized heat transfer equipment to refineries, chemical companies, and various other industrial facilities worldwide. The company's extensive research and development capabilities are focused on creating technologies that enhance thermal efficiency, reduce energy costs, and minimize maintenance requirements. Koch Heat Transfer is a significant player in the global market, leveraging its parent company's vast resources and innovation-driven culture to maintain its competitive edge. The company traditionally reinvests 90 percent of earnings back into its businesses, supporting continued innovation in categories such as biofuels, fertilizers, energy, commodity trading, glass, technology, and other manufacturing-related fields. Koch employs about 120,000 people worldwide, with nearly half of those in the United States and revenue of $69.2 Million

**Hisaka Works, Ltd.**

With over 80 years of experience, Hisaka Works, Ltd. is a leading thermal engineering specialist, renowned for its expertise in heat transfer technology. The company's product offerings include advanced solutions for industrial heating and cooling processes, catering to a diverse range of industries. Hisaka's dedication to innovation and its ability to adapt to the dynamic needs of its clients have earned it a strong reputation in the global market. The company continues to lead the industry in developing efficient and sustainable heat transfer solutions.

**Xylem Inc**. Xylem, a top provider of water solutions, has launched the XP Series, a new line of brazed plate heat exchangers. With its high thermal efficiency and compact design, the XP Series is well-suited for heating and cooling applications in both commercial and residential buildings.

### 3.1.4 Target Customer Identification

This approach enables the identification of target customers within particular industry sectors, such as process industry operators, manufacturers or those engaged in sustainability and energy management efforts. Gaining insight into customers' specific needs, purchasing behaviors, and decision-making processes is crucial.

There are 768 potential customers for ETEKINA HPHE as mentioned earlier, having that the rest of the energy intensive industry companies are all potential customers in the future.

Key customer target groups for heat exchangers can be:

- Chemical industry: Heat exchangers are crucial for recovering waste heat in production processes such as distillation or chemical reactions.
- Steel and metallurgical industry: High energy consumption and waste heat make heat exchangers important for improving energy efficiency.

- Food and beverage industry: Heat exchangers can be used to heat and cool products, thus reducing energy consumption.
- Petrochemical industry: Heat exchangers are key in refining processes, where heat recovery is important for energy efficiency.
- Energy producers: Renewable energy companies, such as biomass, geothermal or solar, can use heat exchangers to integrate different energy sources.
- High-efficiency combined heat and power (CHP) sector: Heat exchangers are essential for CHP systems that combine heat and power production.
- Logistics and refrigeration: heat exchangers can be used in refrigeration systems to recover waste heat, thus reducing energy consumption.

Target Customer Identification for heat exchangers in Europe covers a diverse range of sectors and customer groups seeking to improve energy efficiency, reduce costs. The common goal of these groups is to optimise energy use and minimise environmental impact, making heat exchangers a key element in the sectors' energy modernisation and transformation processes.

### 3.1.5 Regulatory environment

The regulatory environment for heat exchangers in Europe is shaped by several key frameworks aimed at ensuring efficiency, safety, environmental sustainability and compliance with standards. These regulations cover areas such as energy efficiency, emission control, material safety and product labelling. This is particularly relevant in industries with strict environmental, health, and safety standards.

The regulatory framework covered three areas:

***EU (2030 Climate and Energy Policy; EED; IED; RED);***

- **2030 Climate and Energy Policy** sets ambitious targets for reducing greenhouse gas emissions, increasing the share of renewable energy (RES) and improving energy efficiency. Heat exchangers play an important role in meeting these targets in industry, as they can help to save energy, reduce emissions and optimise energy processes
- **Renewable Energy Directive (RED):** In the context of heat exchangers, this directive indirectly influences their application, particularly with regard to the integration of renewable heat sources and heat recovery technologies promoting efficient energy management, including the minimisation of energy losses. Heat exchangers are key in waste heat recovery systems as they enable,n the reuse of heat that would otherwise be lost thus supporting the RED objectives of increasing energy efficiency and reducing CO2 emissions

- **Energy Efficiency Directive (EED) (2012/27/UE):** Heat exchangers play a key role in meeting the objectives of EED Directive 2012/27/EU in industry. They can reduce energy consumption, increase the efficiency of production processes and improve waste heat recovery, all of which are necessary to achieve the energy saving requirements of industry. The directive promotes measures such as energy audits, the use of high-efficiency cogeneration technology and the modernisation of existing installations, which stimulates companies to invest in modern solutions, including more efficient heat exchangers.
- **Industrial Emissions Directive (IED) (2010/75/EU)**: The IED regulates emissions from industrial processes, including those involving heat exchangers in sectors such as chemical manufacturing and energy production. The directive enforces the use of Best Available Techniques (BAT) to minimize emissions of pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO2), and particulate matter.
- **Medium Combustion Plant Directive (MCPD) (EU 2015/2193)**: This directive affects heat exchangers integrated into combustion plants with a thermal input between 1 MW and 50 MW. It sets emission limits for NOx, SO2, and particulate matter, promoting cleaner technology adoption.

## *Member States: National Energy Efficiency Action Plans (NEEAPs); National EE Target; National Implementing Measures*

- **National Energy Efficiency Action Plans (NEEAPs):** In many NEEAPs, Member States are promoting measures to optimise industrial processes through the use of heat recovery technologies. Member States can offer subsidies, tax breaks or preferential loans for the modernisation of industrial heating systems as part of these plans.
- **National Energy Efficiency Targets:** Each EU Member State is required to set its national energy efficiency targets, in line with EU requirements. These targets include reductions in energy consumption in various sectors, including industry, where heat exchangers can be a key tool to meet these targets.
- **National Implementing Measures:** In the context of heat exchangers, National Implementation Measures may include regulations, standards, support programmes or financial initiatives that promote energy efficiency improvements in industry. Examples of implementation measures include Energy Audits, Industrial Retrofit Programmes, Industrial Energy Standards.

*Outcome: conference paper and articles in high impact journals*

- The scale of interest in the topic of heat exchangers is growing year on year. In the Scopus database alone, which contains information on published scientific work, such as articles in scientific journals, books, conference proceedings and patents, the keyword heat exchanger occurs 744,323 times. Heat exchanger in industry has 224,583 occurrences. These figures highlight the importance of the heat exchanger issue.

## 3.2 PESTLE, Porter's Five Forces and SWOT Analysis

### 3.2.1. PESTEL

A PESTEL analysis is a strategic tool used to identify and analyse the key external factors that can influence an organization or industry, or in this case, a technology. It stands for Political, Economic, Social, Technological, Environmental, and Legal factors, each representing a different category of external influence:

Political factors involve government policies, regulations, and political stability. They affect how businesses operate and can include tax policies, trade restrictions, tariffs, and government stability. Political factors are especially prevalent in the EU landscape, and often shape innovation (e.g., Green Deal). These factors are particularly important in the wake of REPOWEREU and the decoupling from Russian energy sources that necessitated a widescale transformation of the EU energy grid.

Economic factors include the economic environment that affects a business, such as economic growth, inflation rates, exchange rates, and unemployment levels. These factors also influence consumer purchasing power and business costs. For EIIs, the most common challenge and priority is the reduction of energy costs.

Social factors relate to the cultural and demographic aspects of the environment, such as population growth, age distribution, cultural trends, and consumer attitudes. Social factors can impact the demand for a company's products and services.

Technological factors encompass the impact of technology on an industry or market. These include innovations in the same or other disciplines, such as material science and digital technologies.

Environmental factors involve ecological and environmental aspects like climate change, environmental regulations, and sustainability initiatives. They can affect resource availability, production costs, and market demand for environmentally friendly products.

Legal factors include laws and regulations that govern how businesses operate. They cover areas such as consumer protection, labor laws, health and safety regulations, and antitrust laws.

### *Political Factors*

The adoption and integration of Heat Pipe Heat Exchangers (HPHEs) into industrial processes are heavily influenced by stringent governmental policies aimed at reducing carbon emissions and improving energy efficiency. The European Union (EU) remains at the forefront of this movement, driven by policies such as the European Green Deal and the Industrial Emissions Directive. These policies mandate significant reductions in greenhouse gas emissions, making technologies like HPHEs essential for compliance. Furthermore, the global push for climate neutrality by 2050, emphasized by international agreements like the Paris Agreement, increases the political impetus for industries to adopt energy-efficient technologies[162].

### *Economic Factors*

Economically, HPHEs present a compelling case for cost savings through enhanced energy efficiency. Industries that adopt HPHEs can expect significant reductions in their energy expenses, as these systems are capable of recovering up to 70% of waste heat. This not only reduces operational costs but also offers a favourable return on investment (ROI). For example, in the aluminium industry, HPHEs have shown a payback period of less than three years, which is attractive for large-scale industrial applications[163]. Moreover, the global market for heat exchangers, including HPHEs, is projected to grow significantly, driven by rising industrialization and the need for energy efficiency across various sectors[164]. Finally, the advantages in more resilient operation and thus reduced downtime for maintenance and repair are also very attractive to end users.

### *Social Factors*

There is an increasing societal expectation for industries to engage in sustainable practices and corporate social responsibility. HPHEs contribute to this by lowering energy consumption and reducing carbon footprints, which enhances the environmental credentials of companies. This not only meets the growing consumer demand for sustainability but also aligns with the expectations of stakeholders, including investors and regulatory bodies. Additionally, the adoption of HPHE technology can stimulate job creation in areas such as manufacturing, installation, and maintenance, which is socially beneficial. Finally, waste heat especially of low grade can be diverted to local district heating grids, providing a source of sustainable heating.

### *Technological Factors*

The HPHE technology is promising for its ability to manage extreme operational environments, including high temperatures and corrosive conditions. The design flexibility and robustness of HPHEs make them suitable for a wide range of industrial applications, especially in the EII sectors. Furthermore, ongoing advancements in materials science, such as the development of more durable heat pipes and advanced coatings, continue to enhance the efficiency and lifespan of HPHEs.

### *Environmental Factors*

Environmental concerns are a significant driver for the adoption of HPHEs. These systems support global efforts to reduce industrial emissions by enabling the recovery and reuse of waste heat, thereby lowering overall energy consumption. The ability of HPHEs to operate efficiently in extreme conditions, such as high temperatures and corrosive environments, makes them particularly valuable in energy-intensive industries like steel and aluminium, where the environmental impact is substantial. Moreover, by reducing the demand for primary energy, HPHEs contribute to the conservation of natural resources and the mitigation of climate change. In a nutshell, HPHEs provide excellent value for EIIs in decarbonising their heating systems.

### *Legal Factors*

The legal landscape surrounding industrial emissions and energy efficiency is increasingly stringent, with global and regional regulations pushing industries towards more sustainable practices. Compliance with these regulations is not optional but a legal necessity, and failure to meet these standards can result in significant fines and other penalties. HPHEs play a critical role in helping industries meet these legal requirements by providing a reliable means of reducing emissions and improving energy efficiency. Additionally, intellectual property rights and patents related to HPHE technology are important legal considerations, as they protect innovations and provide competitive advantages.

### *Conclusions*

By examining the Political, Economic, Social, Technological, Environmental, and Legal factors, this analysis provides a holistic understanding of the challenges and opportunities faced by industries adopting HPHE technology. Politically, stringent regulations, particularly in the EU, drive the necessity for energy-efficient technologies. Economically, HPHEs offer significant cost savings and a favourable return on investment, making them an attractive option for energy-intensive industries. Socially, the adoption of HPHEs aligns with growing societal expectations for corporate sustainability, while technologically, the continuous advancements in HPHE design enhance their efficiency and applicability across various industrial sectors. Environmentally, HPHEs contribute to the reduction of industrial emissions and the conservation of natural resources, which are crucial in the fight against climate change. Legally, the increasing stringency of environmental regulations underscores the importance of HPHEs in ensuring compliance and avoiding penalties. Collectively, these factors highlight the strategic importance of HPHEs in promoting sustainable industrial practices and achieving long-term environmental and economic goals.

### 1.2.2 Porter’s Five Forces

Michael Porter's Five Forces model, introduced in a 1979 article in the Harvard Business Review, remains a fundamental tool for analysing the competitive landscape of industries. Porter identified five forces that influence an industry's structure and profitability: the intensity of internal competition, the threat of new entrants, the bargaining power of suppliers, the bargaining power of customers, and the threat of substitutes. This model critiques "perfectly competitive" business environments, emphasizing the complexities and interdependencies of real-world markets where competitors are not merely rivals, but where entire industries can rise or fall together.

#### *Threat of New Entrants*

There are three main barriers to entry: (a) high CAPEX, (b) economies of scale, as well as (c) system complexity. High capital investment is required for technology and infrastructure in the heat exchanger market, particularly for industrial waste heat recovery systems requiring sophisticated manufacturing equipment capable of producing and testing large units. Moreover, established companies benefit from economies of scale and strong brand recognition, making it challenging for new players to gain a foothold. Finally, the engineering challenges of designing bespoke systems for each installation necessitate a high skill level that is usually treasured by established market players.

**Conclusion**: The threat of new entrants is low due to substantial capital requirements, and the dominance of established players.

#### *Bargaining Power of Suppliers*

The market relies on specialized suppliers for critical components and materials used in heat exchangers. This concentration increases suppliers' bargaining power, especially if alternatives are limited. Switching suppliers can involve significant costs and operational disruptions, which further enhances the power of existing suppliers.

**Conclusion**: The bargaining power of suppliers is moderate, driven by the specialized nature of the components and potential limited supplier options.

#### *Bargaining Power of Buyers*

Buyers, typically large industrial firms, have access to extensive product and pricing information, which enhances their negotiating power. They often seek multiple quotes and negotiate aggressively due to high price sensitivity in capital-intensive sectors. Large buyers of multiple systems can leverage their purchasing volume to secure better terms, further increasing their power.

**Conclusion**: The bargaining power of buyers is high, as they can use their access to information and purchasing volume to negotiate favourable conditions.

### *Threat of Substitute Products*

The threat of substitutes is limited as waste heat is a necessary byproduct of many industrial processes. Nonetheless, continuous innovation in energy efficiency and recovery technologies increases the likelihood of substitutes entering the market, but the main competitor here are electrification technologies such as heat pumps that provide much more efficient heating, minimising waste heat availability. Still, these systems are mainly used for low-average temperatures (up to 150°C currently).

**Conclusion**: The threat of substitute products is low, but can increase to significant, driven by ongoing technological advances.

### *Industry Rivalry*

The heat exchanger market is characterized by numerous competitors, including well-established firms like Mitsubishi Heavy Industries, Siemens, and Alfa Laval (as described in the previous section), leading to intense rivalry, Figure 56Figure 56.

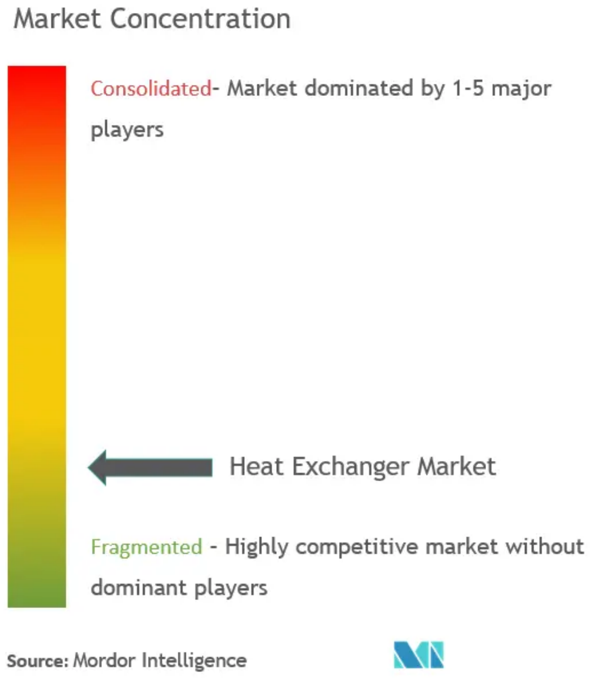



*Figure 56. Market Concentration [35]*

While many products in the market are similar, leading to fierce price competition, some companies differentiate themselves through innovation, quality, and brand loyalty. High fixed costs in the industry drive companies to maintain production even during demand downturns, increasing competitive pressures. Figure 56 presents the concentration of the heat exchanger market.

**Conclusion**: Industry rivalry is high due to the presence of multiple strong competitors, the need for continuous innovation, and the challenges associated with high fixed costs.

### 3.2.3. SWOT Analysis

The SWOT analysis is a management and strategic planning tool used to help individuals or organizations identify their Strengths, Weaknesses, Opportunities, and Threats in relation to business competition. This technique is intended for use in the early stages of decision-making and serves as a tool for assessing strategic positioning. SWOT for HPHEs is discussed below.

#### *Strengths*

**Established technology**: Heat exchangers are a well-established, proven technology for many decades. Waste heat recovery is a staple of modern industry with a wide range of installations across all EIIs and with heating energy end use both within the process or plant, or in heating networks.

**Diverse applications**: The versatility of heat exchangers in different industrial processes, or even in different sections of an industrial process line. The limitations of waste heat recovery are set by the technoeconomic feasibility of the application.

**Contribution to energy efficiency, decarbonisation and ESG criteria**: Heat exchangers contribute decisively in improving energy efficiency in industrial processes, directly impacting the energy and carbon footprint of products, and are considered a reliable option for decarbonisation.

**Technological advancements**: While established, the science of heat exchangers rapidly evolves through innovations in other disciplines, such as the digital and the material sciences. For instance, the development of high-efficiency ceramic and microchannel heat exchangers and new corrosion resistance coatings enhance HX performance, broaden their application and improve market appeal.

**Maintenance excellence**: Certain types of heat exchangers, such as shell-and-tube designs, can be prone to fouling and corrosion, leading to high maintenance costs and potential downtime. In contrast, the HPHE can be designed to withstand extremely hostile conditions, creating a powerful selling point.

### *Weaknesses*

**High initial investment**: The upfront investment required for commissioning a waste heat recovery system can be significant, both in terms of cost and time and effort required. This may deter potential customers, especially in smaller enterprises (for instance Small-Medium Enterprises or micro-SMEs).

**Market Fragmentation**: The market is highly fragmented with numerous competitors offering similar products, leading to intense price competition and slim margins.

### *Opportunities*

**Growing Environmental Regulations**: Increasingly stringent environmental regulations worldwide create a demand for technologies that can reduce energy consumption and emissions, positioning heat exchangers as a vital component in compliance strategies.

**Expanding Markets**: Emerging markets, particularly in Asia-Pacific, are experiencing rapid industrial growth, creating new opportunities for the deployment of heat exchangers in energy-intensive industries .

**Integration with Renewable Energy**: The trend towards integrating renewable energy sources, such as solar thermal systems, with traditional industrial processes offers new avenues for the application of heat exchangers.

**Digitalization and Smart Technology**: The incorporation of IoT and smart technologies into heat exchanger systems can optimize performance, reduce energy use, and extend the lifespan of equipment, providing a competitive edge in the market.

### *Threats*

**Intense Competition**: The market faces stiff competition from both established players and new entrants, particularly in regions with lower production costs, which could lead to market saturation and reduced profitability.

**Economic Uncertainty**: Fluctuations in the global economy, particularly in energy prices, can impact the demand for capital-intensive equipment like heat exchangers.

**Technological Disruption**: Advancements in alternative energy recovery technologies, such as heat pumps or emerging materials for heat exchangers, could potentially reduce the demand for traditional heat exchanger systems.

**Regulatory Risks**: Changes in environmental and safety regulations could impose additional costs or operational constraints, affecting the market's growth potential.

**Resistance from clients**: Company stakeholders may be hesitant to invest in new technology

- The potential for positive deployment could have been clearly shared with industry stakeholders in terms of economic proof of concept, feasibility and evaluation of return on investment,
- The heat pipe design makes it modular, compact and more efficient than conventional heat exchangers, and requires less space in an existing installation and reduced maintenance hours.
- The heat pipe system is installed in self-contained package requiring minor adjustment for further reparations in case of failures

### 3.2.4 Conclusions

The combined analysis of PESTEL, Porter’s Five Forces, and SWOT provides a thorough evaluation of the external and internal factors influencing the Heat Pipe Heat Exchanger (HPHE) industry. The PESTEL analysis highlights the significant external pressures and opportunities that shape the market, such as stringent environmental regulations, economic incentives for energy efficiency, and technological advancements. Porter’s Five Forces further dissects the competitive landscape, revealing the low threat of new entrants due to high capital requirements, moderate bargaining power of suppliers, and high buyer power in a competitive market. Finally, the SWOT analysis identifies the strengths of established technology and market opportunities driven by environmental regulations, while also acknowledging weaknesses like high initial investment and threats from intense competition and technological disruption. Together, these analyses underscore the strategic importance of HPHEs in modern industries, particularly in their role in promoting energy efficiency and sustainability while navigating complex competitive and regulatory environments.

## 3.3 Business model and financial projections

The development of a go-to-market strategy for the ETEKINA HPHE is effectively supported by integrating several critical elements: the Business Model Canvas, Lean Canvas, Customer Lifecycle, Unique Value Proposition Canvas, and Financial Projections. The Business Model Canvas offers a detailed overview of the HPHE's business framework, identifying key activities, resources, and partnerships necessary to deliver significant energy savings and environmental benefits to energy-intensive industries. The Lean Canvas zeroes in on the specific challenges faced by these industries, such as high energy costs and the need for efficient waste heat recovery, ensuring that the HPHE is directly aligned with market demands from the outset. The Customer Lifecycle provides a clear understanding of the stages that potential customers, like those in the ceramics, steel, and non-ferrous metal sectors, progress through—from awareness of the HPHE's capabilities to adoption and long-term retention—allowing the strategy to be fine-tuned for maximum customer acquisition and loyalty. The Unique Value Proposition Canvas ensures that the HPHE's distinct advantages, such as high-efficiency heat recovery and robust design, are clearly communicated and resonate with customer needs, effectively differentiating it in the competitive landscape. Finally, the Financial Projections offer a thorough evaluation of the expected costs, revenue streams, and profitability, validating that the strategy is not only market-driven but also financially sustainable. Together, these elements form an integrated approach that guides the go-to-market strategy, ensuring the HPHE's successful entry and growth in the market while meeting the specific needs of energy-intensive industries.

### 3.3.1 Business model Canvas of the HPHE

The Business Model Canvas (BMC) is a tool developed by Alex Osterwalder and Yves Pigneur that allows business ideas to be easily defined, designed and visualised. The BMC is a suitable technique to create a one-page summary based on key elements of the project for process industries. BMC focuses on customers and their needs. This makes it possible to create a tailored offer that meets the expectations of the audience. BMC identifies nine core elements of any business. These are related to the key areas of the business: customers, offerings, infrastructure and the respective financial position. To create the BMC nine fields of the business model template must be completed, **Error! Reference source not found.**Figure 57.

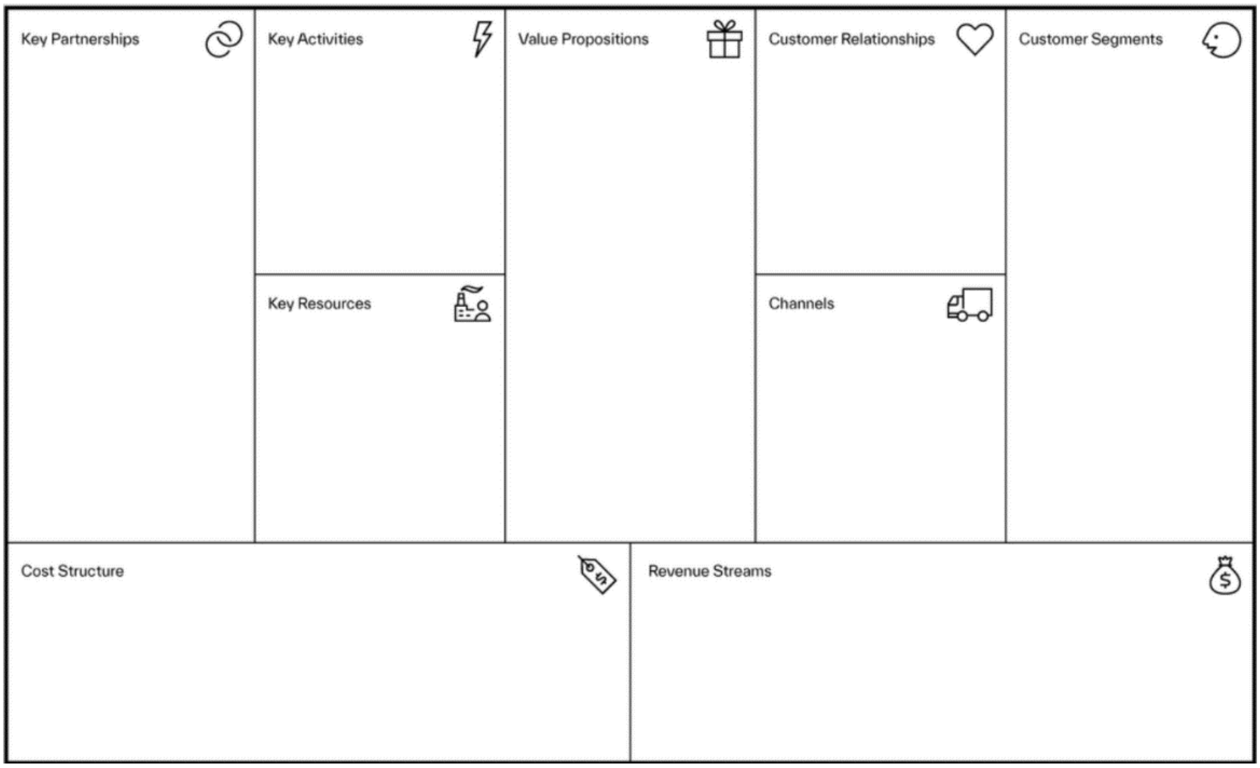



*Figure 57. Business model CANVAS template [36]*

**Customer Segment**: This section identifies the specific groups of individuals and organizations that the company targets. Effective segmentation necessitates a comprehensive analysis of the common characteristics shared by these groups. Understanding these characteristics allows the company to tailor its offerings to more precisely meet the needs of its customers.

- The primary target markets for the ETEKINA HPHE technology are energy-intensive industries (EII), particularly those dealing with high waste heat streams. These include sectors like ceramics, steel, non-ferrous metals, and potentially other industries with significant energy recovery needs. The early adopters include branches of companies involved in the ETEKINA project, such as FED, METAL, and CON. Other potential adopters include equipment manufacturers like INSERTEC, which could integrate HPHE technology into their furnaces.

**Value Proposition**: This section defines the specific customer problems that the product or service aims to solve and the unique value it delivers. The value proposition is a key factor in influencing the customer's decision to choose a particular product, as it directly addresses consumer pain points or fulfils their needs, making the offering indispensable.

- The ETEKINA HPHE technology provides a unique value proposition by enabling the recovery of 40% to 70% of waste heat in challenging industrial environments. Key features include high efficiency in transferring heat even under high temperatures and corrosive conditions, the robust design with automatic fouling management and multi-sink capability, achieving significant reduction in energy costs and greenhouse gas emissions, leading to a high return on investment (ROI) and a short payback period and compact design, able to fit into existing processes with minimal modifications, making it adaptable and scalable across various industries.

**Channels**: The selection of appropriate channels plays a crucial role in shaping the company's relationship with each customer segment. This section specifies the channels through which the company communicates information about its products or services to customers. Depending on the business model, these channels are instrumental in enhancing customer awareness of the offerings, establishing effective contact with customers, and optimizing associated costs.

- ➢ The channels for reaching customers firstly focus on the demonstrations at the three existing ETEKINA demo sites (ceramics, steel, and aluminium industries). The results will be disseminated in industry trade shows, conferences, and events. The technology will also be published and presented in scientific and industrial forums. Moreover, social media platforms like LinkedIn and Twitter, alongside the project website also provide an avenue for dissemination. Finally, the success of the project has provided ETEKINA with substantial prestige and is regularly featured in newsletters and communication in the EII associations.

**Customer Relations**: This section describes the nature of the relationship the company establishes with each customer segment. The interaction strategy must align with other components of the business model and be adapted to the industry context. The costs associated with maintaining different types of customer relationships are also considered, as this element of the business model determines the overall customer experience with the company.

- ➢ The relationship with customers is built through a consultative approach, offering tailored solutions based on the specific needs of each industry. Continuous support is provided through the integration process, and the relationship is strengthened by showcasing successful implementations and the resulting benefits, such as cost savings and rapid payback. The relationship also continues by managing maintenance and repair cycles.

**Revenue Streams**: This section focuses on quantifying the revenue generated by the product or company across different market segments. A single product may generate revenue in multiple forms, and a company may have several revenue streams, each with its own pricing mechanism. The analysis determines whether customers are charged a one-time fee or if a subscription-based model is utilized, and it evaluates the contribution of each revenue stream to the overall revenue.

- For the ETEKINA HPHE, revenue is generated through the sales of bespoke HPHE units tailored to customer specifications. Moreover, consultancy services and design fees for custom heat recovery solutions are provided, and potential royalties from intellectual property, particularly in cases where third-party manufacturers integrate HPHE technology into their systems can be pursued.

**Key Resources**: This section identifies the essential resources required to produce the product, reach customers, and generate revenue. Key resources include financial resources (capital needed to create customer value), physical resources (such as equipment, vehicles, machinery, and warehouses), human resources (human capital), and intellectual resources (such as copyrights and patents). The analysis assesses the resources necessary for maintaining customer relationships, ensuring the effective operation of distribution channels, and delivering the company's value proposition.

- The key resources necessary for delivering the HPHE technology firstly rely on the technical expertise in designing and manufacturing heat exchangers that is built with the experience of over 400 systems, also, the intellectual property, including patents and proprietary knowledge developed through the ETEKINA project, but also before ETEKINA, as background IP. The manufacturing facilities equipped to produce bespoke HPHE units are also key resources, and so are the strategic partnerships with research institutions and industry players in the ETEKINA and other projects (IWAYS, DREAM, SMARTREC and others).

**Key Activities**: This section focuses on identifying the critical activities necessary for revenue generation and the establishment and maintenance of customer relationships. The key activities vary depending on the company’s profile and include actions required to ensure revenue generation, sustain customer relationships, fulfil the value proposition, and ensure the effective functioning of distribution channels.

- Continuous research and development to improve the HPHE technology, especially in handling challenging waste streams.
- Manufacturing and assembly of heat exchangers tailored to the needs of different industries.
- Marketing and sales activities focused on demonstrating the value of the technology through case studies and pilot implementations.

**Key Partners**: This section identifies the key suppliers, contractors, and collaborators upon whom the business or product relies. It assesses the strategic benefits of forming partnerships with other organizations, defining the products and services provided by partners, and identifying the most critical suppliers and business partners.

- ➢ Industrial partners like FED, METAL, and CON, who are both customers and collaborators in the project.
- ➢ Research institutions which provide technical expertise and support for ongoing innovation.
- ➢ Equipment manufacturers like Econotherm and INSERTEC, which could integrate the HPHE technology into their product offerings.

**Cost Structure**: This section is completed after a thorough analysis of the company's resources, activities, and partners, as it is essential to accurately determine costs within this context. Business models may be cost-driven or value-driven, and the analysis focuses on identifying the elements that generate the highest costs, determining the most expensive key resources, and assessing the most resource-intensive activities within the company.

- ➢ Research and development expenses, particularly in improving the efficiency and adaptability of the HPHE system.
- ➢ Manufacturing costs, including materials and labour for producing bespoke units.
- ➢ Marketing and sales costs, including participation in industry events and digital marketing campaigns.
- ➢ Costs associated with maintaining intellectual property rights and developing new patents.

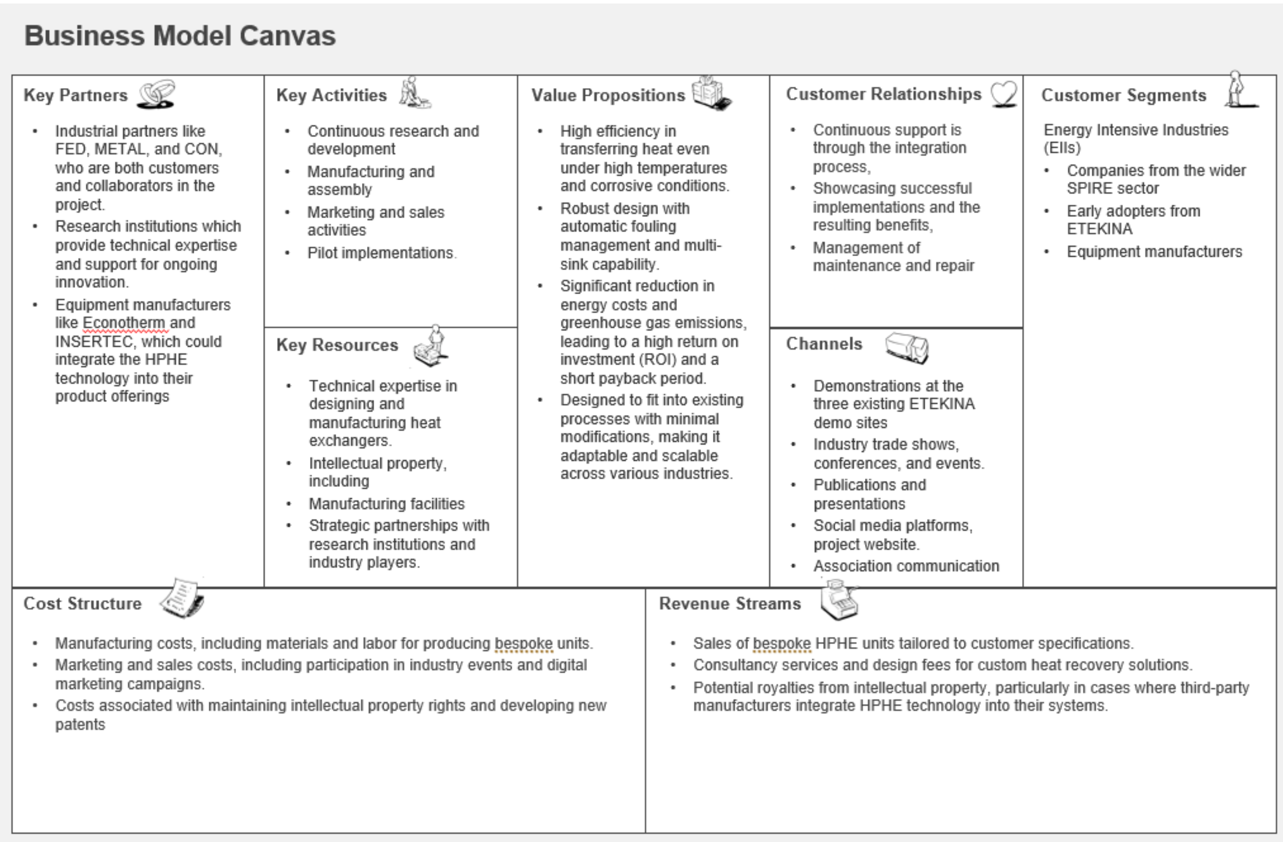



*Figure 58. Business model CANVAS for ETEKINA project*

The ETEKINA HPHE technology is strategically positioned to serve energy-intensive industries (EII) such as ceramics, steel, and non-ferrous metals, where the recovery of waste heat is highly sought after by industrial end users. By offering a uniquely attractive value proposition, the HPHE technology addresses industry-specific challenges, leading to a high return on investment. The business model is supported by targeted channels to effectively reach and engage potential customers, and maintain relationships through a consultative approach and ongoing support. Revenue streams are diversified, key resources are secured and continuous R&D and manufacturing are key pillars to the success of the prospective business. The cost structure is focused on R&D, manufacturing, and maintaining intellectual property, ensuring that the HPHE technology remains competitive and innovative in the market. The results of the analysis are shown in Figure 58.

### 3.3.2 Lean Canvas Business Model

The Lean Canvas is an adaptation of Business Model Canvas. Lean focuses on problems, solutions, key metrics and competitive advantages. Among the different type of canvas, the Lean business model canvas, by Ash Maurya, is the most suited for R&D projects given its simplicity. Therefore, the Lean canvas model was used due to the nature of the project and the innovative technology of ETEKINA HPHE. It has been conducted for the ETEKINA HPHE technology as it is the key element of the project and an innovative product which is bespoke that will have a great impact in the energy intensive industries to recover heat in challenging waste heat streams. This study combines 5 main sections which are technical viability, market viability, business viability, management model viability and economical and financial model viability.

**Problem**: Refers to identifying the main problems that target customers face. Understanding these problems validates if the product or service is designed to solve them. This analysis was carried out in 3.1.1 and the technological (T) and non-technological (N) challenges identified are consolidated into 3 main points:

- Lack of effective, high efficiency available solutions for waste heat recovery from challenging waste heat streams, such as condensation of gases leading to corrosion at cold spots that damage the metallic structure of the heat exchangers.
- Need for reduction in emissions, improving the energy efficiency and reducing costs
- Lack of available space to integrate energy saving solutions in the existing plants.

**Customer Segments**: This area has been defined from the BMC analysis.

<u>Energy Intensive Industries</u>: we take as reference the main industries participating in the ETEKINA project ceramic, steel and Non-ferrous (aluminium). Other companies characterised by waste heat

sources in challenging streams are also main adopters. A more detailed analysis was carried out in 2.3.1.4 Target Customer Identification.

**Unique Value Proposition (UVP)**: The unique characteristics of the product or service. This is analysed in the Unique Selling Points section in 3.3.4.

**Solution**: Top features or the key aspects of the product that solve the problems identified. This section provides a high-level overview of how the solution addresses the customers' needs. Info recovered from 3.3.4 section.

**Channels**: Description of the methods or platforms through which customer segments will be reached. Data taken from the Business model Canvas section (3.3.1).

**Revenue Streams**: As Business model Canvas section (3.3.1).

**Cost Structure**: As Business model Canvas section (3.3.1).

**Unfair Advantage**: Patent, know-how and team with knowledge and experience.

A summary of the Lean Canvas model for ETEKINA HPHE is shown in Figure 59.

| **Lean Canvas Business Model for** ETEKINA HPHE | | | | |
|---|---|---|---|---|
| **Problem**<br><br>•Lack of effective available solutions for waste heat recovery from challenging waste heat streams.<br>•Need for reduction in emissions within energy intensive industries<br>•Need to improve energy efficiency<br>•High energy costs for intensive industries due to high consumption.<br>•Lack of available space to integrate energy saving solutions in the existing plants.<br>•Condensation of gases leading to corrosion at cold spots that damage the metallic structure of the heat exchangers. | **Solution**<br><br>ETEKINA HPHE<br>•Simple, robust structures with multiple redundancies built-in<br>•Failure modes eliminated<br>•Pipes free to expand and contract without applying stress to casing<br>•Isothermal operation eliminates cold spots and condensation<br>• Heat transfer not affected by wall thickness hence thicker walls typically 2.5mm or 3.5mm pipe walls with higher corrosion allowance<br>•System can be maintained in situ<br>• Consequence of failure is minimised and manageable | **Unique Value Proposition**<br><br>•ETEKINA HPHEs- capability to recover waste heat even with several challenging aspects present in the heat streams, such as:<br>1. -Fouling management (presence of particles)<br>2. -High operating temperature<br>3. -Acidic condensation<br>4. -Multi-sink capability<br>•Heat is transferred to a secondary fluid in a safe and passive manner, without contamination.<br>• Recovery of 40% to 70% of the available waste heat energy.<br>• The ETEKINA HPHE can fit within the existing process with minor to no modification needed in the factory.<br>• Reduction in cost of energy due to lower consumption.<br>• Reduction of GHG emissions.<br>• Short payback period, High ROI.<br>• Simple, robust structures with multiple redundancies built-in.<br>• Pipes free to expand and contract without applying stress to casing. | **Unfair Advantage**<br><br>• Patent<br>• Know how<br>• Team with knowledge and experience | **Customer Segments**<br><br>•Energy Intensive Industries:<br>1. o Ceramic<br>2. o Steel<br>3. o Non-ferrous<br>•Companies characterized by waste heat sources in challenging streams |
| **Current Solutions**<br><br>•Adoption of conventional heat exchangers.<br>•Adoption of energy-saving activities along the production chain.<br>•Additional negotiation of price for the main supply of gas and electricity used. | **Key Metrics**<br>• Physical:<br>- Laboratories, manufacturing factories<br>• Intellectual:<br>- IP, know-how,<br>• Human:<br>- Research and Development teams<br>- Consultancies<br>- Manufacturing teams<br>- Marketing teams | | **Channels**<br>• Social media<br>• Publications<br>• Conferences<br>• Presentations at events<br>• Demo Sites<br>• Partners<br>•European Commission | **Early Adopters**<br>•Demo sites FED, METAL and CON, Spain, Slovenia and Italy respectively<br>• INSERTEC |
| **Cost Structure**<br>Employee Payroll, Material cost, Marketing costs, cost of fixed assets. | | **Revenue Streams**<br>HPHE manufacturing price, HPHE design price, IP royalties | | |

*Figure 59. Lean Canvas model for ETEKINA HPHE*

### 3.3.3 Customer life cycle

Customer life cycle (CLC) it is a term used to describe the progression of steps a customer goes through when considering, purchasing, using, and maintaining loyalty to a product or service. There are five main stages in a customer's life cycle: Awareness, Research, Comparison, Purchase and

Retention. A Customer Life Cycle analysis was carried out. The results of this analysis are shown in Figure 60.

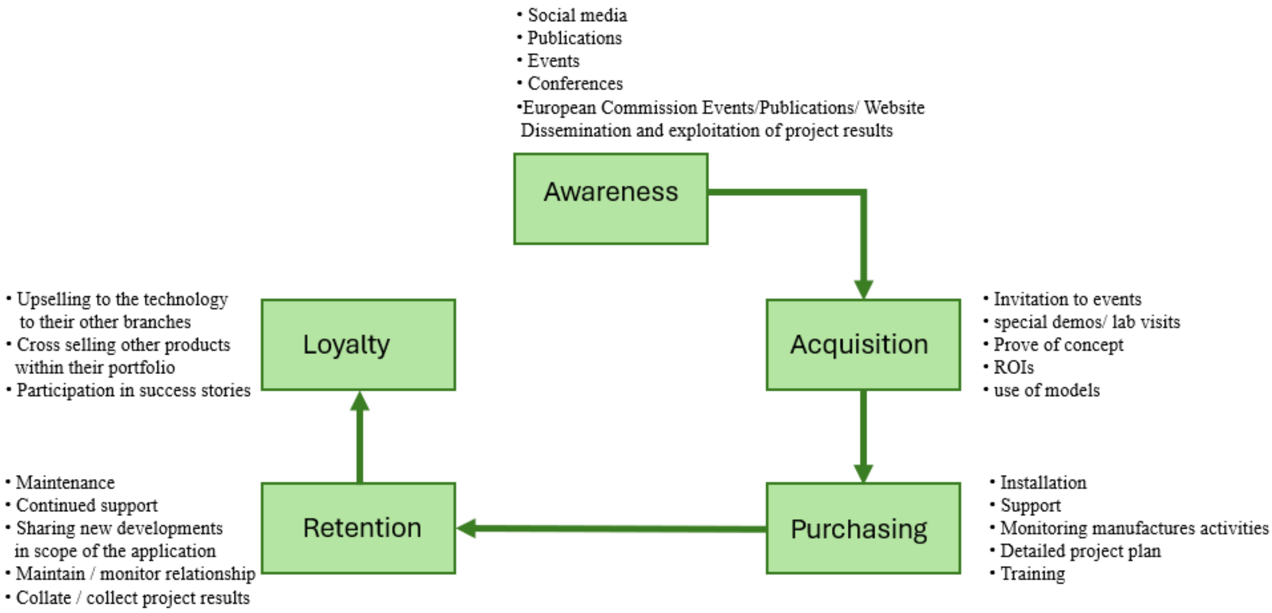



*Figure 60. Customer Life Cycle analysis*

### 3.3.4 Unique Value Proposition Canvas

Value Proposition Canvas (VPC) is a business model tool that helps you make sure that a company's product or service is positioned around customers' values and needs [165]. Value Proposition Canvas investigates further these two (of nine) blocks from the Business Model Canvas: Customer Segment and Value Proposition. The advantage of developing a VPC is to understand the customer and their needs and thus develop the product according to their expectations (Figure 61). This saves time and money by avoiding producing something that nobody needs. The VPC consists of two main sections: the Customer Profile and the Value Map. The Customer Profile defines the customer segment's jobs-to-be-done, pains, and gains. Jobs-to-be-done represent tasks customers aim to accomplish, while pains identify challenges and frustrations in completing those tasks. Gains highlight the desired benefits customers seek. The Value Map, on the other hand, comprises products and services, gain creators, and pain relievers. Products and services list the offerings intended to meet customer needs. Gain creators explain how these offerings create desired outcomes, while pain relievers describe how they alleviate customer challenges. By systematically aligning the Value Map with the Customer Profile, businesses can ensure their value proposition resonates with their target audience, effectively addressing specific needs and providing tangible benefits. The VPC facilitates a structured approach to understanding customer insights, allowing iterative testing and refinement to ensure a strong market fit.

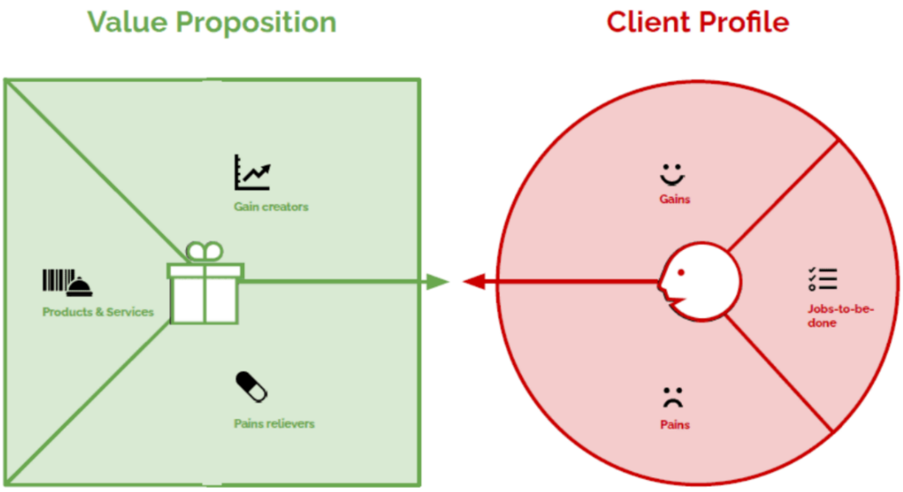
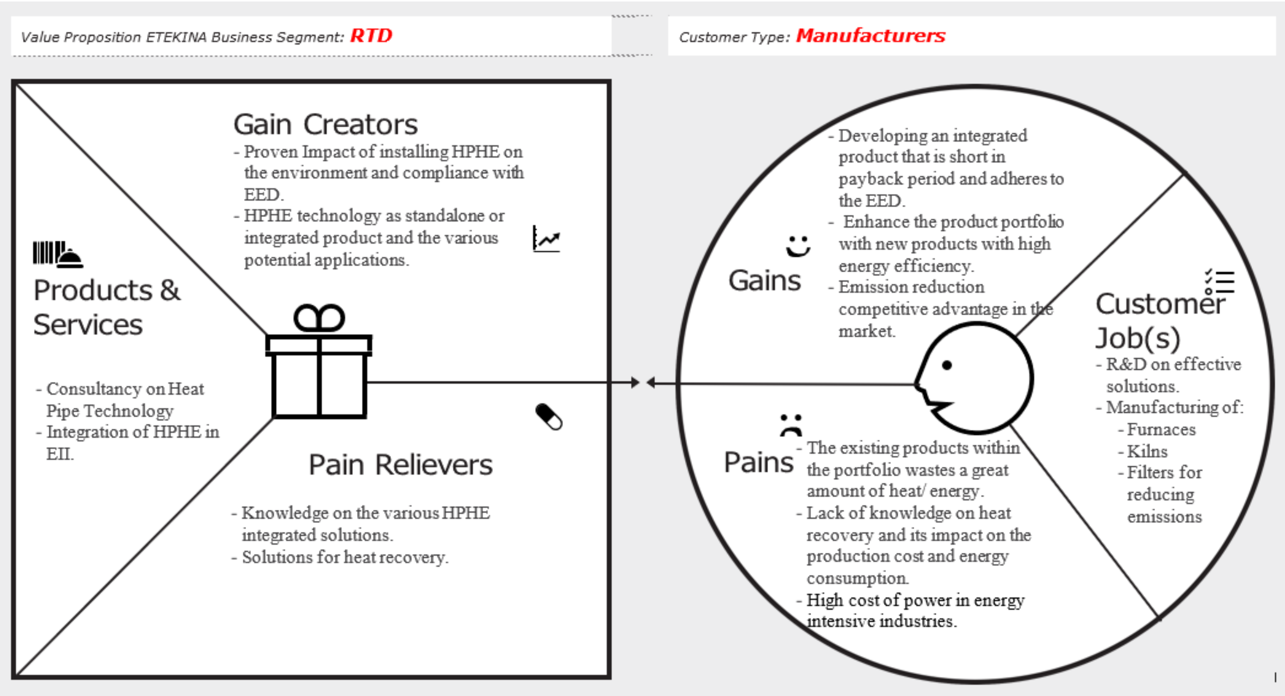
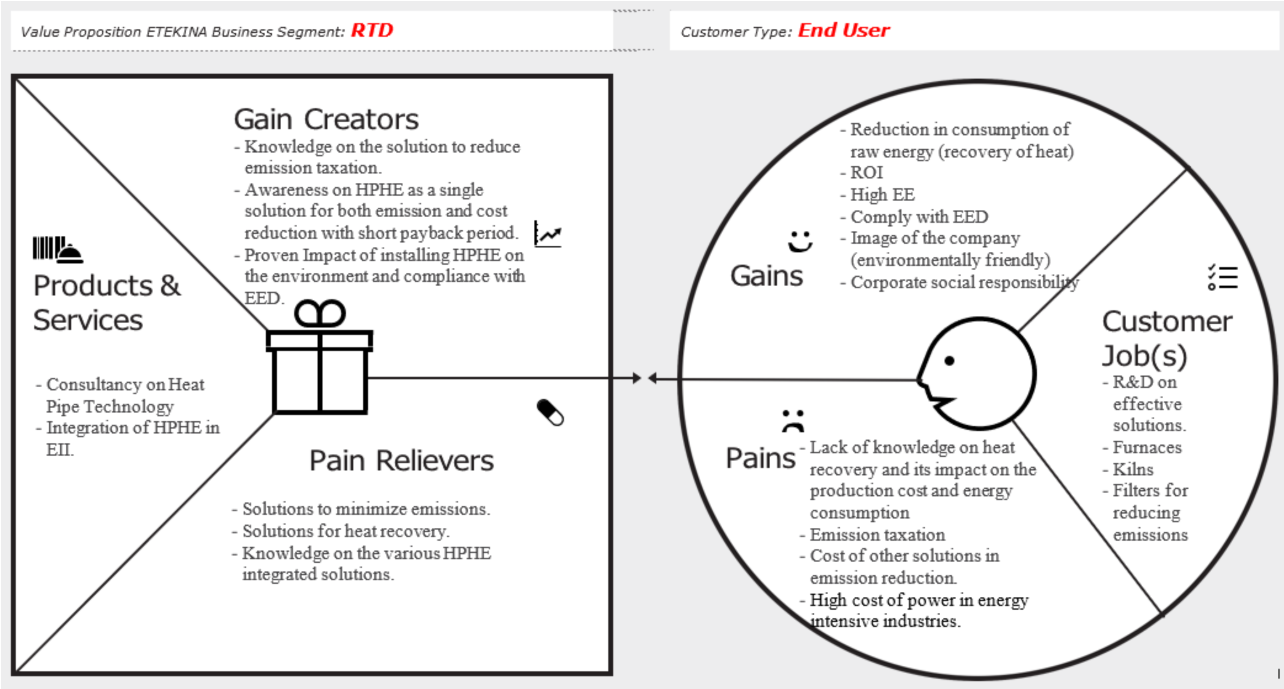



*Figure 61. Value Proposition Canvas*

Value Proposition Canvas was carried out in three scenarios as for the Lean Canvas Business Model. The results of this analysis are shown in Figure 62.





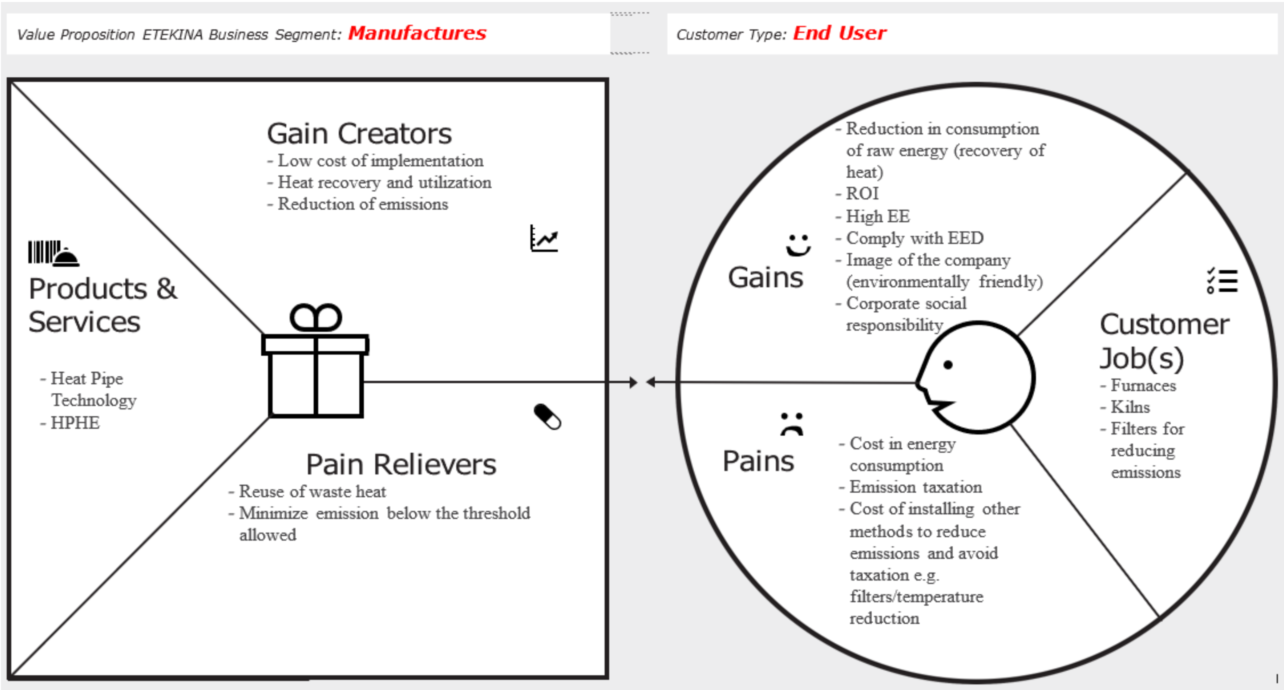




*Figure 62. Value Proposition Canvas for: a) Manufacturer, b) end users c) Manufacturer for end users*

To carry out the VPC analysis, the following steps were taken:

**Definition and understanding of the customer segment**: Identification of the main target group, plus their jobs-to-be-done (tasks they are trying to accomplish), pains (challenges they face), and gains (benefits they seek). More specifically, the HPHE technology is oriented towards the following target groups

**Customer Jobs**: Energy-intensive industries need to (1) reduce energy costs; (2) improve energy efficiency; (3) comply with regulations to reduce greenhouse gas emissions.

**Customer Pains**: EIIs are facing (1) High energy costs due to intensive energy consumption; (2) lack of available space for energy-saving solutions; (3) corrosion and damage to heat exchangers due to gas condensation; (4) difficulty finding effective waste heat recovery solutions; (5) challenges in managing fouling and operating at high temperatures.

**Customer Gains**: EIIs are looking to achieve: (1) reduced energy costs; (2) better energy efficiency; (3) reduced emissions to meet regulations; (4) longer equipment lifespan by avoiding corrosion; (5) effective solutions for waste heat recovery.

**Gain Creators**: HPHEs as proven in the ETEKINA project can: (1) recover 40-70% of available waste heat, improving energy efficiency; (2) operate safely without cross-contaminating the heat streams; (3) help reducing energy costs and greenhouse gas emissions.

**Pain Relievers**: Issues are addressed through the following innovations (1) isothermal operation prevents cold spots and gas condensation, reducing corrosion; (2) fouling is handled and device operates at high temperatures effectively; (3) simple design allows integration into existing factories with minimal modification.

**Products and Services**: The gain creators and pain relievers are achieved through adaptable HPHE products showcasing advantages such as (1) availability of products with robust structure with built-in redundancies; (2) heat pipes with thick walls and other architectures for higher corrosion resistance; (3) device that maintains isothermal operation and efficient heat transfer.

Match Value Proposition to Customer Segment: Align the gain creators and pain relievers of your product/service with the customer segment's jobs, pains, and gains. Ensure there is a strong fit between what the product/service offers and what the customer needs.

Test and Refine: Test the assumptions in your value proposition by engaging with potential customers and getting feedback. Refine the value proposition to better fit the customer needs based on feedback.

Iterate: The VPC is iterative. Revisit the canvas frequently to update it as you learn more about customer needs and how your product/service meets those needs.

In addition, market analysis was carried out, which summarises all the research, inputs and discussions that took place to gather information.

Strategic Value Curve allows you to gather additional information about:

- Competitors who provide solutions in energy recovery
- Survey at the level of potential market for the interest in each of the value aspects
- Quantifying each of the value aspects
- Score for ETEKINA and each of the competitors for each of the value aspects

Based on the data collected, a Strategic Value Curve was developed, quantifying each of the value aspects: ROI/ Payback Period (Number of Months), Adhering to Energy Efficiency Directive (Yes = 10; No = 0), Reduction in energy consumption(MWh/y) (Amount of energy reduction per 100 EUR investment), Reduction in Emissions (t/y) (Amount of emission reduction per 100 EUR investment), Total cost cutting (savings in Energy cost and taxation) (€) (Amount per 100 EUR investment for product lifetime), Figure 63.

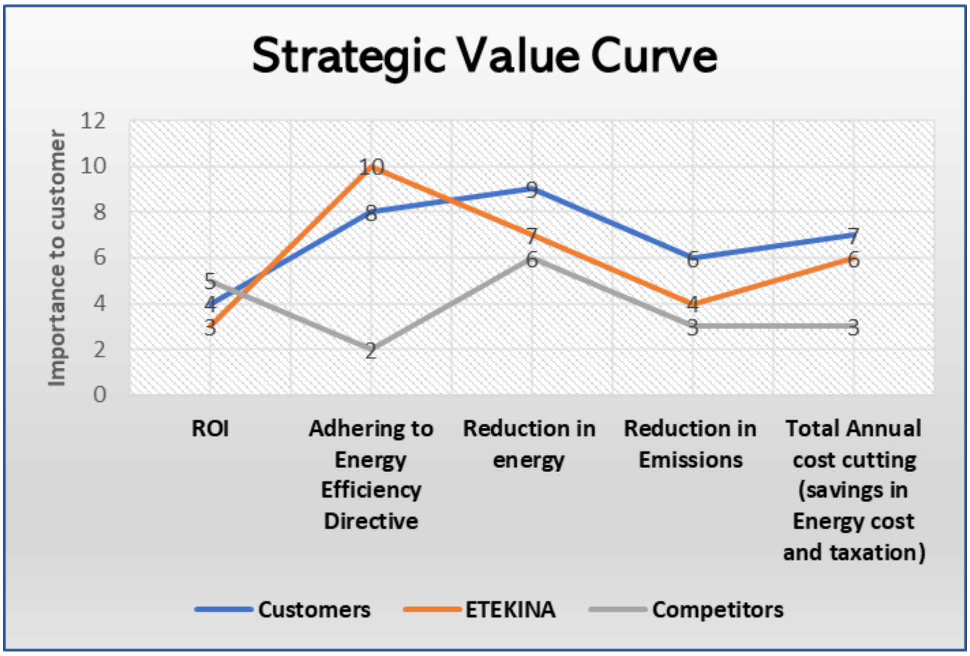



*Figure 63. Strategic Value Curve for ETEKINA HPHE*

### 3.3.5 Financial Projections

Develop financial projections including startup costs, operating expenses, revenue projections, and profitability over time. For innovations in energy systems and process industries, consider the cost implications of manufacturing, installation, maintenance, and potential savings or efficiency gains for customers. The pricing strategy is following the Value Based strategy. Therefore, the price of the unit is based on how many kWs it will transfer from the hot stream to the cold stream. Depending on the extremes and challenges of the scenario for each customer this number varies from €27/kW to €216/kW. The estimated cost of the initial activities and source of coverage is forecasted to be €27,000. Table 12 shows Forecast Sheet for 1 year (2022):

Table 12. Forecast Sheet for 1 year

| Customer name | Forecast size of the deal (£1: €1.08) | Expected closing date | Description |
|---|---|---|---|
| Steel manufacturer UK | €75,000.00 | during 2022 | Initial contact and interest expressed |
| Ceramic and Building materials manufacturer France | €270,000.00 | during 2022 | Expressed interest and consultation in progress |
| Aluminium manufacturer UK | €65,000.00 | during 2022 | Initial discussion |
| FAGOR EDERLAN Spain non-ferrous metals | €60,000.00 | during 2022 | Potential early adopter for integrated HPHE with furnace |

The main revenue stream for the ETEKINA HPHE solution is the revenue generated by selling the HPHE solution. The cost of manufacturing and installing the HPHE unit is approx. 70% of the unit price, which leads for approx. 30% profit on each unit. The cost of designing and manufacturing a new HPHE unit for a new customer will be spread over the contract timeline to manage the cash flow, where potentially 25% of the unit cost deposit will be paid by the customer as down payment following a milestone payment plan. Other revenue streams can be in the form of integrating the ETEKINA HPHE with another product or technology.

As part of the work, a revenue and growth forecast analysis was prepared for ETEKINA HPHE technology, Figure 64. Detailed figures for the next five years are shown in Table 13.

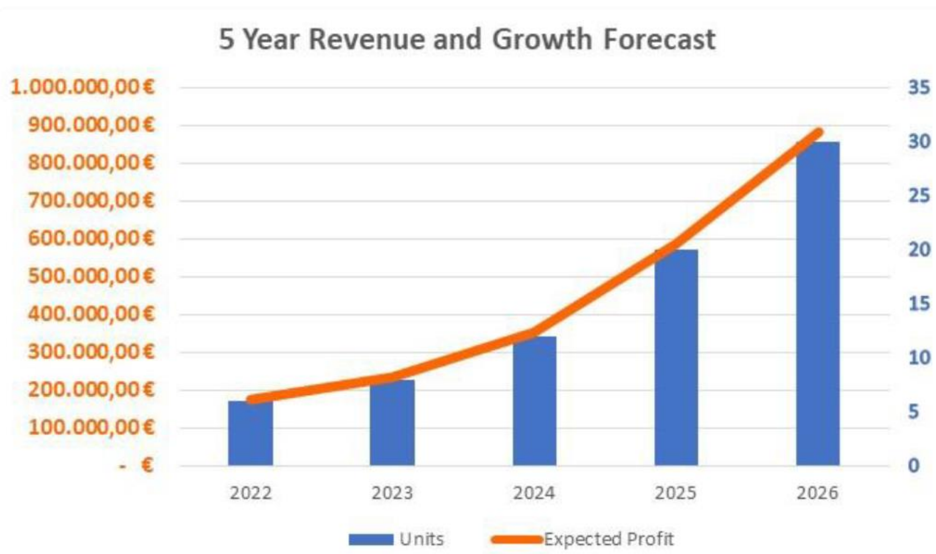


*Figure 64. Revenue and growth forecast analysis*

*Table 13. 5 Years Revenue and Growth Forecast*

| 5 Years Revenue and Growth Forecast | | | | |
|---|---|---|---|---|
| Year | Units | Total Average Cost | Average Revenue | Expected Profit |
| 2022 | 6 | 588,000.00 € | 764,400.00 € | 176,400.00 € |
| 2023 | 8 | 784,000.00 € | 1,019,200.00 € | 235,200.00 € |
| 2024 | 12 | 1,176,000.00 € | 1,528,800.00 € | 352,800.00 € |
| 2025 | 20 | 1,960,000.00 € | 2,548,000.00 € | 588,000.00 € |
| 2026 | 30 | 2,940,000.00 € | 3,822,000.00 € | 882,000.00 € |
| * The average cost per unit is estimated at 98000 Euros | | | | |

The data presented demonstrate economic and financial viability. From the estimations of the three demo sites in this project, the ETEKINA HPHE forecasts a reduction in cost of energy due to lower consumption: this reduction ranges from approx. €18,000 to €155,000 per year, as well as a reduction of GHG emissions of approx. 110 and 850 Tn CO2eq/year, and a short payback period of less than 4 years, high ROI in excess of 160%.

## Go to market strategy

### Pilot Projects and Partnerships

Consider initiating pilot projects or partnerships with industry stakeholders to demonstrate the effectiveness of your technology and gather real-world data. Success stories and case studies from these projects can be powerful tools for marketing and sales efforts.

The innovative technology within an ETEKINA HPHE not only serves an environmental problem by reducing emissions, it also deals with an important economic issue of ‘energy costs’ that affects European growth Gas and electricity. Value Proposition Canvas takes into account the information and knowledge gathered from the partners involved in the ETEKINA project, as well as the research carried out for each of the key exploitation outcomes.

# Chapter 4: Results and discussion

Chapter 4 presents the results and the impact assessment in environmental terms of the LCA models created in Chapter 2. The LCA methodology is applied to quantify the environmental impacts across different impact categories, including global warming potential, fine particulate matter formation, and resource scarcity among other indicators. The results are provided for each of the three case studies.

## 4.1 Case study #1: Ceramic sector

### *Endpoint impact assessment*

The endpoint impacts are shown in Table 14, With regards to damage to ecosystems, the main contributors are Global warming, Terrestrial ecosystems at 58%, Terrestrial acidification at 15.4%, Ozone formation, Terrestrial ecosystems at 7.9%, Terrestrial ecotoxicity at 6.3%, Land use at 5.2%, Freshwater eutrophication at 4.6%, with Water consumption, Terrestrial ecosystem, Freshwater ecotoxicity and Marine ecotoxicity below 1.5%.

Table 15 and Finally, the cost increase due to mineral and fossil extraction increase is also provided, with fossil resource scarcity at 78.1% and Mineral resource scarcity at 21.9%.

Table 16. With regards to the damage to human health, the main contributors are Human carcinogenic toxicity at 60%, Fine particulate matter formation at 25%, Global warming, Human health at 12% while there is also a small contribution of Human non-carcinogenic toxicity at 3%.

*Table 14 Endpoint – damage to human health indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Human health | DALY | 0.0680 | 12% |
| Stratospheric ozone depletion | DALY | 8.74E-06 | 0% |
| Ionizing radiation | DALY | 2.72E-05 | 0% |
| Ozone formation, Human health | DALY | 0.000191 | 0% |
| Fine particulate matter formation | DALY | 0.1425 | 25% |
| Human carcinogenic toxicity | DALY | 0.3407 | 60% |
| Human non-carcinogenic toxicity | DALY | 0.0190 | 3% |
| Water consumption, Human health | DALY | 0.000729 | 0% |
| **Total** | | **5.71E-01** | |

Human carcinogenic toxicity contributes the largest share (60%) to the HPHE's overall environmental footprint, indicating that the majority of the health-related impacts from the HPHE system are related to exposure to carcinogenic substances. The data indicate that hazardous substances are prevalent throughout the HPHE lifecycle, primarily linked to the extraction and processing of steel. Notably, benzo(a)pyrene (BaP), a mutagenic and highly carcinogenic polycyclic aromatic hydrocarbon, is generated during coke production. Additionally, the sintering stage releases emissions such as $CO_2$, $NO_2$, and $SO_2$ into the atmosphere. Dioxins, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) are also emitted during this phase. PCBs, classified as persistent organic pollutants, pose significant risks to human health, particularly due to their carcinogenic properties [166]. Fine particulate matter formation accounts for 25% of the HPHE system's overall footprint, indicating a substantial impact in line with the analysis of the midpoint indicators. Global warming's impact corresponds to 12% of the overall environmental footprint of the HPHE system. This reflects emissions from the materials used in the construction, operation, or auxiliary energy consumption of the HPHE. **Error! Reference source not found.** shows endpoint indicators: damage to human health in ceramic industry.

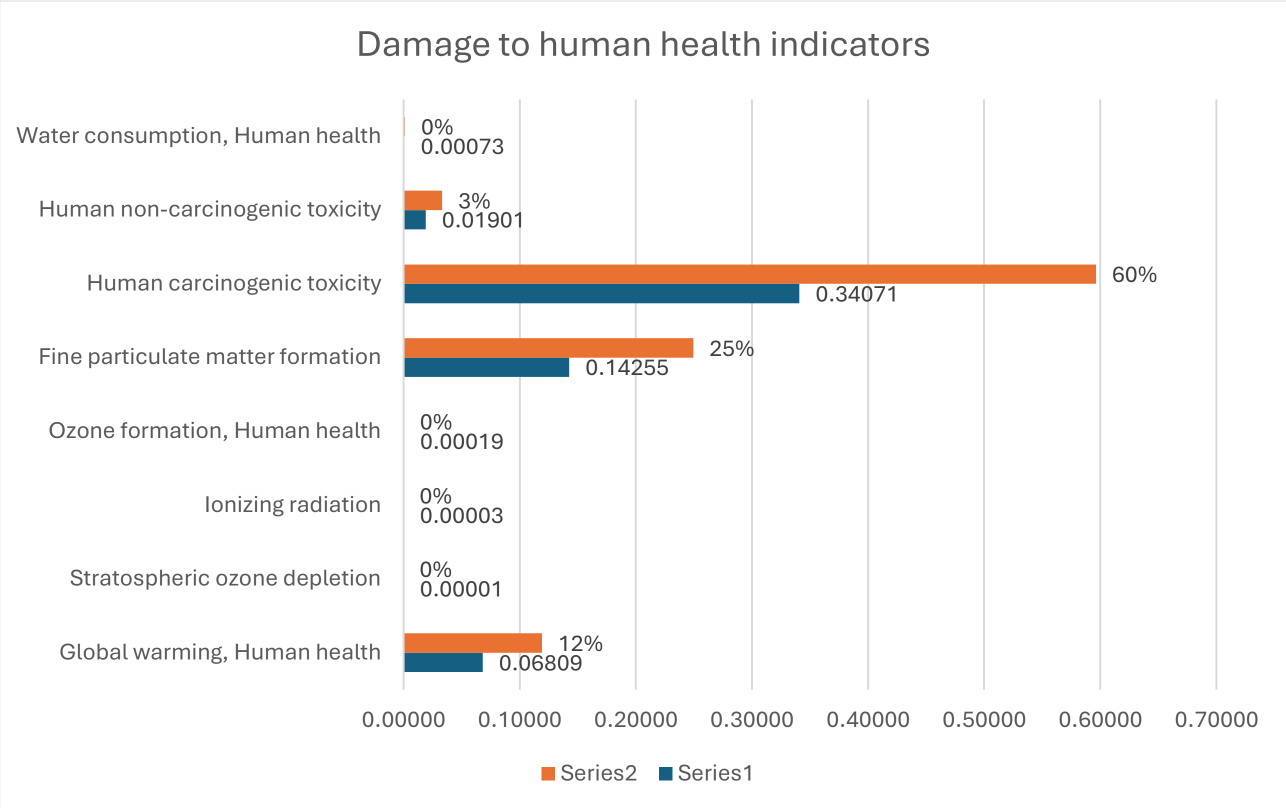



*Figure 65 Endpoint indicators: damage to human health – ceramic industry*

With regards to damage to ecosystems, the main contributors are Global warming, Terrestrial ecosystems at 58%, Terrestrial acidification at 15.4%, Ozone formation, Terrestrial ecosystems at 7.9%, Terrestrial ecotoxicity at 6.3%, Land use at 5.2%, Freshwater eutrophication at 4.6%, with Water consumption, Terrestrial ecosystem, Freshwater ecotoxicity and Marine ecotoxicity below 1.5%.

*Table 15 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to ecosystem indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Terrestrial ecosystems | species.yr | 0.000205 | 58.0% |
| Global warming, Freshwater ecosystems | species.yr | 5.61E-09 | 0.0% |
| Ozone formation, Terrestrial ecosystems | species.yr | 2.82E-05 | 7.9% |
| Terrestrial acidification | species.yr | 5.46E-05 | 15.4% |
| Freshwater eutrophication | species.yr | 1.62E-05 | 4.6% |
| Marine eutrophication | species.yr | 3.48E-09 | 0.0% |
| Terrestrial ecotoxicity | species.yr | 2.22E-05 | 6.3% |
| Freshwater ecotoxicity | species.yr | 3.60E-06 | 1.0% |
| Marine ecotoxicity | species.yr | 8.01E-07 | 0.2% |
| Land use | species.yr | 1.85E-05 | 5.2% |
| Water consumption, Terrestrial ecosystem | species.yr | 4.87E-06 | 1.4% |
| Water consumption, Aquatic ecosystems | species.yr | 5.07E-10 | 0.0% |
| **Total** | | **3.55E-04** | |

Ozone formation is the second most significant contributor, accounting for 7.9% of the total ecosystem damage. Ground-level ozone, a product of nitrogen oxides (NOx) and volatile organic compounds (VOCs) reacting in the presence of sunlight, indicates the contribution of NOx emissions.

Terrestrial acidification ranks as the third largest contributor, responsible for 15.4% of the overall ecosystem damage. Acidification occurs due to emissions of sulphur dioxide ($SO_2$) and nitrogen oxides (NOx), which result in acid rain, negatively impacting soil chemistry and plant life. In the ceramic industry, emissions from fuel combustion contribute to $SO_2$ and NOx levels, a challenge that can be addressed by subsequent HPHE-based developments, such as the Condensing Economiser. Terrestrial ecotoxicity represents 6.3% of the total ecosystem damage, reflecting the harmful effects of toxic chemical releases, such as heavy metals, on land-based species. The contribution is aligned with the findings from the midpoint indicators.

Land use contributes 5.2% to the total ecosystem damage, primarily reflecting the direct and indirect impacts of converting land for industrial use, including habitat destruction and fragmentation. The indicator reflects the contribution of resource extraction in the manufacture of the HPHEs, as well as the extraction of fossil fuel based energy resources, mainly natural gas, used in the spray drying process.

Figure 66 shows endpoint indicators: damage to ecosystems for ceramic industry.

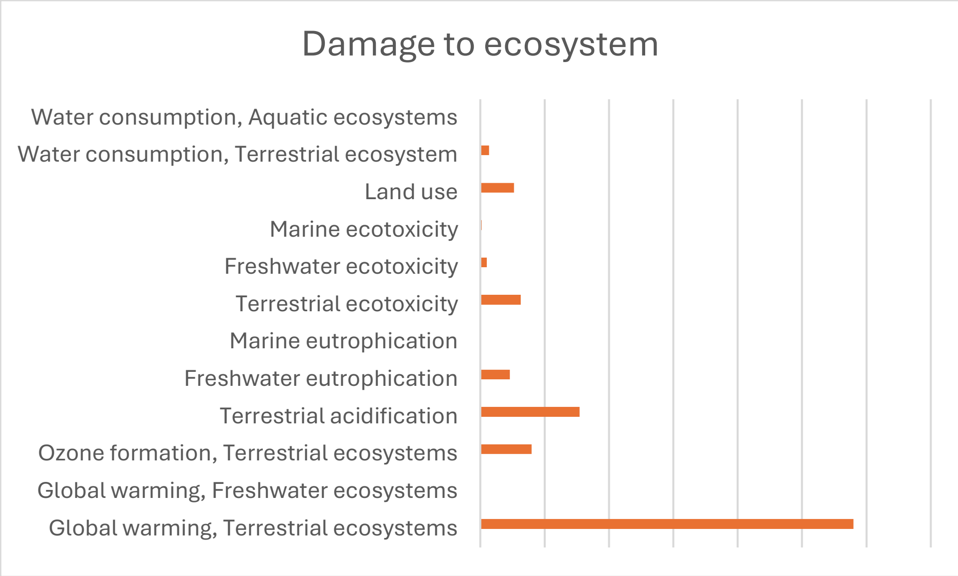



*Figure 66 Endpoint indicators: damage to ecosystems – ceramic industry*

Finally, the cost increase due to mineral and fossil extraction increase is also provided, with fossil resource scarcity at 78.1% and Mineral resource scarcity at 21.9%.

*Table 16 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to resource availability indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Mineral resource scarcity | USD2013 | 1308.84 | 21.9% |
| Fossil resource scarcity | USD2013 | 4673.40 | 78.1% |
| **Total** | | **5982.24** | |

Fossil resource scarcity accounts for the largest share of the total cost increase, representing 78.1% of the total impact on resource availability. This reflects the economic burden associated with the depletion of fossil fuels, primarily natural gas and coal (used in steelmaking).

Mineral resource scarcity contributes 21.9% to the total cost increase. Depletion of abiotic resources is chosen as an impact category because heat exchangers mainly contain different metals. Depletion of abiotic resources focus on the extraction of rare minerals and metals and the depletion factor is determined by the extraction rate and the remaining reserves. The depletion factor for the studied mineral/metal is compared to the factor for Antimony (Sb), which is used as a reference case. The unit for abiotic resources is hence kg Sb-equivalent (Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation, 2005). This impact reflects the material use in the production and maintenance of the HPHE system. Figure 67 shows endpoint indicators: damage to resources for ceramic industry.

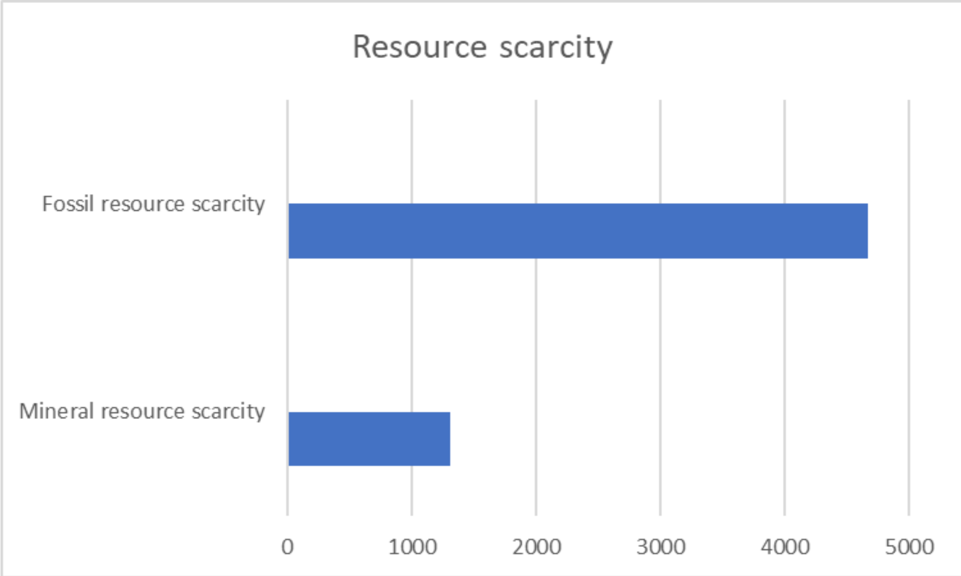



*Figure 67 Endpoint indicators: damage to resources – ceramic industry*

## *Midpoint impact analysis*

Table 17 shows the midpoint environmental impact results. The HPHE results in better environmental performance with respect to all impact categories than the baseline scenario.

*Table 17 ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H/A*

| Impact indicator | Scenario 1 | Scenario 2 |
|---|---|---|
| Global warming | 204.63 | 346.88 |
| Fine particulate matter formation | 0.035 | 0.060 |
| Human carcinogenic toxicity | 3.047 | 5.166 |
| Ozone formation, Terrestrial ecosystems | 0.389 | 0.660 |
| Terrestrial acidification | 0.091 | 0.154 |
| Fossil resource scarcity | 71.30 | 120.87 |
| Mineral resource scarcity | 0.137 | 0.232 |

**Global Warming Potential**: The HPHE scenario shows a substantial reduction in **GWP**, at 204.64 kg $CO_2$ eq compared to 346.89 kg $CO_2$ eq of the baseline scenario, resulting in a 41% decrease, Figure 68. This reflects the HPHE's effectiveness in reducing greenhouse gas emissions by the recovery and reutilisation of waste heat. The GWP footprint of HPHEs is due to two contributors: (a) the remainder of the energy expended for heating in the spray drying process (307kW) in the operation stage and (b) the contribution of the other stages of the HPHE lifecycle. The production of HPHEs involves the extraction and production of steel billets used to fabricate the HPHEs. In future scenarios or more challenging applications it will involve advanced alloys or ceramics for enhanced durability in corrosive or high-temperature environments. Extracting and processing (e.g., refining) these materials is energy-intensive and contributes to $CO_2$ emissions. However, the contribution of the manufacturing stage (in our case, manufacturing consolidates all upstream stages) is miniscule in terms of GWP when compared to the energy saved during the operational phase.

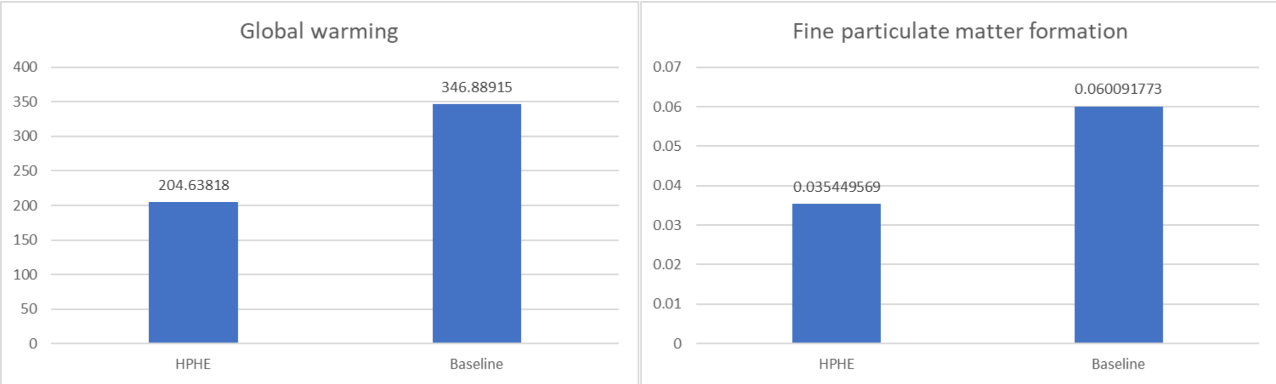



*Figure 68 GWP and fine particulate matter formation comparison*

**Fine Particulate Matter Formation:** Scenario 1 achieves better performance, with an impact of 0.035 kg $PM_{2.5}$ eq versus 0.060 kg $PM_{2.5}$ eq in Scenario 2. Particulate matter is emitted during natural gas combustion[167], and thus reduced gas consumption is directly correlated to reduced particulate emissions. Moreover, PM emissions are also expected during the initial production of heat exchangers that involves processes like mining, smelting, and refining metals. These emissions occur predominantly in regions where mining and metallurgical activities are concentrated.

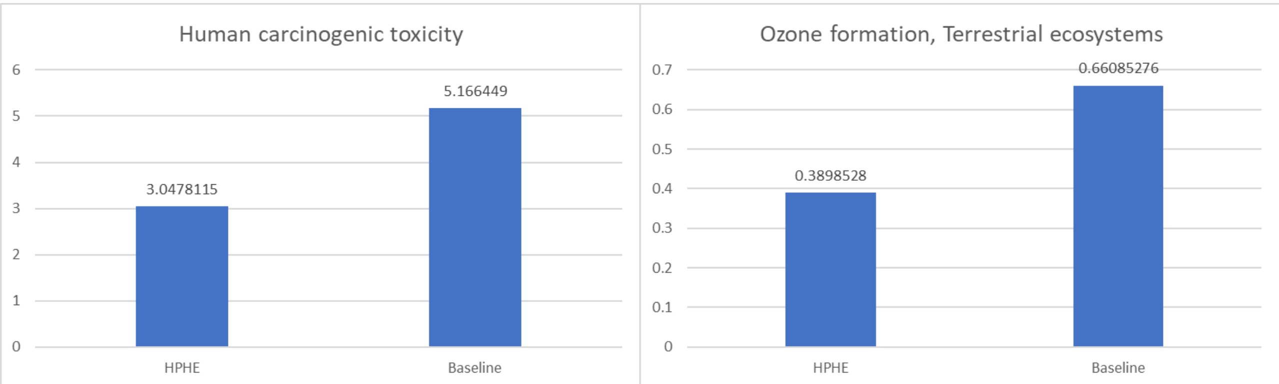



*Figure 69 HCT and Ozone formation in terrestrial ecosystems comparison*

**Human Carcinogenic Toxicity (HCT):** The human toxicity potential in Scenario 1 is 3.05 kg 1,4-DCB eq, significantly lower than 5.17 kg 1,4-DCB eq in Scenario 2, representing a 41% improvement, Figure 69. The production of metals and other materials used in HPHEs involves emissions of heavy metals (e.g., chromium, nickel), which are associated with human carcinogenic toxicity. This impact is most significant in the manufacturing stage. The reduced fuel consumption due to waste heat recovery directly lowers emissions of carcinogenic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) or fine metal particles, often associated with fuel combustion.

**Ozone formation in terrestrial ecosystems**: the HPHE scenario (0.3899 kg NOx eq) reduces impacts by 41% compared to the baseline (0.6609 kg NOx eq). This reduction is due to fewer emissions of nitrogen oxides (NOx) from natural gas combustion.

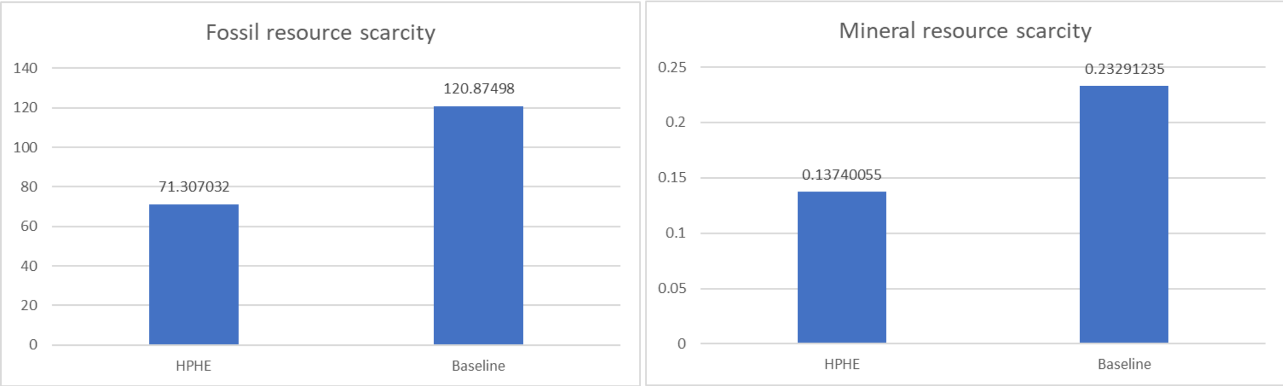



*Figure 70 Fossil and mineral resource scarcity comparison*

**Fossil resource:** Fossil resource scarcity measures the depletion of non-renewable energy sources like oil, natural gas, and coal, Figure 70. As detailed, the ceramic industry is heavily dependent on natural gas for energy, particularly in firing kilns and drying processes. Scenario 2 (baseline) represents the typical energy consumption pattern, relying primarily on natural gas without energy recovery. In Scenario 1 (HPHE), the introduction of WHR significantly reduces the demand for fossil fuels by recovering waste heat and repurposing it within the production cycle.

**Mineral resource scarcity**: the HPHE scenario (0.1374 kg Cu eq) also outperforms the baseline (0.2329 kg Cu eq), yielding a 41% reduction. It would be expected to have a more pronounced contribution of manufacturing to this indicator, however it is again dominated by the reduction of the quantity of natural gas needed to heat the spray dryer.

Similarly, the HPHE system results in a 40.9% decrease in terrestrial acidification, with impacts dropping from 0.1548 kg $SO_2$ eq in the baseline to 0.0913 kg $SO_2$ eq in the HPHE scenario. Terrestrial acidification primarily results from sulfur and nitrogen emissions.

Figure 71 shows terrestrial acidification indicator comparison.

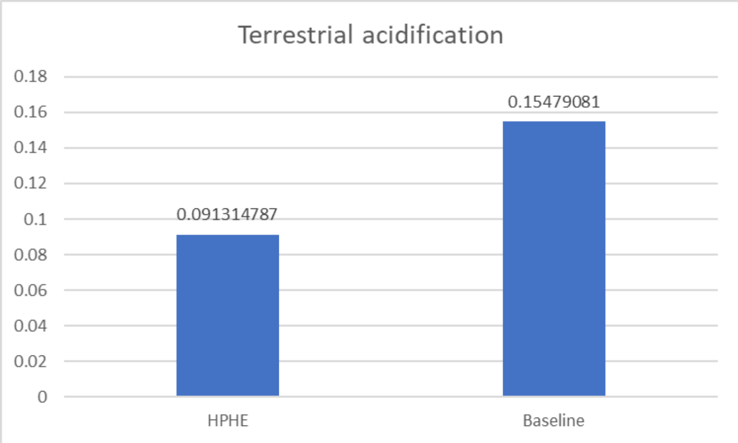



*Figure 71 Terrestrial acidification indicator comparison*

In Table 25, the midpoint lifecycle impacts per stage for the ceramics case are shown, while in Table 19 the % contribution to impacts is distributed per category and per stage. Both calculations are carried out with a 5-year timeframe.

*Table 18 Midpoint lifecycle impacts per stage for the ceramics case (spray drying process) for 5 years*

| | Manufacturing | Airplane | Truck | Use | Total | Unit |
|---|---|---|---|---|---|---|
| Global warming | 60,851.38 | 11,848.17 | 586.05 | 8,901,760.83 | 8,975,046.43 | kg $CO_2$ eq |
| Fine particulate matter formation | | 9.57 | 0.41 | 1,542.06 | 1,552.04 | PM2.5-eq |
| Human carcinogenic toxicity | 102,492.01 | 99.57 | 23.40 | 132,579.80 | 235,194.78 | kg 1,4-DCB |
| Ozone formation, Terrestrial ecosystems | 160.28 | 56.45 | 1.52 | 16,958.60 | 17,176.84 | kg NOx eq |
| Terrestrial acidification | 228.58 | 28.21 | 0.89 | 3,972.19 | 4,229.87 | kg $SO_2$ eq |
| Fossil resource scarcity | 14,010.57 | 3,574.13 | 148.43 | 3,101,855.89 | 3,119,589.03 | kg oil eq |
| Mineral resource scarcity | - | - | - | 5,976.92 | 5,976.92 | kg Cu-eq |
| Ozone formation, Human health | 154.19 | 54.66 | 1.42 | - | 210.27 | kg NOx eq |

*Table 19 Contribution analysis of each stage in total lifecycle impacts*

| | Manufacturing | Airplane | Truck | Transport total | Use |
|---|---|---|---|---|---|
| Global warming | 0.678% | 0.132% | 0.007% | 0.139% | 99.183% |
| Fine particulate matter formation | 0.000% | 0.616% | 0.027% | 0.643% | 99.357% |
| Human carcinogenic toxicity | 43.578% | 0.042% | 0.010% | 0.052% | 56.370% |
| Ozone formation, Terrestrial ecosystems | 0.933% | 0.329% | 0.009% | 0.337% | 98.729% |
| Terrestrial acidification | 5.404% | 0.667% | 0.021% | 0.688% | 93.908% |
| Fossil resource scarcity | 0.449% | 0.115% | 0.005% | 0.119% | 99.432% |
| Mineral resource scarcity | 0.000% | 0.000% | 0.000% | 0.000% | 100.000% |
| Ozone formation, Human health | 73.327% | 25.996% | 0.676% | 26.673% | 0.000% |

Figure 72 presents contribution to midpoint impacts for Ceramic Case Study.

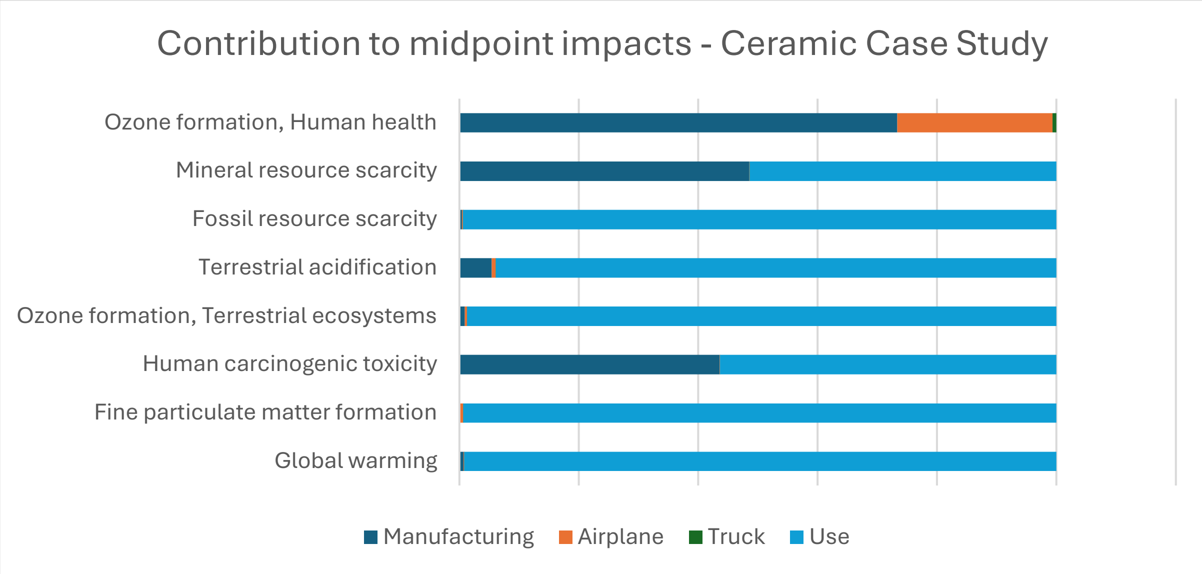



*Figure 72 Contribution to midpoint impacts - Ceramic Case Study*

The lifecycle analysis for the ceramic case over five years confirms that the use phase dominates most environmental impacts, particularly in global warming, fine particulate matter formation, and fossil resource scarcity. The use phase contributes 99.18% of the total global warming impact, emitting 8,901.76 $tCO_2eq$ out of a total of 8,975.04 $tCO_2eq$. This pattern is also seen in fossil resource scarcity, where 99.43% of the impact is due to the use phase, with 3,101.85 t oil eq out of 3,119.58 t oil eq.

In contrast, human carcinogenic toxicity shows a more balanced contribution between stages, with 43.58% of the impact coming from manufacturing and 56.37% from the use phase, reflecting the emissions associated with producing the materials (stainless steel) involved in the HPHE system. Similarly, for ozone formation in terrestrial ecosystems, the use phase accounts for 98.73% of the total impact (16,958.60 kg NOx eq), while manufacturing contributes 0.93%.

Other impact categories, such as terrestrial acidification and mineral resource scarcity, also see major contributions from the use phase, at 93.91% and 100%, respectively. The manufacturing stage, particularly for human carcinogenic toxicity and ozone formation in human health, demonstrates notable impacts, raising attention to emissions reduction during production, potentially by increasing the share of recycled steel and by focusing research on more sustainable material alternatives.

## *Carbon footprint – ceramic industry*

To bring the impacts of the HPHE technology closer to the target customer segments, a conversion to $CO_2eq$ was carried out for the lifecycle of the system. For the manufacturing, transportation and the operation, the converted $CO_2$ burden is shown in Table 20.

*Table 20 CO2 footprint of the HPHE in the ceramic case compared to the baseline for 1 year*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, chromium steel 18/8 (Stainless steel) | 60,851.38 | 5.83% |
| Transportation | Transport, freight, lorry 7.5-16 metric ton | 586.05 | 0.06% |
| | Transport, freight, aircraft, unspecified | 11,848.17 | 1.14% |
| Baseline | Heat, natural gas | 1,769,134.67 | 100% |
| HPHE | Heat, recovered heat, natural gas | 1,043,654.72 | 58.99% |
| Total | HPHE total CO2 footprint for the period | 1,116,940.32 | 63.13% |
| Savings | CO2 reduction | 652,194.34 | **36.87%** |

The carbon footprint analysis reveals significant $CO_2$ savings over both 1- and 5-year periods. During the first year, the HPHE integrated process results in 63.13% of the baseline emissions, reducing $CO_2$ emissions by 36.87% (652.19 $tCO_2eq$). The majority of emissions come from the use phase, where the HPHE reduces reliance on natural gas, lowering process emissions from 1,769.13 $tCO_2eq$ in the baseline process to 1,043.65 $tCO_2eq$, Table 21. Manufacturing and transport contribute by 5.83% and 1.2% correspondingly. The total $CO_2$ footprint of the HPHE outside the use stage is 73,285.60 $kgCO_2eq$, which corresponds to 11% of the $CO_2$ savings achieved over the 1 year period, meaning that the carbon invested into introducing the system in the industrial process is offset over 9 times during the time period. In fact, on the 42$^{nd}$ day of operation the HPHE becomes carbon neutral.

*Table 21 CO2 footprint of the HPHE in the ceramic case for 5 years*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, chromium steel 18/8 (Stainless steel) | 60,851.38 | 0.68% |
| | Transport, freight, lorry 16-32 metric ton | 586.05 | 0.01% |
| | Transport, freight, aircraft, unspecified | 11,848.17 | 0.13% |
| Baseline | Heat, natural gas | 15,089,678.03 | 100% |
| HPHE | Heat, recovered heat, natural gas | 8,901,760.83 | 58.99% |
| Total | HPHE total CO2 footprint for the period | 8,975,046.43 | 59.48% |
| Savings | CO2 reduction | 6,187,917.20 | **41.01%** |

Over 5 years, the HPHE shows an even more substantial reduction, cutting $CO_2$ emissions by 41.01% (6,187.91 $tCO_2eq$). Manufacturing and transportation collectively contribute less than 1% of the total footprint over this time period. An important feature is the effective lack of maintenance over this period.

## 4.2 Case study #2: Aluminium sector

### *Endpoint impact analysis*

The endpoint impacts are shown in Table 22, Table 23 and Table 24. The largest contributor to human health damage is Human carcinogenic toxicity, which accounts for 36.3% of the total impact, followed by Global warming, human health, that is responsible for 30.5% of the total impact, Figure 73. Fine particulate matter formation is the third largest contributor, accounting for 28.7%. The remaining categories—Stratospheric ozone depletion, Ionizing radiation, Ozone formation (human health), Human non-carcinogenic toxicity, and Water consumption (human health)—collectively contribute less than 5% of the total impact.

*Table 22 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to human health indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Human health | DALY | 0.0053 | 30.5% |
| Stratospheric ozone depletion | DALY | 3.97E-07 | 0.0% |
| Ionizing radiation | DALY | 5.51E-07 | 0.0% |
| Ozone formation, Human health | DALY | 1.64E-05 | 0.1% |
| Fine particulate matter formation | DALY | 0.0050 | 28.7% |
| Human carcinogenic toxicity | DALY | 0.0063 | 36.3% |
| Human non-carcinogenic toxicity | DALY | 0.000753 | 4.3% |
| Water consumption, Human health | DALY | 2.04E-05 | 0.1% |
| **Total** | | **1.76E-02** | |

The negligible contributions of Stratospheric ozone depletion and Ionizing radiation indicate that the HPHE technology has minimal direct influence on these categories. However, the 0.000753864 DALY contribution from human non-carcinogenic toxicity (4.3%) and 0.0000204 DALY from water consumption, human health (0.1%) show that the broader health and environmental burden of non-carcinogenic substances and water use in industrial processes is minimal. The interpretation for the prevalence of these indicators is similar to Demo Case 1, with the main differences highlighted due to the different material used: carbon steel instead of stainless steel in the ceramics case.

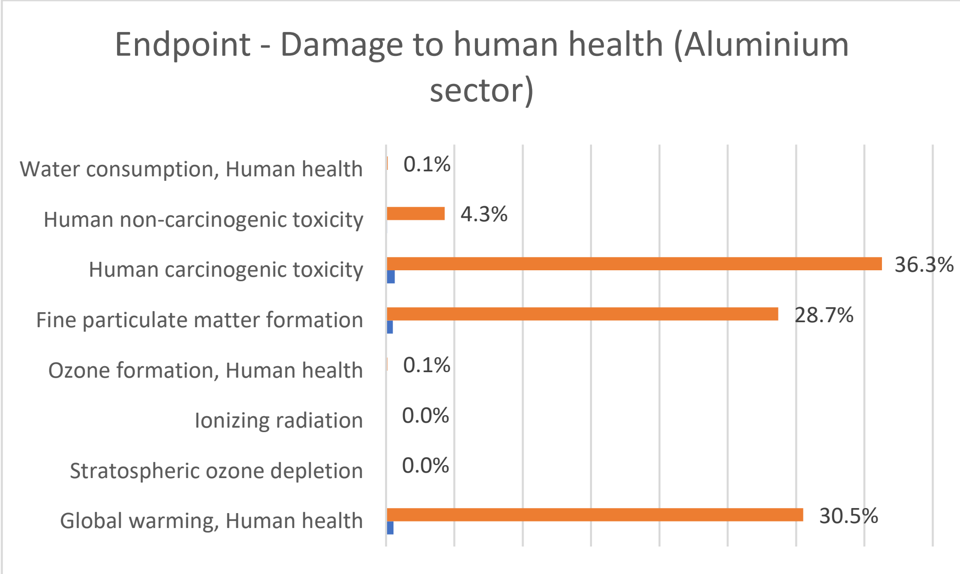



*Figure 73 Endpoint - Damage to human health (Aluminium sector)*

With regards to damage to ecosystems, Figure 74, the main contributors are Global warming, Terrestrial ecosystems at 67.5%, Terrestrial acidification at 12.3%, Ozone formation, Terrestrial ecosystems at 10.3%, are close to their values in the ceramics case study.

*Table 23 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to ecosystem indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Terrestrial ecosystems | species.yr | 1.62E-05 | 67.5% |
| Global warming, Freshwater ecosystems | species.yr | 4.43E-10 | 0.0% |
| Ozone formation, Terrestrial ecosystems | species.yr | 2.47E-06 | 10.3% |
| Terrestrial acidification | species.yr | 2.95E-06 | 12.3% |
| Freshwater eutrophication | species.yr | 1.22E-06 | 5.1% |
| Marine eutrophication | species.yr | 2.39E-10 | 0.0% |
| Terrestrial ecotoxicity | species.yr | 1.29E-07 | 0.5% |
| Freshwater ecotoxicity | species.yr | 1.67E-07 | 0.7% |
| Marine ecotoxicity | species.yr | 3.59E-08 | 0.1% |
| Land use | species.yr | 6.71E-07 | 2.8% |
| Water consumption, Terrestrial ecosystem | species.yr | 1.58E-07 | 0.7% |
| Water consumption, Aquatic ecosystems | species.yr | 2.52E-11 | 0.0% |
| **Total** | | **2.40E-05** | |

Contrary to the ceramics case, terrestrial ecotoxicity is much lower at 0.5% (versus 6.3% in ceramics), and land use at 2.8% (against 5.2% in ceramics). Freshwater eutrophication is close at 4.8% (4.6% in ceramics), with Water consumption, Terrestrial ecosystem, Freshwater ecotoxicity and Marine ecotoxicity below 1.5%.

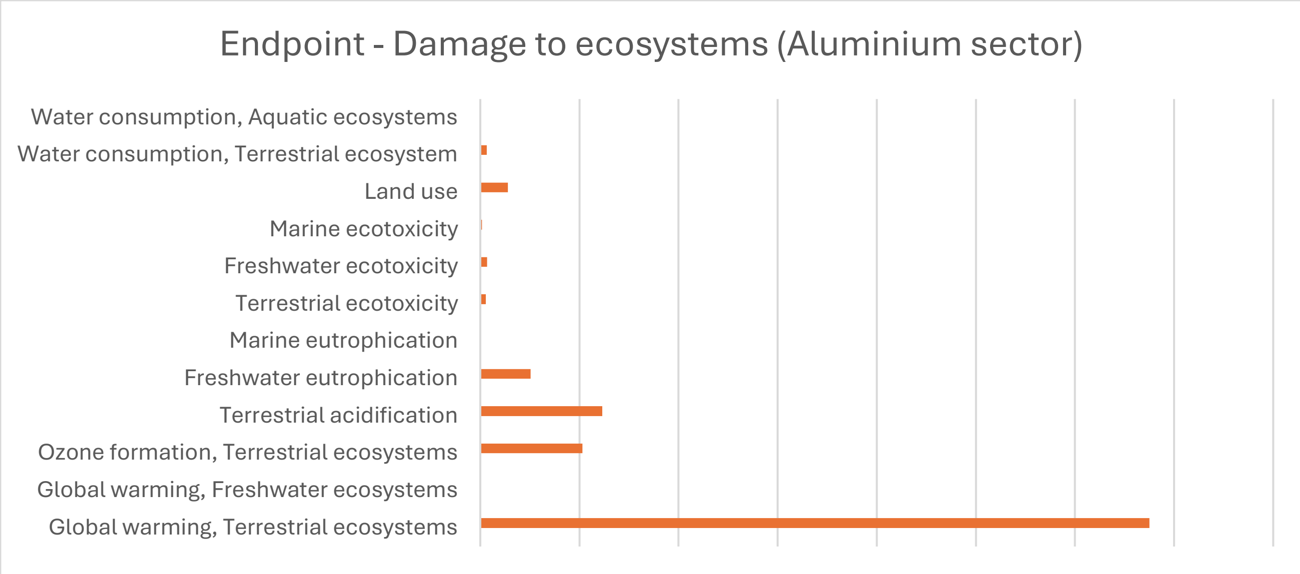



*Figure 74 Endpoint: Damage to ecosystems - Aluminium sector*

Finally, the cost increase due to mineral and fossil extraction increase is also provided, with fossil resource scarcity at 92.6% and Mineral resource scarcity at 7.4%.

*Table 24 Damage to resources*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Mineral resource scarcity | USD2013 | 31.72 | 7.4% |
| Fossil resource scarcity | USD2013 | 394.59 | 92.6% |
| **Total** | | **426.32** | |

The most significant contributor to resource damage is fossil resource scarcity, accounting for a substantial 92.6% of the total impact, Figure 75. In contrast, mineral resource scarcity accounts for a much smaller portion, 7.4%. While the depletion of mineral resources is still a notable concern—especially in industries that rely on rare or critical materials—the relatively low contribution to overall resource damage highlights that, for this system, fossil fuel usage remains the dominant environmental challenge. This is due to the higher capacity to source recycled carbon steel as opposed to the reduced capacity and availability of recycling stainless steel. Potentially, the strict performance specifications may necessitate virgin steel as raw material.

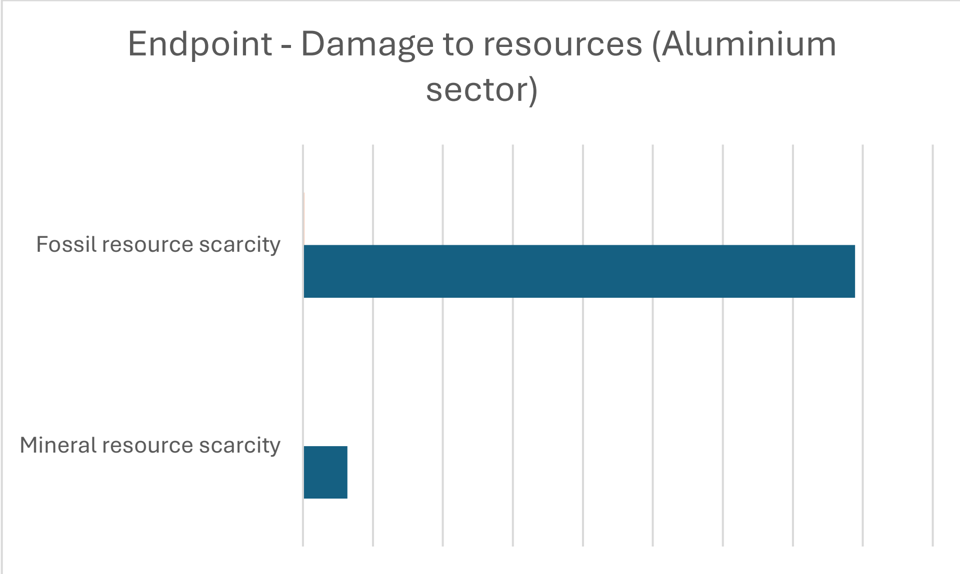



*Figure 75 Endpoint - Damage to resources (Aluminium sector)*

## *Midpoint impact analysis*

Table 25 shows the midpoint environmental impact results. The innovative HPHE (scenario 1) results in better environmental performance with respect to all impact categories than the baseline (scenario 2) scenario.

*Table 25 ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H/A*

| Impact indicator | Scenario 1 | Scenario 2 |
|---|---|---|
| Global warming | 23.77 | 41.86 |
| Fine particulate matter formation | 0.0041 | 0.0072 |
| Human carcinogenic toxicity | 0.3541 | 0.6234 |
| Ozone formation, Terrestrial ecosystems | 0.045296 | 0.0797 |
| Terrestrial acidification | 0.01061 | 0.0186 |
| Fossil resource scarcity | 8.28 | 14.58 |

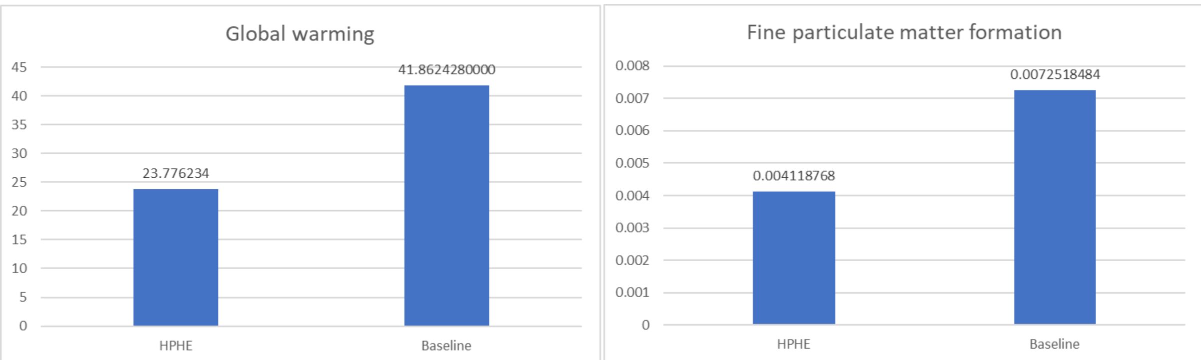



*Figure 76 GWP and fine particulate matter formation comparison*

The global warming potential in Scenario 1 is 23.77 kg $CO_2$ eq, a considerable reduction of 43.2% compared to 41.86 kg $CO_2$ eq in Scenario 2, Figure 80. The result highlights the HPHE improvement in greenhouse gas emissions during the operation stage. As the functional unit is the industrial process, the GWP is still significant as not all the energy is provided sustainably by the HPHE. Nonetheless, based on end user data, natural gas is used to provide the required fossil-based heating, contributing to the GWP indicator in this case.

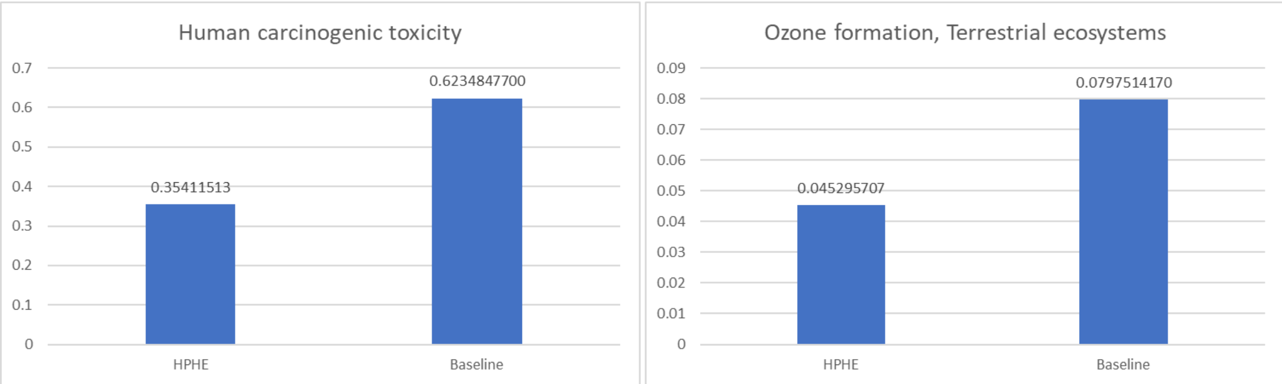



*Figure 77 HCT and Ozone formation in terrestrial ecosystems comparison*

Similarly, the fine particulate matter formation indicator, at 0.0041 kg PM2.5 eq in Scenario 1, demonstrates a 43.2% improvement over Scenario 2's 0.0072 kg PM2.5 eq. This reduction is indicative of fewer pollutants being released into the atmosphere, through the reduction of natural gas required for heating energy. The same applies for human carcinogenic toxicity (0.354 kg 1,4-DCB compared to 0.623 kg 1,4-DCB in the baseline), ozone formation in terrestrial ecosystems (from 0.0797 kg NOx eq to 0.0452 kg NOx eq in Scenario 1), terrestrial acidification potential (0.0186 kg $SO_2$ eq to 0.0106 kg $SO_2$ eq) and fossil resource scarcity, reducing the consumption of fossil resources from 14.587 kg oil eq to 8.284 kg oil eq, shown in Figure 77.

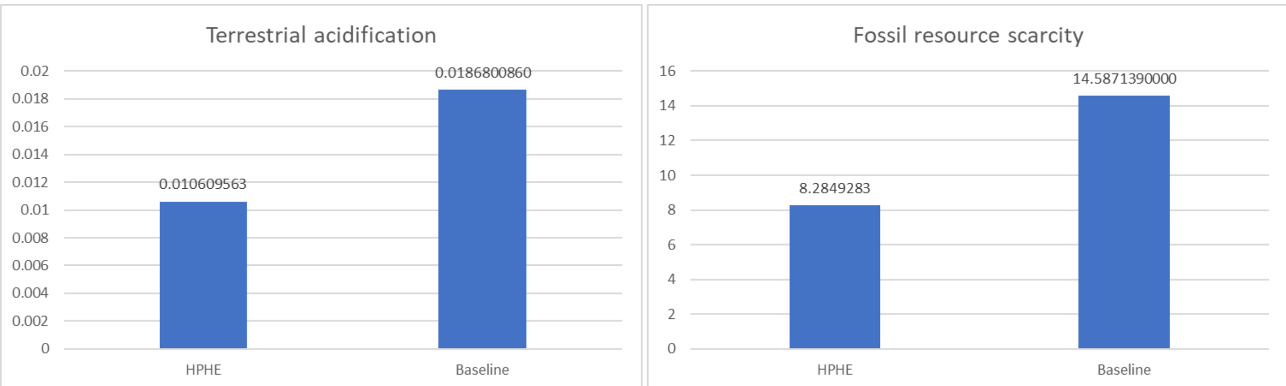



*Figure 78 Fossil and mineral resource scarcity comparison*

Figure 78 shows fossil and mineral resource scarcity comparison.

In Table 26, the midpoint lifecycle impacts per stage for the aluminium case are shown, while in Table 27 the % share is distributed per category and per stage. Both calculations are carried out with a 5-year timeframe.

*Table 26 Midpoint lifecycle impacts per stage for the aluminium case*

| | Manufacturing | Airplane | Truck | Use | Total | Unit |
|---|---|---|---|---|---|---|
| Global warming | 3859.65 | 1642.99 | 259.33 | 1034266.18 | 1040028.15 | kg CO2 eq |
| Fine particulate matter formation | 6.4995781 | 1.33 | 0.20 | 179.17 | 187.20 | PM2.5-eq |
| Human carcinogenic toxicity | 1893.84 | 13.81 | 15.55 | 15404.01 | 17327.20 | kg 1,4-DCB |
| Ozone formation, Terrestrial ecosystems | 10.55 | 7.83 | 0.74 | 1970.36 | 1989.49 | kg NOx eq |
| Terrestrial acidification | 9.54 | 3.91 | 0.47 | 461.52 | 475.43 | kg SO2 eq |
| Fossil resource scarcity | 844.13 | 495.63 | 80.14 | 360394.38 | 361814.28 | kg oil eq |
| Mineral resource scarcity | 844.13 | 0.719 | 0.778 | 135.82 | 981.45 | kg Cu-eq |
| Ozone formation, Human health | 9.72 | 7.58 | 0.69 | 0.00 | 17.99 | kg NOx eq |

*Table 27 Share of each stage in total lifecycle impacts*

| | Manufacturing | Airplane | Truck | Transport total | Use |
|---|---|---|---|---|---|
| Global warming | 0.371% | 0.158% | 0.025% | 0.183% | 99.446% |
| Fine particulate matter formation | 3.472% | 0.709% | 0.109% | 0.817% | 95.711% |
| Human carcinogenic toxicity | 10.930% | 0.080% | 0.090% | 0.169% | 88.901% |
| Ozone formation, Terrestrial ecosystems | 0.531% | 0.393% | 0.037% | 0.431% | 99.039% |
| Terrestrial acidification | 2.006% | 0.823% | 0.098% | 0.921% | 97.073% |
| Fossil resource scarcity | 0.233% | 0.137% | 0.022% | 0.159% | 99.608% |
| Mineral resource scarcity | 86.009% | 0.073% | 0.079% | 0.153% | 13.839% |
| Ozone formation, Human health | 54.029% | 42.138% | 3.833% | 45.971% | 0.000% |

The midpoint lifecycle impacts for the aluminium case, as shown in Table 19, indicate that the use phase dominates most environmental impact categories. For global warming, the use phase contributes 99% of the total, generating over 1,034,266 kg$CO_2$eq, while manufacturing, transportation by airplane, and truck contribute minor shares. Similarly, fossil resource scarcity is mainly impacted by the use phase, accounting for the vast majority (99%) of the 361,814 kg oil eq consumed. Human carcinogenic toxicity also sees significant contributions from the use phase (89%), with 15,404 kg 1,4-DCB. Here, manufacturing impact is due to the carbon steel footprint contribution, and the minor transportation impact is due to transport fuel emissions. Fine particulate matter formation and terrestrial acidification both show small contributions from manufacturing and transport, but the use phase remains the largest contributor. Mineral resource scarcity is mainly tied to the manufacturing stage, with limited impact from the use phase, due to natural gas emissions.

In summary, the use phase drives the bulk of environmental impacts in aluminum production, while the manufacturing stage primarily contributes to mineral resource depletion, Figure 79.

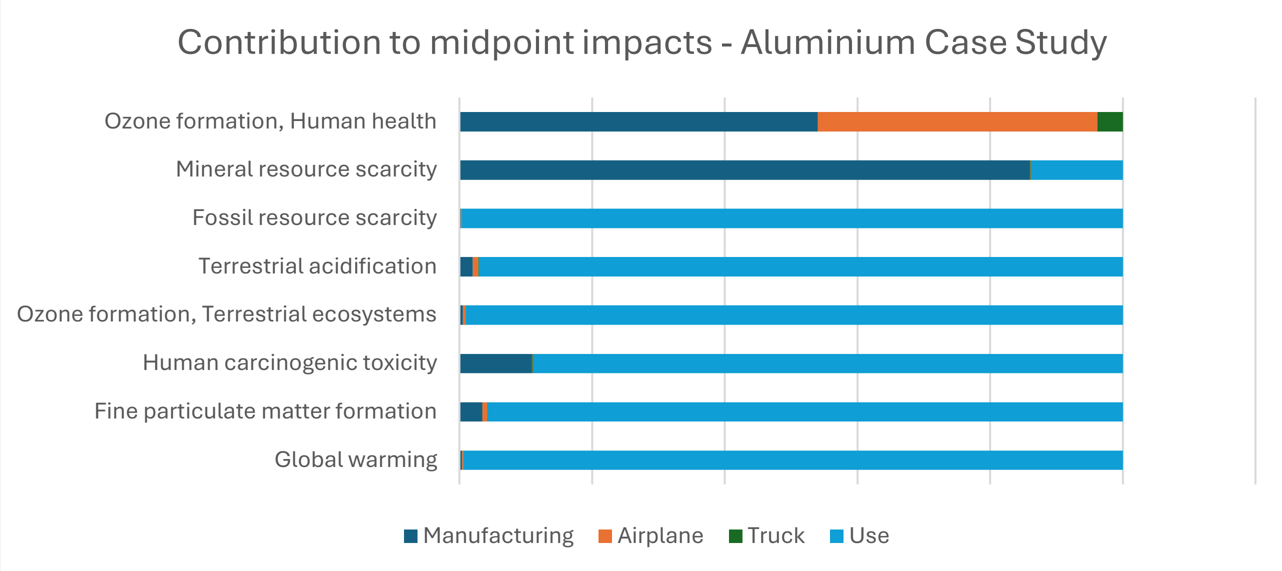



*Figure 79 Contribution to midpoint impacts - Aluminium Case Study*

## *Carbon footprint*

To bring the impacts of the HPHE technology closer to the target customer segments, a conversion to $CO_2$eq was carried out for the lifecycle of the system. For manufacturing, transportation and operation, the converted $CO_2$ burden is shown in Table 34.

*Table 28 CO2 footprint of the HPHE in the ceramic case compared to the baseline for 1 year*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, unalloyed (carbon steel) | 3,859.65 | 0.36% |
| Transportation | Transport, freight, lorry 3.5-7.5 metric ton | 259.33 | 0.02% |
| | Transport, freight, aircraft, unspecified | 1,642.99 | 0.15% |
| Baseline | Heat, natural gas | 1,904,740.47 | 100.00% |
| HPHE | Heat, recovered heat, natural gas | 1,081,818.65 | 56.80% |
| Total | HPHE total CO2 footprint for the period | 1,087,580.62 | 57.10% |
| Savings | CO2 reduction | 817,159.85 | **42.90%** |

The HPHE integrated process reduces $CO_2$ emissions by 42.90% (817.16 $tCO_2eq$), with the total $CO_2$ footprint for the period being 57.10% of the baseline. The use phase is the primary contributor, with 1,081.82 $tCO_2eq$ from recovered heat versus 1,904.74 $tCO_2eq$ in the baseline process. Manufacturing and transport together account for only 0.53% of the total footprint, Table 35. The carbon footprint outside the use phase is 5,761.97 $kgCO_2eq$, which represents 7% of the savings achieved, indicating that the carbon invested in the system is offset over 14 times during the year. The HPHE becomes carbon neutral on the 26th day of operation.

*Table 29 CO2 footprint of the HPHE in the ceramic case for 5 years*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, unalloyed (carbon steel) | 3,859.65 | 0.07% |
| | Transport, freight, lorry 3.5-7.5 metric ton | 259.33 | 0.00% |
| | Transport, freight, aircraft, unspecified | 1,642.99 | 0.03% |
| Baseline | Heat, natural gas | 9,523,702.37 | 100.00% |
| HPHE | Heat, recovered heat, natural gas | 5,409,093.24 | 56.80% |
| Total | HPHE total CO2 footprint for the period | 5,414,855.21 | 56.86% |
| Savings | CO2 reduction | 4,108,847.16 | **43.14%** |

Over five years, $CO_2$ emissions are reduced by 43.14% (4,108.85 $tCO_2eq$). Manufacturing and transportation contribute only 0.10% of the total emissions, reinforcing the significant impact of the use phase. The lack of maintenance during this period further emphasizes the efficiency of the HPHE system, ensuring sustained emissions reductions without additional operational burdens.

## 4.3 Case study #3: Steel sector

### *Endpoint impact analysis*

Table 30, Table 31 and Table 32 show the endpoint impacts of the HPHE integrated process in the steel case study. For human health, global warming (32%) and human carcinogenic toxicity (35%) have the highest contribution. As in the previous cases, these indicators are associated with fossil fuels. Fine particulate matter formation is also a major contributor at 29%, due to the combustion of natural gas in the use phase. The other impact categories, including stratospheric ozone depletion, ionizing radiation, and water consumption, show a minimal contribution (0%-4%), indicating a smaller direct effect on human health.

*Table 30 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to human health indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Human health | DALY | 0.008192312 | 32% |
| Stratospheric ozone depletion | DALY | 5.53E-07 | 0% |

| | | | |
|---|---|---|---|
| Ionizing radiation | DALY | 7.55E-07 | 0% |
| Ozone formation, Human health | DALY | 2.61E-05 | 0% |
| Fine particulate matter formation | DALY | 0.0074 | 29% |
| Human carcinogenic toxicity | DALY | 0.0089 | 35% |
| Human non-carcinogenic toxicity | DALY | 0.001058513 | 4% |
| Water consumption, Human health | DALY | 2.88E-05 | 0% |
| **Total** | | **2.57E-02** | |

With regards to damage to ecosystems, the total damage to ecosystems, expressed in species.yr (a measure of species loss per year), is 3.65E-05 species.yr. The largest contribution by far is from Global Warming in Terrestrial Ecosystems, accounting for 67.7% of the total impact. Terrestrial Acidification contributes 12.3%, and Ozone Formation in Terrestrial Ecosystems, at 10.8% are second and third, respectively, both associated with the NOx emissions of natural gas.

*Table 31 ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A – damage to ecosystem indicators*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Global warming, Terrestrial ecosystems | species.yr | 2.47E-05 | 67.7% |
| Global warming, Freshwater ecosystems | species.yr | 6.75E-10 | 0.0% |
| Ozone formation, Terrestrial ecosystems | species.yr | 3.92E-06 | 10.8% |
| Terrestrial acidification | species.yr | 4.50E-06 | 12.3% |
| Freshwater eutrophication | species.yr | 1.70E-06 | 4.7% |
| Marine eutrophication | species.yr | 3.56E-10 | 0.0% |
| Terrestrial ecotoxicity | species.yr | 1.82E-07 | 0.5% |
| Freshwater ecotoxicity | species.yr | 2.32E-07 | 0.6% |
| Marine ecotoxicity | species.yr | 5.00E-08 | 0.1% |
| Land use | species.yr | 9.54E-07 | 2.6% |
| Water consumption, Terrestrial ecosystem | species.yr | 2.25E-07 | 0.6% |
| Water consumption, Aquatic ecosystems | species.yr | 3.61E-11 | 0.0% |
| **Total** | | **3.65E-05** | |

Lastly, resource scarcity is overwhelmingly driven by fossil resource scarcity, which constitutes 92.6% of the total economic burden, measured at 394.59376 USD2013. Mineral resource scarcity is a minor contributor at 7.4%.

*Table 32 Damage to resources in the steel case study*

| Impact indicator | Unit | Value | % |
|---|---|---|---|
| Mineral resource scarcity | USD2013 | 31.72 | 7.4% |

| | | | |
|---|---|---|---|
| Fossil resource scarcity | USD2013 | 394.59 | 92.6% |
| **Total** | | 426.32 | |

## *Midpoint impact analysis*

Table 33 shows the midpoint environmental impact results. The HPHE results in reduced environmental impacts with respect to all impact categories relative to the baseline scenario.

*Table 33 ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H/A*

| Impact indicator | HPHE | Baseline |
|---|---|---|
| Global warming | 80.270 | 151.192 |
| Fine particulate matter formation | 0.0139 | 0.0261 |
| Human carcinogenic toxicity | 1.195 | 2.251 |
| Ozone formation, Terrestrial ecosystems | 0.152 | 0.288 |
| Terrestrial acidification | 0.0358 | 0.0674 |
| Fossil resource scarcity | 27.97 | 52.68 |

Similar to the other case studies, the HPHE integrated process produces significantly reduced environmental impacts, highlighting the efficiency of the technology in providing sustainable heating energy.

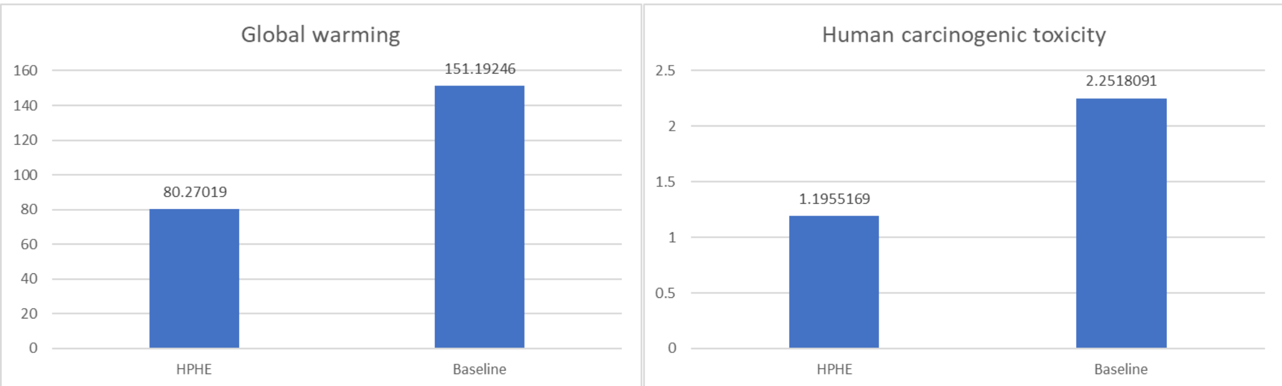
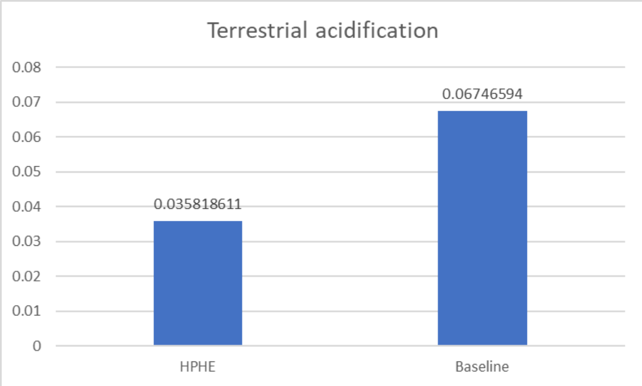



*Figure 80 Global Warming Potential and Human Carcinogenic Toxicity indicators in the two scenarios*

In the HPHE integrated process, the global warming potential is 80.27 kg CO2-eq, lower by 47% than the 151.19 kg CO2-eq in the baseline process, Figure 80. A similar reduction is observed in the other indicators such as Human Carcinogenic Toxicity, Fine Particulate Matter Formation, Ozone Formation by Terrestrial Ecosystems, and Terrestrial Acidification, Figure 81 and Figure 82.



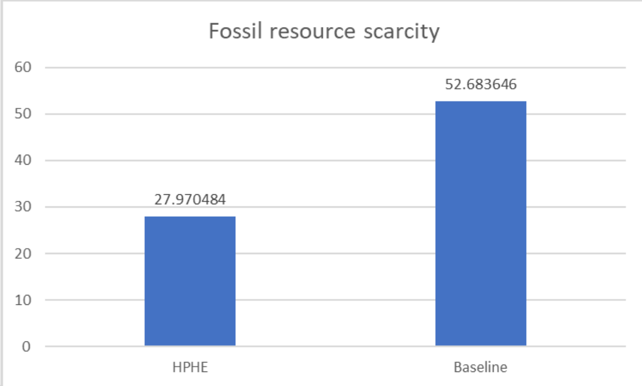
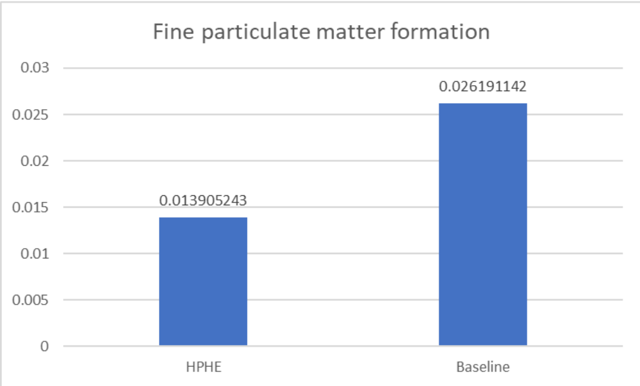




*Figure 81 Terrestrial Acidification and Fossil Resource Scarcity indicators in the two scenarios*



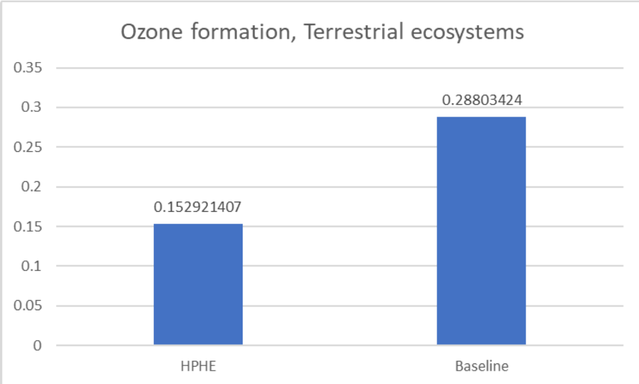




*Figure 82 Midpoint impact indicator comparison for the steel case study*

In Table 34, the midpoint lifecycle impacts per stage for the steel case are shown, while in Table 35 the % share is distributed per category and per stage.

*Table 34 Midpoint lifecycle impacts per stage for the steel case*

| | Manufacturing | Airplane | Truck | Use | Total | Unit |
|---|---|---|---|---|---|---|
| Global warming | 5,421.89 | 3,129.51 | 196.48 | 3,491,753.27 | 5,421.89 | kg CO2 eq |
| Fine particulate matter formation | 9.13 | 2.53 | 0.16 | 604.88 | 9.13 | PM2.5-eq |
| Human carcinogenic toxicity | 2,660.39 | 26.30 | 9.32 | 52,004.99 | 2,660.39 | kg 1,4-DCB |
| Ozone formation, Terrestrial ecosystems | 14.83 | 14.91 | 0.60 | 6,652.08 | 14.83 | kg NOx eq |
| Terrestrial acidification | 13.39 | 7.45 | 0.35 | 1,558.11 | 13.39 | kg $SO_2$ eq |
| Fossil resource scarcity | 1,185.80 | 944.05 | 61.19 | 1,216,716.05 | 1,185.80 | kg oil eq |

**Global Warming**: The Use phase is the main contributor to Global Warming, responsible for 99.75% of the total 5,421.89 kg CO2-eq impact. This is due to the substantial energy consumption during the operational stage. The manufacturing, transport via airplane, and truck contribute minimally to this category, collectively making up less than 0.25% of the total impact.

**Fine Particulate Matter Formation**: Fine Particulate Matter Formation follows a similar pattern, with the Use phase dominating the impact at 98.08%, reflecting 604.88 PM2.5-eq. Particulate matter is emitted during fuel combustion, while manufacturing and transportation via truck and airplane do contribute, their collective share of the total impact remains under 2%.

**Human Carcinogenic Toxicity**: In the Human Carcinogenic Toxicity indicator, the Use phase again leads, contributing 95.07% of the total 52,004.99 kg 1,4-DCB-eq. Manufacturing is noticeably responsible for 4.86%, reflecting the footprint of carbon steel used in the manufacturing stage.

**Terrestrial Acidification**: Terrestrial Acidification is largely driven by the Use phase, contributing 98.66% of the total 1,558.11 kg $SO_2$-eq. This reflects the emissions of sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) during the steel production process.

**Fossil and Mineral Resource Scarcity**: The Use phase has a nearly exclusive impact on Fossil Resource Scarcity, contributing 99.82% of the total 1,216,716.05 kg oil-eq. This reflects the high demand for energy derived from fossil fuels during the operational phase of steel production. Manufacturing, airplane, and truck transport together make up less than 0.2% of the total fossil resource depletion.

*Table 35 Contribution of each stage in total lifecycle impacts*

| | Manufacturing | Airplane | Truck | Transport total | Use |
|---|---|---|---|---|---|
| Global warming | 0.155% | 0.0894% | 0.0056% | 0.0950% | 99.750% |
| Fine particulate matter formation | 1.481% | 0.4097% | 0.0257% | 0.4354% | 98.084% |
| Human carcinogenic toxicity | 4.864% | 0.0481% | 0.0170% | 0.0651% | 95.071% |
| Ozone formation, Terrestrial ecosystems | 0.222% | 0.2231% | 0.0091% | 0.2322% | 99.546% |
| Terrestrial acidification | 0.848% | 0.4718% | 0.0224% | 0.4942% | 98.658% |
| Fossil resource scarcity | 0.097% | 0.0775% | 0.0050% | 0.0825% | 99.820% |

Figure 83 shows contribution to midpoint impacts - Steel Case Study.

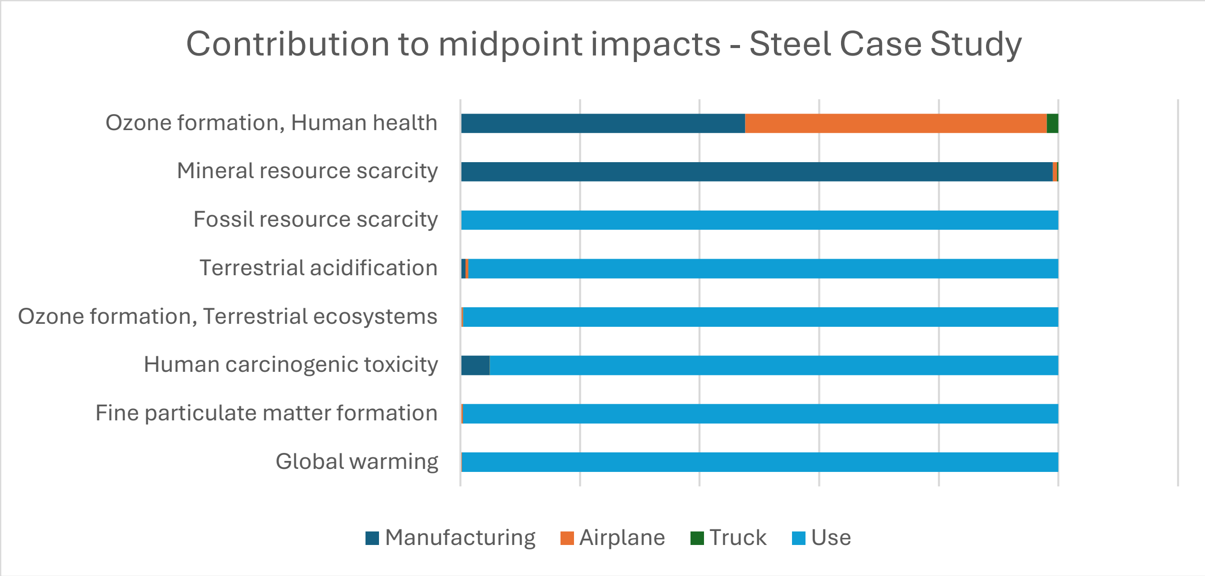



*Figure 83 Contribution to midpoint impacts - Steel Case Study*

## *Carbon footprint*

To bring the impacts of the HPHE technology closer to the target customers, a conversion to $CO_2$eq was carried out for the lifecycle of the system. For the manufacturing, transportation and the operation, the converted $CO_2$ burden is shown in Table 36**Error! Reference source not found.**.

*Table 36 CO2 footprint of the HPHE in the ceramic case compared to the baseline for 1 year*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, unalloyed (carbon steel) | 5,421.89 | 1.23% |
| Transportation | Transport, freight, lorry 7.5-16 metric ton | 196.48 | 0.04% |
| | Transport, freight, aircraft, unspecified | 3,129.51 | 0.71% |
| Baseline | Heat, natural gas | 831,558.53 | 100.00% |
| HPHE | Heat, recovered heat, natural gas | 441,486.05 | 53.09% |
| Total | HPHE total CO2 footprint for the period | 450,233.92 | 54.14% |
| Savings | CO2 reduction | 381,324.61 | **45.86%** |

The HPHE integrated process reduces $CO_2$ emissions by 45.86% (381.32 t$CO_2$eq), with a total $CO_2$ footprint of 450.23 t$CO_2$eq, representing 54.14% of the baseline. The use phase contributes the most with 441.49 t$CO_2$eq (53.09%). Manufacturing and transportation contribute 1.98% of the total footprint, with manufacturing alone accounting for 1.23% (5.42 t$CO_2$eq). The total $CO_2$ footprint outside the use phase is 8,747.87 kg$CO_2$eq, representing 2.29% of the savings achieved. This means that the carbon invested in introducing the HPHE system is offset 20 times over the year, becoming carbon neutral around 18 days into operation.

*Table 37 CO2 footprint of the HPHE in the ceramic case for 5 years*

| Stage | Material and process | kg CO2 eq | % |
|---|---|---|---|
| Manufacturing | Steel, unalloyed (carbon steel) | 5,421.89 | 0.25% |
| | Transport, freight, lorry 7.5-16 metric ton | 196.48 | 0.01% |
| | Transport, freight, aircraft, unspecified | 3,129.51 | 0.14% |
| Baseline | Heat, natural gas | 4,157,792.65 | 100.00% |
| HPHE | Heat, recovered heat, natural gas | 2,207,430.23 | 53.09% |
| Total | HPHE total CO2 footprint for the period | 2,216,178.10 | 53.30% |
| Savings | CO2 reduction | 1,941,614.55 | **46.70%** |

Over five years, the HPHE achieves a 46.70% reduction in $CO_2$ emissions (1,941.61 $tCO_2eq$), Table 37. The total footprint is 53.30% of the baseline, with the use phase contributing 99.61% of emissions. Manufacturing and transportation contribute 0.40% of the total footprint, confirming that operational energy savings dominate the carbon reduction benefits. The HPHE remains highly efficient throughout this period with minimal maintenance required.

## 4.4 Comparative discussion of results

The results from the three industrial case studies (ceramic, aluminium, and steel) presented, demonstrate the environmental and operational benefits of HPHE technology in waste heat recovery. In the ceramics sector, the integration of HPHEs into the spray drying process enabled the recovery of 700 kW of thermal energy, reducing natural gas consumption by 40% and achieving annual $CO_2$ savings of 160 tonnes.

In the aluminium case, the HPHE system recovered 88.6 kW of waste heat from solution treatment furnaces, reducing natural gas use in ageing furnaces by 50% and cutting $CO_2$ emissions by 86 tonnes annually. The midpoint impact analysis further identified human carcinogenic toxicity as a hotspot (23% of total impacts), primarily from stainless steel production—a finding absent in earlier aluminium-sector LCAs focused solely on operational energy savings.

For the steel industry, the dual-stage HPHE system recovered 350 kW of heat, achieving a 34% reduction in natural gas consumption for billet reheating and preheating combustion air. This aligns with the IEA's emphasis on WHR as a key decarbonization lever for steel, but the study extends prior literature by quantifying trade-offs: while fossil resource scarcity decreased by 41%, mineral resource scarcity increased by 18% due to steel-intensive HPHE manufacturing.

The three cases reveal distinct lifecycle impacts and $CO_2$ savings through HPHE thermal energy recovery and reutilisation during the operational phase. In the ceramic tile firing stage, a high-temperature process, waste heat recovery using heat pipes offers significant $CO_2$ savings due to the large recoverable energy flux. However, the lifecycle impacts are influenced by the need for durable materials to withstand extreme temperatures, increasing embodied energy during manufacturing. Conversely, the ceramic spray dryer, acting as a heat sink, operates at lower temperatures, resulting in moderate $CO_2$ savings but lower lifecycle impacts due to simpler heat exchanger designs. For aluminum production, another energy-intensive industry, heat recovery from processes like smelting reduces reliance on external energy sources, yielding $CO_2$ savings comparable to the ceramic firing stage. However, integration challenges and material requirements for high-temperature applications may elevate initial lifecycle impacts. In the steel case, heating water to 90°C provides substantial flexibility to the end user, from process water, preheating or utilisation for space heating or integration in district heating networks. Out of the three cases, the ceramic case HPHE (5.83%) corresponds to the highest footprint of extraction and manufacturing compared to the aluminium (0.36%) and steel (1.23%) HPHE units. This is due to the unit size and material selection (stainless steel). Transportation contributions are marginal, contributing by up to 1.2%, mainly due to the air transportation. $CO_2$ savings are more pronounced in the steel (45.86%), with aluminium second (42.9%) and ceramic case third (36.87%).

## 4.5 Proposed Business Models for Each Industrial Case

In this section, based on the business modelling carried out in Chapter 3, propositions for the exploitation of the HPHE technology are provided.

The ceramics sector is dominated by SMEs with limited capital for upfront investments, with many factories using infrastructure that is several decades old. The sector is challenging to innovate, as is the case with many production facilities that are usually family owned. As such, an Energy-As-A-Service (EaaS model) would be attractive. Under this structure, the HPHE provider retains ownership of the unit, offering heat recovery as a subscription service. Customers pay a fixed monthly fee based on recovered energy (€/kWh), with performance guarantees tied to predefined temperature and efficiency thresholds. This aligns with the sector's need to mitigate energy cost volatility (30% of production expenses) while complying with the EU Energy Efficiency Directive (EED). Revenue streams include service fees, maintenance contracts, and carbon credit monetization. The lean canvas analysis (Section 3.3.2) supports this model, as 78% of ceramic firms surveyed prioritized OPEX reduction over CAPEX savings.

The aluminium sector, characterized by large, vertically integrated manufacturers like Fagor Ederlan, demands high-uptime solutions with minimal operational disruption. A Build-Own-Operate-Transfer (BOOT) model would involve the HPHE provider financing, installing, and operating the system for 5–7 years, after which ownership transfers to the client. This addresses the industry's reluctance to divert capital from core processes (e.g., die casting) while ensuring ROI through shared savings—e.g., splitting the €155,000 annual energy cost reduction estimated through ETEKINA. The SWOT analysis (Section 3.2) highlights regulatory alignment (EU ETS) and energy security as key drivers, with competitive threats from Chinese producers mitigated by the HPHE's corrosion resistance, a unique value proposition in high-chloride exhaust environments.

For steel plants like SIJ Metal Ravne, which require flexible, multi-sink heat recovery, a hybrid model combining product sales and lifecycle services is optimal. HPHE units would be sold outright, bundled with IoT-enabled predictive maintenance packages (e.g., SCADA integration for fouling alerts). Financial projections (Section 3.3.5) indicate a 22% IRR over 10 years, leveraging the steel sector's higher tolerance for CAPEX (40% of operational costs are energy-related). Additionally, offering carbon offset certification—using the quantified 850 $tCO_2e$/year savings per unit—could premium-price the solution in markets with strict emissions trading. The PESTLE analysis (Section 3.2) underscores the regulatory tailwinds from the Carbon Border Adjustment Mechanism (CBAM), making this model resilient to global steel market fluctuations.

# Chapter 5: Conclusions and future work

## 5.1 General conclusions

This thesis analysed the environmental impacts of the HPHE technology applied in three different case studies in industrial sectors, as part of the ETEKINA project: ceramics, aluminium, and steel. Each case study demonstrated the efficient energy recovery and emission reduction, highlighting the performance of the HPHE. One of the gaps in the ETEKINA work was the lack of an LCA on the component itself, and this is the area where the current work aims to generate value. From each of the case studies, useful conclusions can be drawn, with many applying and reinforcing the case for the HPHEs.

In all three cases, the use phase is the largest contributor to environmental impacts, accounting for over 90% of the impact in categories like global warming, fine particulate matter formation, and fossil resource scarcity. The Global Warming Potential, measured in kg CO2-eq, is in fact the dominant environmental indicator in all three case studies, as the indicator is influenced by the reduction in natural gas consumption, the fuel used to heat the processes in all three case studies. Similarly, the use stage highlights other indicators that contribute to the environmental impacts:

Fine Particulate Matter emissions, while present in all stages, their contribution is occurs mainly at the use stage. FPM reflects the combustion of fossil fuels, natural gas during the use stage, but also oil and coal in transportation and manufacturing. The reduction of FPM through the utilisation of the HPHE will have beneficial effects on the incidence of various negative health effects and reduction in life expectancy, including both chronic and acute respiratory and cardiovascular conditions, increased mortality, lung cancer, diabetes, and adverse birth outcomes [168].

Human Toxicity (Carcinogenic and Non-Carcinogenic) is also reduced through the use stage, but also demonstrates substantial contributions in the manufacturing stage (5% to 45%). This is due to the method of calculation prioritising emissions of metals [169], in addition to the emissions of the processes themselves and the fuel emissions. Beyond the impacts on human health in the areas of extraction, manufacturing and other involved industrial sites, the increased visibility of this indicator will render the adoption of schemes, such as the Organisation Environmental Footprint (OEF) and Product Environmental Footprint (PEF), smoother for HPHE technology developers.

Ozone formation, Terrestrial ecosystems and Human health, can aggravate respiratory diseases such as asthma, reduce lung function, and increase the risk of premature death, but also impair photosynthesis, damage leaves, and reduce crop yields, significantly affecting biodiversity and agricultural productivity. By employing HPHE, the reduction in NOx emissions leads to a lower formation of ozone.

Similar to ozone formation, Terrestrial acidification is also linked to the emissions from fossil-fuel combustion. Terrestrial acidification reflects the release of sulphur oxides and nitrogen oxides that lead to soil and water acidification.

Fossil and mineral resource scarcity are indicators where the manufacturing stage is increasing in contribution. This is due to the extraction and processing of carbon and stainless steel used to fabricate the HPHE systems. Beyond the scope of the study, it is important to note the negligible maintenance and replacement rates for HPHEs during the first 5 years of the system, that reduce damage to mineral resources. On the other hand, fossil resource scarcity is largely owed to the use stage.

Finally, transportation contributed minimal impacts in all stages.

## 5.2 Conclusions from a business perspective

Having carried out the LCA, the results and conclusions can be viewed also from a business perspective. The primary conclusion drawn from the study is the capacity of HPHE systems to deliver substantial energy savings and reduce greenhouse gas emissions across diverse industrial applications, thus aligning with broader sustainability, resilience and decarbonisation priorities. The heat exchanger market is dynamic, fragmented and vibrant: there is ample opportunity for new, especially disruptive, technologies and solutions. With Europe's process industries accounting for 20% of total GHG emissions and 25% of Final Energy Consumption, the market for HPHE technology is substantial, and more importantly, driven by aggressive regulations such as RePOWEREU.

The main selling point is naturally the reduction of energy consumption in the industrial process. While the LCA is not needed to draw this conclusion, the work provides additional clarity on the environmental impacts associated with this reduction. Beyond $CO_2$, the reduction of other pollutants such as NOx, SOx, and particulate matter, quantified via established indicators, provides actionable insight to end users and other stakeholders, such as investors.

Moreover, the HPHE stands out due to its ability to handle challenging waste heat streams (e.g., acidic condensation, fouling), recover 40%-70% of waste heat, and achieve substantial energy and cost savings. Additionally, it is robust and low-maintenance, which further reduces the risks of downtime and disruption of the production process.

From a business model perspective, HPHE systems have been shown to provide a high return on investment, given the short payback periods (less than 4 years). This positions HPHEs as both an environmentally sustainable and economically viable technology for industries looking to reduce operational costs and comply with tightening emissions regulations.

## 5.3 Recommendations for future research

The current work was envisioned as an initial step towards assessing and quantifying the environmental impacts of HPHEs in industrial settings. However, several aspects of the study remain unfulfilled, creating avenues for future research. The recommendations for future work include a deeper exploration of areas such as the working fluid footprint, primary data from installation processes, and the end-of-life (EOL) stages.

Firstly, in the current study, the working fluid footprint was omitted due to its assessed low environmental impact and the complexity involved in the calculations. Working fluids in HPHE systems, such as water, ammonia, or refrigerants, typically have a low impact because they are not consumed or replenished frequently; they remain sealed within the system unless leaks or replacements occur. The first five years of operation usually require no replenishment, as the HPHE does not demand working fluid changes unless it reaches the end of its operational life. Despite the low contribution during the study, future research should focus exclusively on the working fluids to quantify their potential environmental impacts, especially concerning fluorinated gases or other chemicals with high global warming potential. As HPHE systems become more advanced or are used in environments with stricter regulations, the choice of working fluids and their leakage potential may become more critical.

Secondly, the current research model relies heavily on secondary data sources and standardized datasets (e.g., Ecoinvent). While these datasets offer generalized insights, they lack the specificity required for installation processes across various industries. Future research should aim to collect primary data from the installation and setup of HPHE systems in EIIs. This is crucial as different industries may have varying parameters and HPHEs are bespoke systems, thus highlighting the need for real, operational data. Moreover, primary data can reduce data uncertainty and provide more accurate calculations for the initial life cycle stages, such as extraction and processing.

Thirdly, the end-of-life phase was not included in the present study due to a lack of operational primary data, as the ETEKINA HPHE systems have not yet reached their full lifespan. The EOL phase includes the disassembly of the HPHE units, the recycling of materials (e.g., steel), and the disposal of non-recyclable components. This omission leaves a gap in the overall environmental assessment because the recycling potential of the materials used in HPHEs, especially stainless steel and carbon steel, could significantly reduce the life cycle environmental impacts, further underlining the attractiveness of the solution.

Fourthly, heat exchanger development is not a static field, as shown in Chapter 3. Creating an expandable model able to incorporate innovations will not only yield more accurate assessments of HPHE technologies but also align these technologies with evolving regulatory requirements. For instance, as industrial emissions directives grow stricter, understanding the full life cycle impacts, including working fluids and end-of-life disposal, becomes crucial for compliance and improving sustainability metrics. Additionally, the integration of new materials (e.g., advanced alloys) and innovations in working fluids may introduce new complexities that need to be addressed in future studies. Therefore, now that the foundational work is complete, more complex LCA models can be created to describe innovative HPHE-based technologies such as the Condensing Economiser, capable of recovering SOx, NOx and other emissions. Factoring these innovations into the LCA model, it will be possible to further highlight the competitive "unfair" advantage of the HPHE technology over competitors.

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