

Faculdade de Engenharia da Universidade do Porto



**Estudo de viabilidade de aproveitamento e reutilização de calor residual de  
uma indústria**

Miguel Gomes de Amorim Oliveira Nunes

Mestrado em Engenharia Mecânica

Orientadora: Isabel Azevedo

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## Resumo

A União Europeia (UE) é responsável por 11% das emissões de CO<sub>2</sub> a nível mundial e 12% do uso final de energia, sendo responsável por uma parte significativa do impacto ambiental. No entanto, a UE tem feito um esforço por reduzir a sua contribuição nas emissões de gases com efeito de estufa, tendo reduzido as emissões anuais em 23% relativamente a 1990. De forma a mitigar as alterações climáticas, e limitar o aquecimento global em 1.5°C, a UE tem como objetivo a redução das emissões em pelo menos 40% até 2030, promovendo a utilização de fontes de energia renováveis.

Uma das ações com potencial para contribuir de forma significativa para este objetivo é a recuperação de calor residual, envolvendo a recuperação de calor residual de processos industriais e a sua utilização para suprir outras necessidades de calor dentro ou fora da unidade indústria ou convertê-lo numa forma mais útil. O valor de mercado dos sistemas de recuperação de calor residual em 2021 ronda os 65 mil milhões de euros, tendo sido promovido pelas preocupações com os custos de energia e os objetivos de redução das emissões. A Europa detém uma quota de mercado de 38% para a recuperação de calor residual a nível mundial, o que releva o empenho da região no avanço das tecnologias energéticas sustentáveis.

O presente trabalho tem como foco a avaliação do potencial de recuperação e utilização do excesso de calor n um caso concreto de uma indústria de resina. De forma a atingir os objetivos propostos, são simulados diferentes cenários de reutilização do calor residual, considerando a integração de diferentes tecnologias. Os cenários têm como principal objetivo encontrar soluções que aumentem a eficiência dos processos dentro da própria unidade, convertam o calor residual em eletricidade ou permitam o fornecimento do mesmo a edifícios comerciais e residenciais adjacentes.

A análise efetuada teve por base a plataforma EMB3Rs, criada para apoiar diferentes stakeholders na avaliação do potencial de recuperação e reutilização do calor ou frio. A plataforma apresenta uma abordagem integrada e abrangente, que permite a análise de potencial no âmbito de um processo industrial, sistema energético mais alargado, ou numa ótica de mercado. Com base nos resultados das simulações de cenários de oferta e procura, a plataforma permite aos utilizadores industriais e às várias partes interessadas avaliar o potencial financeiro do seu investimento.

Dos diferentes tipos de simulação disponíveis na plataforma, três foram utilizados neste trabalho: simulação *ORC*, *Pinch Analysis* e *Full Simulation*. No total, foram efetuadas seis simulações de acordo com critérios pré-estabelecidos e agrupadas em três grandes grupos, Calor residual utilizado na unidade industrial, Calor residual utilizado fora da unidade industrial e Abordagem combinada, com o objetivo de obter resultados que permitissem encontrar a solução com melhor relação custo/benefício.

Após a apresentação e análise dos resultados, a solução com aproveitamento dentro e fora da unidade industrial, como sendo a mais vantajosa. Esta solução inclui uma caldeira com economizador no sistema de geração de vapor da indústria e sistema de compressão de ar para uso externo, com permutadores de calor e, caldeiras e bombas de calor como tecnologias utilizadas nesta solução. Esta solução apresenta menores custos iniciais, cerca de 25 mil euros, operacionais, 31450€, e de rede, 3. 8 milhões de euros, relativamente às outras soluções com aproveitamento externo à unidade industrial. A solução apresenta uma produção de calor na unidade industrial de cerca de 1.5 GWh, uma redução de emissões de CO<sub>2</sub> de 1.5 tCO<sub>2</sub>eq e uma poupança monetária de 2544€/ano em comparação com a solução convencional com caldeiras.

Para uso interno, a solução com três permutadores de calor para recuperação do calor residual mostrou ser a mais vantajosa, com 387 MWh/ano de calor residual recuperado, e com um custo inicial de 37 mil euros e custos operacionais de 3721€/ano.



## Abstract

The European Union (EU) contributes 11% of the world's final CO<sub>2</sub> emissions and 12% of the world's final energy consumption, making it a significant contributor to environmental damage. However, the EU has made efforts to reduce greenhouse gas emissions, achieving a 23% decrease from 1990 levels. To prevent climate change, the EU aims to reduce emissions by at least 40% by 2030, primarily using renewable energy sources.

One potential strategy for achieving this goal is waste heat recovery, which involves collecting waste heat from industrial processes and using it to supply other heat demands or converting it into a more useful form, such as power or cooling. Waste heat recovery systems were expected to exceed 65 billion euros in value by the end of 2021, driven by concerns over energy costs and emissions reduction targets. Europe holds a 38% market share for waste heat recovery globally, indicating the region's commitment to advancing sustainable energy technologies.

This work focuses on assessing the potential for recovery and use of excess heat in a specific case study, a resin industry. For this purpose, different scenarios are simulated, considering the integration of different possible technologies, such as heat pumps, power cycles, heat exchangers, burners, economisers and waste heat boilers, to increase the efficiency of the process, converting it into electricity or supply it to adjacent commercial and residential buildings.

This analysis was performed using the EMB3Rs platform, created to assess the recovery and reuse of waste heat and cooling (HC) from a comprehensive viewpoint inside an industrial process, an energy system environment, or in a market that is both underregulated and liberalized for district heating and cooling (DHC) systems. Based on the simulation of supply-demand scenarios, the platform enables industrial users and stakeholders to assess the financial potential of their investment in the recovery of waste HC as an energy resource. Different possible scenarios are considered and run through this platform to obtain the best possible solutions with the best cost/benefit ratio.

From this platform, only three types of simulations were performed for this work, ORC simulation, Pinch Analysis and Full Simulation. Six simulations were made according to pre-established criteria and grouped into three large groups, Waste heat used in the industrial unit, Waste heat used outside the industrial unit and Combined approach with the objective of obtaining results that would allow finding the best cost-effective solution.

After presenting and analysing the results, the solution of the boiler with the economizer and air compression system was chosen for external usage, with heat exchangers and, boilers and heat pumps as the technologies used in these solutions, due to the fact that is the one with the lowest capital, 25298€, operational, 31450€, and network costs, 3780000€. Regarding the characteristics of this solution, it has a total heat generation in the industrial unit of 1534880 kWh, CO<sub>2</sub> savings of 1519 kgCO<sub>2</sub>eq and costs savings of 2543.72€/year in comparison with the conventional solution with boilers for heating the water.

For internal usage, the solution with three heat exchangers for recovering the waste heat was chosen, with 387 MWh/year of waste heat recovered, with capital cost of 37214€ and operational costs per year of 3721€.



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# 1 Introduction

## 1.1 Background

Portugal, as a country with limited fossil natural resources or even without their existence, is strongly dependent on the import of fuels such as petrol, coal and natural gas. This situation leads to the fact that almost all primary energy used at the national level is imported. However, this energy dependence is slowly declining, fixed in 65.8% in 2022, according to data from the Direção Geral de Energia e Geologia (DGEG) [1].

Comparing the years 2000 and 2020, it is possible to conclude that consumption of non-renewable resources had a significant decrease over the last decades, being substituted by renewable energy sources, that gained relevance in the Portuguese energetic panorama, as it is shown in the charts, Figure 1 and Figure 2, below, respectively [1].

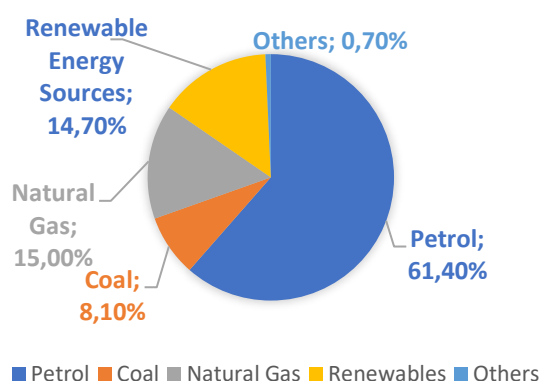


Figure 1 - Total primary energy consumption 2000.

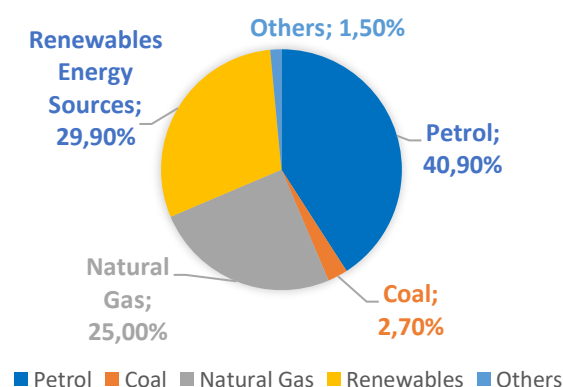


Figure 2 - Total primary energy consumption 2020.

At the sectoral level, transport is the sector that consumes the most and that represents the highest share of final energy, secondly is manufacturing industry and thirdly domestic usage. It is possible to observe the evolution of the total consumption use of final energy per sector in the chart below, Figure 3 [2].

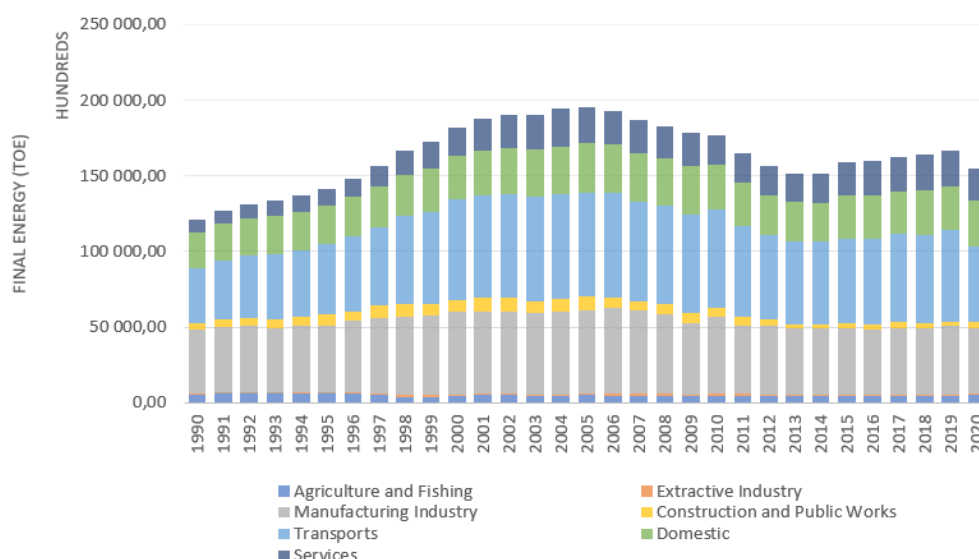


Figure 3 - Evolution of the total final energy consumption in Portugal from 1990 to 2020, disaggregated per sector.

## 1.2 Climate future perspectives and the role of industry for Portugal, Europe, and the World

In 2015, the Paris Agreement (PA) marked a paradigm shift in society with the clear acknowledgement at the global level that only by working together can the challenge of climate change be overcome and the limiting the planet's warming to just 2°C over pre-industrial levels be achieved.

With the aim of supporting the energy transition in the decade 2021–2030, the European Commission introduced the Legislative Package "Clean Energy for all Europeans" in 2016. This was done to comply with the Paris Agreement while also fostering economic growth and job creation. This package mandates that all Member States create and submit a National Integrated Energy and Climate Plan (NECP) to the European Commission for the 2030 time frame. This plan must address greenhouse gases, renewable energy, energy efficiency, energy security, the internal market, research, innovation, and competitiveness, as well as a clear strategy for achieving these goals. The NECP will serve as the primary tool for energy and climate policy over the years 2021–2030 [2].

At the European Union level, ambitious targets have been set, calling for a 32% share of renewable energy in gross final energy use, a 32.5% decrease in final energy consumption, a 40% decrease in greenhouse gas emissions compared to 1990 levels, and a 15% increase in the capacity of electrical interconnections by 2030 [2].

Regarding this fact, Portugal has established the goal of increasing the share of renewable energy sources to 47% by 2030 and decrease the greenhouse effect gases emissions between 45% and 55%, compared to 2005 level. Portugal has compelling reasons to press ahead with its plan for a carbon-neutral economy based on renewable energy sources, with a focus on energy efficiency and the energy consumer [2].

Despite generating almost a quarter of the world's GDP and jobs, industry is also responsible for 28% of greenhouse gas emissions. This reality is linked to growing political pressure to halt environmental degradation around the world.

It won't be easy to decarbonise the industrial sector, which is one of the biggest challenges of the energy transition, especially the four industries that account for 45% of total carbon dioxide emissions: cement, steel, ammonia and ethylene. The process of transition requires a complete rethinking of industrial methods and the upgrading of existing sites through costly rebuilds or retrofits. However, companies that use high-carbon manufacturing processes will see their costs increase in the short to medium term, with the increase in carbon prices, which will ultimately put them at a disadvantage in the global commodity market.

At the EU and national level, there are clear targets for the decarbonization of the industry sector, as well as different policy instruments to support this transition.

Although the National Energy and Climate Plan does not define a specific sectoral emission reduction targets for the industrial sector, which is a major contributor to GHG emissions and where decarbonisation is expected to take longer, there is a strong motivation to address issues of resource efficiency, energy efficiency, competitiveness and innovation. Therefore, the industrial sector will necessarily have to make a significant contribution to the national target of reducing emissions by 45% to 55%, alongside the energy production sector [2].

The investment led by the IAPMEI (Instituto de Apoio às Pequenas e Médias Empresas e à Inovação), IP (Infraestruturas de Portugal) to promote and financially support the national industry's sustainable initiatives represents a multifaceted approach is one of the main instruments in place to addressing the environmental challenges facing the industrial sector.

The four priority areas (low-carbon processes and technologies, energy efficiency measures, integration of renewable energy sources and energy storage, and support for business capacity building) highlight the need for a comprehensive and integrated strategy aimed at fostering innovation, promoting long-term sustainable practices and mitigating the negative impacts of industrial activity [2].

By encouraging the adoption of new processes, products, and business models, promoting the use of renewable materials, and supporting the development of efficient monitoring and management systems, this investment seeks to reduce the carbon footprint of the industry, enhance its energy efficiency, and contribute to the realization of international environmental commitments.

Within the different technical measures considered in the decarbonization process, the use of waste heat may have a crucial role, especially to maximize the energy efficiency of the processes and to support the (partial) decarbonization of hard-to-abate uses, as the uses associated with high-temperature heating processes. This corresponds to a significant untapped potential for energy savings and GHG emissions within the industrial sector, which must be explored further.

### 1.3 Objectives of the project

This work aims to study the technical and economic viability of the recovery and reuse of waste heat from an industrial unit, exploring the use within the industrial unit as well as in the vicinity by other users (including services buildings). The work will be performed using the tool developed under in the scope of the EMB3RS project (Heat and Cold Matching Platform), which allows for the simulations of different scenarios for this exploitation and assessing their feasibility in real use cases, as well as identifying the most advantageous solution.

### 1.4 Methodology

The methodology used to assess the feasibility of the use and reuse of waste heat of an industrial unit is composed by three main steps:

1st - Diagnosis: The first step corresponds to the assessment of the current situation, aiming to provide a detailed characterization of the industrial process and the energy use within the industrial unit, in order to identify the waste heat sources and opportunities for its reuse in the resin industry. Given the impossibility of doing onsite measurements, the characterization was done based on the data from the most recent energy audit of the factory. This step also included the analysis of the productive system diagram and completed with the identification and characterization of the heat demand in the different transformation processes, as well as the technologies and systems that are used to supply the respective demands. This step results in a detailed characterisation of the process of the industrial unit under study, including the associated energy use and emissions, and the identification of the processes that must be included in the assessment of the use of waste heat.

2nd - Simulations: After the performance of the diagnosis, different simulation scenarios were developed and run using the EMB3Rs Heat and cold Matching Platform. The selection of the scenarios was done so that they allowed for the assessment of different solutions (including reuse within the industrial unit and the use of waste heat in the vicinity).

The EMB3RS platform is used to perform simulations for heat recovery and reuse to support the identification of the best alternative for the industrial unit used as a case study. To this end, the platform allows the simulation of different alternatives for the reuse of waste heat, but in this project only three simulations will be performed with the aim of obtaining the best scenario:

- i) ORC Report: The simulation assesses for a single or multiple streams, the amount of recoverable excess heat, and its conversion to electricity by implementing an ORC unit based in the Organic Rankine Cycle. The output of this simulation are the 3 best ORC designs in terms of lowest specific cost of electrical generation (€/kWh).
- ii) Pinch Analysis: The objective of this method is to identify the maximum heat recovery by counter assessing current heat exchange within a process such that the overall energy consumption of the process is minimal. The simulation assesses heat recovery alternatives within the different streams of the industrial process, by performing a series of pinch analyses to the streams' combinations. The output of this routine is the 3 best pinch designs in terms of CO<sub>2</sub> emission reductions/savings (kgCO<sub>2</sub>/year), amount of heat recovered (MWh/year), and heat recovery specific cost (€/MWh).
- iii) Full Simulation: A complete simulation that uses all the resources of the platform and provides an overview of all the solutions given by the program to the waste heat recovery system, making it easier to decide on which scenario will be the most advantageous for the problem at hand.

3rd - Analysis and discussion of the results and conclusion: The third step corresponds to the critical assessment of the simulations output. All the data obtained is treated and analysed, to understand whether it is viable to use the residual heat from the industry under study considering the economic, technological and energy criteria. When viable, the best solution is considered to be the one which, ideally, uses the greatest amount of waste heat, with the most profitability and the lowest installation investment costs.

## 1.5 EMB3RS Heat and cold matching platform

EMB3RS platform was created in the scope of a Horizon 2020 project to assess the recovery and reuse of waste heating and cooling (HC) from a comprehensive viewpoint inside an industrial process, an energy system environment, or in a market that is both underregulated and liberalized for district heating and cooling (DHC) systems. Based on the simulation of supply-demand scenarios, the platform enables industrial users and stakeholders to assess the financial potential of their investment in the recovery of waste HC as an energy resource. Different possible scenarios are simulated through this platform to obtain the best possible solution with the best cost/benefit ratio.

There are five modules that compose the platform:

- 1 Geographical Information System (GIS): For the study of the network and spatial aspects in the context of reusing extra heat or cold in a District Heating and Cooling (DHC) system, the GIS module was created. It examines potential linkages between heat/cold sources and sinks using data from the Open Street Map (OSM) road network. The module figures out the heating and cooling losses linked to the suggested network solution. It accepts data from the platform/user, knowledge base, and core functions module, and it exchanges data with other calculating modules like the market module, business module, and market module. The DHC network routing, as well as the evaluation of heat/cold losses and investment costs, are some of the major calculations carried out by this module [3].
- 2 Core Functionalities (CF) – The main functionalities of this module enable a thorough characterization of the EMB3Rs platform's objects (sinks and sources), as well as to provide technical data to all analysis modules namely, the graphical information systems (GIS), techno-economic (TEO), market (MM), and business (BM) modules so that they can run simulations. Both the sinks and the sources submodules are divided into two primary categories by the CF module: characterisation and simulation. The characterization process of an object is focused on receiving user inputs and carrying out the necessary computations to characterize the created objects. The simulation focuses on performing analysis based on the characterization information, for example, the conversion simulation will assess the amount of energy that can be provided to a district heating network (DHN) for a source's excess heat streams (which were computed in the characterization) [3].
- 3 Techno-Economic Optimization (TEO) – It determines the least-cost technology combinations for utilizing and transporting surplus Heat and Cold (HC) from specified sources to specified sinks. The user needs to assess the possibilities for using surplus HC generated to meet the heating/cooling demand for one or more known or assumed sinks. The goal of optimization is to identify the least expensive combination of technologies and match between sources and sinks that meets requirements while considering limits imposed by regulations, heat availability, load profiles, techno-economic properties of technologies and investment plans [3].
- 4 Market Module (MM) - Economic and fairness metrics including energy transactions, market pricing, social welfare, and price fairness are all provided to the user by this module. Short-term and long-term market assessments that replicate different market structures and incorporate business conditions and network models will be used to do this. In addition to new variations of a decentralized market built on peer-to-peer and community systems, the MM will consider the current Pool market. Flexibility, pricing, and business preferences will all be considered when modelling heat/cold sources and sinks [3].
- 5 Business Market Module (BM) - Evaluates different business models for DHC incorporating excess heat. This is done by calculating matrices such as Net Present Value (NPV), Levelized Cost of Heat (LCOH) and Internal Rate of Return (IRR) under different ownership structures and market conditions [3].

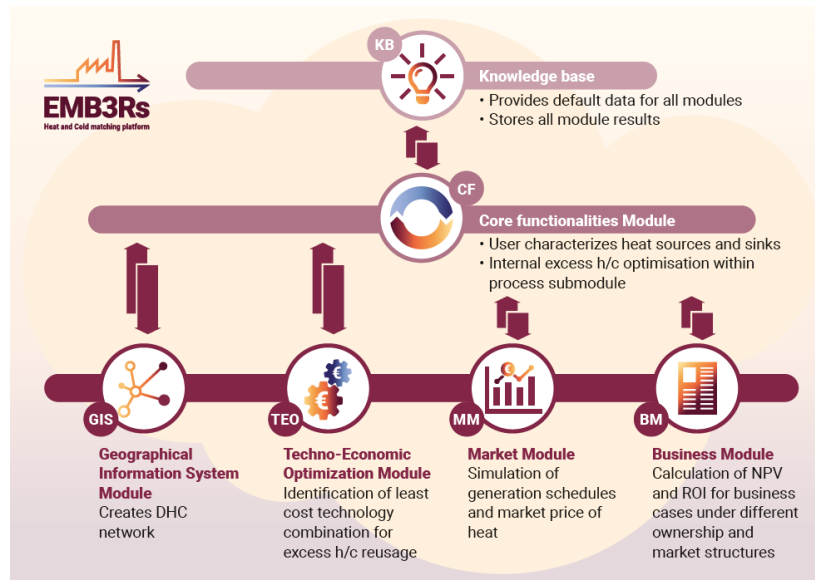


Figure 4 - EMB3RS platform modular workflow (Retrieved from [3]).

## 1.6 Structure of the Dissertation

This dissertation is divided into six chapters:

Chapter 1 - The introduction, where the national and world panorama of energy use is discussed, as well as the perspectives and actions to rationalise the use of energy and the fight against global warming, the methodology that will be followed in the case study and a presentation of the programme where the simulations will be carried out.

Chapter 2 - The state of the art, consisting of the definition of waste heat and listing and explaining the technologies currently used for its recovery, as well as the advantages and disadvantages.

Chapter 3 - The case study, which characterises the industry and the sector to which it belongs, the processes inherent to its operation and the presentation of relevant data for the study in question.

Chapter 4 – Description of the simulations scenarios, characterisation of the industry and of the points where the residual heat potential is to be used is made, besides the inputs that need to be inserted in the desired programme.

Chapter 5 – Results and the analysis of the different scenarios, whether they are viable or not and decision making as to which, if any, will be the most advantageous for the use of the residual heat from the industry.

Chapter 6 - Conclusions and verification of the initial objectives of the dissertation, setbacks and observations that arise in the development of this project and some suggestions for future developments are presented.

## 2 State of the Art

### 2.1 Definition of waste heat

There are various definitions of waste heat in the literature. It can be defined as a by-product of industrial processes [4], as the sum of exergy available in a process after heat recovery and utility integration [5], but, during this work, the one that will be used is that industrial heat is defined as the sum of residual heat rejected from the processes on a site and residual heat rejected from the site utility system designed to satisfy the energy demand, namely heating, cooling, refrigeration and power [6].

Industrial waste heat, the one that will be analyzed in this work, is the waste heat that is generated in industrial processes and is not utilized any process, rejected to the environment. They include heat loss by conduction, convection, radiation, equipment and combustion processes discharged of heat [7].

Looking to the European Union (EU), which contributes 11% of the world's final CO<sub>2</sub> emissions and 12% of the world's final energy consumption, has a significant negative influence on the environment. Yet, the EU has actively participated in lowering greenhouse gas emissions, with a 23% decrease from 1990 levels. The EU has set a goal to reduce emissions by at least 40% by 2030 through the use of renewable energy sources in order to better prevent climate change [8].

Waste heat recovering includes gathering waste heat from industrial processes and transforming it into a more useful form, like power or cooling. The market for development and use of waste heat recover systems have reached over 65 billion euros by the end of 2021 due to the increased concern over energy costs, security, and emissions reduction targets. With a 38% market share as of 2012, Europe is the market leader for waste heat recovery globally, highlighting the region's dedication to advancing sustainable energy technologies [8].

Using 2000-2003 data from 425 UK industries on heat consumption, waste heat fractions were calculated to determine the waste heat potential per temperature level, industrial sector, and EU country. The estimated waste heat potential in the EU is around 300 TWh/year, with the majority of it falling within the 100-200°C range. Waste heat is scarce below 100 °C, but is abundant between 200 °C and 500 °C. A new report suggests that will be a annual growth rate of 4.8% by the end of 2025 [8].

Figure 5 below gives a general representation of an industrial process with entering and leaving material and energy flows.

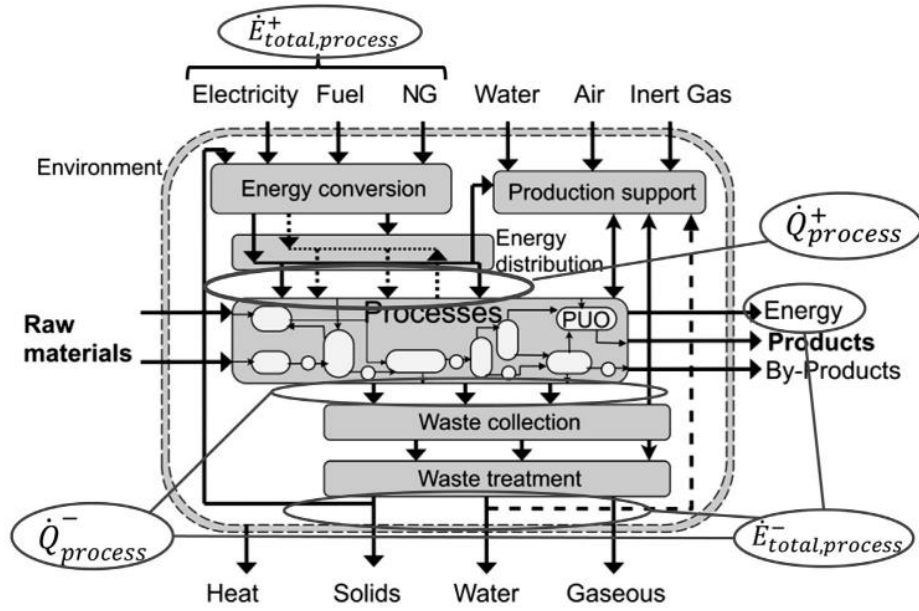


Figure 5 - General representation of an industrial process with entering and leaving material and energy flows (imported from [6]).

High temperature, medium temperature, and low temperature categories can be used to categorize heat loss. To achieve the highest possible efficiency of waste heat recovery, Waste Heat Recovery systems (WHR) are developed for each type of waste heat. A high degree WHR involves recovering waste heat at temperatures above 400 °C, between 100 and 400 °C for the medium temperature range, and below 100 °C for the low temperature range. Most of the waste heat typically comes from direct combustion operations in the high temperature range, combustion unit exhaust in the medium temperature range, and process unit parts, products, and equipment in the low temperature range.

The amount of waste heat available for being recovered can be calculated with the expression shown below.

$$Q = V \times \rho \times C_p \times \Delta T \quad (1)$$

where  $Q$  (J) is the heat content,  $V$  is the flowrate ( $m^3/s$ ),  $\rho$  is density of the gas ( $kg/m^3$ ),  $C_p$  is the specific heat of the substance ( $J/kg.K$ ) and  $\Delta T$  is the temperature difference (in K) between the final highest temperature in the outlet ( $T_{out}$ ) and the initial temperature in the inlet ( $T_{in}$ ) of system [7].

## 2.2 Industrial Waste Heat Recovery Systems

Waste heat recovery systems are technologies that capture and reuse waste heat generated by industrial processes or other sources. By recovering this heat, businesses can increase their energy efficiency, reduce their carbon footprint, and save money on energy costs [4].

There are many different heat recovery technologies [7]:

- energy recovery heat exchangers: air preheaters including recuperators, regenerators, including furnace regenerators and rotary regenerators or heat wheels and run around coil, regenerative and recuperative burners, heat pipe heat exchangers, plate heat exchangers, economisers waste heat boilers and direct electrical conversion device;
- thermodynamic cycles used for waste heat recovery (Organic Rankine Cycle and Kalina cycle, trilateral cycle);
- heat pumps;
- direct electrical conversion devices (thermoelectric, piezoelectric, thermionic, and thermophotovoltaic devices for electricity generation).
- Run-around Coil

Heat recovery technologies can be classified in two groups: “active” and “passive”. If the recovered heat is used directly at the same or a lower temperature is called “passive”, when it is converted into other forms of energy or is used at higher temperature is called “active”. Other common classification is dividing them into direct or indirect waste heat treatment mode if waste heat is transformed in another type of energy during its recovery [9].

Figure 6 below gives an overview of the existing Waste Heat recovery technologies [10].

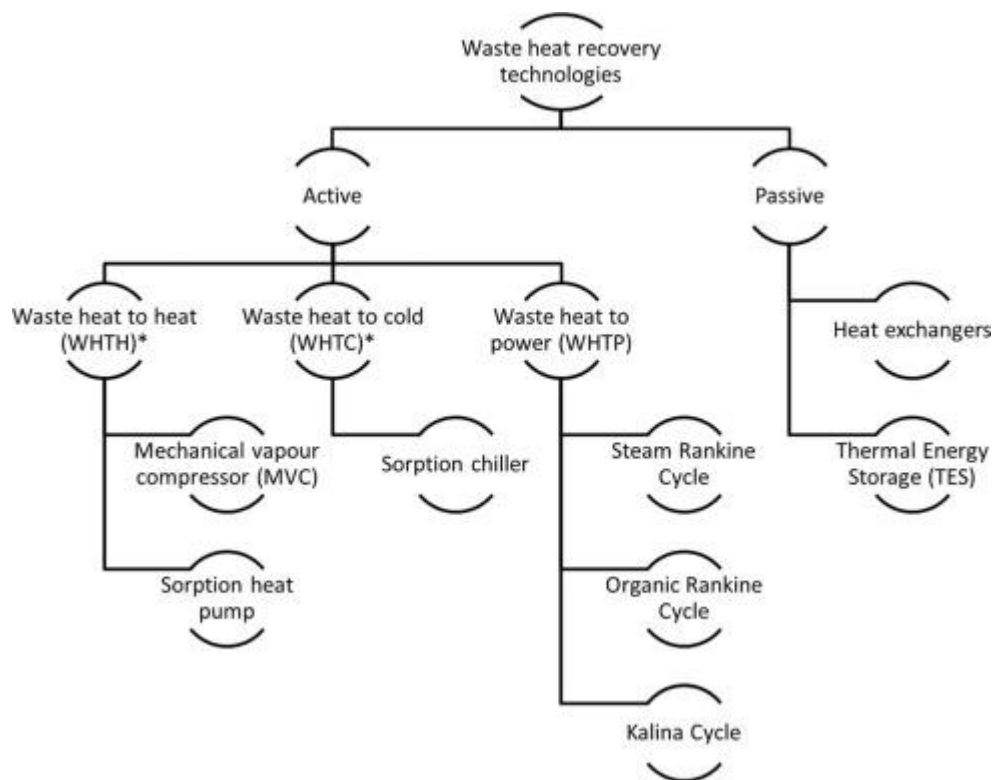


Figure 6 - Waste Heat recovery technologies overview (Retrieved from [10]).

Therefore, direct heat recovery technologies like heat pumps, heat exchangers, heat pipes, boilers, and refrigeration cycles are typical for upgrading waste heat, whereas indirect technologies like the Organic Rankine Cycle, Kalina Cycle and Trilateral Cycle are typical for converting waste heat into other types of energy like electric and mechanical power [9].

### 2.2.1 Heat recovery by heat pump

The working principle of heat pumps is simple. It transfers low-temperature heat to high-temperature heat while consuming a small amount of energy. It uses as a source of heat air, water, geothermal energy, and other renewable energy. However, a heat pump uses a refrigerant cycle to produce hot air and water by collecting heat from a heat source and transferring that on to an evaporator to heat the refrigerant at low pressure. It operates on the same principles as refrigerators and air conditioners. In order to supply high pressure and temperature gas to a heat exchanger (condenser), this is subsequently sent to a compressor. Heat pumps are beneficial for low-temperature waste heat recovery because they have the potential to upgrade waste heat to a higher temperature and quality. Reclaiming the waste heat, with the heat pump, that was previously rejected to the environment, it is possible to obtain useful heat and apply it directly into the process, reducing the energy intake and improving the efficiency of the system [7].

The possible savings strongly depend on the scenario where the heat pump is used and the required temperature rise from source to sink. For industrial applications, payback periods are typically between 2 and 5 years. This can be explained on the one hand by the low energy costs, increasing savings through the application of heat pumps, and on the other hand by the high investment costs involved [11].

Figure 7 gives a simple representation of a working diagram for this technology.

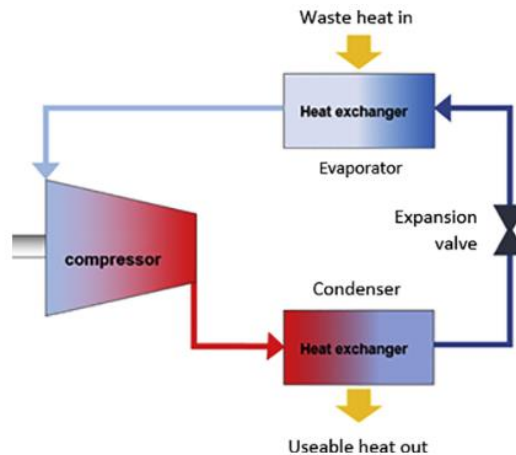


Figure 7 - Heat Pump working diagram in context of waste heat  
(Imported from [7]).

### 2.2.2 Heat recovery by a boiler

Heat recovery boilers consist of water tubes placed in parallel to each other in the direction of heat leaving the system. They are commonly used for recovering waste heat from medium/high temperature, producing steam [7].

Condensing boilers have long been used as the primary technology for waste heat recovery. They have an additional condensing heat exchanger installed at the flue gas outlet where it exchanges heat with a cold fluid, such as boiler return water, and some of the vapour condensates. Part of the latent heat is recovered, allowing the boiler to operate at a higher efficiency. [12].

The temperature of the waste heat is the primary determinant of the pressure and rate of steam production. An auxiliary burner unit or an after burner in the exhaust gases can be added to the system to make up the difference if the waste heat is insufficient for the system to generate the necessary amount of steam. The efficiency of waste heat boilers can be increased by preheating the feed water and, if necessary, producing superheated steam when combined with additional waste heat recovery equipment such as afterburners, pre-heaters, and finned-tubed evaporators [7]. Figure 8 below shows a diagram of a Condensing Boiler.

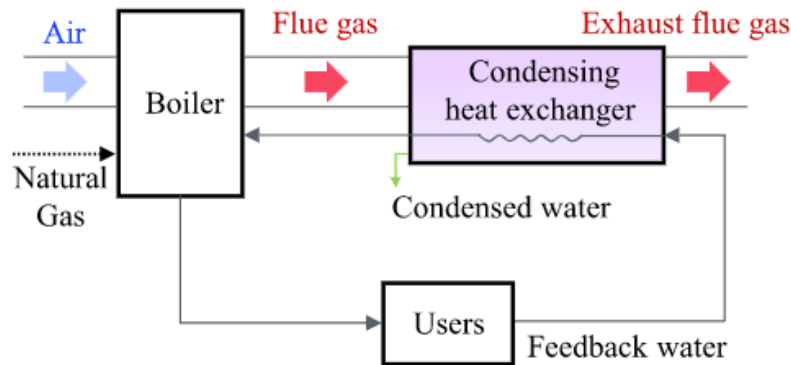


Figure 8 - Diagram of a Condensing Boiler (Imported from [12]).

Waste heat recovery boilers are found in association with high temperature processes, such as those in the glass or metal industries. This equipment can be coupled with other heat recovery equipment, such as recuperators, in order to improve efficiency by preheating the feed and/or producing superheated steam if required. The use of waste heat boilers is generally considered only at the design stage, as their subsequent installation is of great complexity [13].

Waste heat recovery can be carried out before or after flue gas cleaning. The possible savings obtainable with this technology may vary, but it should be noted that this type of boilers are quite efficient equipment, reaching values close to 80%, in addition to reducing the emissions released [13].

### 2.2.3 Heat Pipe Systems

Heat pipes are highly effective heat transfer devices that can recover waste heat in industrial processes with their simple configuration, high thermal conductivity, and environmental adaptability. Heat pipes work by transferring waste heat over a long distance from the hot source to a cold sink, without requiring any power or movable mechanical parts [13]. A typical application of heat pipes for waste heat recovery from combustion gases involves inserting the end of the heat pipe into the hot waste gas as the evaporator to recover the waste heat from the flue gas. The heat-carrying medium in the pipe turns from liquid into vapor and flows to the condenser end, which is embedded into the cold/inlet air and preheats the intake air. The cooled vapor condenses and returns to the evaporator by capillary action. An adiabatic section is also a necessary part in the middle of the heat pipe to maintain a temperature difference between the evaporator end and the condenser end [7].

The effectiveness of heat pipes depends on the heat transfer rate of the device, which can be improved by broadening the heat pipe and arranging heat pipes in line. Although increased hot/waste gas temperature contributes to higher heat transfer rates, it is not always beneficial because the higher temperature of waste gas also means more heat loss from the combustion process in the furnace. By taking full advantage of heat pipes, up to 20% of fuel consumption can be saved in the furnace [9].

Traditional and modern heat pipes can be implemented as thermal connections and highly effective heat exchangers in different systems to transfer waste heat. Heat pipes are regarded as the main component of the heat recovery system for improving the energy efficiency of the whole system. Recent studies have found that heat pipes can be combined with a thermoelectric system for generating power using waste heat. A new concept of a passive heat transfer system was introduced, composed of a thermoelectric generator (TEG) with heat pipes to heat up one side of the TEG by transferring the heat from the lower duct to the upper duct, resulting in cooling the other side [9]. A theoretical model was first described to provide a good start for understanding the performance of the new system, laying the foundation for more detailed experimental analysis. The energy performance of the system was greatly influenced by the ratio of mass flow rate from the upper duct to the lower duct. Increasing the air velocity in the cold duct could also improve the effectiveness of the heat pipes by recovering more free energy from industrial waste heat. Overall, heat pipes are a promising technology for waste heat recovery and can significantly improve the energy efficiency of industrial processes [7].

Figure 9 below shows a schematic representation of a Heat Pipe System.

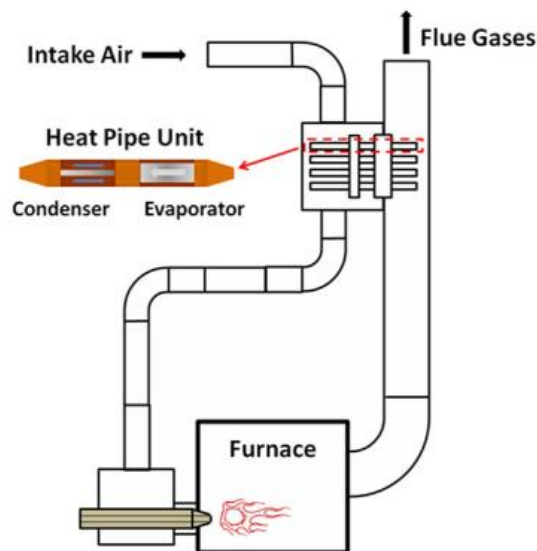


Figure 9 - Waste Heat Recovery System using Heat Pipes  
(imported from [9]).

### 2.2.4 Economizers

Economizers or finned tube heat exchangers are often used to recover low to medium waste heat in order to heat liquids. The heat transmission rate and surface area of these systems tubes, which are clad in metallic fins, are increased. The system is often installed in the exhaust gas duct, allowing hot exhaust gases to travel through several finned tube-covered sections. The liquid is pumped back into the system after passing through the tubes and soaking up heat from the fins, increasing thermal efficiency. They can recover waste heat and improve system efficiency by pre-heating the fluid in the system, such as feedwater in a steam generator or boiler, reducing the energy required to achieve boiling temperature. Finned tubes, coiled tubes, non-condensing, and condensing economisers are some of the different types of economisers that are available for use in diverse applications [7].

In conclusion, economisers are successful at recovering waste heat and enhancing thermal efficiency in many systems. These technologies' use lower fuel consumption, which lowers costs and carbon emissions. The type of economiser used depends on the application, but the aim is always the same: to increase the surface area for heat absorption and transfer, while reducing the energy required to reach the boiling point [7].

### 2.2.5 Regenerative and Recuperative Burners

Regenerative and recuperative burners are used to improve energy efficiency in combustion processes by capturing and using waste heat.

Regenerative burners have two burners with separate control valves that are alternately connected to the furnace and heat the combustion air entering it. The exhaust gases from the furnace heat up refractory material, such as aluminium oxide, which stores the heat energy that is transferred to the inlet air entering the burner.

Recuperative burners have heat exchanger surfaces that capture energy from heated gas passing through the body of the burner, which preheats the combustion air before mixing it with the fuel. The burners consist of an internal heat exchanger with grooves, counter-current flow, and fins that establish thermal contact between the exhaust gases and the combustion air. Both types of burners transfer waste heat to the burner by convection from the exhaust gases, improving thermal efficiency and reducing fuel consumption [7].

Figure 10 below shows a mechanism of a Regenerative Burner.

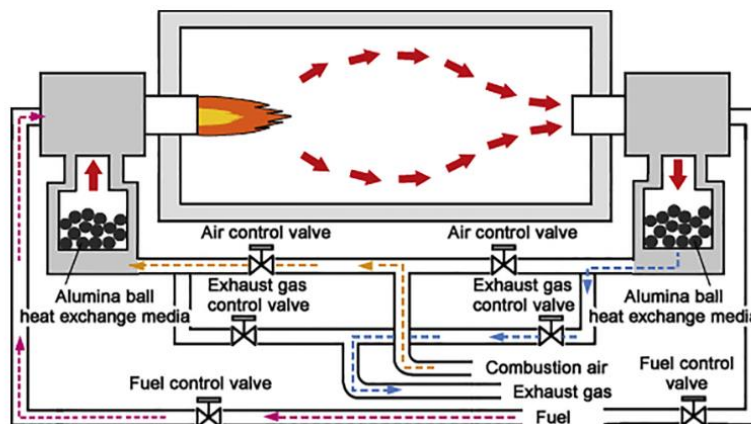


Figure 10 - Regenerative Burner mechanism (Imported from [7]).

### 2.2.6 Thermodynamic cycles

Waste heat recovery through thermodynamic cycles can be used directly to obtain electricity and improve the energy efficiency of the process [7] or it can be transferred to other places for residential or commercial use. Organic Rankine Cycle, Kalina Cycle and Trilateral Cycle are the solutions of power generation [9]:

- Organic Rankine Cycle (ORC) – This cycle is a variant of the classical Rankine cycle and uses organic fluids with low boiling points and high vapour pressures as the working fluid. It is composed by an evaporator/heat recovery boiler, condenser, turbine and a working fluid pump. Figure 11 shows a schematic representation of the Organic Rankine Cycle.

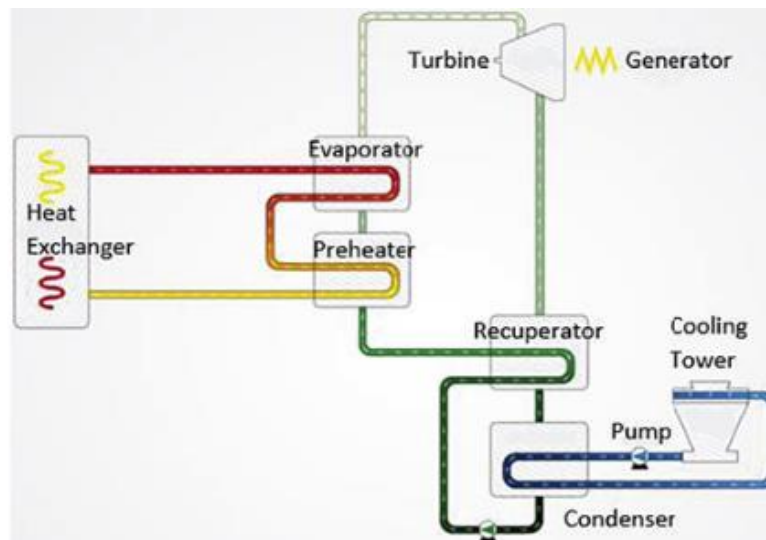


Figure 11 - Schematic representation of the Organic Rankine Cycle (Imported from [7]).

This technology enables waste heat from different sources, such as exhaust gases from turbines, boilers or furnaces, to be used, regardless of how this heat is produced. Any process that produces waste heat in a certain quantity and temperature can drive a ORC. There are many industrial sectors where ORC can be applied, such as chemical, ceramic, agro-food, metallurgical and pulp and paper [14].

The design and performance of an ORC system depends on the correct selection of the working fluid and its specifications in terms of thermodynamics, environmental and safety criteria [14].

- Kalina Cycle – All the possible iterations of the Kalina Cycle, the working fluid is a mixture of ammonia and water, so, the temperature of each fluid is increased separately during the evaporation, resulting in having different boiling points and condensing temperatures, resulting in lower exergy destruction. It usually has a regenerator and a separator in addition to the other components of the Rankine Cycle. Figure 12 shows a schematic representation of the Kalina Cycle.

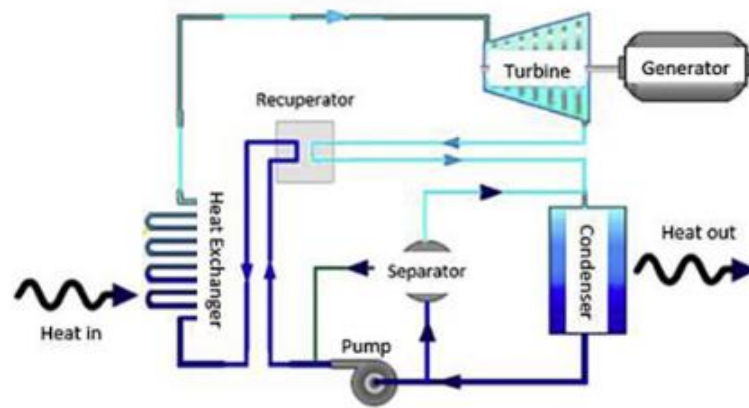


Figure 12 -Schematic representation of the Kalina Cycle (Imported from [7]).

- Trilateral cycle – The difference of this cycle and the two cycles presented before is that this one is able to match the expected temperature profile on the source and sink sides of the profile [9]. The components that take part in this cycle are a pump, a heater, a two-phase expander and a condenser. Figure 13 shows a schematic representation of the Trilateral Cycle.

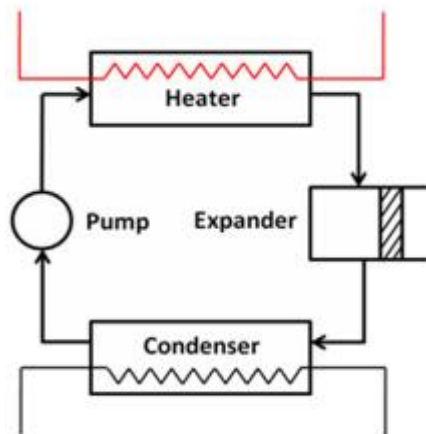


Figure 13 - Schematic representation of the Trilateral Cycle (Imported from [9]).

### 2.2.7 Thermoelectric devices

The ability to transform temperature differences into useable electrical energy is only possessed by thermoelectric devices. Even though their low efficiency has historically been a limiting factor, new developments in nanotechnology have demonstrated considerable advances in their performance, with electrical generating efficiencies of 15% or more being obtained. These technologies have tremendous potential for gathering and transforming waste heat from industrial operations into useable energy. However, maintaining a considerable temperature difference and attaining high heat transfer rates across the device's surfaces remain difficult in practice. Integration of thermoelectric generators with heat pipes has shown to raise the mass flow rate ratio between upper and lower ducts, improving power production and system performance, and is one promising solution. To solve the problems at hand and realize the full potential of thermoelectric devices as an important part of future energy systems, more study and development are required [7].

### 2.2.8 Piezometric power generation

Thin-film membranes that convert ambient vibrations into electricity are used in the process known as piezoelectric power generation (PEPG), which transforms low-temperature heat energy directly into electricity. Unfortunately, a number of technological obstacles, including as low efficiency, high internal impedance, and the requirement for long-term durability, limit the efficiency of PEPG devices in heat recovery. The main problems with PEPG devices are their high production costs and the difficulties in developing systems that allow for power generation, dependability, and stability [7].

Figure 14 below shows a representation of a Piezometric Power Generator [15].

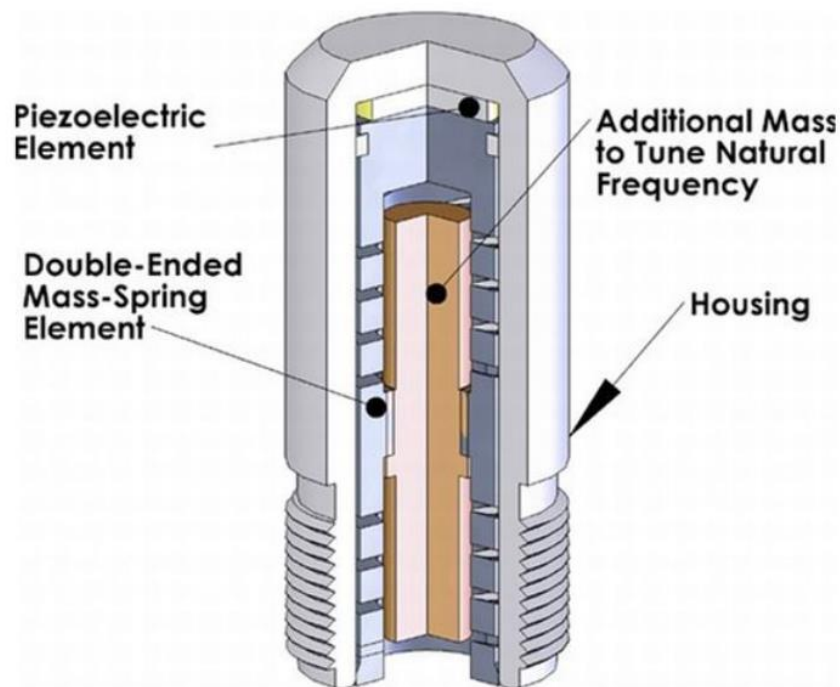


Figure 14 - Piezometric Power Generator (Imported from [15]).

### 2.2.9 Thermionic Generator

Thermionic power generators use a temperature difference between two electron reservoirs to generate electrical power by transporting high-energy electrons against an electrochemical potential gradient. These devices can also operate in reverse as refrigerators by removing high-energy electrons from the colder reservoir. To achieve the required energy selectivity, a barrier is used between the hot and cold reservoirs. These generators have advantages such as high-power densities and the ability to operate at high temperatures, but also face challenges such as the need for high-temperature materials and potential radiation hazards [16]. Similar to thermoelectric devices, thermionic devices generate an electric current via a difference in temperature between two mediums. They do, however, function via thermionic emission. In this technique, electricity is produced by a flow of electrons between metal and metal oxide surfaces through a vacuum in the interelectrode gap, which is created by a hot cathode (Emitter) and a cooled anode (Collector). Although this technology's usefulness is restricted to high-temperature uses and is thought to be inefficient, efforts have been undertaken to increase its efficiency and make it usable for low-temperature uses [7]. Figure 15 shows a schematic representation of a Thermionic Device.

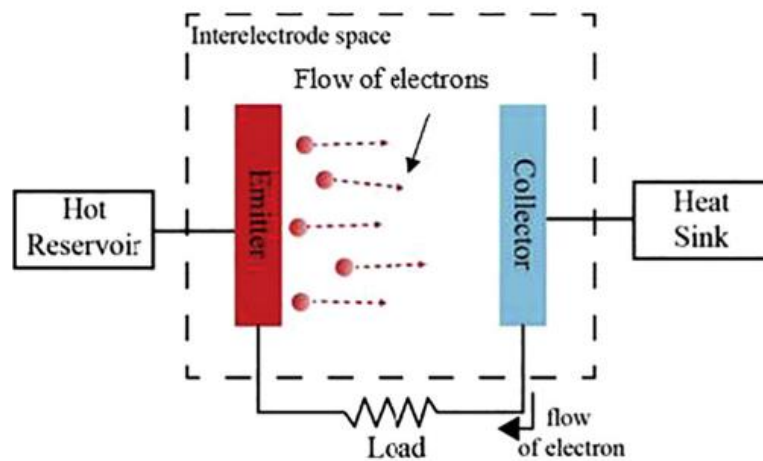


Figure 15 – Schematic Representation of a Thermionic Device (Imported from [7]).

### 2.2.10 Thermophotovoltaic Generator

A Thermophotovoltaic (TPV) generator is an energy system with a heat source, emitter, filter, and PV cell array, offering high fuel utilization, low noise, easy maintenance, and fuel flexibility. It converts thermal energy into light energy, filters out the desired wavelength, and converts it into electricity [17]. With no moving parts, it is easy to maintain and can run on a range of fuels, making it suitable for various applications, including off-grid locations and combined heat and power systems. These devices are a type of energy technology that can directly convert radiant energy into electricity, establishing a new method of waste heat recovery due to their ability to convert heat into electricity. The system emits electromagnetic radiation when heated, which is then filtered through a spectral filter to ensure that only the radiation waves with the correct wavelength matching pass through. The PV cell then converts the radiation into electrical energy. TPV devices have an efficiency range of 1-20% and the technology has been shown to improve the energy efficiency of industrial processes such as iron and steel production plants. However, PV cells have a limited operating temperature range and their efficiency decreases as the cell temperature increases. Although high-efficiency PV cells that can withstand high temperatures are available, they are expensive, which can increase system costs [7].

Figure 16 shows a schematic representation of a Thermophotovoltaic Generator.

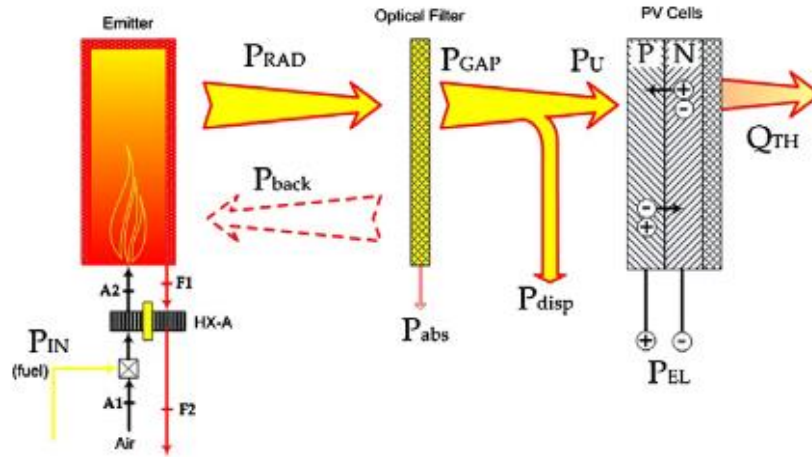


Figure 16 – Schematic representation of a Thermophotovoltaic Generator (Imported from [17]).

### 2.2.11 Run-around Coil

Heat recovery systems are crucial for improving energy efficiency in buildings and industrial processes. Two commonly used systems are the run-around coil heat recovery system and the liquid round coil system. The run-around coil system is composed of at least two coiled heat exchangers connected through a loop where a fluid, such as a mix of water and anti-freeze, flows. The heat from the hot side is transferred to the cold side through the brine fluid, while cooling energy can be recovered during warm days. The flow rate to the supply heat exchanger is controlled by a three-way valve or a speed-controlled pump to prevent overheating [18]. Conversely, the liquid round coil system uses a pair of coiled heat exchangers connected by a run-around coil filled with a fluid, such as water or glycol, to transfer heat. This system is used when direct recuperation is not feasible or when cross-contamination needs to be prevented due to distance or contaminants. However, the liquid round coil system's effectiveness is lower than that of a direct recuperator and requires a pump to operate, increasing its energy consumption and maintenance needs. Nevertheless, the system can be improved by using a secondary heat source. Both systems play a crucial role in reducing energy consumption by recovering waste heat and transferring it to useful applications, thereby contributing to a more sustainable future [7]. Figure 17 shows a schematic representation of Run-around Coil System.

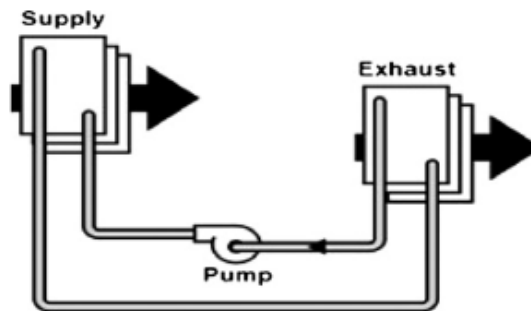


Figure 17 – Schematic representation of a Run-around Coil System (Imported from [18]).

### 2.2.12 Absorption chillers

Absorption chillers are heat-operated refrigeration cycles where a secondary or absorbing fluid in the liquid phase is responsible for absorbing the primary or refrigerant fluid. The absorption cycle is usually used where there is waste heat or where heat can be obtained through solar thermal systems [19]. Figure 18 shows an example of an Absorption Chiller.



Figure 18 - Absorption Chiller.

The absorption cycle is similar to the vapor compression cycle except the prime mover (typically an electric motor) and compressor are replaced by a thermal compressor system consisting of an absorber, solution pump, and generator [19]. Figure 19 shows a schematic representation of a single stage Absorption Chiller.

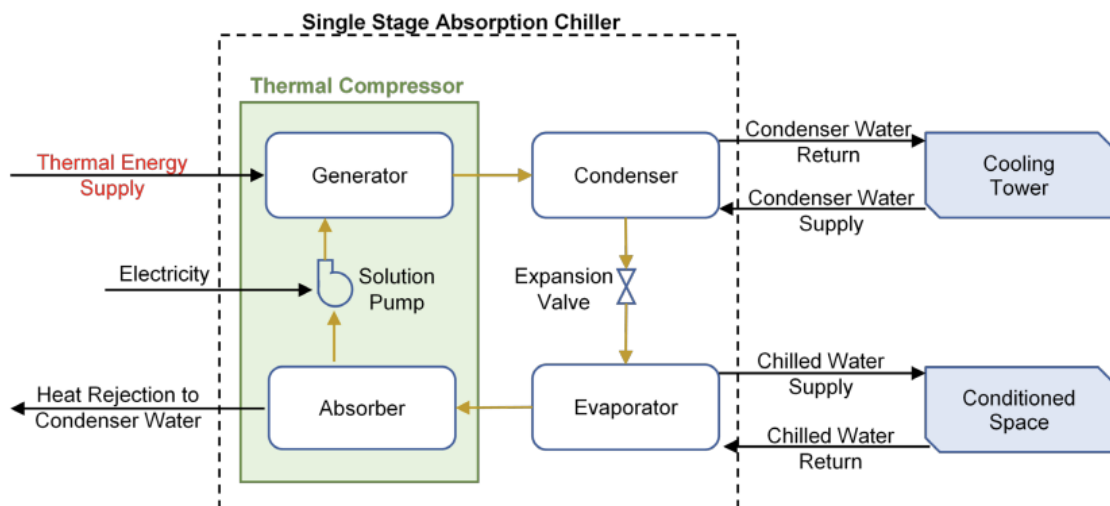


Figure 19 - Scheme of a single stage absorption chiller (Retrieved from [19]).

This technology can be used in any type of industry that needs industrial cold. As it is a system that uses thermal energy to obtain cold, if there is a source of waste heat or a solar thermal energy system, it becomes a very attractive solution. Several industrial sectors, such as brewing, chemical, oil or paper industries are examples of industries that can benefit from using this technology [19].

The efficiency of an absorption chiller is measured by the coefficient of performance (COP), which is defined as useful thermal energy output (i.e., chiller load) divided by heat input. COP is a unit-less number and does not include energy consumed by pumps, fans, or other ancillary components. COP values for single stage chillers are less than one, and COP values for two stage systems are greater than one (i.e., chilled energy delivered exceeds heat required to drive the system) [19].

Table 1 below summarises all the heat recovery technologies mentioned in this chapter.

Table 1 - Waste Heat Recovery technologies overview ([7, 9, 17, 20-22]).

| Technologies      | Temperature range utilization | Benefits                                                                                                                                                                                                                                                                                                                              | Limitations                                                                                                                                                                                                                                                                                 |
|-------------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Heat Pump         | Medium – High                 | <p>High efficiency.</p> <p>Recovery of high-grade heat.</p> <p>Can use a small amount of energy while working, being economically efficient.</p>                                                                                                                                                                                      | <p>It is necessary to assess the method of capturing the waste heat based on its source.</p> <p>First, the grade must be analysed, and then the proper heat exchanger and system installation must be put up.</p> <p>The performance decreases as the temperature difference is rising.</p> |
| Waste Heat Boiler | Medium                        | <p>Is used to generate steam as an output.</p>                                                                                                                                                                                                                                                                                        | <p>When the quantity of steam produced is not enough with the waste heat recovered, it is necessary to add an auxiliary burner.</p>                                                                                                                                                         |
| Heat Pipe Systems | Medium - High                 | <p>It has a high thermal conductivity that allows heat to be transported while keeping temperatures almost uniform along its heated and cooled parts.</p> <p>Can transfer heat over long distances with only a minimal temperature drop.</p> <p>In comparison to other types of heat exchangers, they have lower operating costs.</p> | <p>In order to achieve the best possible performance from a heat exchanger, it is necessary to carefully consider and select the appropriate design, material, working fluid, and wick type based on the specific application and temperature range of the waste heat being dealt with.</p> |

| Technologies                          | Temperature range utilization | Benefits                                                                                                                                                                            | Limitations                                                                                                                                                                                   |
|---------------------------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Economisers                           | Low - Medium                  | Fuel savings.<br>Enhances a system's thermal efficiency by recovering low- to medium-temperature heat from waste flue. gas to warm up or pre-heat liquids entering the system.      | The material that the economiser is done must withstand corrosion.                                                                                                                            |
| Regenerative and Recuperative Burners | High                          | Saving fuel, increasing the efficiency of the combustion.<br>It is generated more heat from the nozzle.                                                                             | Designs more complicated must be used to achieve a higher efficiency, as well as different components that can be complex.<br>The furnace may be changed to insert the burner and the nozzle. |
| Rankine Cycle                         | Low - Medium                  | Possibility of operation at lower lower temperatures than the classic Rankine cycle.                                                                                                | The working fluids must be chosen and chosen and handled with care.                                                                                                                           |
| Kalina Cycle                          | Low - Medium                  | Better efficiency than ORC.<br>Can be operated at lower temperatures than ORC.                                                                                                      | Nominal pressions higher than the ORC.                                                                                                                                                        |
| Piezometric Generator                 | Low                           | Converts directly heat into electricity.                                                                                                                                            | The systems have been found to have low efficiency, high internal impedance, the need for long-term durability and very high cost.                                                            |
| Thermionic Generator                  | High                          | The device generates electricity through the temperature difference between two media, without the usage of any moving parts, and is used for high temperature waste heat recovery. | Limited to high temperature applications and to be wasteful.                                                                                                                                  |

| Technologies                 | Temperature range utilization | Benefits                                                                                                                                                                                  | Limitations                                                                                                                      |
|------------------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Thermophotovoltaic Generator | Low - High                    | Directly convert radiant energy into electricity.                                                                                                                                         | They have a limited temperature range and their efficiency decreases as the temperature increases.                               |
| Run-around Coil              | Medium - High                 | They are used when the sources of heat are far from each other.                                                                                                                           | Needs a pump to operate, so, an additional energy input and maintenance.                                                         |
| Absorption Chillers          | Medium                        | Very effective in the reduction of CO <sub>2</sub> emission and very promising in saving energy. Absorption refrigeration systems are very durable with expected lifetimes of 20–30 years | Absorption refrigeration systems still suffer from a relatively low energy performance in comparison with the conventional VCRSs |

### 3 Case Study Description

#### 3.1 Overview of the resin industry

A variety of natural resins, including pine resin, damar resin, copal resin, and other, are produced and traded on a global scale in the natural resin market. These resins are applied in a diversity of products including varnishes, adhesives, and coatings.

The increasing use of natural resins in various applications is projected to fuel the growth of the global market for natural resin, which was valued at around 2.3 billion euros in 2020 and is anticipated to increase at a compound annual growth rate of about 5% from 2021 to 2026. The biggest producers of natural resins are Indonesia, Brazil, China, and India, that represent 90% of the global production [23].

In terms of consumption, the Asian-Pacific region dominates, followed by North America and Europe. In 2019, 1.8 million metric tons of natural resin were consumed worldwide and this number is expected to grow, driven by the awareness of the environmental benefits of using natural products, as well as the increasing demand for sustainable and eco-friendly materials in various industries. The natural resin market contributes significantly to the global economy thanks to its wide range of uses and rising consumer demand for products that are ecologically friendly and sustainable [23].

#### 3.2 Resin industry in Portugal

The use of natural resins in Portugal began several years ago, being mainly used in the naval sector. Different forest policies and favourable conditions for the growth of pine tree and other species allowed Portugal to become one of the worldwide top resin producers. In the 70s, around 140 thousand tonnes were produced per year, putting Portugal as second in ranking of exporters of natural resin in the world.

In the decade of the 1980s, the panorama changed. The use of new synthetic resins, the exodus from rural areas to urban centres, the abandonment of pine forests and the emergence of major players such as China and Brazil, which contributed to the fall in prices, led to the decline of the resin industry in Portugal (from a hundred thousand tonnes in the decade of the 1980s to almost five thousand tonnes at the beginning of the century) [24].

After reaching a historical minimum in production in 2008, when only 4.5 thousand tonnes of natural resins were produced, a steady growth has been observed, which now stands at 7 to 8 thousand tonnes of annual production. The creation of a national association for this industry, ResiPinus, the more competitive prices and the growing interest in national products can justify this growth.

However, current resin production in Portugal represents only 10% of total national consumption, with the remainder being imported to meet demand, mainly from Brazil. In addition, exports represent only 0.42% of the national forest products exports, so there is potential to increase imports and exports [24].

Figure 20 shows a graph of the resin production in Portugal between 2003 and 2018.

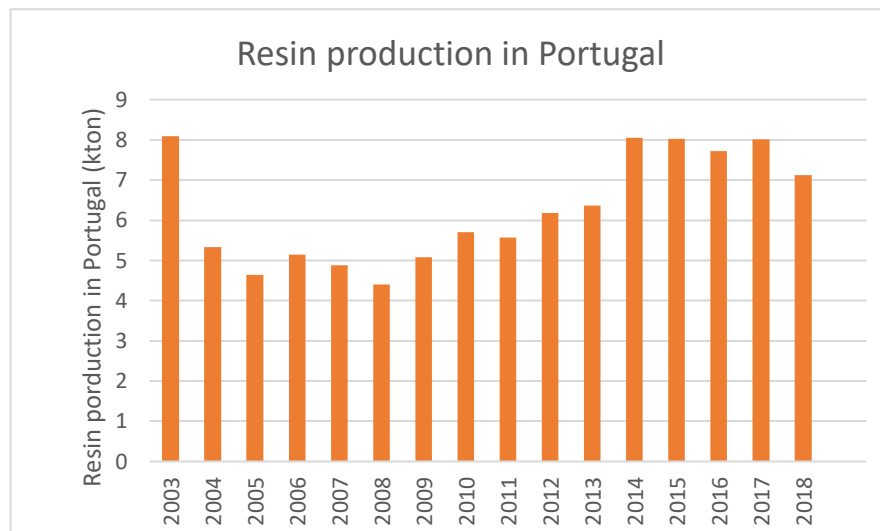


Figure 20 - Resin production in Portugal between 2003 and 2018 (Data imported from [23]).

### 3.3 Resin processing industry

Once extracted, the resin needs to be processed, as there are no direct industrial uses for the raw resin, i.e. for the resin as it is extracted from the pine tree. The manufacturing process comprises several stages, namely: extraction, first transformation process, and second transformation process (Figure 21). The following paragraphs provide a brief description of these different stages.

Firstly, the resin needs to be extracted from nature, being considered as raw resin.

- Firstly, the resin undergoes a first transformation process, where colophony and turpentine are obtained, as a derivative of the natural resin. After the resin extraction campaign is complete, the resin is delivered to the industrial facilities dedicated to the first processing, starting the resin derivatives production process. Within the first transformation process, the main stages are: malaxing, filtering, cleaning and distillation. Malaxing refers to the initial industrial stage, where it overcome a first stage cleaning and the removal of impurities recurring form the extraction from the pine tree, to be ready for the posterior utilization. Following this step is filtering, which tries to get rid of any contaminants (such as leaves, insects, dirt, etc.) resulting from the resin extraction process or from the resin's continued presense in the forest's collection containers. When the resin is cleaned, it is ready to move on to the distillation stage. The two primary derivatives of resin, colophony or turpentine, are produced during the distillation step. The volatile component, turpentine, can be separated from the non-volatile colophony by heating to 110°C and pumping steam up to 170°C into the resin [24].

Once these first derivatives are obtained, they undergo a second transformation process. Within this stage, colophony and turpentine are subject to industrial processes to obtain their derivatives for use in other industries, such as food, adhesives, paint, cleaning products and disinfectants [24].

Figure 21 shows a diagram that summarizes the resin transformation cycle.

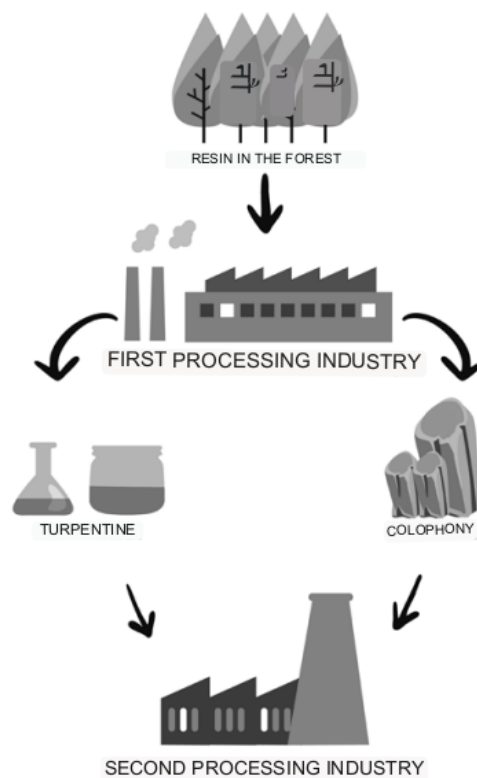


Figure 21 - Resin transformations diagram (Retrieved from [24]).

### 3.4 Case-study general description

#### 3.4.1 Identification of the industrial unit

The case-study assessed in the following sections is based in the analysis of a real industrial unit located in Portugal, dedicated to the transformation of resin as a raw material to resin derivatives. It is an industry focused on the second transformation process, where, as mentioned before, colophony and turpentine are subject to different processing steps to obtain their derivatives for use in other industries, such as food, adhesives, paint, cleaning products and disinfectants. In this specific case, only colophony is utilized for obtaining the final product.

The majority of the real data used throughout the analysis was retrieved from an energy audit of the industrial unit, from the year 2020. Additionally, data not provided by the audit report was requested directly to the unit. This year was atypical due to the outbreak of the COVID-19 pandemic, which may account for the reduction in production and energy use in the month of May.<sup>1</sup>

Overall, the unit has an Energy Intensity, the ratio between the total energy use and the Gross Added Value, of 0.157 kgoe/€, and a Carbon Intensity value, the ratio between the emissions of greenhouse gases emissions and the total use of energy, of 2.51 tCO<sub>2</sub>/toe.

---

<sup>1</sup> In order to comply with GDPR, the unit is not identified nor its exact location.

### 3.4.2 Description of the productive Process

Depending on the product and the various applications, different raw materials are added to the colophony to modify its structural properties. Some of goods that use natural resin include:

- Resins for Adhesives (labels, tapes);
- Resins for Chewing Gum market;
- Resins for Printing Inks;
- Hot melt resins and resins for road marking.

Independently of the final product, the colophony needs to undergo a transformation process which can be decomposed into the following five main steps: transport and storage of the raw materials, chemical reaction, unloading of the reactors, packaging, and storage of the final product. A brief description of each of these steps is presented in the following subsections.

#### 3.4.2.1 *Transport and storage of raw materials:*

The raw materials used are received in solid form, packaged in metal drums (Colophony), paper bags, big bags and cardboard packaging (solid raw materials) as well as in liquid form, packaged in tankers, metal drums and plastic packaging.

If received in liquid form, the colophony is incorporated into the manufacturing process by pumping it from the storage tanks to the tanks on the building level above the reactor platform with a pump.

#### 3.4.2.2 *Chemical reaction:*

The chemical reaction takes place inside the reactors where, after the molten colophony has been introduced, all other raw materials are added, according to the specifications of the manufacturing process of each product.

The solid raw materials are previously weighed and prepared for each product batch in the solid raw materials warehouse, then transported and unloaded by the operator of the intermediate tank for subsequent addition to the reactor.

The reactors are heated with thermal oil through external coils welded to the reactor body.

The vapours produced during the chemical reaction are routed to condensers and stored in tanks and the wastewater is then sent to the respective licensed disposal companies. The chemical reaction process is monitored by continuous analysis of samples taken from inside the reactor to check that the product specifications are met and, if necessary, corrective actions can be activated.

#### 3.4.2.3 *Unloading the reactors:*

Once the chemical reaction is complete, the product is discharged through the bottom valve of the reactor and can have one of two destinations:

- For the cooling screen (flocculator) - the product is pumped into a "spreader" which spreads the product over a surface of the screen in a very thin, adjustable film. As the screen is cooled by the impact of water jets on the opposite side, the liquid product film is in contact with the screen, so that at the end of the flocculator it is already in a solid state and then transported to a silo;

- To the liquid product deposit - by pressurising the reactor with steam. The product can then be packed into drums, unloaded into tankers, and finally sent to the cooling screen at a later stage if flocculation is required.

#### 3.4.2.4 Packaging:

The product in the silo is unloaded into 25 kg paper bags, 500 kg big-bags, 1000 kg big-bags or any other type of packaging agreed with the customer.

In the case of liquid product deposition, the product can be packed into drums.

#### 3.4.2.5 Storage of the finished product:

After being packed in the different types of packaging, products proceed to palletising, which consists of placing each type of packaging on the corresponding pallet (i.e. 40 bags of 25 kg) and the whole set is laminated with the identification of the product, batch number, weight, etc. It is then transported by forklift truck to the finished product warehouse where it is stored, waiting the shipment to the customer(s).

### 3.5 Characterization of energy use and GHG emissions of the industrial unit

The industrial unit under study uses both electricity and natural gas, being the later only used for thermal processes. This section provides a detailed characterization of the energy use for the year 2020, with an overall characterization per energy carrier, and a more detailed characterization of the energy use associated to each of the different phases of the transformation process.

#### 3.5.1 Overall energy use and GHG emissions

Figure 22 provides a graphical representation of the variation of energy use throughout the year under analysis. The plot illustrates the disaggregation between electricity and natural gas, showing that the use of natural gas is prevalent within the whole period.

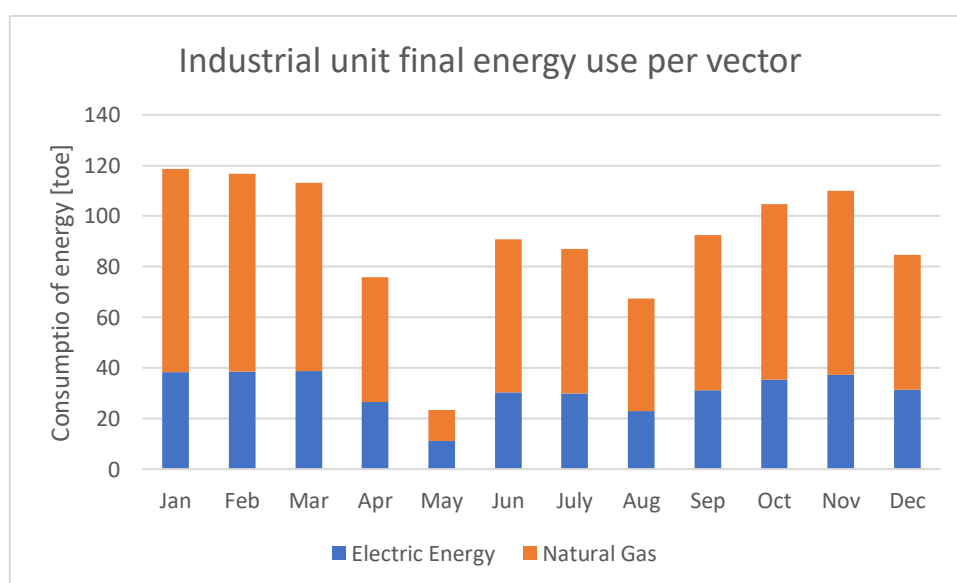


Figure 22 - Disaggregation of the energy consumption in 2020, per vector and per month, in tonnes of oil equivalent [toe].

In the following graphic (Figure 23) it is presented the variation of greenhouse effect gases throughout the year (referred in tons of CO<sub>2</sub> equivalent), associated with the use of each energy source, namely natural gas and electricity. The emissions associated with the use of natural gas represent 70% of the yearly energy-related emissions, corresponding to 1913 tCO<sub>2</sub> eq. , while electricity related emissions correspond to 813 tCO<sub>2</sub> eq.

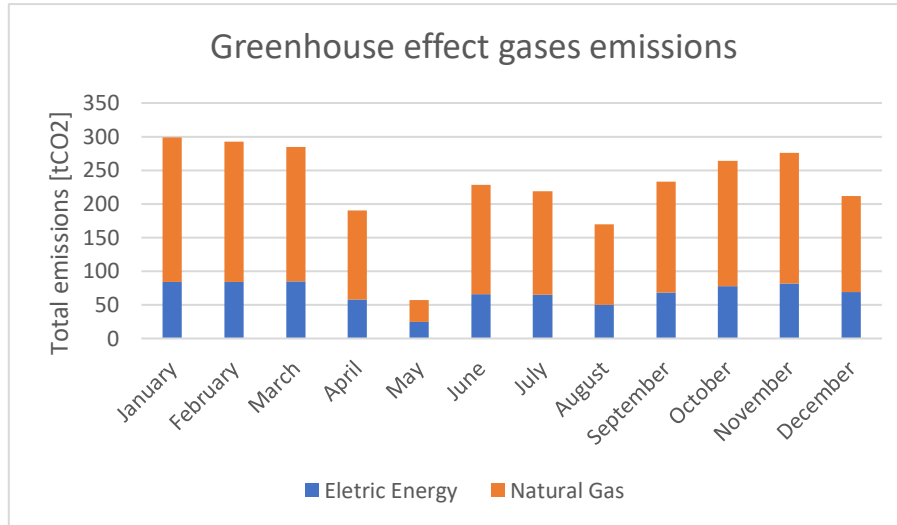


Figure 23 - Disaggregation of the energy-related GHG emissions in 2020, per vector and per month, in tonnes of CO<sub>2</sub> equivalent [tCO<sub>2</sub> eq.].

### 3.6 Energy use in the transformation process

The industrial process under study comprises several procedures which require energy in different forms, namely heat, cold and driving force. A brief description of the main energy uses within the production line and with the auxiliary equipment are presented in this section, as well as the distribution of the main components of each phase.

#### 3.6.1 Description of the energy use in the production line

This subsection is dedicated to the characterization of the energy use in the production line, comprising the four different phases described above - transport and storage of raw materials, foundry of the colophony into liquid state, chemical reactors and discharged of the reactors into cooling mats.

Figure 24 provides a schematic representation of the production line, including the associated equipment and different forms of energy used throughout the process.

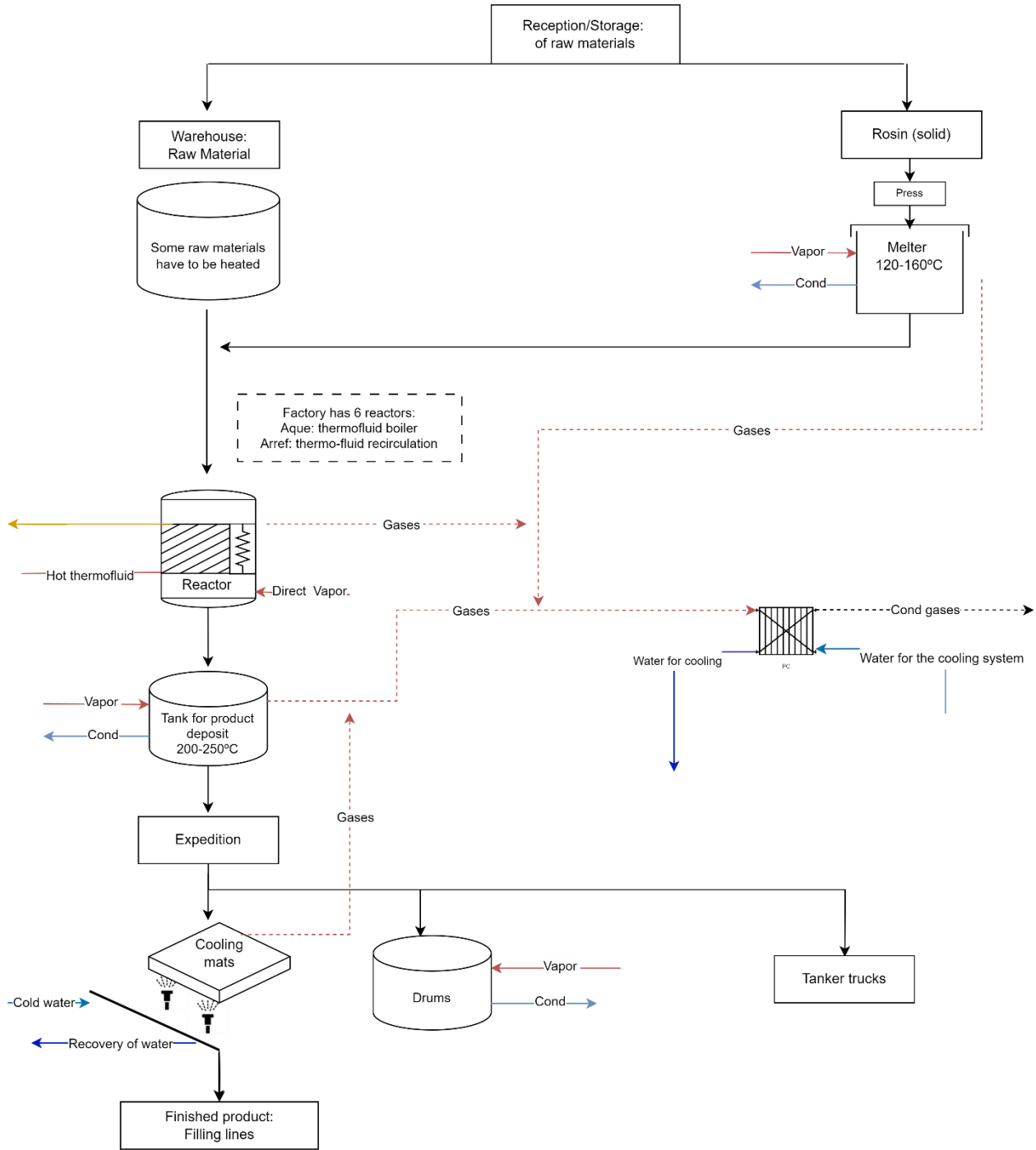


Figure 24 - Diagram of the production line of the industrial unit under study.

### 3.6.1.1 *Transport and storage*

In this phase, it necessary to transport the raw material to the top level and unload it onto a scale. This transport is ensured by **electric pumps** pumping the liquid raw material, or by a **hydraulic hoist**, powered by an electric motor. On the upper level, the raw material is transported and **lifted through two overhead cranes**, where it is unloaded onto scales that control the dosage of raw material necessary to produce the reactor.

The predominant force during this part of the process is the **driving force**, created by the electrical energy converted into mechanical energy in the motors.

### 3.6.1.2 *Foundry of the colophony into liquid state*

Within this stage, the colophony is melted in drums, using steam coils. The thermal energy required to produce the **vapor is obtained with a natural gas boiler**, where the water is heated to the desired temperature.

The Table 2 below gives the characteristics of the respective natural gas boiler.

Table 2 - Natural gas boiler characteristics.

|                   |                                  |
|-------------------|----------------------------------|
| Brand and Model   | Siegfried Schneider & Sohn MDO-S |
| Quantity          | 1                                |
| Vapour Production | 6000 Kg/h                        |
| Nominal Pressure  | 10 bar                           |
| Fuel              | Natural Gas                      |
| Year              | 1970                             |

Also, to transport the colophony between the reactors and the storage, **electric motors** (that convert electrical energy into mechanical energy to power the pumps) are used for the pumps that will move the raw material in liquid stated.

### 3.6.1.3 Chemical reactors

In the six chemical reactors present in the production line, the resin is mixed with other raw materials to obtain the final product by mechanical agitators that will originate the finished product.

The heating of the reactors is achieved with the thermal fluid coming directly from **the thermal-fluid boilers supplied with natural gas**, which provides the thermal energy required to keep the temperature as needed by the process.

The Table 3 below gives the characteristics of the thermal-fluid boiler.

Table 3 - Thermal-fluid boilers characteristics.

|                 |                        |
|-----------------|------------------------|
| Brand and Model | Ambitermo TFC-H e 3000 |
| Quantity        | 2                      |
| Calorific Power | 3488 kW                |
| Capacity        | 2400 L                 |
| Fuel            | Natural Gas            |
| Year            | 2020                   |

As regards cooling, this is ensured by the recirculation of the cooled thermal-fluid after the first circulation through the reactors.

Without any difference from the other components, the reactors have **electric motors** that ensure their functioning, with speed drives that control their rotational speed.

### 3.6.1.4 Cooling Mats

In the final stage of the production line, the finished product is discharged from the reactors into liquid storage directly or into cooling mats, scales or pearls, depending on its final demand. The mats are supplied with **cold water** which promotes the cooling of the material.

## 3.6.2 Description of the energy use of the auxiliary equipment

### 3.6.2.1 Thermal-fluid circuit

The industry under study has a thermo-fluid circuit, used to generate heat for the chemical reactors and the discharge pipelines, in order to keep the chemical compounds in a liquid state in specific sections of the production line.

Each chemical reactor consists of a section of serpentine piping that surrounds its body of high temperature according to the needs of the resin production process. There is a pump for each reactor to overcome the high load loss in this section of the circuit and, after the thermo-fluid has lost some of its heat, the pump is switched on again. Therefore, the pumping system consists of a main pump in the boiler, which circulates the thermos-fluid from the reactors and transports it to the boiler to recover heat and start a new cycle. Four thermo-fluid pumps are in this circuit and a variable speed drive for their control.

### 3.6.2.2 Vapour circuit

The steam is generated by a **natural gas-fired steam generator**. This is mainly used in the casting process, for heating the colophony transport pipes and for maintaining the temperature of the products in the warehouse. This is the same natural gas boiler described above.

Steam is generated and distributed at a pressure of 10 bar (180°C) and enthalpy recovery of condensates takes place in the condensates collection tank at 100°C. These condensates, together with the water reposition, are preheated in the heat recovery unit of the steam generator.

The Figure 25 below illustrates this process.

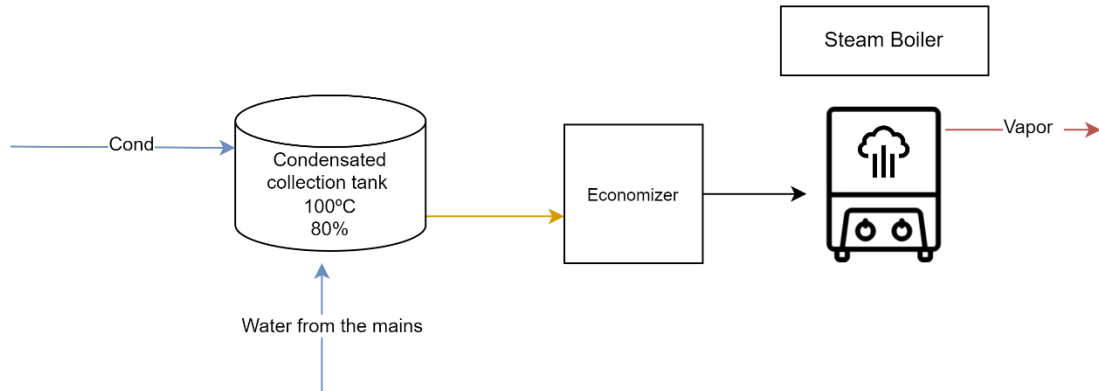


Figure 25 - Schematic representation of the vapour circuit of the industrial unit under study.

### 3.6.2.3 Compressed air system

Finally, the building contains two compressors, one for primary use and one for backup, that are connected to a 1100 litres reservoir. The system operates at a service pressure of 7 bar and is primarily used for pneumatic guns and electro-pneumatic valves in the reactors, casting, and nitrogen generators. The compressed air needs are continuous throughout the operation of the industrial unit, and the installation operates non-stop.

### 3.6.3 Breakdown of energy demand in the whole transformation process

As noted in the previous sections, the energy required varies significantly between the different phases of the transformation process, in terms of both the form of energy and the overall energy demand. The following Table 4 shows the breakdown of electricity and natural gas consumption and total consumption per equipment/usage category.

Table 4 - Final energy use of the industrial unit under study per sector of the production line, for the year 2020.

| Sector                  | Electricity demand [kWh] | Natural Gas demand [ton] | Total final energy demand [toe] | Share of total final energy demand [%] |
|-------------------------|--------------------------|--------------------------|---------------------------------|----------------------------------------|
| Discharged Bombs        | 17969                    | -                        | 3.9                             | 0.4                                    |
| Water Supply Pumps      | 255279                   | -                        | 54.9                            | 5.1                                    |
| Production              | 812397                   | -                        | 174.7                           | 16.1                                   |
| WWTP                    | 197471                   | -                        | 42.5                            | 3.9                                    |
| Foundry                 | 18784                    | -                        | 4                               | 0.4                                    |
| Central office building | 103277                   | -                        | 22.2                            | 2.0                                    |
| Thermo-fluid Pump       | 35650                    | -                        | 7.7                             | 0.7                                    |
| Reactors                | 194534                   | -                        | 41.8                            | 3.9                                    |
| Exterior lightning      | 25520                    | -                        | 5.5                             | 0.5                                    |
| Heat Generators         | -                        | 663                      | 713                             | 65.7                                   |
| Others                  | 69429                    | 0                        | 15                              | 1.3                                    |
| Total                   | 1730312                  | 662                      | 1084.8                          | 100                                    |

A pie chart (Figure 26) is presented below for an easy visualization of the weight that every sector of the industrial unit has on the overall final energy demand.

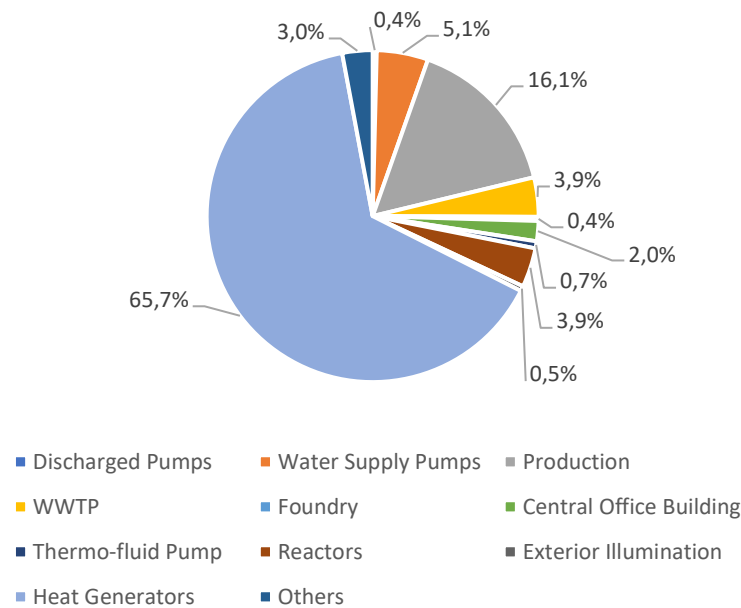


Figure 26 - Breakdown of the final energy use of the industrial unit under study per sector of the production line, for the year 2020 (in %).

Analysing the graph, the sector that consumes the most energy in this factory is the heat generation, which consists of the steam generation boiler that provides the heated steam for subsequent use in the industrial unit. The following sectors with the most energy use, production, with the higher number of equipment, therefore with a high energy consumption and water supply pumps, rely on the electric energy for their operation.

### 3.7 Characterization of the heat generation processes and the respective technology

As referred previously, the use of natural gas is merely associated to thermal uses, more specifically with the water boiler, used for steam generation, and the thermal-fluid boiler, used to heat the thermal-fluid.

The following Table 5 presents the measurements data related to the flue gases from both boilers, as well as the respective efficiency, which was estimated based on the different parameters of the flue gases.

Table 5 - Parameters and efficiency of the boilers of the industrial unit under study.

| Parameters                  | Units | Heating Generator | Thermo-fluid Boiler |
|-----------------------------|-------|-------------------|---------------------|
| O <sub>2</sub>              | %     | 3.8               | 3.0                 |
| CO <sub>2</sub>             | %     | 9.8               | 10.11               |
| Excess of air               | %     | 1.22              | 1.17                |
| Gas temperature             | °C    | 86                | 124                 |
| Atmospheric air temperature | °C    | 22                | 21                  |
| Fuel                        | -     | Natural Gas       | Natural Gas         |
| Efficiency                  | %     | 92.71             | 91.3                |

The high efficiency of the thermo-fluid and steam generation systems, 92.71% and 91.3% respectively, can be explained by the presence of an economizer for the recuperation of the waste heat potential of the exhaust gases released by the boiler for preheating the feeding water, providing an indication of the waste heat utilisation potential of this industry. With these values, there is a great utilisation of the heat supplied by the natural gas to heat the thermal fluid and the steam, while the remaining heat can be utilised, but in a reduced quantity.

## 4 Simulation exercise

Considering the characterization of the transformation process and of the baseline situation for the industrial unit under study (Chapter 3), different scenarios were built and simulated in order to assess the viability of using the waste heat within and outside the industrial site. This chapter is dedicated to the description of the considered scenarios, as well as the rationale beyond the choices and assumptions made.

### 4.1 Overall approach and main assumptions

The main objective of this exercise is to study different possibilities of use of wasted heat from the industrial unit under study and identify the most advantageous scenario in terms of energy and GHG emissions reduction and in terms of cost (investment and operational).

In order to do so, three main approaches were considered: (1) reusing the wasted heat within the industrial facility, in the same or other sectors of the production line; (2) using the wasted heat in the vicinity of the industrial facility (including service buildings), i.e., beyond the boundaries of the industrial facility; and (3) a mixed approach, considering both possibilities.

The first approach can be implemented by running of a Pinch Analysis simulation and describing the industrial process as a combination of multiple hot and cold streams, which will allow to map possible uses of the excess heat within the transformation process and to identify the potential investment requirements and operational savings associated with the solution. Moreover, this can also be done by considering the possibility of using excess heat to generate electricity, which can be implemented in the platform with an ORC simulation.

The second can be implemented by running a full simulation that considers the facility as a single source of waste heat, with a single stream, and the introduction of potential users outside the boundaries of the industrial site (sinks).

Finally, the mixed approach is implemented by considering a source with multiple streams and running a full simulation which considered potential sinks outside the boundaries of the industrial facility.

Moreover, in order to implement the proposed approaches, it was necessary to identify and select potential users of the waste heat. Here, given the high level of efficiency of the baseline situation, as referred in section 3.5, the identification of possible sinks was limited to a relatively small geographical area with 3 km radius around the industrial unit. This area was screened in order to identify medium to large users of heat, namely other industrial facilities, and large service buildings. After a detailed analysis of the considered area, three buildings were identified as suitable to be included in the analysis: a local hospital, a small hotel and a camping park (Figure 27).

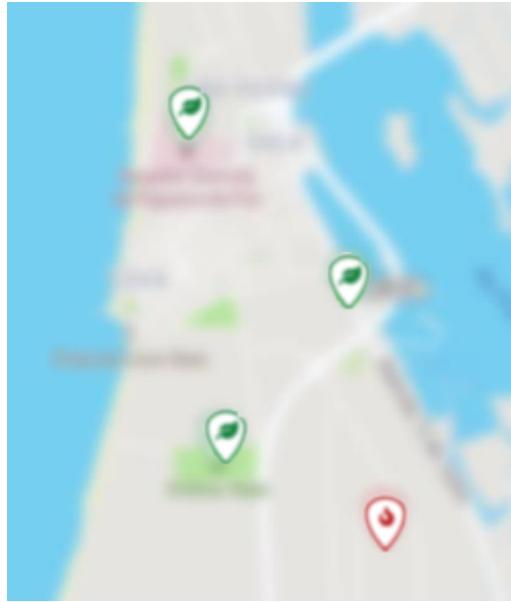


Figure 27 – Scheme of the relative location of the Source (red) and respective Sinks (green).

Even though the unit under study is located in an industrial park, most of the surrounding facilities do not include manufacturing processes, being mostly storage units or retailing companies, to which heat (or thermal energy) is not a relevant energy service for the fulfilment of their activities. In addition, given the small amount of waste heat that is generated by the industrial unit, the supply to other industries nearby would not be feasible.

## 4.2 Sources and sinks description

This section is dedicated to the description of the potential users of the waste heat (sinks), the waste heat sources within the industrial unit and other relevant heat and cold streams, that were used in the different simulations.

### 4.2.1 Sources description

The simulation exercise that was performed as part of this dissertation only considers one source of waste heat, which is the industrial unit. Nonetheless, and in order to assess different opportunities to use the waste heat from the transformation process, within and outside the boundaries of the industrial unit, it was necessary to simulate the same source in different ways. Within this section, the rationale as well as the input parameters that were used to characterize the source(s) are presented.

#### 4.2.1.1 Source 1: Boiler with heat recovery

This corresponds to the description of the heating system that is already in place in the industrial site, considering a boiler with economizer which allows to partially recover the heat from the exhaust gases (as is currently done).

The economizer has the function of preheating the water that comes from the condensate tank, using the exhaust gases that leave the boiler before releasing them to the outside through a chimney. In other words, using the waste heat potential of the exhaust gases to increase the water inlet temperature of the boiler and, consequently, increasing the water outlet temperature and the efficiency of the boiler. Figure 28 represents a scheme of the solution described above.

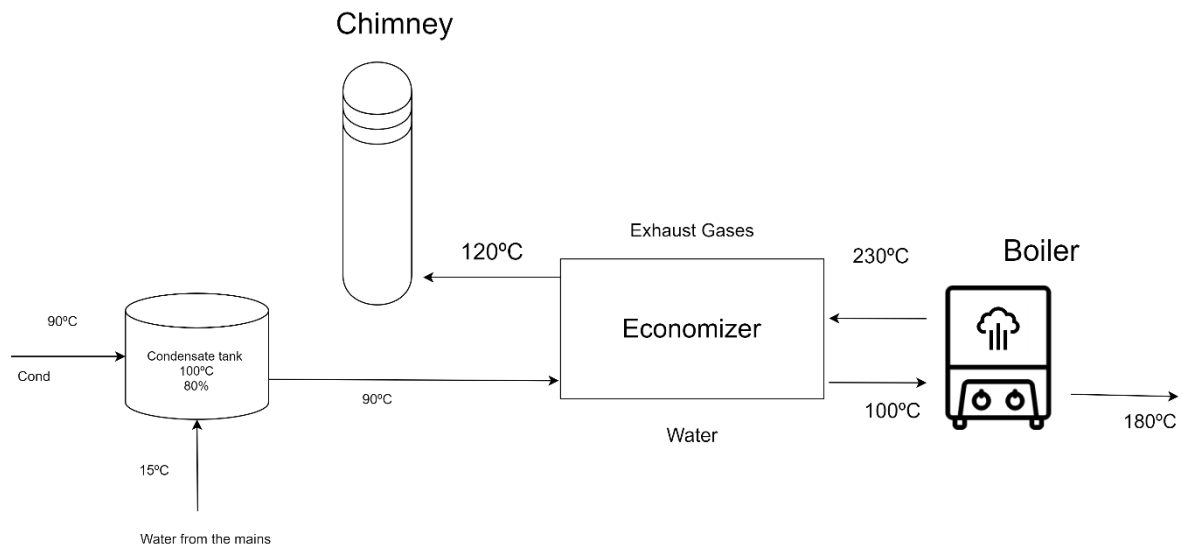


Figure 28 - Schematic representation of the waste heat recovery solution of scenario 1, with boiler and economizer.

To simulate this source, there is the need to consider two flows (streams) within the industrial unit (source) that go through the economizer, which have to be characterized and introduced in the characterization of the source.

The **first flow** corresponds to the water that is supplied to the boiler, going through the economizer. This is a water flow with a mass flow rate of 1000 kg/h which is preheated before being supplied to the boiler.

The **second flow** corresponds to the flue gases that leave the boiler and pass through the economizer, heading to the chimney. As the composition of these gases was not available, air specific heat capacity is used as an approximation. The gases flow is estimated to have a flow rate of 6565 kg/h, reaching the economizer at 230°C. The gases release the residual heat, preheating the water, and exit at 120°C.

Regarding more general characteristics of the waste heat source, the production line is assumed to operate 24 hours per day, without interruption. Throughout the year, three shutdown periods are considered for the industrial unit, which were defined based on the observed variation of energy use in the reference year (2020). Under this assumption, the factory is considered out of operation in the following periods: two weeks in May, one week in August and one week in December.

The following tables summarise the inputs, as entered into the platform. For this scenario, the source has two distinct streams, water and air, which need to be characterized separately.

Table 6 - Inputs for the feeding water stream.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Feeding water                     |
| Fluid                               | Water                             |
| Supply Temperature (°C)             | 90                                |
| Target Temperature (°C)             | 100                               |
| Fluid cp (kJ/kgK)                   | 4.180                             |
| Mass Flowrate (kg/h)                | 1000                              |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

Table 7 - Inputs for the exhaust gases' stream.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Exhaust Gases                     |
| Fluid                               | Air                               |
| Supply Temperature (°C)             | 230                               |
| Target Temperature (°C)             | 120                               |
| Fluid cp (kJ/kgK)                   | 1.04                              |
| Mass Flowrate (kg/h)                | 6565                              |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

#### 4.2.1.2 Source 2: Boiler without heat recovery

As the current level of waste heat is relatively low, and to be able to simulate scenarios without heat recovery within the industrial process, an alternative description of the waste heat source was considered. This alternative source description enables a comparative assessment of the potential for use of waste heat outside the boundaries of the industrial facility between a low and high efficiency heating generation system.

It was assumed that the heat generation system would not include an economizer for heat recovery. Theoretically, in the absence of the economizer, the potential for the use of the waste heat via a district heating network would increase. This solution would imply that the heat from the exhaust gases would not be recovered to preheat the water fed into the boiler, being released at 230°C. Moreover, and to avoid corrosion, it was assumed that the exhaust gases should not be released at temperatures lower than 120°C. Figure 29 provides a schematic representation of this solution.

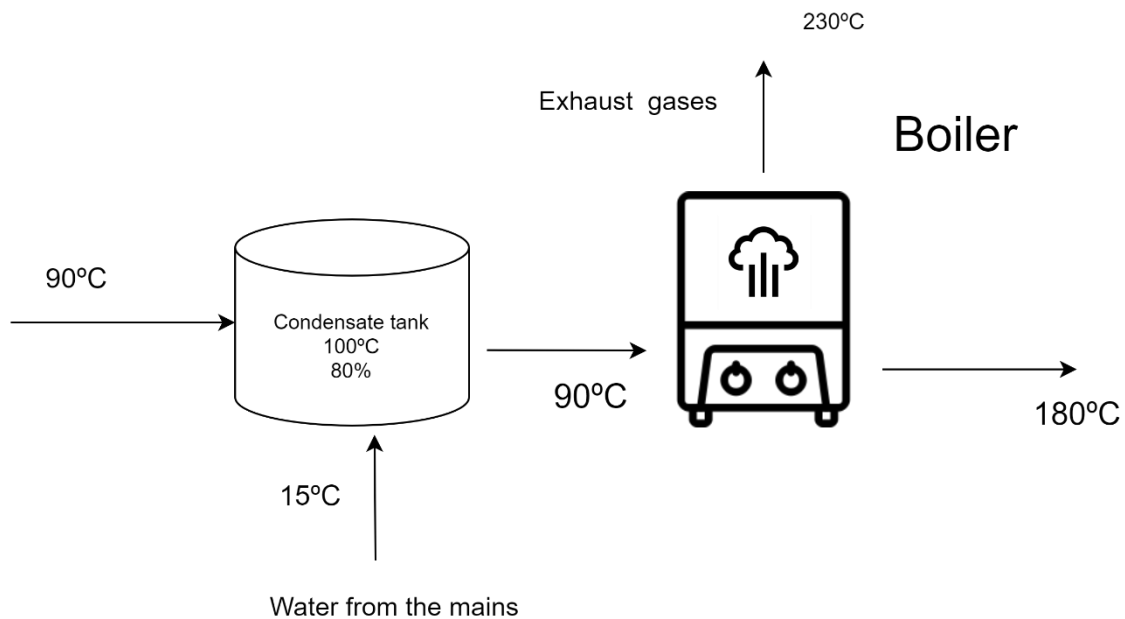


Figure 29 - Schematic representation of the solution "Boiler without economizer".

To simulate this source, a single air flow is represented, from which will result the waste heat. Here, the air mass flow rate will be 6565 kg/h (similarly to what was considered for the air flow in the previous source) and its feed and target temperatures will be 230°C and 120°C, respectively.

The general characterization of the operation conditions, as operating and shutdown periods, were assumed to be the same as for the first source, as the required maintenance would be the same.

The following Table 8 summarises the inputs that are inserted into the platform to simulate this source.



For the simulation of this use case, there is the need to consider, in addition to the economiser before the boiler, the compressed air system which will preheat the water coming from the network before entering the economiser. This preheating is achieved with the heated oil coming from the compressor at 90°C, with a mass flow rate of 147.7 kg/h. The residual heat is used to heat the water from the network from 15°C (ambient temperature) to 34°C, with the same mass flow rate of 1000 kg/h.

Therefore, the source will comprise four distinct flows, including the two considered in the first source, and two other to enable the heat exchange between the heated oil and water from the mains.

The operating conditions are considered the same as for the other two sources. Thus, the daily periods of functioning and the shutdown periods of the factory are considered the same as the first case.

The following tables summarise the inputs inserted in the platform to characterize the source, with the four streams (feeding water to the boiler, thermal oil, water from the mains and exhaust gases) that make up this source.

Table 9 - Inputs for the feeding water stream.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Feeding Water to the boiler       |
| Fluid                               | Water                             |
| Supply Temperature (°C)             | 90                                |
| Target Temperature (°C)             | 100                               |
| Fluid cp (kJ/kgK)                   | 4.180                             |
| Mass Flowrate (kg/h)                | 1000                              |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

Table 10 - Inputs for thermal oil from the compressor.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Oil from the compressor           |
| Fluid                               | Thermal Oil                       |
| Supply Temperature (°C)             | 90                                |
| Target Temperature (°C)             | 40                                |
| Fluid cp (kJ/kgK)                   | 1                                 |
| Mass Flowrate (kg/h)                | 147.7                             |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

Table 11 - Inputs for the water from the mains.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Water from the mains              |
| Fluid                               | Water                             |
| Supply Temperature (°C)             | 15                                |
| Target Temperature (°C)             | 100                               |
| Fluid cp (kJ/kgK)                   | 4.180                             |
| Mass Flowrate (kg/h)                | 366                               |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

Table 12 - Inputs for the exhaust gases stream.

| Platform Input Field                | Input Data                        |
|-------------------------------------|-----------------------------------|
| Name                                | Exhaust gases in the compressor   |
| Fluid                               | Air                               |
| Supply Temperature (°C)             | 230                               |
| Target Temperature (°C)             | 120                               |
| Fluid cp (kJ/kgK)                   | 1.04                              |
| Mass Flowrate (kg/h)                | 6565                              |
| Daily Periods (h)                   | [[0,24]]                          |
| Saturday On                         | yes                               |
| Sunday On                           | yes                               |
| Shutdown Periods (days of the year) | [[120,134], [301,308], [344,351]] |

#### 4.2.2 Sinks description

Contrarily to the source that will vary its characterization in order to allow the simulation of different scenarios, the sinks, i.e., the buildings in the vicinity that have the potential to use the waste heat from the factory under study, are assumed to be the same for all the scenarios where the use of waste heat outside the industrial facilities is considered. The three sinks considered are the hospital, the campsite and the hotel.

The waste heat use within these buildings is assumed to be only for the supply of hot water, considering a supply temperature of 15°C (ambient temperature) and a target temperature of 65°C (reference temperature for water heating systems). To estimate the average mass flowrate, an average daily consumption of 60 L/h per person was assumed for the hotel and for the camping site. For the hospital, the expression  $0.077 \times Area_{Hospital}(m^2)$  was used to estimate the average consumption of a building of this typology.<sup>2</sup> Within this subsection, a description of the main assumptions and considered inputs is presented for each of the proposed sinks.

##### 4.2.2.1 Hospital

The estimation of the use of hot water in the hospital was based on a reference value for the use of hot water per m<sup>2</sup> per day. The mass flow rate of hot water consumed in the hospital per day was then achieved by multiplying the reference value for the area of the hospital. The floor area was estimated with the google maps tools, 18078 m<sup>2</sup>. The estimated value for the average flow rate was 1389 L/h.

Moreover, it was assumed that, in the baseline situation, the hot water is supplied with the use of a natural gas boiler, with an overall efficiency of 90%, an average value for this technology.

Finally, in what concerns the operating hours, it is assumed a constant and continuous use of hot water, without a daily or yearly differentiation. This assumption is based on the fact that hospitals operate on a continuous basis and, even though there may be some variation on hot water needs throughout the day, these are not significant to be included in the simulations.

<sup>2</sup> This unitary value for hot water in the hospital was estimated based on energy audits to different health units that have been performed over the last three years and experts' advice.

The Table 13 below shows the inputs required by the platform to characterize the hospital as a sink.

Table 13 - Inputs of the Hospital.

| Platform Input Field                | Input Data  |
|-------------------------------------|-------------|
| Name                                | Hospital    |
| Fluid                               | Water       |
| Supply Temperature (°C)             | 15          |
| Target Temperature (°C)             | 65          |
| Fluid cp (kJ/kgK)                   | 4.180       |
| Mass Flowrate (kg/h)                | 1389        |
| Daily Periods (h)                   | [[0,24]]    |
| Saturday On                         | yes         |
| Sunday On                           | yes         |
| Shutdown Periods (days of the year) | []          |
| Ref System – Fuel Type              | Natural Gas |
| Ref System – Equipment Efficiency   | 0.9         |

#### 4.2.2.2 Camping Park

To characterize the use of hot water in the camping park, the mass flow rate was estimated by assuming an average occupancy of one hundred people per day and an average consumption of hot water of 60L/h per person per day. This led to an estimated flow rate of 6000L per day. To obtain the hourly rate, this value was divided by 24h, obtaining a consumption of 250 L/h.

As for the hospital, it was assumed that the hot water is supplied with the use of a natural gas boiler, with an overall efficiency of 90%, an average value for this technology.

It is considered that the campsite is closed in winter season.

The Table 14 below shows the inputs needed for the program for the camping park.

Table 14 - Inputs of the Camping Park.

| Platform Input Field                | Input Data   |
|-------------------------------------|--------------|
| Name                                | Camping park |
| Fluid                               | Water        |
| Supply Temperature (°C)             | 15           |
| Target Temperature (°C)             | 65           |
| Fluid cp (kJ/kgK)                   | 4.180        |
| Mass Flowrate (kg/h)                | 250          |
| Daily Periods (h)                   | [[0,24]]     |
| Saturday On                         | yes          |
| Sunday On                           | yes          |
| Shutdown Periods (days of the year) | [[355,172]]  |
| Ref System – Fuel Type              | Natural Gas  |
| Ref System – Equipment Efficiency   | 0.9          |

#### 4.2.2.3 Hotel

For the hotel, it was assumed an average occupancy of 8 people per day, given the small size of the site. Considering the average usage of 60L/day per person, a daily usage of 480 L of hot water is considered, corresponding to a mass flow rate of 20 L/h.

The hotel is assumed to be open, with a constant usage profile throughout the whole year.

The supply of hot water is, as for the previous sites, supplied with natural gas, using a boiler with 90% efficiency. The table below shows the inputs needed for the program for the hotel.

Table 15 below shows the inputs needed for the program for the hotel.

Table 15 - Inputs for the hotel.

| Platform Input Field                | Input Data  |
|-------------------------------------|-------------|
| Name                                | Hotel       |
| Fluid                               | Water       |
| Supply Temperature (°C)             | 15          |
| Target Temperature (°C)             | 65          |
| Fluid cp (kJ/kgK)                   | 4.180       |
| Mass Flowrate (kg/h)                | 20          |
| Daily Periods (h)                   | [[0,24]]    |
| Saturday On                         | yes         |
| Sunday On                           | yes         |
| Shutdown Periods (days of the year) | []          |
| Ref System – Fuel Type              | Natural Gas |
| Ref System – Equipment Efficiency   | 0.9         |

### 4.3 Simulations description

In order to consider all the three approaches referred in section 4.1, six distinct simulations were performed. This section is dedicated to the description of these simulations and respective rationale.

Table 16 provides a summary of the simulations performed.

Table 16 -Description of simulations, including identification of type of simulation, considered sources and sinks.

| Objective                                   | Name         | Type            | Sources considered | Sinks considered         |
|---------------------------------------------|--------------|-----------------|--------------------|--------------------------|
| Waste heat used in the industrial unit      | Simulation 1 | Pinch Analysis  | Source 1           | n.a.                     |
|                                             | Simulation 2 | Pinch Analysis  | Source 3           | n.a.                     |
|                                             | Simulation 3 | ORC             | Source 2           | n.a.                     |
| Waste heat used outside the industrial unit | Simulation 4 | Full simulation | Source 2           | Hospital, Camping, Hotel |
| Combined approach                           | Simulation 5 | Full simulation | Source 1           | Hospital, Camping, Hotel |
|                                             | Simulation 6 | Full simulation | Source 3           | Hospital, Camping, Hotel |

Simulations of heat recovery opportunities within the industrial unit:

1. Pinch analysis with the baseline situation: This simulation enables the quantification of the heat that is currently recovered, due to the introduction of the economizer and the use of the heat from the exhaust gases to preheat the water that is fed to the boiler.
2. Pinch analysis with additional heat recovery: This aims at simulating the potential additional heat recovery that can be achieved within the industrial unit, by using the heat from the oil used in the air compression system to preheat the water that is delivered to the tank.
3. ORC analysis without direct use of waste heat in the process: This simulation intends to model the situation where, instead of using waste heat from the exhaust gases to preheat the water, the waste heat would be used to generate electricity.

Simulation with heat recovery and use outside the boundaries of the industrial unit:

4. Full simulation without heat recovery within the unit: This use case represents the situation where waste heat from the industrial unit is only used to supply other facilities outside the boundaries of the unit, through a district heating network.

Simulation with mixed approach for the use of waste heat:

5. Full simulation with heat recovery inside the unit: This simulation provides a quantification of the potential to use current waste heat (excess heat which is not used to preheat the water fed to the boiler) in the vicinity, with a district heating network.
6. Full simulation with complete heat recovery inside the unit: This intends to simulate the situation where the additional heat recovery from the simulation 2 is combined with the possibility of using excess waste heat to supply heat demand from the three service buildings considered as sinks.

## 5 Results and discussion

Following the description of the rationale and parameters that were used to perform the simulations on the EMB3RS platform, this chapter is dedicated to the results obtained in the different simulations, including the presentation and discussions of the simulation outputs.

In a first instance, the simulations outputs will be presented individually for each simulation, and respective analysis, according to the different approaches mentioned in the previous chapter: waste heat used in the industrial unit, waste heat used outside the industrial unit and the combined approach of both of them.

Secondly, a discussion among all simulations belonging to the same approach will be done, in order to conclude which is the best solution in terms of recovered waste heat, CO<sub>2</sub> emissions and monetarily more advantageous, except for the waste heat used outside the industrial unit, where only one simulation was performed, the Full Simulation, due to the others not being interesting for this study.

At last, a general discussion between all the simulations will be done with the objective of finding the most suitable solution for the industrial unit on the exploitation internally and externally of the maximum use of available waste heat, as well as the most economically viable solution with lower CO<sub>2</sub> emissions.

The platform produces a report for each simulation that compiles the obtained results regarding the different parameters assessed by the platform modules, with graphs and tables. As the platform includes simulation modules that are not explored in the scope of this work, the outputs regarding those specific criteria are neither provided nor discussed within this chapter. The outputs that will be assessed for each type of simulation are the following:

- For the Pinch Analysis, the inputs including minimum flows and heat exchangers  $\Delta T$  and, the confirmation on whether all possible combinations of flows have been analysed or not. If not, the list of infeasible flow combinations is displayed. The three best solutions in each category, CO<sub>2</sub> emission savings, heat recovery and specific cost of heat recovery are also represented with a detailed analysis of each designed solution in each category.
- In the ORC simulation, the information provided includes a table with the streams that were assessed whose supply temperature is larger than the ORC's evaporator temperature, an overview on the three best ORC solutions that were found, the electrical generation specific cost, a detailed technical analysis on each solution designed and a detailed economic analysis on each solution designed.
- Relatively to the Full Simulation, the most complete, not all the outputs will be assessed. The ones considered include the capacity of technologies used in the different sinks and sources, the storage capacity and operational conditions, operational and capital costs, distribution of the heat consumption throw all the destinations and the CO<sub>2</sub> emissions. Moreover, the heating network layout is also modelled and presented.

## 5.1 Waste heat used in the industry unit

This section presents and discusses the results referring to the simulations 1, 2 and 3. Here, the main objective is to compare the waste heat recovery obtained in the current situation (simulation 1) with a situation where additional hot and cold streams are considered and with the use of heat from the exhaust gases to generate electricity instead of using it directly to preheat the water fed into the boiler.

### 5.1.1 Simulation 1: Pinch Analysis

This simulation, as referred in Chapter 4, reflects the current situation, i.e., where exhaust gases pass through an economizer that preheat the water that goes from the condensates tank to the boiler. In order to do so, both streams, hot air and cold water, were considered to simulate this waste heat recovery solution. As is in reality, the solutions resulting from the simulation require a single heat exchanger. It is relevant to refer that the solutions obtained with this simulation are all very similar, and the one presented below refers to the most advantageous in terms of heat recovery, and cost.

Observing the streams description presented in the simulation report, in Table 17 below, it is possible to understand that only 11 kW of the total exhaust gas stream (hot stream) capacity of 201 kW were used to heat the water stream (cold stream) from 90°C to 100°C, the target temperature.

Table 17 - Streams Table.

| Stream ID | Name    | Fluid | Supply Temperature [°C] | Target Temperature [°C] | Capacity [kW] | mc <sub>p</sub> [kJ/K] | Stream Type |
|-----------|---------|-------|-------------------------|-------------------------|---------------|------------------------|-------------|
| 1         | stream1 | water | 90.0                    | 100.0                   | 11            | 1.2                    | Cold        |
| 2         | stream2 | air   | 230.0                   | 120.0                   | 190           | 1.7                    | Hot         |

The Table 18 below provides the information for the heat recovered per year, in MWh, from this solution, which stands at 94 MWh. Considering the yearly consumption of natural gas in the industrial unit, this value corresponds to around 1% of the use of energy for thermal services

Table 18 - Overview of the best design solution for the simulation 1.

| Solution ID | CO <sub>2</sub> Savings [kgCO <sub>2</sub> /year] | Monetary Savings [€/year] | Heat Recovered [MWh/year] | CAPEX [€] | OM Fix [€/year] |
|-------------|---------------------------------------------------|---------------------------|---------------------------|-----------|-----------------|
| 1           | -                                                 | -                         | 94                        | 12401     | 1240            |

As previously said, this solution comprises the introduction of a heat exchanger.

Moreover, looking to the network diagram displayed below, Figure 31, it is possible to visualize the heat exchanger with 11 kW of capacity responsible for heating the water stream up to the target temperature. In addition, due to the fact that the target temperature for the exhaust gases' stream was not reached exclusively with the heat transfer between the streams, lowering its temperature to 223°C, far from the 120°C objective, a Cold Utility - an external source of cooling additional to the heat recovered between streams - with 179 kW of capacity, may be introduced in the system in order to reach the target temperature.

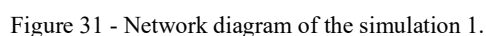


Table 19 - Heat Exchangers Technical Data.

Table 20 - Heat Exchangers Economic Data of this solution.

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### 5.1.2 Simulation 2: Pinch Analysis

Within this simulation, the possibility of increasing the heat recovery comparing to the current situation is enabled by the consideration of two additional streams, a cold and a hot stream associated with the cooling of the air compression circuit. The results show that only three of the four considered streams were used in the most advantageous solutions, being the feeding water, the water from the mains and the air stream. The fourth stream, with thermal oil, was neglected in the simulations due to the very low capacity (2 kW) and it was not used in any of the identified solutions. Table 21 below summarizes the characteristics of all the streams.

Table 21 - Streams' table of the simulation 2.

| Stream ID | Name    | Fluid       | Supply Temperature [°C] | Target Temperature [°C] | Capacity [kW] | $m\dot{c}_p$ [kJ/K] | Stream Type |
|-----------|---------|-------------|-------------------------|-------------------------|---------------|---------------------|-------------|
| 1         | stream1 | water       | 90.0                    | 100.0                   | 11            | 1.2                 | Cold        |
| 2         | stream2 | air         | 230.0                   | 120.0                   | 208           | 1.9                 | Hot         |
| 3         | stream3 | thermal oil | 90.0                    | 40.0                    | 2             | 0.0                 | Hot         |
| 4         | stream4 | water       | 15.0                    | 100.0                   | 36            | 0.4                 | Cold        |

The first and second optimal solutions are very similar, using only one heat exchanger that transfers the heat from the exhaust gases stream to the feeding water stream, neglecting not only the thermal oil stream, but also the heating of the water from the mains. A possible explanation for this might be the reduction of costs, avoiding the utilization of more than one heat exchanger and consequently the increment of the investment costs.

Note that the first and second solutions, because they use only the same two streams from simulation one, give the same solution with similar results, so it is not necessary to present those results because they are already described above

The third solution uses all the streams except the one that uses thermal oil as a fluid. Although the utilization of three heat exchanger increases the capacity and therefore the utilization of the waste heat, it also implies a large increase in the cost of the solution, significantly increasing the investment by three times, as well as the annual operation and maintenance costs.

The Table 22 below summarizes the characteristic of all the streams used in the simulation, as well as the neglected thermal oil stream.

Table 22 - Optimal solution 3 streams' table.

| Stream ID | Name    | Fluid       | Supply Temperature [°C] | Target Temperature [°C] | Capacity [kW] | mc <sub>p</sub> [kJ/K] | Stream Type |
|-----------|---------|-------------|-------------------------|-------------------------|---------------|------------------------|-------------|
| 1         | stream1 | water       | 90.0                    | 100.0                   | 11            | 1.2                    | Cold        |
| 2         | stream2 | thermal oil | 90.0                    | 40.0                    | 4             | 0.1                    | Hot         |
| 3         | stream3 | water       | 15.0                    | 100.0                   | 36            | 0.4                    | Cold        |
| 4         | stream4 | air         | 230.0                   | 120.0                   | 208           | 1.9                    | Hot         |

As for the heat recovered per year, in MWh, from this solution, the value is the same for all the 3 solutions, standing in 387 MWh, making this solution more advantageous than the one verified in the simulation 1, only with 94 MWh of heat recovered per year. This information is shown in Table 23 below, with the costs (CAPEX and OM Fix per year).

Table 23 - Best design solutions for simulation 2.

| Solution ID | CO <sub>2</sub> Savings [kgCO <sub>2</sub> /year] | Monetary Savings [€/year] | Heat Recovered [MWh/year] | CAPEX [€] | OM Fix [€/year] |
|-------------|---------------------------------------------------|---------------------------|---------------------------|-----------|-----------------|
| 3           | -                                                 | -                         | 387                       | 37214     | 3721            |
| 4           | -                                                 | -                         | 387                       | 37214     | 3721            |
| 5           | -                                                 | -                         | 387                       | 37215     | 3721            |

This solution implies the integration of three heat exchangers. Table 24 below presents more succinctly the technical data of the heat exchangers as well as the streams, their supply and target temperatures, and the position of the cold utility, necessary to cool the hot stream of the exhaust gases to the target temperature

Table 24 - Heat exchangers technical data of the optimal solution 3.

| HX Info |               | Cold Stream |                        |                      |                       | Hot Stream |                        |                      |                       |
|---------|---------------|-------------|------------------------|----------------------|-----------------------|------------|------------------------|----------------------|-----------------------|
| HX ID   | HX Power [kW] | ID          | mc <sub>p</sub> [kJ/K] | T <sub>in</sub> [°C] | T <sub>out</sub> [°C] | ID         | mc <sub>p</sub> [kJ/K] | T <sub>in</sub> [°C] | T <sub>out</sub> [°C] |
| 1       | 32            | 3           | 0.38                   | 15.0                 | 100.0                 | 4          | 1.79                   | 230.0                | 212.1                 |
| 2       | 11            | 1           | 1.16                   | 90.0                 | 100.0                 | 4          | 1.79                   | 212.1                | 205.6                 |
| 3       | 4             | 3           | 0.05                   | 15.0                 | 100.0                 | 4          | 0.11                   | 230.0                | 191.1                 |

On the economic side, using three heat exchangers, the investment (CAPEX) roughly tripled to 37214€, while the operation and maintenance cost (OPEX) increased in the same ratio to 3721€ per year, as shown on the Table 25 below.

Table 25 - Economic Data of the Optimal solution 3.

| HX ID | Type             | CAPEX [€] | OM Fix [€/year] |
|-------|------------------|-----------|-----------------|
| 1     | hx kettle boiler | 12419     | 1241            |
| 2     | hx kettle boiler | 12403     | 1240            |
| 3     | hx kettle boiler | 12391     | 1239            |

The network diagram of this solutions gives the perfect overview of the hypothesis mentioned above: The use of three heat exchangers, connecting the exhaust gases stream (hot) with the two water streams (cold), is well represented here. The Figure 32 below shows this diagram.

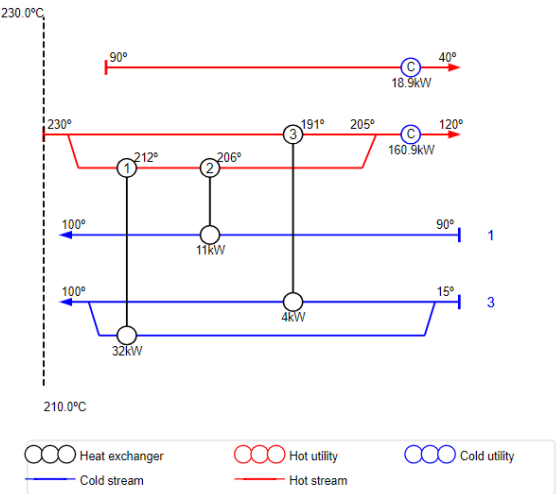


Figure 32 - Network diagram of the third best solution of the simulation 2.

### 5.1.3 Simulation 3: ORC

This simulation assesses the possibility of using the waste heat from the exhaust gases to generate electricity, instead of using it to supply other thermal needs within the industrial unit.

The obtained solution provides, for the ORC cycle, 208 kW of residual heat for electricity production, proving a great potential comparing with previous solutions, when using heat exchangers, with smaller capacities. An overview of the characteristics of the stream and the capacity available is shown in the Table 26 below.

Table 26 - Stream table of the simulation 3

| Stream ID | Name                      | Supply Temperature [°C] | Target Temperature[°C] | Fluid | Capacity [kW] |
|-----------|---------------------------|-------------------------|------------------------|-------|---------------|
| 1         | Boiler without economizer | 230.0                   | 120.0                  | air   | 208           |

This solution corresponds to a reduction in CO<sub>2</sub> emissions of 80 [tCO<sub>2</sub>] yearly, allying with a yearly electrical generation of 131 MWh, as shown in the Table 27 below. This corresponds to a reduction of around 3% of the overall GHG emissions, and the electricity generation would cover around 7% of the electricity consumption of the industrial unit.

Table 27 - Best design solution for the simulation 3.

| Solution ID | Streams ID | CO <sub>2</sub> Savings [kgCO <sub>2</sub> /year] | Monetary Savings [€/year] | Yearly Electrical Generation [MWh] | CAPEX [€] | OM Fix [€/year] |
|-------------|------------|---------------------------------------------------|---------------------------|------------------------------------|-----------|-----------------|
| 1           | [1]        | 79707                                             | 11706                     | 131                                | 170950    | 17095           |

The monetary savings associated with this solution are estimated to be around 17 thousand euros, which is 1/10 of the required initial investment (170950€). Making an overly simplified analysis of these values, the payback period of this investment would be around 15 years.

The detailed technical data is presented in the Table 28 below, with the value of the ORC Power - ORC's nominal electrical power, ORC eff (ORC's Heat to electricity conversion efficiency), T<sub>evaporator</sub> (ORC's evaporator temperature) and T<sub>condenser</sub> (ORC's condenser temperature). The simulation only considered one fluid, thus, it was not possible to assess how the change of fluid would impact the process efficiency.

Table 28 - ORC Design Technical Details for the simulation 3.

| Solution ID | ORC Power [kW] | ORC eff [%] | T <sub>evaporator</sub> [°C] | T <sub>condenser</sub> [°C] |
|-------------|----------------|-------------|------------------------------|-----------------------------|
| 1           | 16             | 8.6         | 110.0                        | 35.0                        |

#### 5.1.4 Overall assessment of the solutions for using the waste heat in the industry

After analyzing the results obtained for the different simulations, it is possible to reach the conclusion that, in what concerns the heating of the boiler feeding water, the use of the heat from the thermal oil is not considered to be viable, since the best solutions found in the first simulation are very similar to the best solutions for the simulation where the usage of that additional stream was enabled. Nevertheless, it was found that there is still some untapped potential regarding the usage of heat from exhaust gases.

Although the 3<sup>rd</sup> simulation (ORC cycle) allows a greater use of waste heat, the increase in investment in comparison with the other solutions cost may not justify the increase in heat recovered and reused.

Thus, the simulation chosen for the internal use of the waste heat from the industrial unit will be simulation 2, which, despite having higher capital and operational costs, recovers more heat per year than simulation 1, 387 MWh against 94 MWh, becoming profitable in a faster rate than the first simulation.

### 5.2 Waste heat used outside the industrial unit

As mentioned before, the assessment of the opportunities for using the waste heat outside the boundaries of the industrial unit was performed by running three scenarios with Full Simulations. The respective analysis will cover the technologies used in the sinks and sources, the storage, operational and capital costs, distribution of the heat consumption throw all the destinations and the CO<sub>2</sub> emissions.

For a better visualisation of the results, each topic will be divided into subchapters.

#### 5.2.1 Simulation 4: Full Simulation

This simulation refers to a scenario where all waste heat to be recovered from the exhaust gases will be used outside the industrial unit, among the three different services buildings which were identified as possible sinks. The delivered solutions consider the development of a heating pipeline network linking the source and three sinks, as shown in Figure 33 (green lines).



Figure 33 – Schematic representation of the heating pipeline network obtained for simulation 4.

The pipeline-specific results are available the Table 29 below are a collection of the pipes connecting a source and sink. It is possible for a pipe to be used to connect multiple sources and sinks. Therefore, the sum of the values given in the table is not equal to the total for the whole network.

Table 29 - Pipeline Specific results for the simulation 4.

| From                      | To           | Thermal Losses [kW] | Installed Capacity [kW] | Length [km] | Total Cost [MEUR] |
|---------------------------|--------------|---------------------|-------------------------|-------------|-------------------|
| Boiler without economizer | Hospital     | 130.07              | 84.88                   | 5.51        | 2.81              |
| Boiler without economizer | Camping Park | 93.03               | 14.44                   | 4.48        | 2.22              |
| Boiler without economizer | Hotel        | 62.05               | 1.22                    | 3.11        | 1.54              |
| Grid Backup               | Hospital     | 42.83               | 84.88                   | 2.01        | 0.98              |
| Grid Backup               | Camping Park | 34.37               | 14.44                   | 2.13        | 0.99              |
| Grid Backup               | Hotel        | 39.50               | 1.22                    | 2.22        | 1.07              |

The aggregated results for the network of the solution 4 are presented in the Table 30 below.

Table 30 - Aggregated results for the network for the simulation 4.

| Total Thermal Loss [kW] | Total Installed Capacity [kW] | Total Network Length [km] | Total Costs [MEUR] |
|-------------------------|-------------------------------|---------------------------|--------------------|
| 159.64                  | 313.92                        | 8.06                      | 3.93               |

#### 5.2.1.1 Heat recovery and heat generation technologies

The provided solution requires the installation of additional heating technologies, as it considers centralised heat generation combined with a multiple heat exchanger located in the source and single heat exchanges in each of the sinks. The identification of technologies for all sources and sinks for the last year of the analysis period, with respective installed capacity, is shown in the table below.

This Table 31 can be used to analyse which technologies are selected by the TEO module for each source and sink. Three distinct technologies were selected by the model: heat exchangers, located in the source and in the three sinks, and a natural gas boiler and a heat pump, located in the grid (centralised). As expected, the 173 kW capacity installed in the industry, because it is the responsible for providing the waste heat to its destinations, followed by the grid specific natural gas boiler, 96 kW and in the third place the hospital with 81 kW of capacity. In the opposite direction, the hotel, with only 1.16 kW of installed capacity is the one that needs less, because it is the one with lower flowrate of hot water needed to supply its needs.

Table 31 - Final Source and Sink Capacities in kW for the simulation 4.

| TECHNOLOGY                                                | Installed capacity (kW) |
|-----------------------------------------------------------|-------------------------|
| Boiler without economizer Stream1 Multiple Heat Exchanger | 173.39                  |
| Camping Park Stream1 Single Heat Exchanger                | 13.76                   |
| Grid Specific Heat Pump                                   | 43.68                   |
| Grid Specific Natural gas Boiler                          | 96.31                   |
| Hospital Stream1 Single Heat Exchanger                    | 80.85                   |
| Hotel Stream1 Single Heat Exchanger                       | 1.16                    |

The Figure 34 below provides the total cumulative capacity of this solution, in addition to the representation of the individual capacity of each technology of the sinks and the source for the big picture.

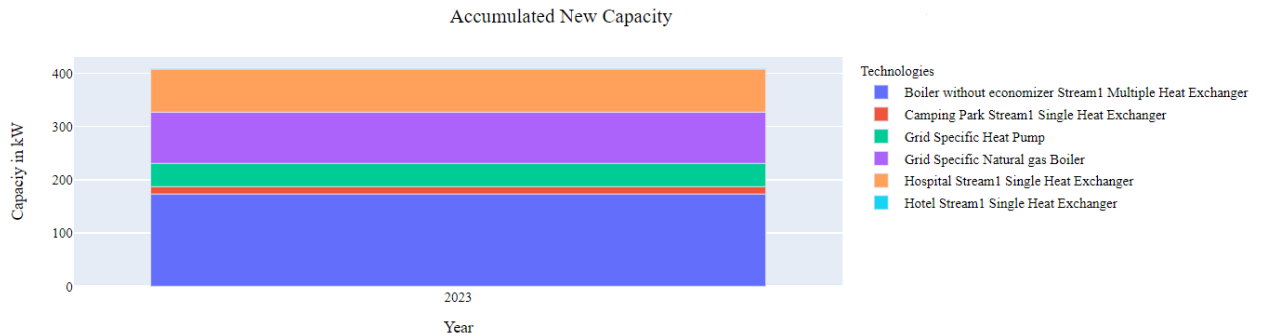


Figure 34 - Installed capacity of technologies for all sources and sinks for the simulation 4.

#### 5.2.1.2 Storage new installed capacity

The platform defined, by the TEO module, that two types of storage were required for this solution, inside the source with 1000 kWh of capacity and an additional storage tank with 1000 kWh, as shown in the Table 32 below. The installed storage capacity for the last year of the analysis period is shown in the table below.

Table 32 - Storage Capacities in kWh for the simulation 4.

| Storage       | Installed storage capacity (kWh) |
|---------------|----------------------------------|
| sourcestorage | 1000.00                          |
| tankstorage   | 1000.77                          |

The graphs below allow us to see that the intra-annual operation of storage the dispatch of the systems and how the variability of excess heat availability is balanced in the system. It is important to underline that both storage technologies have the same behaviour throughout the year.

It is possible to observe in the Figure 35 below that there are moments in the year when the maximum energy storage capacity is reached, in February, May and July, and there may have been energy wastage in these months if residual heat production exceeded this storage capacity.

On the contrary, in March there was no energy storage, being totally used for the processes.

In the month of May the storage was fully used and there was no energy stored at the beginning of the month of June.

Although there is a correlation between the charging of the storage and the time where the industrial unit is closed in May, is important to mention that it is not a correct assumption for the whole year, because in the months of August and December this isn't verified.

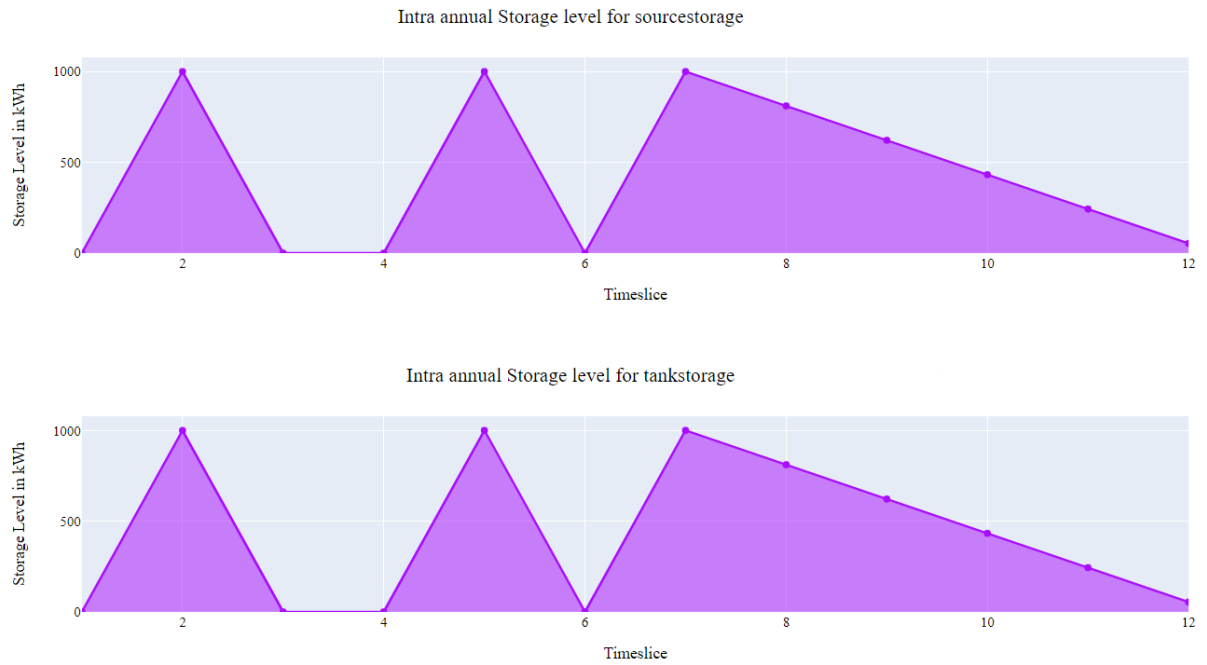


Figure 35 - Intra annual storage levels for the simulation 4.

The charge and discharge pattern of the storage tank is presented on the graph below. In addition to the operation referred before, is important to mention that there is only discharging from July to the end of the year, represented by the straight line that covers the last five months of the year, situated in the negative side of the storage charge and discharge scale.

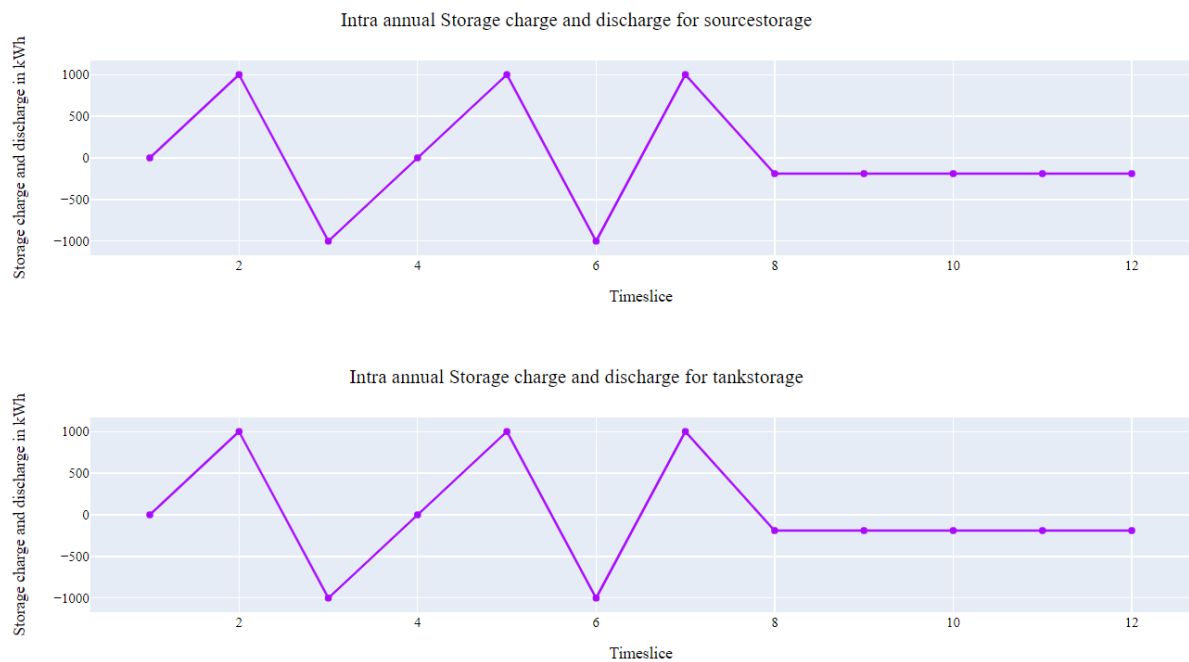


Figure 36 - Intra annual storage charge and discharge pattern for the simulation 4.

In conclusion, the purpose of using the energy stored in each tank is used to cover the needs of the months when the residual heat production is not sufficient to meet all the needs, as well as to avoid a high energy waste in the months when the needs are lower than this production.

### 5.2.1.3 Overall Heat Generation and Consumption

The heat production for all sources and the consumption of the sinks for the whole analysis period is presented in this subchapter. The heat production is only present in the industrial unit, with a total production of 1519113 kWh of energy, as shown in Table 33 below.

Table 33 - Total Heat Generation in kWh for the simulation 4.

| Total production in kWh | Source                    |
|-------------------------|---------------------------|
| 1519112.93              | Boiler without economizer |

The distribution of thermal energy consumption per customer, additionally to the usage from the industrial unit, is shown in the following Table 34. Here it is also possible to observe that the hospital is the building that consumes the most thermal energy, being clearly the one with the highest heat demand, due to the fact that the consumption flow rate is higher in this service building than in the others, resulting in higher heating needs.

Table 34 - Total Heat Consumption in kWh of the simulation 4.

| Total Consumption in kWh | Sink         |
|--------------------------|--------------|
| 708253.80                | Hospital     |
| 64427.15                 | Camping Park |
| 10198.04                 | Hotel        |

The pie chart gives an easier visualization of the share of the total waste heat availability that every service building uses to fulfil their needs. The hospital represents more than 91% of this consumption, contrary to the hotel, which represents roughly 1% of this use.



Figure 37 - Share of the waste heat consumption by every sink in the simulation 4.

#### 5.2.1.4 Emissions

The total emission for each technology is shown in the Table 35 below, being possible to see that the natural gas boiler used in the grid is responsible for most of the emissions, with 224453 kgCO<sub>2</sub>eq.

Table 35 - Emissions in Kg CO<sub>2</sub>eq of the simulation 4.

| Technology                                                | Emissions (kg CO <sub>2</sub> ) |
|-----------------------------------------------------------|---------------------------------|
| Boiler without economizer Stream1 Multiple Heat Exchanger | 1519.11                         |
| Grid Specific Heat Pump                                   | 28993.33                        |
| Grid Specific Natural gas Boiler                          | 224453.04                       |

The accumulation graph below provides a better visualization of this representation in the total emissions of this solution.

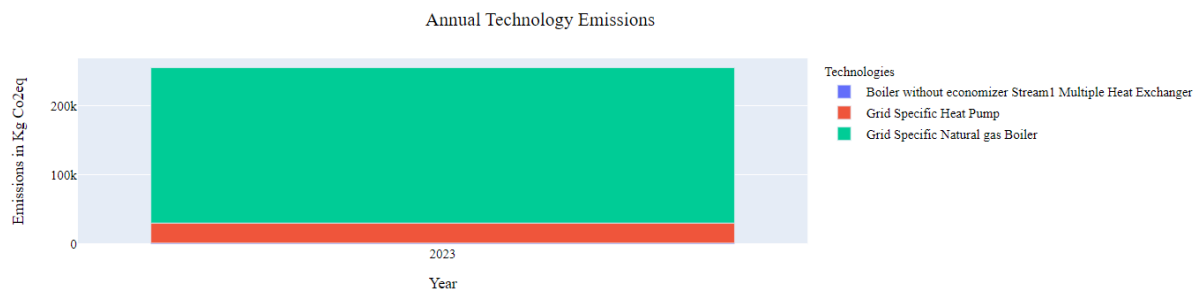


Figure 38 - Annual technology emissions for the simulation 4.

#### 5.2.1.5 Costs

The techno-economic optimization from the TEO determines a cost-optimal solution for matching sources and sinks. They are divided into capital costs and operating costs. In addition, the costs of the storage solution will also be presented.

Firstly, the capital/investment costs will be presented in the Table 36 below- The grid specific heat pump price, 17290€ constitutes more than a half of the costs for this solution, fixed in 29651€. This total capital cost is divided into 2677€ for the heat exchanger used in the source, 6186€ for the technologies used in the sinks and 23678€ for the grid.

Table 36 - Capital Costs in Euros for the technologies of the simulation 4.

| Technology                                                | Capital costs (Euros) |
|-----------------------------------------------------------|-----------------------|
| Boiler without economizer Stream1 Multiple Heat Exchanger | 2677.04               |
| Camping Park Stream1 Single Heat Exchanger                | 909.27                |
| Grid Specific Heat Pump                                   | 17290.83              |
| Grid Specific Natural gas Boiler                          | 6384.96               |
| Hospital Stream1 Single Heat Exchanger                    | 2062.34               |
| Hotel Stream1 Single Heat Exchanger                       | 324.21                |
| Stream1 Stream1                                           | 2.09                  |

The graphic below gives a clear overview of the price of each technology separately, with the grid specific heat pump price clearly standing out from the rest.

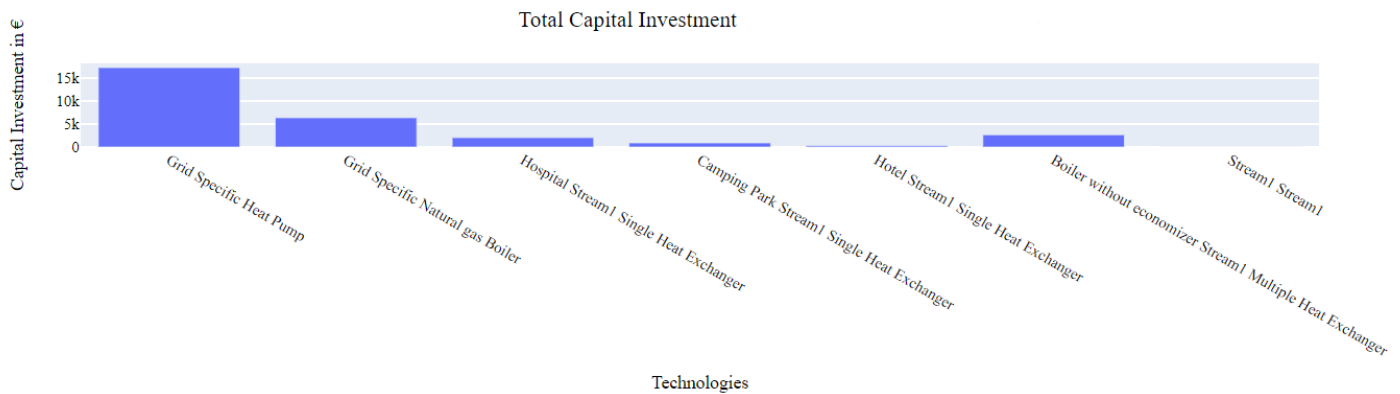


Figure 39 - Capital Cost per technology of the simulation 4.

Secondly, the operational costs will be presented in the Table 37. The grid specific natural boiler price, 22100€ constitutes more than a half of the costs for the operation and maintenance per year, for this solution, fixed in 34230€. This operational cost is divided into 1717€ for the heat exchanger used in the source, 827€ for the technologies used in the sinks and 31686€ for the

Table 37 - Operational Costs in Euros for the simulation 4.

| Technology                                                | Operating costs (Euros) |
|-----------------------------------------------------------|-------------------------|
| Boiler without economizer Stream1 Multiple Heat Exchanger | 1716.96                 |
| Camping Park Stream1 Single Heat Exchanger                | 240.37                  |
| Grid Specific Heat Pump                                   | 9586.64                 |
| Grid Specific Natural gas Boiler                          | 22099.72                |
| Hospital Stream1 Single Heat Exchanger                    | 419.78                  |
| Hotel Stream1 Single Heat Exchanger                       | 166.61                  |

grid.

The graphic below gives a clear overview of cost for the operation and maintenance of each technology separately, with the grid specific natural gas boiler price clearly standing out from the rest.

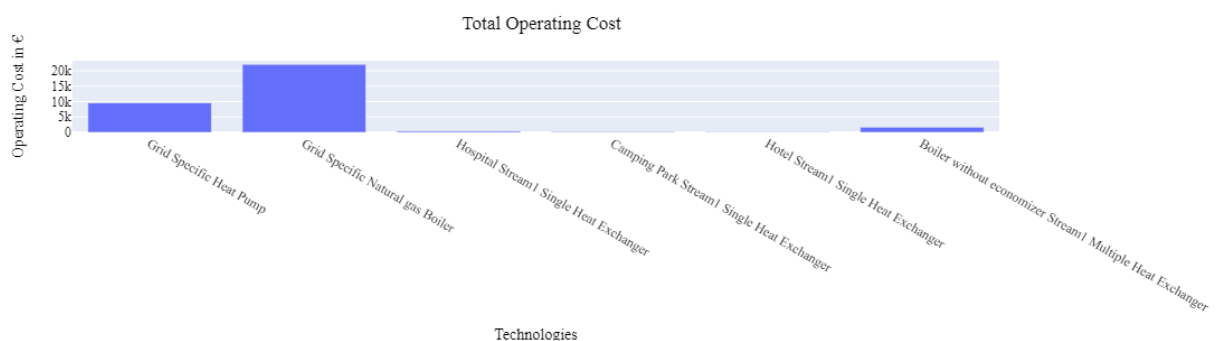


Figure 40 - Operational costs per technology of the simulation 4.

Finally, the costs of the storage solution are shown in the table below.

Table 38 - Storage Capital Costs in Euros for the simulation 4.

| <b>Storage</b> | <b>Capital costs (Euros)</b> |
|----------------|------------------------------|
| sourcestorage  | 450000.00                    |
| tankstorage    | 750577.09                    |

#### 5.2.1.6 Reference System and Savings

The operational costs for the reference heating technology, using a natural gas boiler, 19782€ for all the sinks, are presented in the Table 39 below, as well as its emissions, 182605 kgCO<sub>2</sub> in total.

Table 39 - Operational Costs in Euros and Emissions in Kg CO<sub>2</sub> for the reference system

| <b>Sink Name</b>     | <b>Cost (Euros)</b> | <b>Emissions (Kg CO<sub>2</sub>)</b> |
|----------------------|---------------------|--------------------------------------|
| Hospital Stream1     | 17896.01            | 165199.15                            |
| Camping Park Stream1 | 1627.93             | 15027.54                             |
| Hotel Stream1        | 257.68              | 2378.68                              |

In order to have a point of comparison between the waste heat recovery solution with the reference solution, the operational cost and emission for this simulation are also provided in Table 40.

Table 40 - Cost Savings in Euros and Emission savings in Kg CO<sub>2</sub> when is used the solution provided by the simulation 4.

| <b>Cost Savings (Euros)</b> | <b>Emission Savings (kg CO<sub>2</sub>)</b> |
|-----------------------------|---------------------------------------------|
| 17237.9                     | 181086.26                                   |

The total operational and emissions savings are the difference between the costs of the reference system and the heat recovery solution, 2544€/year and 1509 kgCO<sub>2</sub>, respectively.

#### 5.2.2 Overall assessment of the solution with usage of waste heat outside the industrial unit

This solution suggests that there may be benefits, in terms of both emissions and operational costs, of adopting a centralised heat generation system to supply the sinks, while also taking advantage of the waste heat from the industrial unit. Nonetheless, it should also be noted that this solution is far from being the best, as the estimated monetary benefits (2544€) are considerably lower than the monetary savings estimated for the solution of simulation 3 (11706€), while the investment costs are much higher, with the network cost corresponding to a highest share of the required investment.

### 5.3 Combined approach

Within this section, the results from simulations 5 and 6 are analysed in order to understand whether there are advantages in taking a combined approach, with use of excess heat within and outside the industrial unit.

#### 5.3.1 Simulation 5: Full Simulation

This simulation refers to a scenario where a boiler with an economizer the partially recover of the heat from the exhaust gases, and the waste heat will be used outside of the industrial unit, among the three different services buildings which were identified as possible sinks, which corresponds to the description of the heating system that is already in place. The delivered solutions consider the development of a heating pipeline network linking the source and three sinks, as shown in Figure 41 (green lines).



Figure 41 – Schematic representation of the heating pipeline network obtained for simulation 5.

The pipeline-specific results are available the Table 41 below are a collection of the pipes connecting a source and sink. It is possible for a pipe to be used to connect multiple sources and sinks. Therefore, the sum of the values given in the table is not equal to the total for the whole network.

Table 41 - Pipeline Specific results for the simulation 5.

| From                   | To           | Thermal Losses [kW] | Installed Capacity [kW] | Length [km] | Total Cost [MEUR] |
|------------------------|--------------|---------------------|-------------------------|-------------|-------------------|
| Boiler with economizer | Hospital     | 125.20              | 84.88                   | 5.31        | 2.71              |
| Boiler with economizer | Camping Park | 88.16               | 14.44                   | 4.28        | 2.11              |
| Boiler with economizer | Hotel        | 57.18               | 1.22                    | 2.91        | 1.44              |
| Grid Backup            | Hospital     | 42.83               | 84.88                   | 2.01        | 0.98              |
| Grid Backup            | Camping Park | 34.37               | 14.44                   | 2.13        | 0.99              |
| Grid Backup            | Hotel        | 39.50               | 1.22                    | 2.22        | 1.07              |

The aggregated results for the network of the simulation 5 are presented in the Table 42 below.

Table 42 - Aggregated results for the network for the simulation 5.

| Total Thermal Loss [kW] | Total Installed Capacity [kW] | Total Network Length [km] | Total Costs [MEUR] |
|-------------------------|-------------------------------|---------------------------|--------------------|
| 154.71                  | 307.44                        | 7.86                      | 3.83               |

#### 5.3.1.1 Heat recovery and generation technologies

The provided solution requires the installation of additional heating technologies, as it considers centralised heat generation combined with a multiple heat exchanger located in the source and single heat exchanges in each of the sinks. The identification of technologies for all sources and sinks for the last year of the analysis period, with respective installed capacity, is shown in the table below.

This Table 43 can be used to analyse which technologies are selected by the TEO module for each source and sink. Three distinct technologies were selected by the model: heat exchangers, located in the source and in the three sinks, and a natural gas boiler and a heat pump, located in the grid (centralised). As expected, the 174 kW capacity installed in the industry, because it is the responsible for providing the waste heat to its destinations, followed by the grid specific natural gas boiler, 96 kW and in the third place the hospital with 81 kW of capacity. In the opposite direction, the hotel, with only 1.16 kW of installed capacity is the one that needs less, because it is the one with lower flowrate of hot water needed to supply its needs.

Table 43 - Final Source and Sink Capacities in kW for the simulation 5.

| TECHNOLOGY                                             | Installed capacity (kW) |
|--------------------------------------------------------|-------------------------|
| Boiler with economizer Stream2 Multiple Heat Exchanger | 173.39                  |
| Camping Park Stream1 Single Heat Exchanger             | 13.76                   |
| Grid Specific Heat Pump                                | 37.11                   |
| Grid Specific Natural gas Boiler                       | 96.31                   |
| Hospital Stream1 Single Heat Exchanger                 | 80.85                   |
| Hotel Stream1 Single Heat Exchanger                    | 1.16                    |

The figure below provides the total cumulative capacity of this solution, in addition to the representation of the individual capacity of each technology of the sinks and the source for the big picture.

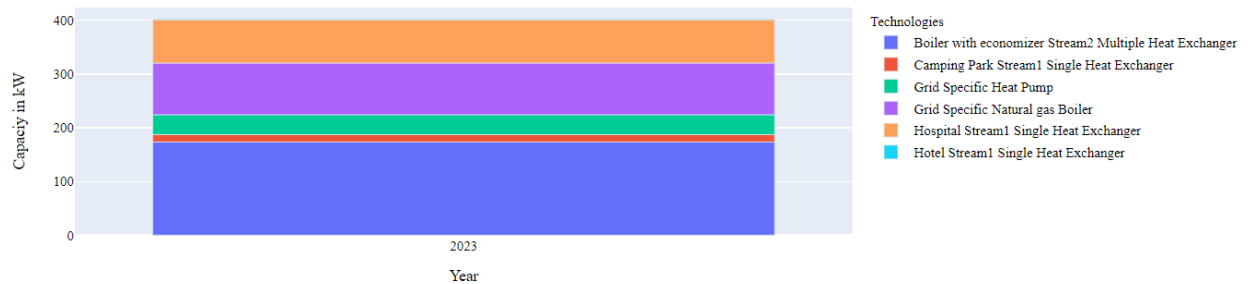


Figure 42 - Installed capacity of technologies for all sources and sinks for the simulation 5.

### 5.3.1.2 Storage new installed capacity

The platform defined, by the TEO module, that two types of storage were required for this solution, inside the source with 1000 kWh of capacity and an additional storage tank with 1000 kWh, as shown in the table 44 below. The installed storage capacity for the last year of the analysis period is shown in the Table 44 below.

Table 44 - Storage Capacities in kWh for the simulation 5.

| Storage       | Installed storage capacity (kWh) |
|---------------|----------------------------------|
| sourcestorage | 1000.00                          |
| tankstorage   | 1000.77                          |

The graphs below allow us to see that the intra-annual operation of storage the dispatch of the systems and how the variability of excess heat availability is balanced in the system. It is important to underline that both storage technologies have the same behaviour throughout the year.

It is possible to observe in the Figure 43 below that there are moments in the year when the maximum energy storage capacity is reached, in February, May and July, and there may have been energy wastage in these months if residual heat production exceeded this storage capacity.

On the contrary, in March there was no energy storage, being totally used for the processes.

In the month of May the storage was fully used and there was no energy stored at the beginning of the month of June.

Although there is a correlation between the charging of the storage and the time where the industrial unit is closed in May, is important to mention that it is not a correct assumption for the whole year, because in the months of August and December this isn't verified.

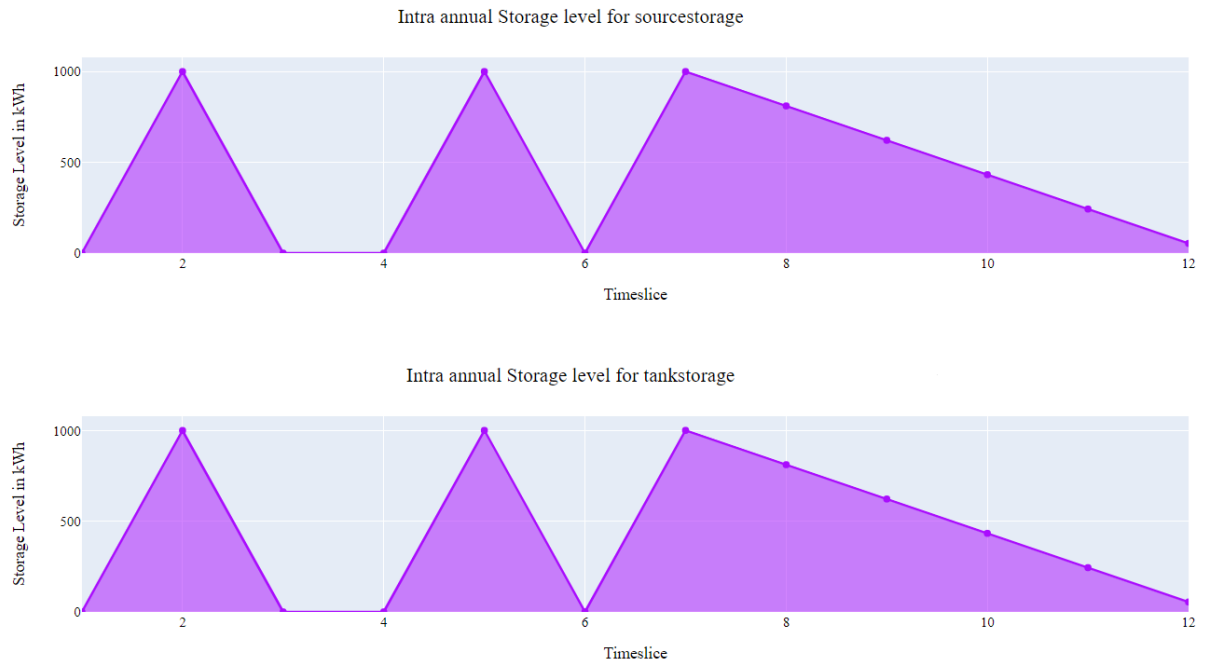


Figure 43 - Intra annual storage levels for the simulation 5.

The charge and discharge pattern of the storage tank is presented on the graph below. In addition to the operation referred before, is important to mention that there is only discharging from July to the end of the year, represented by the straight line that covers the last five months of the year, situated in the negative side of the storage charge and discharge scale.

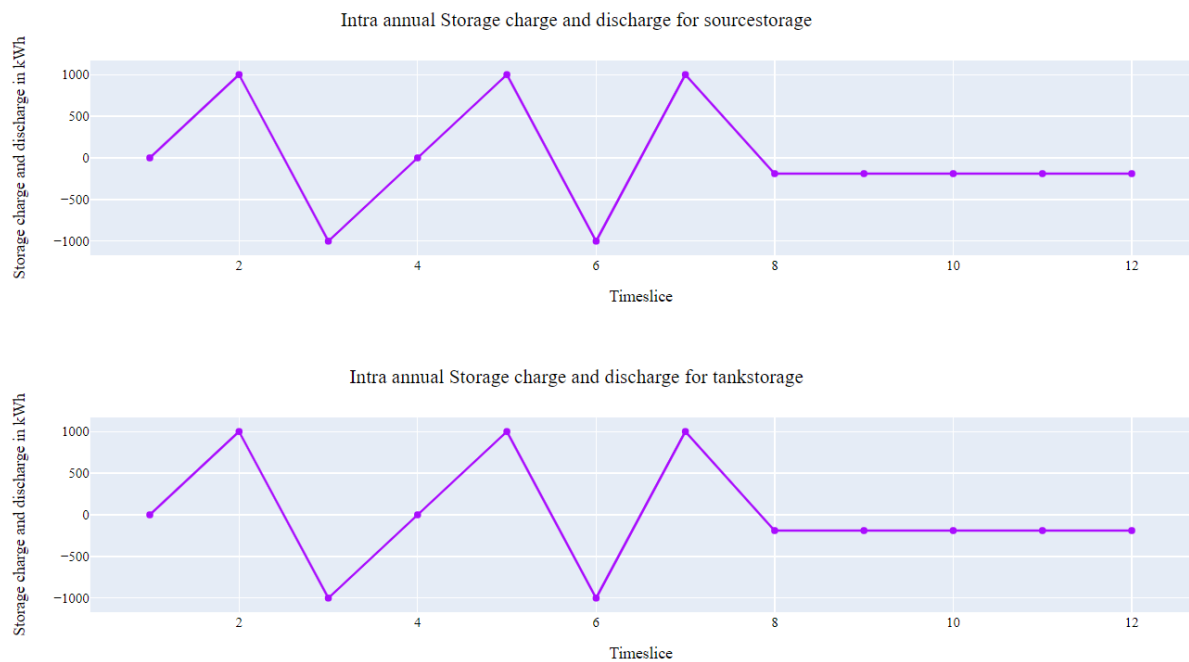


Figure 44 - Intra annual storage charge and discharge pattern for the simulation 5.

In conclusion, the purpose of using the energy stored in each tank is used to cover the needs of the months when the residual heat production is not sufficient to meet all the needs, as well as to avoid a high energy waste in the months when the needs are lower than this production.

### 5.3.1.3 Overall Heat Generation and Consumption

The heat production for all sources and the consumption of the sinks for the whole analysis period is presented in this subchapter. The heat production is only present in the industrial unit, with a total production of 1519113 kWh of energy, as shown in Table 45 below.

Table 45 - Total Heat Generation in kWh for the simulation 5.

| Total production in kWh | Source                 |
|-------------------------|------------------------|
| 1519112.93              | Boiler with economizer |

The distribution of thermal energy consumption per customer, additionally to the usage from the industrial unit, is shown in the following Table 46. Here it is also possible to observe that the hospital is the building that consumes the most thermal energy, being clearly the one with the highest heat demand, due to the fact that the consumption flow rate is higher in this service building than in the others, resulting in higher heating needs.

Table 46 - Total Heat Consumption in kWh of the simulation 5.

| Total Consumption in kWh | Sink         |
|--------------------------|--------------|
| 708253.80                | Hospital     |
| 64427.15                 | Camping Park |
| 10198.04                 | Hotel        |

The pie chart gives an easier visualization of the share of the total waste heat availability that every service building uses to fulfil their needs. The hospital represents more than 91% of this consumption, contrary to the hotel, which represents roughly 1% of this use.



Figure 45 - Share of the waste heat consumption by every sink in the simulation 5.

#### 5.3.1.4 Emissions

The total emission for each technology is shown in the Table 47 below, being possible to see that the natural gas boiler used in the grid is responsible for most of the emissions, with 224453 kgCO<sub>2</sub>eq.

Table 47 - Emissions in Kg CO<sub>2</sub>eq of the simulation 5.

| Technology                                             | Emissions (kg CO <sub>2</sub> ) |
|--------------------------------------------------------|---------------------------------|
| Boiler with economizer Stream2 Multiple Heat Exchanger | 1519.11                         |
| Grid Specific Heat Pump                                | 23872.68                        |
| Grid Specific Natural gas Boiler                       | 224453.04                       |

The accumulation graph below provides a better visualization of this representation in the total emissions of this solution.

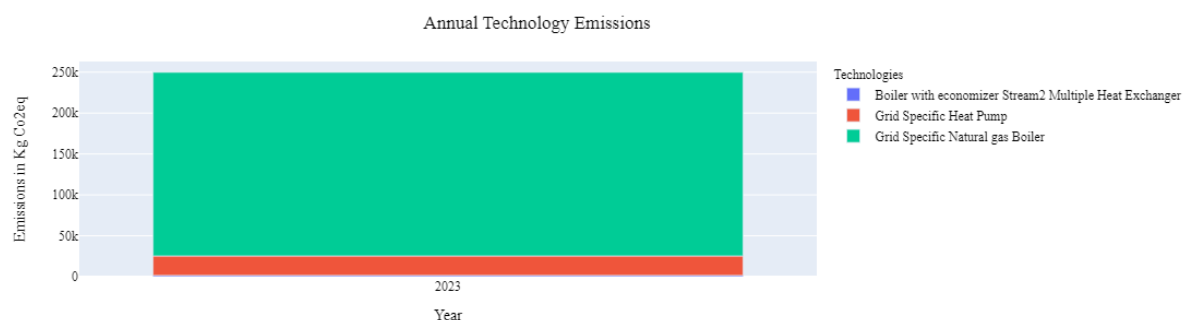


Figure 46 - Annual technology emissions for the simulation 5.

#### 5.3.1.5 Costs

The techno-economic optimization from the TEO determines a cost-optimal solution for matching sources and sinks. They are divided into capital costs and operating costs. In addition, the costs of the storage solution will also be presented.

Firstly, the capital/investment costs will be presented in the Table 48 below. The grid specific heat pump price, 14691€ constitutes more than a half of the costs for this solution, fixed in 27051€. This total capital cost is divided into 2677€ for the heat exchanger used in the source, 3296€ for the technologies used in the sinks and 21076€ for the grid.

Table 48 - Capital Costs in Euros for the technologies of the simulation 5.

| Technology                                             | Capital costs (Euros) |
|--------------------------------------------------------|-----------------------|
| Boiler with economizer Stream2 Multiple Heat Exchanger | 2677.04               |
| Camping Park Stream1 Single Heat Exchanger             | 909.27                |
| Grid Specific Heat Pump                                | 14691.08              |
| Grid Specific Natural gas Boiler                       | 6384.96               |
| Hospital Stream1 Single Heat Exchanger                 | 2062.34               |
| Hotel Stream1 Single Heat Exchanger                    | 324.21                |
| Stream2 Stream2                                        | 2.09                  |

The graphic below gives a clear overview of the price of each technology separately, with the grid specific heat pump price clearly standing out from the rest.

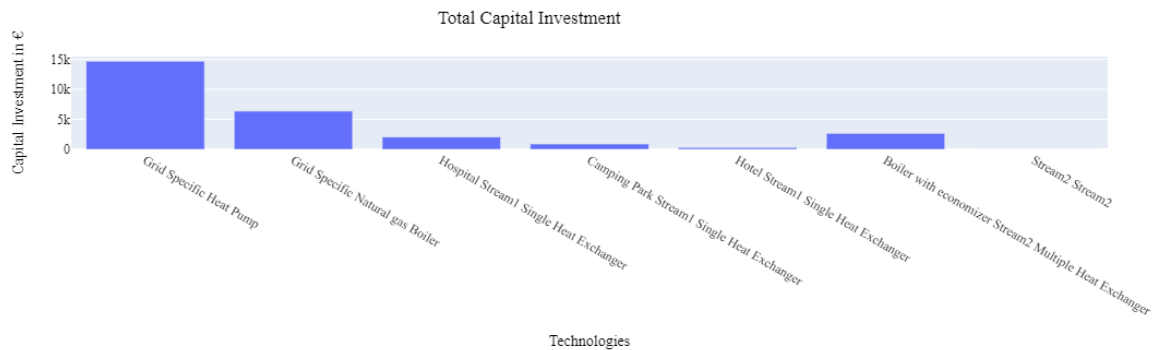


Figure 47 - Capital Cost per technology of the simulation 5.

Secondly, the operational costs will be presented in the Table 49. The grid specific natural boiler price, 22100€ constitutes more than a half of the costs for the operation and maintenance per year, for this solution, fixed in 32571€. This operational cost is divided into 1717€ for the heat exchanger used in the source, 827€ for the technologies used in the sinks and 30027€ for the grid.

Table 49 - Operational Costs in Euros for the simulation 5.

| Technology                                             | Operating costs (Euros) |
|--------------------------------------------------------|-------------------------|
| Boiler with economizer Stream2 Multiple Heat Exchanger | 1716.96                 |
| Camping Park Stream1 Single Heat Exchanger             | 240.37                  |
| Grid Specific Heat Pump                                | 7927.58                 |
| Grid Specific Natural gas Boiler                       | 22099.72                |
| Hospital Stream1 Single Heat Exchanger                 | 419.78                  |
| Hotel Stream1 Single Heat Exchanger                    | 166.61                  |

The graphic below gives a clear overview of cost for the operation and maintenance of each technology separately, with the grid specific natural gas boiler price clearly standing out from the rest.

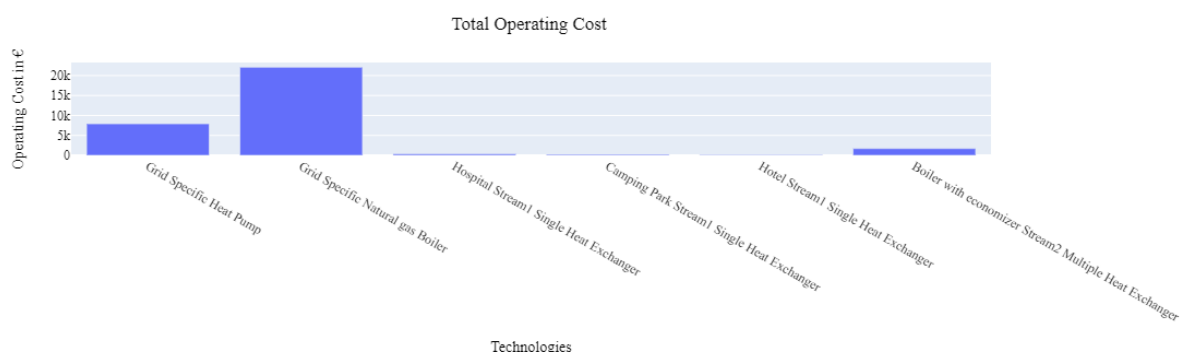


Figure 48 - Operational costs per technology of the simulation 5.

Finally, the costs of the storage solution are shown in the Table 50 below.

Table 50 - Storage Capital Costs in Euros for the simulation 5.

| <b>Storage</b> | <b>Capital costs (Euros)</b> |
|----------------|------------------------------|
| sourcestorage  | 450000.00                    |
| tankstorage    | 750577.09                    |

#### 5.3.1.6 Reference System and Savings

The operational costs for the reference heating technology, using a natural gas boiler, 19782€ for all the sinks, are presented in the Table 51 below, as well as its emissions, 182605 kgCO<sub>2</sub> in total.

Table 51 - Operational Costs in Euros and Emissions in Kg CO2 for the reference system.

| <b>Sink Name</b>     | <b>Cost (Euros)</b> | <b>Emissions (Kg CO2)</b> |
|----------------------|---------------------|---------------------------|
| Hospital Stream1     | 17896.01            | 165199.15                 |
| Camping Park Stream1 | 1627.93             | 15027.54                  |
| Hotel Stream1        | 257.68              | 2378.68                   |

In order to have a point of comparison between the waste heat recovery solution with the reference solution, the operational cost and emission for this simulation are also provided in Table 52.

Table 52 - Cost Savings in Euros and Emission savings in Kg CO2 when is used the solution provided by the simulation 5.

| <b>Cost Savings (Euros)</b> | <b>Emission Savings (kg CO2)</b> |
|-----------------------------|----------------------------------|
| 17237.9                     | 181086.26                        |

The total operational and emissions savings are the difference between the costs of the reference system and the heat recovery solution, 2543€/year and 1519 kgCO<sub>2</sub>, respectively.

### 5.3.2 Simulation 6: Full Simulation

This simulation refers to the last scenario, using the heat from the oil from the compressed air system to preheat the water supplied to the boiler. This waste heat will be used in the outside, for the service buildings. The delivered solutions consider the development of a heating pipeline network linking the source and three sinks, as shown in Figure 49 (green lines).



Figure 49 – Schematic representation of the heating pipeline network obtained for simulation 6.

The pipeline-specific results are available the Table 53 below are a collection of the pipes connecting a source and sink. It is possible for a pipe to be used to connect multiple sources and sinks. Therefore, the sum of the values given in the table is not equal to the total for the whole network.

Table 53 - Pipeline Specific results for the simulation 6.

| From          | To           | Thermal Losses [kW] | Installed Capacity [kW] | Length [km] | Total Cost [MEUR] |
|---------------|--------------|---------------------|-------------------------|-------------|-------------------|
| Feeding Water | Hospital     | 122.80              | 84.88                   | 5.21        | 2.66              |
| Feeding Water | Camping Park | 85.76               | 14.44                   | 4.19        | 2.06              |
| Feeding Water | Hotel        | 54.79               | 1.22                    | 2.82        | 1.39              |
| Grid Backup   | Hospital     | 42.83               | 84.88                   | 2.01        | 0.98              |
| Grid Backup   | Camping Park | 34.37               | 14.44                   | 2.13        | 0.99              |
| Grid Backup   | Hotel        | 39.50               | 1.22                    | 2.22        | 1.07              |

The aggregated results for the network of the simulation 6 are presented in the Table 54 below.

Table 54 - Aggregated results for the network for the simulation 6.

| Total Thermal Loss [kW] | Total Installed Capacity [kW] | Total Network Length [km] | Total Costs [MEUR] |
|-------------------------|-------------------------------|---------------------------|--------------------|
| 152.29                  | 304.22                        | 7.77                      | 3.78               |

#### 5.3.2.1 Heat recovery and generation technologies

The provided solution requires the installation of additional heating technologies, as it considers centralised heat generation combined with a multiple heat exchanger located in the source and single heat exchanges in each of the sinks. The identification of technologies for all sources and sinks for the last year of the analysis period, with respective installed capacity, is shown in the table below.

This Table 55 can be used to analyse which technologies are selected by the TEO module for each source and sink. Three distinct technologies were selected by the model: heat exchangers, located in the source and in the three sinks, and a natural gas boiler and a heat pump, located in the grid (centralised). As expected, the 174 kW of capacity installed in the industry, because it is the responsible for providing the waste heat to its destinations, followed by the grid specific natural gas boiler, 96 kW and in the third place the hospital with 81 kW of capacity. In the opposite direction, the hotel, with only 1.16 kW of installed capacity is the one that needs less, because it is the one with lower flowrate of hot water needed to supply its needs.

Table 55 - Final Source and Sink Capacities in kW for the simulation 6.

| TECHNOLOGY                                    | Installed capacity (kW) |
|-----------------------------------------------|-------------------------|
| Camping Park Stream1 Single Heat Exchanger    | 13.76                   |
| Feeding Water Stream2 Multiple Heat Exchanger | 173.39                  |
| Feeding Water Stream3 Single Heat Exchanger   | 1.89                    |
| Grid Specific Heat Pump                       | 32.07                   |
| Grid Specific Natural gas Boiler              | 96.31                   |
| Hospital Stream1 Single Heat Exchanger        | 80.85                   |
| Hotel Stream1 Single Heat Exchanger           | 1.16                    |

The figure below provides the total cumulative capacity of this solution, in addition to the representation of the individual capacity of each technology of the sinks and the source for the big picture.

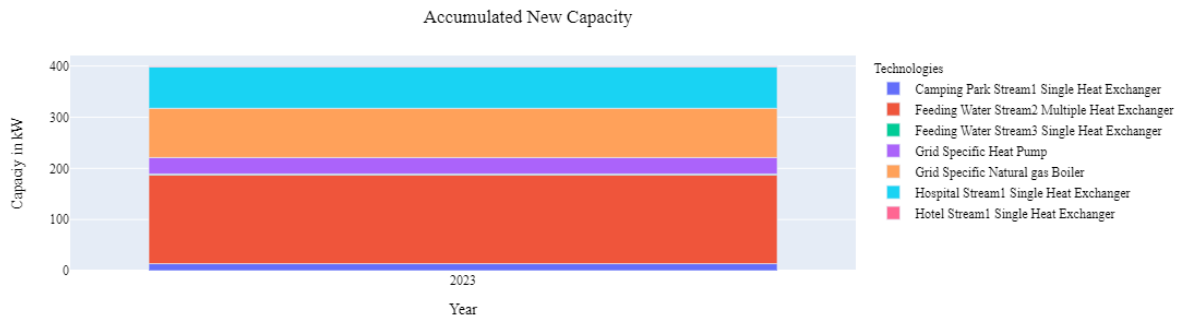


Figure 50 - Installed capacity of technologies for all sources and sinks for the simulation 6.

### 5.3.2.2 Storage new installed capacity

The installed storage capacity for the last year of the analysis period is shown in the table below. The platform defined, by the TEO module, that two types of storage were required for this solution, inside the source with 1000 kWh of capacity and an additional storage tank with 1000 kWh, as shown in the Table 56 below.

Table 56 - Storage Capacities in kWh for the simulation 6.

| Storage       | Installed storage capacity (kWh) |
|---------------|----------------------------------|
| sourcestorage | 1000.00                          |
| tankstorage   | 1000.77                          |

The graphs below allow us to see that the intra-annual operation of storage the dispatch of the systems and how the variability of excess heat availability is balanced in the system. It is important to underline that both storage technologies have the same behaviour throughout the year.

It is possible to observe in the Figure 51 below that there are moments in the year when the maximum energy storage capacity is reached, in March, May and July, and there may have been energy wastage in these months if residual heat production exceeded this storage capacity.

On the contrary, in January there was no energy storage, being totally used for the processes.

In the months of March and May the storage is fully used and there was no energy stored at the beginning of the months of April and June, respectively.

Although there is a correlation between the charging of the storage and the time where the industrial unit is closed in May, is important to mention that it is not a correct assumption for the whole year, because in the months of August and December this isn't verified.

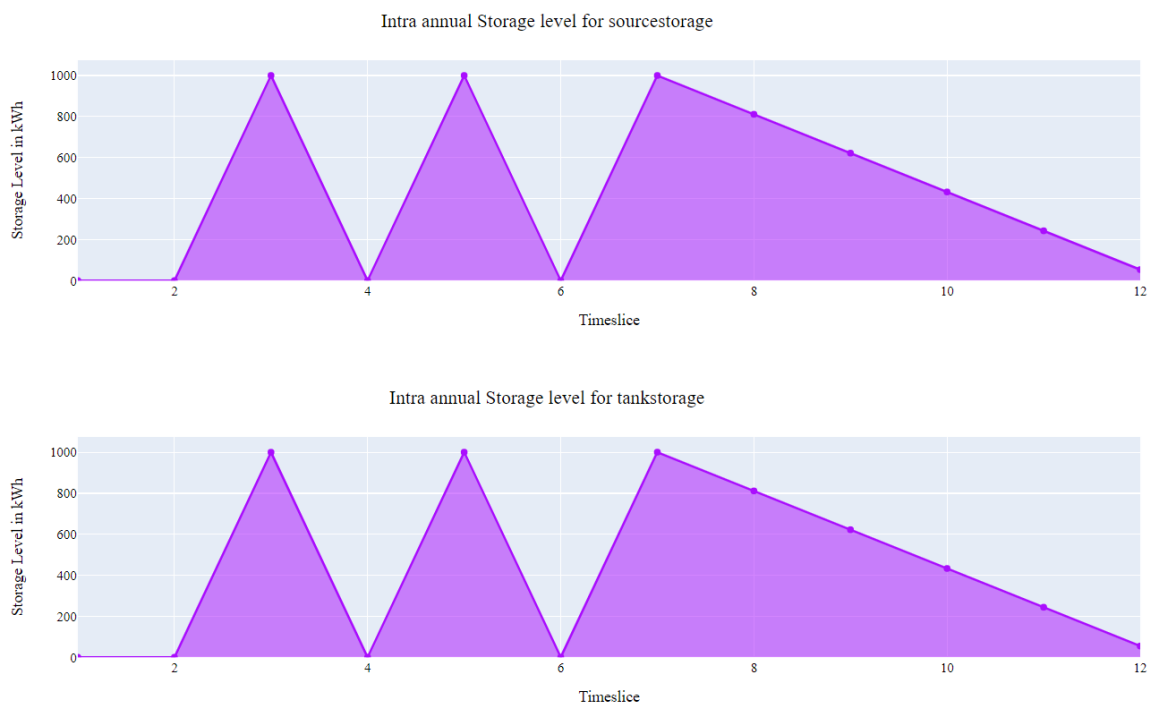


Figure 51 - Intra annual storage levels for the simulation 6.

The charge and discharge pattern of the storage tank is presented on the graph below. In addition to the operation referred before, is important to mention that there is only discharging from July to the end of the year, represented by the straight line that covers the last five months of the year, situated in the negative side of the storage charge and discharge scale.

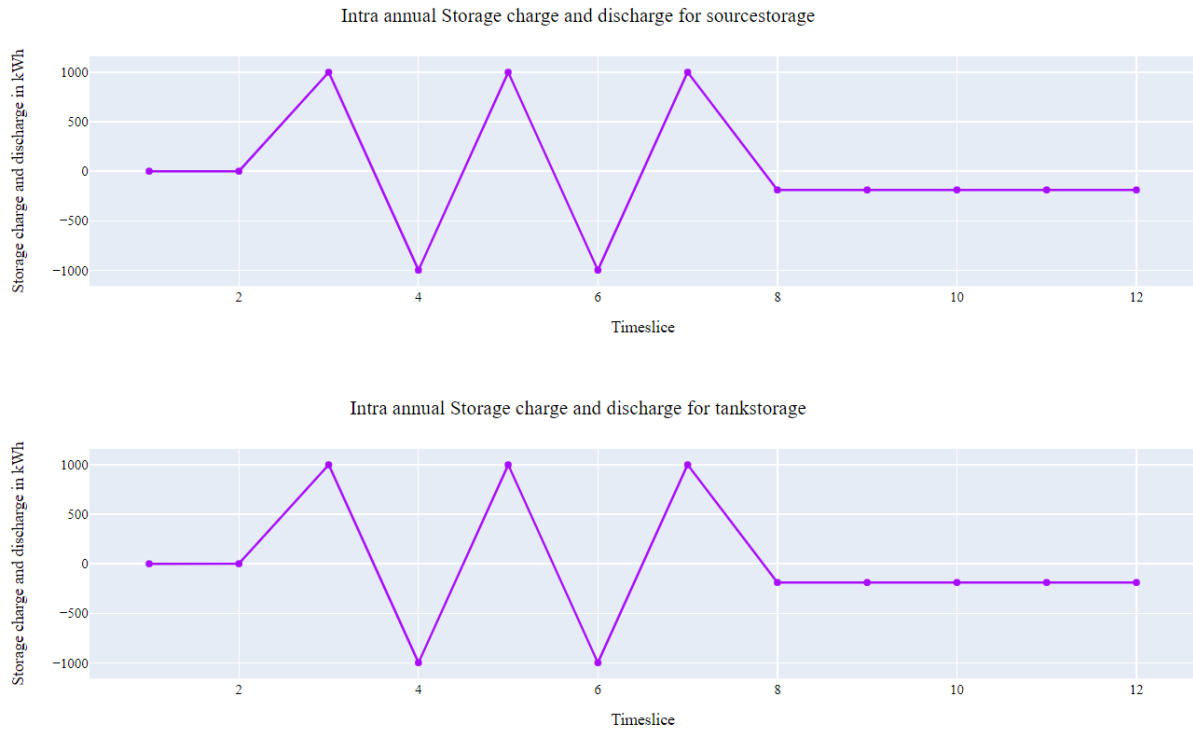


Figure 52 - Intra annual storage charge and discharge pattern for the simulation 6.

In conclusion, the purpose of using the energy stored in each tank is used to cover the needs of the months when the residual heat production is not sufficient to meet all the needs, as well as to avoid a high energy waste in the months when the needs are lower than this production.

### 5.3.2.3 Overall Heat Generation and Consumption

The heat production for all sources and the consumption of the sinks for the whole analysis period is presented in this subchapter. The heat production is only present in the industrial unit, with a total production of 1534880 kWh of energy, as shown in Table 57 below.

Table 57 - Total Heat Generation in kWh for the simulation 6.

| Total production in kWh | Source        |
|-------------------------|---------------|
| 1534880.35              | Feeding Water |

The distribution of energy consumption per customer is shown in the following Table 58. Here it is also possible to observe that the hospital is the building that consumes the most energy, being clearly the one with the highest consumption needs, due to the fact that the consumption flowrate is higher in this service building than in the others, resulting in higher needs of heating.

Table 58 - Total Heat Consumption in kWh of the simulation 6.

| Total Consumption in kWh | Sink         |
|--------------------------|--------------|
| 708253.80                | Hospital     |
| 64427.15                 | Camping Park |
| 10198.04                 | Hotel        |

The pie chart gives an easier visualization of the share of the total waste heat availability that every service building uses to fulfil their needs. The hospital represents more than 91% of this consumption, contrary to the hotel, which represents roughly 1% of this use.



Figure 53 - Share of the waste heat consumption by every sink in the simulation 6.

#### 5.3.2.4 Emissions

The total emission for each technology is shown in the Table 59 below, being possible to see that the natural gas boiler used in the grid is responsible for most of the emissions, with 224453 kgCO<sub>2</sub>eq.

Table 59 - Emissions in Kg CO<sub>2</sub>eq of the simulation 6.

| Technology                                    | Emissions (kg CO <sub>2</sub> ) |
|-----------------------------------------------|---------------------------------|
| Feeding Water Stream2 Multiple Heat Exchanger | 1519.11                         |
| Grid Specific Heat Pump                       | 19945.75                        |
| Grid Specific Natural gas Boiler              | 224453.04                       |

The accumulation graph below provides a better visualization of this representation in the total emissions of this solution.

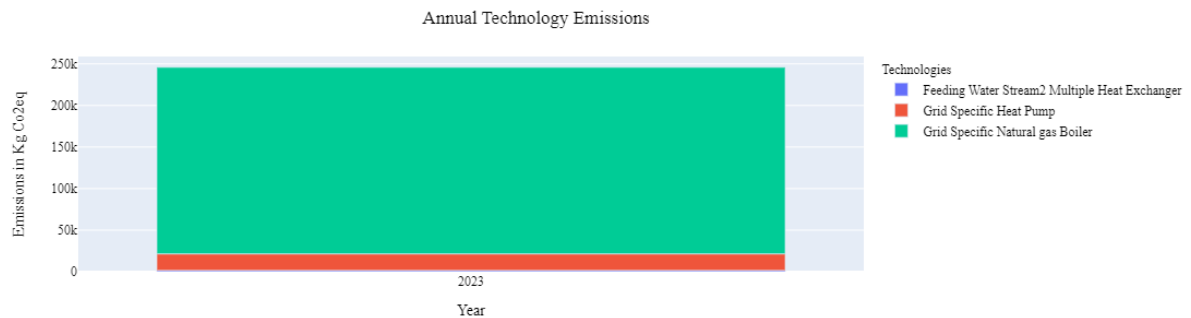


Figure 54 - Annual technology emissions for the simulation 6.

#### 5.3.2.5 Costs

The techno-economic optimization from the TEO determines a cost-optimal solution for matching sources and sinks. They are divided into capital costs and operating costs. In addition, the costs of the storage solution will also be presented.

Firstly, the capital/investment costs will be presented in the Table 60 below- The grid specific heat pump price, 12697€ constitutes more than a half of the costs for this solution, fixed in 25298€. This total capital cost is divided into 2917€ for the heat exchangers used in the source, 3296€ for the technologies used in the sinks and 19085€ for the grid.

Table 60 - Capital Costs in Euros for the technologies of the simulation 6.

| Technology                                    | Capital costs (Euros) |
|-----------------------------------------------|-----------------------|
| Camping Park Stream1 Single Heat Exchanger    | 909.27                |
| Feeding Water Stream2 Multiple Heat Exchanger | 2677.04               |
| Feeding Water Stream3 Single Heat Exchanger   | 240.27                |
| Grid Specific Heat Pump                       | 12697.38              |
| Grid Specific Natural gas Boiler              | 6384.96               |
| Hospital Stream1 Single Heat Exchanger        | 2062.34               |
| Hotel Stream1 Single Heat Exchanger           | 324.21                |
| Stream2 Stream2                               | 2.09                  |
| Stream3 Stream3                               | 0.02                  |

The graphic below gives a clear overview of the price of each technology separately, with the grid specific heat pump price clearly standing out from the rest.

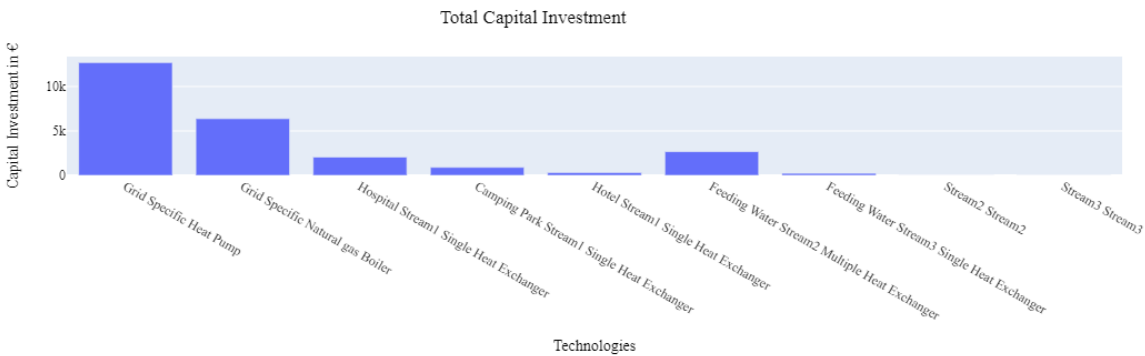


Figure 55 - Capital Cost per technology of the simulation 6.

Secondly, the operational costs will be presented in the Table 61. The grid specific natural boiler price, 22100€ constitutes more than a half of the costs for the operation and maintenance per year, for this solution, fixed in 31450€. This operational cost is divided into 1717€ for the heat exchangers used in the source, 1868€ for the technologies used in the sinks and 28755€ for the grid.

Table 61 - Operational Costs in Euros for the simulation 6.

| Technology                                    | Operating costs (Euros) |
|-----------------------------------------------|-------------------------|
| Camping Park Stream1 Single Heat Exchanger    | 240.37                  |
| Feeding Water Stream2 Multiple Heat Exchanger | 1716.96                 |
| Feeding Water Stream3 Single Heat Exchanger   | 151.04                  |
| Grid Specific Heat Pump                       | 6655.28                 |
| Grid Specific Natural gas Boiler              | 22099.72                |
| Hospital Stream1 Single Heat Exchanger        | 419.78                  |
| Hotel Stream1 Single Heat Exchanger           | 166.61                  |

The graphic below gives a clear overview of cost for the operation and maintenance of each technology separately, with the grid specific natural gas boiler price clearly standing out from the rest.

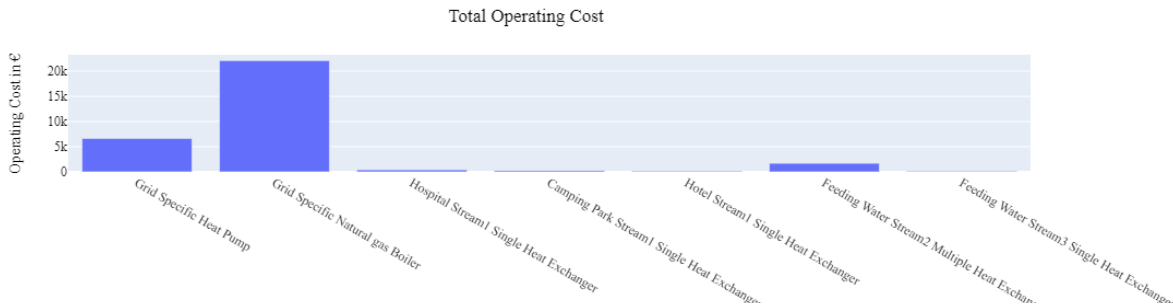


Figure 56 - Operational costs per technology of the simulation 6.

Finally, the costs of the storage solution are shown in the Table 62 below.

Table 62 - Storage Capital Costs in Euros for the simulation 6.

| <b>Storage</b> | <b>Capital costs (Euros)</b> |
|----------------|------------------------------|
| sourcestorage  | 450000.00                    |
| tankstorage    | 750577.09                    |

#### 5.3.2.6 Reference System and Savings

The operational costs for the reference heating technology, using a natural gas boiler, 19782€ for all the sinks, are presented in the Table 63 below, as well as its emissions, 182605 kgCO<sub>2</sub> in total.

Table 63 - Operational Costs in Euros and Emissions in Kg CO2 for the reference system.

| <b>Sink Name</b>     | <b>Cost (Euros)</b> | <b>Emissions (Kg CO2)</b> |
|----------------------|---------------------|---------------------------|
| Hospital Stream1     | 17896.01            | 165199.15                 |
| Camping Park Stream1 | 1627.93             | 15027.54                  |
| Hotel Stream1        | 257.68              | 2378.68                   |

In order to have a point of comparison between the waste heat recovery solution with the reference solution, the operational cost and emission for this simulation are also provided in Table 64.

Table 64 - Cost Savings in Euros and Emission savings in Kg CO2 when is used the solution provided by the simulation 6.

| <b>Cost Savings (Euros)</b> | <b>Emission Savings (kg CO2)</b> |
|-----------------------------|----------------------------------|
| 17237.9                     | 181086.26                        |

The total operational and emissions savings are the difference between the costs of the reference system and the heat recovery solution, 2544€/year and 1519 kgCO<sub>2</sub>, respectively.

#### 5.4 Optimal solution for the industrial unit

After the results have been presented and analysed in the previous subchapters, it is important to discuss on the viability of the solutions found for the different approaches, taking into account both economic and environmental impacts.

When comparing the solutions obtained for the use of excess heat inside the unit, with the ones found for outside the unit or for a combined approach, it is clear that the additional investment for a combined approach is much higher than was found in 5.1. Thus, and even though the use within the industrial unit (as simulated in the scope of this work) is not sufficient to take advantage of the available waste heat, the required investment to reach/supply the buildings in the vicinity may be too high to be viable. This may be justified by the low amount of excess heat from the industrial unit under study.

Moreover, concerning the Full Simulations performed (4, 5 and 6), it is possible to verify that the solutions are quite similar in several levels: installed capacity, technologies used, energy production and CO<sub>2</sub> emissions. Nonetheless, the increase in the use of excess heat within the industry seems to lower the overall capital investment. Indeed, the capital and operational costs estimated for the solution for simulation 4 are higher than in the solutions for simulations 5 and 6.

The Table 65 below summarizes the capital and operational costs for all the simulations, as well as the network costs for simulations 4,5 and 6.

Table 65 - Overall costs overview for all the simulations.

|              | Capital Costs (in €) | Operational Costs (in €) | Network Costs (in €) |
|--------------|----------------------|--------------------------|----------------------|
| Simulation 1 | 12401                | 1240                     | -                    |
| Simulation 2 | 37214                | 3721                     | -                    |
| Simulation 3 | 170950               | 17095                    | -                    |
| Simulation 4 | 29651                | 34230                    | 3930000              |
| Simulation 5 | 27051                | 32571                    | 3830000              |
| Simulation 6 | 25298                | 31450                    | 3780000              |

Thus, it is possible to conclude that the optimal solution is **simulation 6, " Boiler with economizer and air compression system"**, as it has the lowest costs in all the parameters, capital, operational and network costs and, together with the **simulation 2 with the utilization of three heat exchangers** already chosen in the other chapter, are **the optimal solutions for using waste heat externally and internally**, respectively.

## 6 Conclusions

This work was carried out with the objective of identifying and assessing viable solutions for the waste heat recovery from a resin industry through different possible technologies, such as heat pumps, power cycles, heat exchangers, burners, economisers and waste heat boilers, in order to or mainly to increase the efficiency of the process or convert this waste heat into electricity and provide it to adjacent commercial buildings.

In order to do so, the EMB3Rs heat and cold matching platform was used for running different simulations in accordance to pre-established criteria with the purpose of obtaining the optimal solution for the waste heat recovery in this industrial unit and was chosen three types of simulations of this program among all: ORC cycle, Pinch Analysis and Full Simulation. From this platform, six simulations divided into three different purposes different: waste heat used in the industrial unit, Waste heat used outside the industrial unit and Combined approach for obtaining results that would allow finding the best cost-effective solution.

After presenting and analysing the results, the solution of the boiler with the economizer and air compression system was chosen for external usage, with heat exchangers and, boilers and heat pumps as the technologies used in these solutions, due to the fact that is the one with the lowest capital, 25298€, operational, 31450€, and network costs, 3780000€. Regarding the characteristics of this solution, it has a total heat generation in the industrial unit of 1534880 kWh, CO<sub>2</sub>savings of 1519.11 kgCO<sub>2</sub>eq and costs savings of 2544€/year in comparison with the conventional solution.

For internal usage, the solution with three heat exchangers for recovering the waste heat was chosen, with 387 MWh/year of waste heat recovered, with capital cost of 37214€ and operational costs per year of 3721€.

Main limitations of this work are associated with the lack of more detailed data on energy use within the industrial unit, which prevented a more detailed analysis on the heat recovery and use opportunities within the industrial facility. Moreover, given the fact that excess heat from this industry is not that significant also had an impact on the opportunities for excess heat usage outside the unit's boundaries.

Nevertheless, despite the little potential of the waste heat from the industry under study due to the process already being quite optimized, this program constitutes a new approach in the waste heat field, making the evaluation of complex situations faster and more efficient, which will surely constitute interesting proposals in real cases.

As far as future work is concerned, it would be interesting to make a more detailed approach to all the potentialities of the programme, including the market and business module. Due to the lack of time and the fact that it was not possible to visit the industrial unit, the data had to be taken from an audit, as mentioned before, which did not allow to expand the horizons about all the possibilities of waste heat utilization. Besides, a more detailed characterization of the public buildings could be made, including also additional potential sources of excess heat.



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