Master's Thesis

Master's Degree

Improving the energy efficiency of an industrial site by utilizing waste heat and thermal energy storage

REPORT

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Call: July, 2023

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Abstract

This master thesis is based on a real project for an industrial client of SENER that works in the field of metallurgy. The main objective is to provide initial recommendations and feasibility study on how to best utilize the waste heat that is available in the exhaust gasses from the production processes of the client. This would be done by improving the energy efficiency of the site by means of Waste Heat Recovery (WHR). The recovered heat would be used to drive a steam turbine that produces electricity, as no thermal uses of this heat are available in the installation. Furthermore, this thesis also aims to quantify the positive environmental impact of the WHR system, and how many tons of CO_2 emissions would be avoided. Additionally, due to large fluctuations in the mass flow rate of the exhaust gasses, a thermal energy storage might be introduced in order to balance the supply. Two different energy storage systems will be analyzed: steam accumulation and molten salts.

The scientific fundamentals of this thesis are based on the science of thermodynamics, or more precisely, mass and energy balances. They would have to be done on each individual component, as well as a global balance. This is done mainly with the help of the “Thermoflex” software, which is used to model the system. However, for some equipment, in-house tools have been developed, in order to understand their behavior and temporal evolution. In order to obtain the properties of the fluids, the open source library CoolProp has been used.

The obtained results from the analysis suggest that there is a potential for the implementation of a WHR system. Such a system could yield more than 160000 MWh of yearly production of electricity. Depending on the electricity prices, this amount of electricity produced could be valued at more than 10 million euros. Furthermore, by using waste heat as source of energy, essentially a carbon-free electricity would be produced, which would save approximately 8600 tCO_2 emissions.

To conclude, it has been decided that such a project is worthwhile pursuing into more detail. This would imply contacting manufacturers of components, basic and detailed engineering, as well as giving a firm offer to the client. However, it should be noted that other factors have to be taken into consideration, such as the treatment of exhaust gasses and to which degree they can be used. This could be a limiting factor, for maximizing the energy efficiency of the entire site.

Content

Glossary and nomenclature

BAT	Best Available Technology
bd	blowdown
CAPEX	Capital Expenditures
CCS	Carbon capture and storage
CO2 – eq.	CO2 equivalent gases
CSP	Concentrated Solar Power
°C	Degree Celsius
h	Enthalpy [J/kg or kJ/kg]
s	Entropy [kJ/kgK]
EU	European Union
GWP	Global Warming Potential
hl	Heat loss
HRSG	Heat Recovery Steam Generation
HTF	Heat Transfer Fluid
J	Joules
Kg	kilogram
kW	kiloWatt
kWh	kiloWatt hour
m	Mass [kg]
$\dot{m}$	Mass flow rate [kg/s]
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditures
ORC	Organic Rankine Cycle

c_p	Specific heat capacity at constant pressure [J/kgK]
SMR	Steam Methane Reforming
StC	Steam Rankine Cycle
SDG	Sustainable Development Goals
T	Temperature (either in K or °C)
Q	Thermal energy [kJ]
TES	Thermal Energy Storage
$\dot{Q}$	Thermal power [kW]
W	Thermodynamic Work [kW]
UN	United Nations
WHR	Waste Heat Recovery

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1. Preface

I am delighted to submit this master's thesis on the topic of "Improving the energy efficiency of an industrial site by utilizing waste heat and thermal energy storage". Working on this project has been an inspiring and fulfilling journey, driven by my passion for sustainable energy solutions and the desire to contribute to the field of industrial energy optimization.

Throughout this study, I've done my best to explore the realm of waste heat recovery and thermal energy storage. The main goal has been to maximize the production of electricity from the waste heat recovery system, while not compromising the production processes of the site by any means.

To achieve this, I've focused on incorporating thermal energy storage into the system in order to optimize the energy utilization and address the intermittent nature of waste heat availability. My aspiration with this work is to give my modest contribution to the growing field of industrial energy efficiency. By exploring the interplay between waste heat recovery, thermal energy storage, and sustainable manufacturing practices, we can pave the way for a greener and more efficient industrial sector, which is an absolute necessity.

Kosta Peev

2. Introduction

This master thesis analyses the possibility of recovering heat from exhaust gasses that are present in the production processes of an industrial client. At the site, an existing waste heat recovery system (WHR) is present. As new manufacturing processes are being introduced, the client would like to know if it is possible to expand the already existing WHR system to accommodate these processes. Due to the variable character of the new processes, thermal energy storage would have to be introduced as well.

The scope and objectives of this work is to analyze if the WHR system can be expanded from thermodynamic point of view. As the client has long history with SENER, this work builds upon previously done projects and analysis, that aimed at the decarbonization of the "old" WHR system. This was done by getting rid of a super-heater that was using fossil fuel (natural gas) for its operation and installing a new steam turbine that is able to work with saturated or slightly super-heated steam. Thus, this project is a logical continuation of the previous work that has been done by SENER.

Additionally, the positive environmental impact that this project might have is briefly discussed. Historical evolution of the environmental impact the industrial sector has in the European Union (EU) is analyzed to provide context for energy efficiency and waste heat recovery.

2.1. Literature review

Industrial decarbonization and waste heat recovery have gained significant attention in recent years as crucial strategies for mitigating greenhouse gas emissions and improving energy efficiency in industrial processes.

Industrial decarbonization involves reducing carbon emissions from industrial activities, through various strategies, technologies, and policy interventions. Both the energy sources and the feedstock should be the subject of decarbonization. Various studies and reports have tried to modelize what is the best approach in order to reach all of the set targets of the energy transition. For example, in one report [1] eight different scenarios were analyzed in order to find suitable pathways. The scenarios consisted of assumptions on technology options, including: improvement of energy efficiency, fuel switching, employing carbon capture and storage (CCS), recycling and reusing, as well as improving material efficiency. This report has claimed that it is possible to reduce the greenhouse gas emissions of industry by 80 to 95% by 2050 when compared to 1990. However, it claims that it is not only matter of employing the best available technologies (BAT) in order to maximize energy efficiency, but also it is of utmost importance to introduce the necessary legislature.

Another study [2] also reiterates the need for not only technical, but also policy intervention.

On the supply side, it identifies several technologies that can be of great help for achieving net zero industrial emissions by 2070. Key technologies on the supply-side for this goal are: energy efficiency (particularly at the system level), carbon capture, electrification and zero-carbon hydrogen that can be used as both a heat source and a chemical feedstock. The same study also highlights the importance of energy efficiency, particularly for steam systems and heat recovery. A good example for this claim are the results from a different study that investigated the integration of a steel mill, cement plant, fertilizer plant and recycled paper facility. It was concluded that a 21% energy savings could be obtained by colocation and intra-site transfer of heat. [3] Usually industrial sites are located in industrial zones, meaning they're relatively close to each other. Thus, the approach of "colocation and intra-site transfer of heat" might be suitable in many cases, and might have a drastic impact on the decrease of energy consumption.

It should be noted, that steam systems are present in many different industries. Hence, it shouldn't be surprising that one of the biggest end-uses of energy in industry is exactly steam. Research into the improvement of steam systems has been present for a long time, and it is still a topic of interest. It is a bit paradoxical that even though technologies for steam production are mature, there is still a lot of untapped potential when it comes to energy savings. Common causes of inefficiency include, but are not limited to: aging boilers; improper system control; insulation and maintenance; and fouling of heat transfer surfaces. Furthermore, low fuel prices are an unmotivating factor when it comes to improving current practices. [2]

Beside the demand for steam systems in the industry, the global market for thermal energy storage (TES) could triple in size by 2030. [4] This would mean an increase in installed capacity from 234 GWh 2019, to over 800 GWh in a little bit more than a decade. Furthermore, investments in TES applications are expected to reach between USD 13 billion and USD 18 billion over the same period. [4] Maximizing the use of thermal energy storage in industry where the end use is heat (in a form of steam for example) could lead to drastic improvements in the energy efficiency of industrial sites. This is due to the fact that thermal storage on heat-to-heat basis has much higher efficiency, compared to thermal storage on heat-to-power basis.

From the literature review it can be deducted that the topics of waste heat recovery and thermal energy storage are going to be very important in the future. This is especially true in the industry sector, where often times steam is the final end-use of energy. In order to reach the goals of net-zero CO_2 emissions by the industry sector, these technologies would have to be employed to a bigger degree than they're today. Thus, the topic of this thesis is very relevant, and may contribute to the improvement of practices in the industry.

2.2. Motivation

As a person that throughout his studies has been dealing with the vast science that is thermodynamics, I was negatively surprised to learn how little attention has been paid to energy efficiency at industrial sites. In the past, energy (i.e. fossil fuels) was cheap and available, carbon taxes and environmental legislative were almost non-existent. This has led to a decades-long industrial development where maximizing profits was the only parameter that mattered. As industries play a crucial role in global energy usage, it becomes essential to explore innovative approaches that enhance energy efficiency while also ensuring uninterrupted manufacturing operations. Hence, my motivation was to give my modest and humble contribution towards improving energy efficiency, as well caring for the environment.

On a more holistic bases, this thesis has also been motivated by the Sustainable Development Goals (SDGs) of the United Nations (UN). It is mainly inspired by SDG 7 (Affordable and Clean energy), and to a lesser extent SDG 9 (Industry, innovation and infrastructure). One of the aims of SDG 7 is: “By 2030, double the global rate of improvement in energy efficiency”.[5] Although “energy efficiency” is a broad term, in my opinion this thesis is fully aligned with SDG 7.

To end on a positive note, it seems that the industrial sector has also been motivated to improve its practices. According to a recent survey by ABB, 97% of the surveyed companies have stated that they already do or plan on to invest in order to make energy usage more efficient. [6] Thus, the future of industry decarbonization seems to be safe.

2.3. Scope of work

The scope of this work is limited to the initial thermodynamic analyses that would assess if it is worth exploring the possibility of expanding the already existing waste heat recovery system. That is, it is limited, to the mass and energy balances of the individual components as well as the global system. That being said, the balances have been done by employing some assumptions (more on the assumptions in the later part of the thesis), which means that the balances are not perfect, complete or ideal. Additionally, this work also aims at giving rough cost estimates for the sizing of the entire system. This project would be best described as a feasibility study, upon which the client can decide whether this project is worth pursuing further. Future steps would include, but wouldn’t be limited to: basic engineering, detailed engineering, contacting suppliers, firm offer, etc.

Furthermore, this thesis will try to do a simple financial analysis that would give order of magnitude for the savings from expanding the WHR system. However, the financial analysis in no way aims to be fully detailed. Finally, a simple environmental impact analysis (EIA) has been done, that will try to quantify the amount of CO_2 emissions that have been avoided. Depending on the local regulations, as well as if the projects is deemed viable by the client, a full EIA might have to be done, by licensed companies.

To conclude, this thesis, aims at giving preliminary estimates when it comes to expanding an already existing WHR system. Topics such as exergy analysis, transient operation analysis and similar, lay outside of the scope of this work. This decision is justified by the fact that for such a complex system a detailed analysis would take lot of time and resources. Furthermore, by committing to a complex study, the final results might not be in line with what has been expected, which would result with wasted time and resources. Hence, doing an initial feasibility study can provide a guidance whether the project is worth exploring. Any future work would build upon this feasibility study, thus the approach that has been taken is justified.

2.4. Objective of the work

The main objective of this master thesis is to analyze different options when it comes to waste heat utilizations and give recommendations for future actions for an industrial client. The client is a big corporation in the field of metallurgy that manufactures various equipment and parts. Within their manufacturing processes there are waste heat streams that can be utilized either for electricity production or for meeting their thermal demands.

Beside the main or general objective, there are many specific objectives that are closely connected with the tasks that have to be carried out, in order to meet the general objective. Hence, the following are the specific objectives:

- Creating a tool for the simulation of the behavior of a steam accumulator. This tool would help with the physical sizing of the steam accumulator; with the mass and energy and balances; with the behavior of the accumulator over a longer period of time.
- Mass and energy balances, as well as simulation of the entire system (using the “Thermoflex” software).
- Choosing the design point for each configuration.
- Performance of the system at off-design conditions.
- Cost estimate and financial analysis.
- CO_2 emissions that have been avoided due to the proposed solution as well as the positive environmental impact.
- Analyzing the energy consumption of the industrial sector in the EU.
- Analysis on the current state of the decarbonization, as well as the financial and environmental benefits it might bring.

3. Grupo SENER

SENER is an engineering and technology group with more than 65 years of history. It was the first Spanish engineering company, founded in 1956 as a naval technical office, soon diversified its activity to become a multidisciplinary international group, with presence in the Aerospace, Infrastructure, Energy and Naval sectors, with about 2,500 highly qualified professionals in offices around the world and recognized for its capacity for innovation.

It is currently composed of 4 business units: Aerospace; Infrastructure & Transport; Renewables, Power, Oil and Gas; Marine. It also has its own foundation, that aims at giving back to the community, as well as a specially dedicated division to investments into the renewable sector (Sener Renewable Investments - SRI).

SENER is part of the UN's Climate Ambition Accelerator program. This program encourages companies to accept a commitment to reduce emissions based on science, in line with the "Science Based Targets" initiative. On this note, SENER's activities in industrial decarbonization, solar power and green hydrogen stand out the most. However, it shouldn't be underestimated the positive societal impact that other projects provide. Namely, 77% of all SENER projects are considered sustainable.

3.1. Industrial decarbonization

When it comes to industrial decarbonization, SENER has been active in many different fields, helping their clients limit their CO2 output, improve their energy efficiency, decrease the expenses for carbon taxes, as well as implement renewables into their sites. Their clients come from various industries, such as: steel and other metals manufacturers, plastic manufacturers, glass manufacturers, breweries, etc. In this type of projects SENER is in charge from the initial feasibility studies, up to the detailed engineering design and construction supervision, to finally commissioning the plant and operation and maintenance.

3.2. Solar Power

In the field of solar power, SENER is a world leader in concentrated solar power (CSP). They have installed more than 29 thermosolar plants, totaling over 2000 MWe. Some of the more renowned are the following:

I. The NOOR I, II and III projects in Morocco with 160MWe, 200MWe and 150MWe of installed power. NOOR I and II are using parabolic-trough solar collectors, while NOOR III is using heliostats that are focusing the solar radiation onto a central tower. The construction began in 2013 and it finished in 2018.
II. GEMASOLAR near Sevilla, Spain with installed power of 19.9MW that can produce

110 GWh annually, being operational since 2011. It was the first commercial plant to use central tower receiver and heliostat field technology in combination with a molten salt thermal storage system. It can operate up to 6450 hours per year at full capacity. In the summer of 2013 the plant had achieved continuous production operating 24 hours per day for 36 consecutive days. [7]

III. ANDASOL 1 and 2 near Granada, Spain. It was the first parabolic-trough power plant in Europe. Construction began in 2005 and finished in 2010. It has capacity of 50MW and has the capability to supply 180 GWh/year.[8] Similar to Gemasolar, it has molten salt thermal energy storage.

3.3. Green hydrogen

SENER is part of the consortium for the BENORTH2 project, the first green hydrogen plant in Spain. It will be based in Amorebieta in Biscay (Spain), maximizing the use of existing infrastructures. White Summit, CCI, Nortegas, Bizkaia Energy and Sener are the companies in charge of the development of this project and start-up.

4. Theoretical background

The terms “industrial de-carbonization” and “energy efficiency” have been very popular in recent times. With the “energy transition” these terms have additionally increased their popularity. Press releasees from companies, boasting about their improved processes that have led to lower emissions and better energy efficiency have been a frequent sight. However, at the core of the changes that companies might have introduced, lie technologies that have been present for quite some time, but the incentives to introduce them were lacking.

When it comes to energy efficiency, it is usually connected with better optimization of the thermal streams and flows of a plant. Practically, this might include installing heat exchangers that would improve the overall efficiency of the plant by rejecting as little heat as possible to the environment and increasing the recovery of the energy from the waste heat streams. This practice is usually costly and it will not yield a dramatic increase in the overall energy efficiency of the plant. However, with the introduction of carbon taxes, it may lead to substantial benefits. Furthermore, depending on the site, a more tangible systems might be employed, such as heat recovery steam generation (HRSG) or organic Rankine cycles (ORC).

On the other hand, industrial decarbonization is connected more with using renewable energy sources as an energy input at the site. For example, this could be employing solar thermal technologies, such as CSP, in order to generate steam for the industrial processes (instead of burning fossil fuels). Another example can be using photo-voltaic panels or wind turbines, to satisfy the demand for electricity. Industrial decarbonization, can also apply to the feedstock that is being used. In the chemical industries, the feedstock for methanol production is hydrogen. The main technology for obtaining hydrogen is steam methane reforming (SMR) of natural gas. A study done in 2017, claimed that 95% of all hydrogen produced in the United States of America is made by SMR. [9] Hence, in this case the feedstock can be decarbonized by using green hydrogen, that has been produced with the help of electrolyzers and electricity obtained from renewables.

In other words, “industrial decarbonization” and “energy efficiency” may refer and employ various technologies. More often than not, these technologies are well known, and can be readily deployed and used. In the context of this project, various technologies have been analyzed. Although in the scope of this project no renewables are employed, the energy efficiency of the site is improved by using exhaust gasses as a source of energy. Technologies that have been analyzed are steam accumulation and molten salts when it comes to thermal energy storage. The thermal energy storage is to be coupled with a heat recovery steam generation system. Thanks to the HRSG, a steam turbine is powered, which produces electricity. All of these technologies have been present for quite some time, but combining all of them is a unique challenge, as every site has their own specific boundaries and limitations.

4.1. Steam accumulation

Steam accumulation is a mature technology that has been present for more than 100 years. Although the name suggests that with this technology steam is accumulated, in fact pressurized saturated liquid water is being accumulated. It has been developed due to the fact that storing saturated or superheated steam is not economical, due to the low volumetric energy density. In other words, if steam is directly stored, the storage vessel would have to occupy lots of space. The volume specific thermal density depends strongly on the variation of the saturation temperature resulting from the pressure drop during discharge. Characteristic values are in the range 20-30 kWh/m^3. [10]

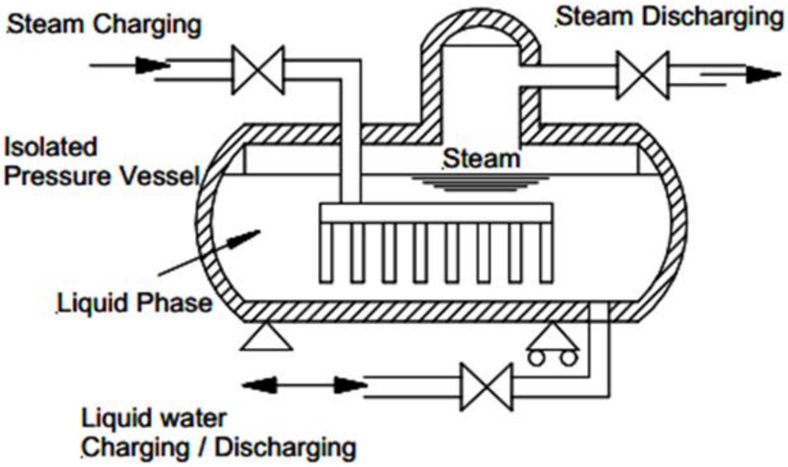


Figure 1: Visual representation of a steam accumulator [10]

A steam accumulator produces steam by lowering the pressure of the saturated liquid during discharge. [10] In Figure 1 a visual representation of a steam accumulator is given. As can be seen, in the steam accumulator there are two phases: liquid and vapor. The steam accumulator is usually charged directly with a superheated or saturated steam (which would be the case in this project), but it can also be charged indirectly by means of a heat exchanger that would be integrated in the liquid volume. If the charging is done with a heat exchanger, the fluid flowing inside of it doesn’t necessarily have to be water and it can be at a lower pressure. When it is charged directly with superheated steam, the temperature (and hence the pressure) inside the tank is increasing as a result of the condensation of superheated steam. There is one constraint for this process, and that is that the pressure of the superheated steam has to be higher than the pressure inside the tank. On the other hand, when it is charged with a saturated liquid water the mass in the system is increased, while the temperature doesn’t experience notable change.

During the discharge process, saturated steam leaves the steam accumulator. The pressure of the saturated steam has to be controlled, as it depends on the pressure inside the tank, which in turn is dependent on the charging process. Hence, after discharging saturated vapor, an expansion valve follows to get the vapor to the desired pressure level. This expansion would result with a slightly super-heated vapor. Depending on the use, the super-heated vapor might have to be cooled in order to bring back to a saturated vapor state. This is the case for the project, as in the manufacturing processes the client works with latent heat.

In order to assess if a steam accumulator can be incorporated in the project, the size of it and its' effect on the performance of the plant have to be calculated. The steam accumulator can be used for satisfying the demand from the industrial processes or it can be used for storing thermal energy in order to balance the electricity production. It was decided that a three-day simulation of the steam accumulator operations would be done. For the purpose of this simulation a "Microsoft Excel" tool was developed.

4.2. Molten salts

As the name suggests, molten salts are simply salts that are in liquid state due to having elevated temperature. Molten salt is a very general term, and the composition as well as their properties can vary significantly. They have various applications in the industry, such as catalyzers and solvents, to name just a few. [11] The first use of molten salts dates back to 1950, which is when Oak Ridge National Laboratory (ORNL) started to develop and test nuclear powered aircraft engine using molten salts. [12] The molten salts that are used for indirect heat transfer are in general synthetic salts, so-called "Hitec salt". [13] They can be binary or tertiary (made out of two or three different components/salts) mixtures.

When it comes to their use in the field of renewables, molten salts have become very popular in the construction of Concentrated Solar Power (CSP) plants. For this purpose, the salt mixture is usually 60% $NaNO_3$ and 40% KNO_3. Depending on the type of CSP plant, molten salts can have the function of storing thermal energy (usually this is the case with parabolic-trough collectors), or can also act as a heat transfer fluid (usually in CSP plants with power towers). In CSP plants, when radiation is available, the excess thermal energy is stored in well insulated storage tanks, that contain molten salts. During night time, or when radiation is low, this thermal energy is used in order to produce electricity with the help of a steam turbine (Rankine Cycle). Usually, there are two tanks, one for storing the cold molten salts, while the other tank is for storing the hot molten salts. This way, the thermal losses are brought to minimum. One other important aspect of using molten salts, is that only sensible heat is stored, which makes the process of heat exchange much easier (when compared to using latent heat).

Molten salts used for Thermal Energy Storage (TES) are in solid state at room temperature and liquid state at the operation temperatures, which are significantly higher. High-temperature properties such as the volumetric storage density, viscosity and transparency are similar to water at room temperature. The major advantages of molten salts are low costs, non-toxicity, non-flammability, high thermal stabilities and low vapor pressures. The low vapor pressure results in storage designs without pressurized tanks.[14] As previously mentioned, molten salts are used to store sensible heat, hence their capacity for storing energy can be calculated as:

$$Q_{sensible} = m \cdot \left(h_{highT} - h_{lowT}\right) \cong m \cdot c_p \cdot (T_{high} - T_{low}) = m \cdot c_p \cdot \Delta T \qquad \textit{(Eq. 1)}$$

Where:

- m – mass of the molten salts [kg]
- h – enthalpy of the molten salts at high and low temperatures [kJ/kg]
- c_p – average specific heat of the molten salt [kJ/kgK]
- T – highest and lowest allowed temperatures of the molten salt during charging and after discharging [K or °C]
- Q – energy stored in the molten salts [kJ]

A well-known constraint of using molten salts is that their liquidus temperature is 250°C. In other words, at 250°C the salts start to crystalize, effectively converting them to solids. This can be very dangerous for the entire system as the crystallization can damage many components, such as pumps for example. Hence the minimum operation temperature of molten salts used in CSP is set to 290°C – 300°C in order to have a safety margin. On the other hand, the maximum operation temperature is in the region of 550°C - 560°C. If we assume a temperature difference of 250K, the volumetric capacity for storing energy would be around 200kWhm^{-3}. It is important to note that thermal energy storage by using molten salts is cheaper than thermal oil, which is another popular fluid that is used as HTF. For large-scale systems, molten salt costs are in the range of 4-20 € kWh^{-1} [14] depending on exact market prices and temperature difference.

4.3. Steam turbines

The basic concept behind steam turbines, is that they transform thermal energy in order to produce mechanical energy. The mechanical energy is usually converted to electrical energy by means of an electrical generator. However, the steam turbine can also be used to drive a pump, fan, or other rotating equipment.

Steam turbines are a very mature technology and have been present for almost 150 years. The first practical designs of a steam turbine are credited to the Englishman Sir Charles Parsons, who patented them in 1884. His turbine was able to produce 7.5 kW. In 1890, the first of four 75 kW Parsons designed turbines were installed in England. In Sweden in 1889, Carl de Laval had patented a 3.7kW turbine. [15]

As time progressed and manufacturing technologies and processes improved, the size and power of steam turbines increases as well. Novel concepts were introduced as well. For example, in order to improve thermal efficiency, reheating the steam partway through the expansion phase had been introduced in the 1930s. This practice became the standard for steam turbine in the 1950s. In the 1960s, manufacturers were producing double-reheat turbines that had supercritical pressures at the inlet. In this era, the highest inlet pressure levels were in the order of 340 bars, and the inlet pressures were approximately 650°C. However, due to higher initial costs (CAPEX) and maintenance (OPEX) costs, the turbines that were sought by the market had lower inlet pressure and temperature, usually around 160 bars and 540 °C. [15]

When it comes to the industry, the needs are different, compared to those of the utilities companies. The business model of utility companies is to sell electricity, and sometimes heat for district heating purposes. Thus, maximizing the electrical production is what drives the design of the steam turbine. In the industry, the main need is usually steam for processes, and electrical energy that might be produced is considered a by-product that improves the overall energy efficiency of the site. Hence, a turbine that would be used at an industrial site, should guarantee that the needs for process steam are satisfied, and not to maximize the electrical output. Back-pressure steam turbines, that expand the steam to a level that is needed to satisfy the demand for steam, are usually used in the industry.

Both utility and industrial markets are tending towards emphasizing lower operating costs, greater operating flexibility and lower environmental emissions. This has led to the development of various systems configurations, such as the combined-cycle. In the combined cycle, gas and steam turbines are combined, in order to increase the overall thermal efficiency. More precisely, a large gas turbine is used to produce electricity. Then, energy of the waste heat from the exhaust of the gas turbine is recovered using a heat recovery steam generator (HRSG). The generated steam is then used to drive a steam turbine.

4.3.1. Rankine cycle

The thermodynamic cycle that is employed by steam turbines is called “Rankine cycle”. In this section a brief outlook of the ideal Rankine cycle will be given. A simplified schematic diagram of a steam power plant is given in Figure 2. A T-s diagram of an ideal Rankine cycle is given in Figure 3.

The ideal Rankine cycle is composed of the following processes:

I. **Process 1-2, isentropic compression in a pump:** water enters the pump at state 1, as a saturated liquid. It is compressed isentropically to the operating pressure of the boiler and turbine. The temperature increases, but it is almost negligible (in Figure 3 this temperature increase has been exaggerated in order to be visible).

II. **Process 2-3, isobaric heat gain in the boiler:** water enters the boilers at state 2, as a compressed liquid. Superheated vapor leaves the boiler at state 3. The boiler is fundamentally a heat exchanger. The fuel for the boiler can be coal, oil, gas and even nuclear. In the ideal cycle, this process is considered isobaric.

III. **Process 3-4, isentropic expansion in a turbine:** the superheated vapor at state 3 enters the turbine. It expands in the turbine, and exits the turbine at state 4 as a wet steam. In the ideal cycle, the expansion is considered isentropic. The expansion produces mechanical work by rotating the connected shaft. This shaft is usually connected to a generator, which in turn produces electricity.

IV. **Process 4-1, constant pressure heat rejection in the condenser:** after expanding in the turbine, the working fluid enters the condenser at state 4, as a wet steam. In the condenser it rejects heat at a constant pressure, until it reaches state 1 as saturated liquid. In this state it enters the feed pump, thus completing the entire cycle.

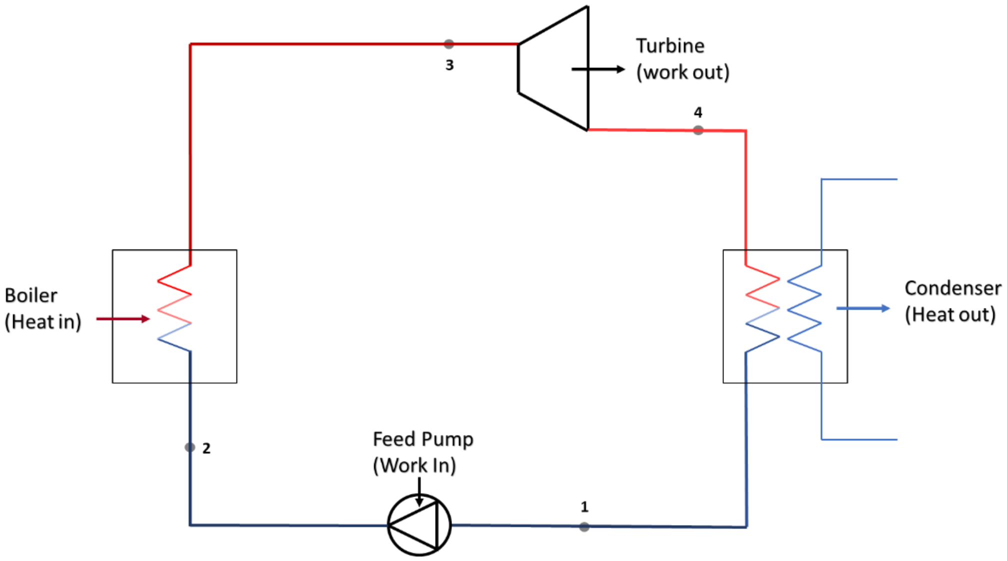


Figure 2: Schematic diagram of a steam power plant

When analyzing the Rankine cycle, it is usually assumed that all of the components are connected by conduits that allow the transport of the working fluid from the outlet of one component to the inlet of another component, without any kind of change to the state of the working fluid. In other words, it is assumed that the parameters of the fluid at the exit of the boiler are the same as the parameters of the working fluid at the inlet of the turbine. Additionally, it is assumed that the system is in steady state, hence the steady state conservation equations are applicable. This is appropriate to most situations, as power plants operate at steady state for significant lengths of time. Therefore, transient operations at startup and shutdown are special cases, that will not be considered.

In the ideal Rankine cycle shown in Figure 3, steam expands adiabatically and reversible, or isentropically through the turbine to a lower temperature and pressure at the condenser entrance. Starting from the First Law of Thermodynamics:

$$\Delta E = Q - W \qquad \text{(Eq. 2)}$$

Where:

- ΔE – change in total energy of the system [J]
- Q – heat transfer in or out of the system [J]
- W – work done by the system [J]

Considering that the turbine is in steady state (meaning $\Delta E = 0$) and that the expansion is adiabatic (Q = 0). Hence the work done by the turbine would be equal to:

$$W_{turbine} = h_3 - h_4 \ \left[\frac{kJ}{kg}\right] \qquad \text{(Eq. 3)}$$

$$\dot{W}_{turbine} = \dot{m}(h_3 - h_4) \ \left[\frac{kJ}{s}\right] \qquad \text{(Eq. 4)}$$

For the boiler (or steam generator) the process is similar. It also starts with the First Law of Thermodynamics, however in this case the work done is equal to zero. Hence, the heat supplied to the system is equal to:

$$Q_{boiler} = h_3 - h_2 \ \left[\frac{kJ}{kg}\right] \qquad \text{(Eq. 5)}$$

$$\dot{Q}_{boiler} = \dot{m}(h_3 - h_2) \ \left[\frac{kJ}{s}\right] \qquad \text{(Eq. 6)}$$

For the condenser, the reasoning is very similar to the boiler. The main difference is that negative values will be obtained for the heat transferred. This is in line with the conventions, as in the condenser heat is rejected by the working fluid. Hence the following will be obtained:

$$Q_{condenser} = h_1 - h_4 \ \left[\frac{kJ}{kg}\right] \qquad \text{(Eq. 7)}$$

$$\dot{Q}_{condenser} = \dot{m}(h_1 - h_4) \ \left[\frac{kJ}{s}\right] \qquad \text{(Eq. 8)}$$

A pump is a device that moves liquid from a region of low pressure to a region of high pressure. The derivation of the work that is done by the pump is similar to that of the turbine, as there is no heat transfer, only work. The work by the pump will have negative sign, which is in line with the convention of thermodynamics, as the negative sign indicates that work and power must be supplied in order to operate the pump.

$$W_{pump} = h_2 - h1 \ \left[\frac{kJ}{kg}\right] \qquad \text{(Eq. 9)}$$

$$\dot{W}_{pump} = \dot{m}(h_2 - h_1) \left[\frac{kJ}{s}\right] \qquad \text{(Eq. 10)}$$

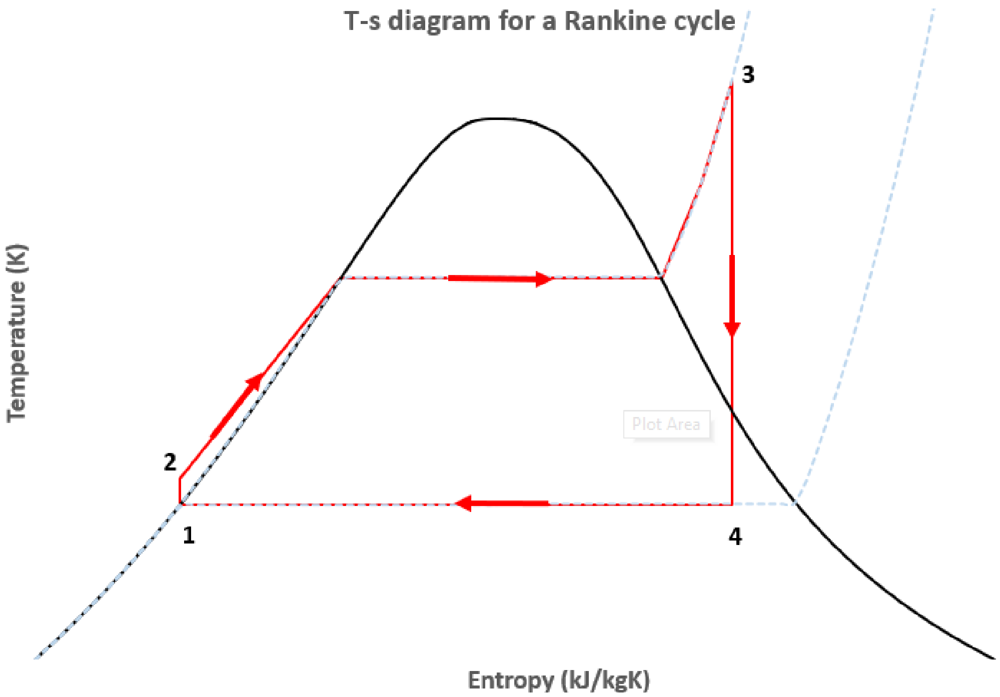


Figure 3: T-s diagram of a Rankine cycle

4.4. Heat recovery steam generator (HRSG)

Heat recovery steam generators are a mature technology that have been used for many decades, if not a century. Fundamentally, they are heat exchangers, composed of three different units: economizer, evaporator and super-heater. Usually, exhaust gases from a gas turbine act as the source of thermal energy that is used in order to generate steam. HRSG are present in various industrial plants, as well as in power plants. They can be operated in cogeneration mode (Figure 4) or in combined-cycle (Figure 5). In cogeneration mode, the steam that is produced is used for process applications. On the other hand, in combined-cycle, the obtained steam is used to drive a steam turbine that employs a Rankine cycle. For the needs of this project, the HRSG will operate in both cogeneration and combined-cycle mode. This means that the produced steam will be used for manufacturing processes, but it will also be used by the steam turbine. Furthermore, the HRSG will be coupled with steam accumulation.

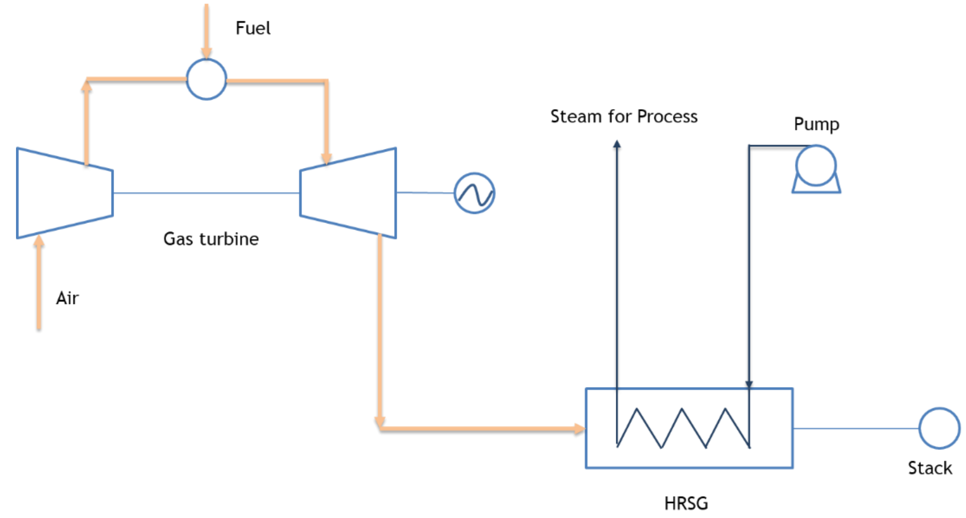


Figure 4: Example of a HRSG operating in cogeneration mode

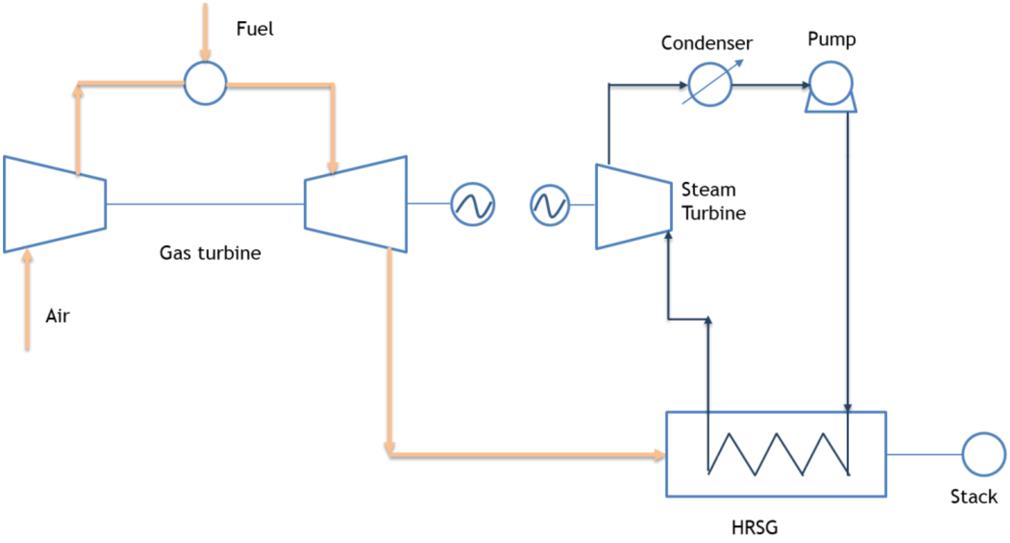


Figure 5: Example of a HRSG operating in combined-cycle mode

4.4.1. Basic thermodynamic calculations

In order to be able to do initial calculations for the HRSG, two variables have to be assumed. Those are the pinch point and the approach point. Pinch point is the temperature difference between the lowest temperature of the exhaust gas in the evaporator (the temperature of the gas at the outlet) and the saturation temperature of water at the operating pressure. The approach point is the temperature difference between the temperature of the water at the inlet of the evaporator and the saturation temperature. This can be better understood from Figure 6. The values of these variables directly impact the size of all of the heat exchangers. Usual values for the pinch and approach points, taking into consideration the financial aspect, is in the range of 8 to 15°C. [16]

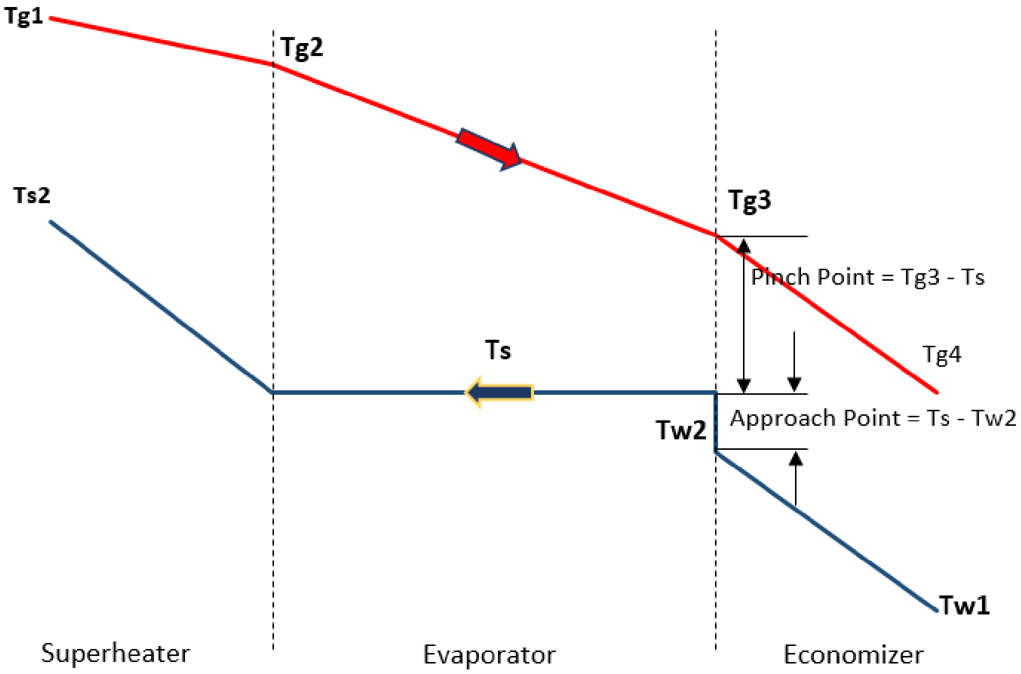


Figure 6: Temperature profile of a HRSG

$$\dot{Q}_{SH+EV} = \dot{m}_g \cdot c_{pg} \cdot \left(T_{g1} - T_{g3}\right) \cdot (hl) = \dot{m}_s \cdot \left[(h_{s2} - h_{w2}) + (bd) \cdot \left(h_f - h_{w2}\right)\right] \quad \text{(Eq. 11)}$$

$$\dot{Q}_{SH} = \dot{m}_s \cdot (h_{s2} - h_v) = \dot{m}_g \cdot c_{pg} \cdot (T_{g1} - T_{g2}) \cdot (hl) \quad \text{(Eq. 12)}$$

$$\dot{Q}_{ECO} = \dot{m}_s \cdot (h_{w2} - h_{w1})(1 + bd) = \dot{m}_g \cdot c_{pg} \cdot \left(T_{g3} - T_{g4}\right) \cdot (hl) \quad \text{(Eq. 13)}$$

Where:

- $\dot{Q}_{SH+EV}$ – Energy exchanged across the superheater and evaporator; [kW]
- $\dot{Q}_{SH}$ – Superheater duty; [kW]
- $\dot{Q}_{ECO}$ – Energy exchanged across the economizer; [kW]
- $\dot{m}_g$ – Exhaust gas flow rate; [kg/s]
- c_{pg} – Specific heat of the exhaust gasses; [kJ/kgK]
- T_{g1} – Temperature of the exhaust gas at the inlet of the superheater; [K]
- T_{g2} – Temperature of the exhaust gas at the outlet of the superheater and the inlet of the evaporator; [K]
- T_{g3} – Temperature of the exhaust gas at the outlet of the evaporator and at the inlet of the economizer [K]
- T_{g4} – Temperature of the exhaust gas at the outlet of the economizer; [K]
- $\dot{m}_s$ – Mass flow rate of the water/steam; [kg/s]
- h_{s2} - Enthalpy of the superheated steam at the outlet of the superheater; [kJ/kg]
- h_{w2} – Enthalpy of the subcooled liquid at the inlet of the evaporator (or outlet of the economizer) [kJ/kg]
- h_f – Enthalpy of saturated liquid [kJ/kg]
- hl – Heat loss (usually ranges between 0.5 and 2%, depending on the size of HRSG)

- bd – Blowdown, fraction
- h_v – Enthalpy of saturated vapor entering the superheater [kJ/kg]
- h_{w1} – Enthalpy of water entering the economizer [kJ/kg]

The first step towards determining the temperature profiles of the HRSG, are the values of the pinch and approach points. This is always a compromise, between efficiency and the cost of the HRSG system. Afterwards, the values that are known are the gas flow rate ($\dot{m}_g$), gas temperature at the inlet of the HRSG (T_{g1}), temperature of the feedwater (T_{w1}), temperature of the steam at the outlet of the superheater (T_{s2}), as well as the steam pressure. It is necessary to assume a reasonable pressure drop in the superheater, so that the saturation temperature (T_s) can be determined. Since the pinch point has been selected, the temperature of the gas leaving the evaporator (T_{g3}) is known. Likewise, the approach point gives the temperature of the water leaving the economizer (T_{w2}).

With (Eq.11) the energy balance for the superheater and the evaporator is given. Since T_{g1} and T_{g3} are known, the energy exchanged across the superheater and evaporator can easily be computed. From there, by reshuffling the equality, the design mass flow rate of the steam ($\dot{m}_s$) can easily be determined. From the energy balance for the super-heater that is given by (Eq. 12), the temperature of the gas at the outlet of the super-heater (T_{g2}) can be found. Finally, from the energy balance for the economizer in (Eq.13) the gas temperature at the outlet of the economizer (T_{g4}) can be computed. At this point, a complete gas/steam profile has been obtained.

5. Methodology

The aim of this master thesis is to do a feasibility study for the incorporation of new waste heat streams into the already existing waste heat recovery system. As such, the goal is to give general orders of magnitude for the necessary components, and not go into detailed engineering. In other words, this thesis will mainly analyze the problem from a thermodynamical side, and less from a practical side.

The starting point of this project is the data that has been provided by the client. This data is considered as input data, and it must not be interfered with in any way. In order to satisfy the client needs, it is necessary to work “around” the constraints that have been imposed by the client and the manufacturing processes. Hence, the need to do an initial feasibility study, to understand if the projects is viable from thermodynamic point of view with the constraints that have been put into place.

In order to do the preliminary assessment, some assumptions are made for the components that compose the entire systems. For example, turbines are considered to be isentropic, heat exchangers are considered not to have any thermal and pressure losses, and valves are considered to be isenthalpic. Of course, all of these assumptions can be considered valid, only for the initial sizing. Once that has been done, with the help of the “Thermoflex” software, more accurate and precise heat and mass balances are obtained.

It is important to mention, that this thesis only deals with the analysis of a system in a steady state. In other words, the steady state at different operating points is analyzed. This is done in order to define what is the “design point” of the system, as well as to maximize the efficiency and the production of electricity from the waste heat recovery system. Since the load is variable for various parameters, the performance of the system at off-design conditions is that much more important. It should be mentioned that the only component on which a temporal analysis has been done, is the steam accumulator. However, for the steam accumulator, many of the variables are either assumed (the initial conditions for example), or are considered to be steady over a 24-hour period.

The main limitation of this thesis is that it is just an initial analysis, and in order to obtain more representative values, suppliers would have to be contacted directly. Furthermore, this thesis does not deal with the treatment of the exhaust gasses. These gases may be very contaminated, and the treatment they ought to undergo is not considered. This is limiting the maximum energy efficiency that can be obtained, as in some scenarios, the exhaust gases after rejecting heat, still have temperatures that are higher than 200°C. Finally, transient analysis hasn’t been done for the majority of the components, such as the steam turbine and the heat recovery steam generator.

To conclude, this thesis tries to assess the behavior of a waste heat recovery system, and initially size the system. This is done by doing all of the individual mass and energy balances. They are first done by “hand” in order to obtain orders of magnitude and then a software is used to obtain more precise parameters. These two approaches are complementing each other, as in this way it is less likely for an error to occur, and an engineer should not allow to trust any software “blindly”. The approach that has been chosen for this project is not without its flaws, however for the purpose of this project, the assumptions that have been knowingly incorporated, do not negatively impact the overall quality.

6. Results and discussion

In this section the results will be presented, together with the entire process leading up to the obtained results. Additionally, the results will be discussed and analyzed, and the reasoning behind accepting or rejecting a certain solution will be provided.

First, a general overview of the project will be given. This is important, as this work is a direct continuation of a previous project, hence the need to introduce briefly the work that has already been done. Afterwards, each and every technology that was taken into consideration will be presented, together with the obtained results.

6.1. Background of the project

The project is for an industrial client that has a manufacturing site. On the site, an existing heat recovery system that was utilizing the waste heat streams from production was present. This system uses a conventional steam turbine in order to produce electricity. However, after recovering the energy from the waste heat streams, the steam (working fluid) needs to be super-heated before entering the steam turbine. Hence, this system had a natural gas fired super-heater, as can be seen in Figure 7. Furthermore, at different points in the system, part of the steam is collected in order to be used for the needs of the manufacturing processes. Table 1 shows the mass flowrate (as percentage of the maximum flowrate) and the state of the working fluid at different points. As can be seen, considerable amount of steam is needed for the processes. It should be mentioned that the purpose of Figure 7 and Table 1 is to only introduce and give a general idea of the waste heat recovery (WHR) system. In practice the system is much more complicated, with numerous internal heat exchangers and bleed streams from the turbine. A more detailed representation of the system is given in Appendix A.

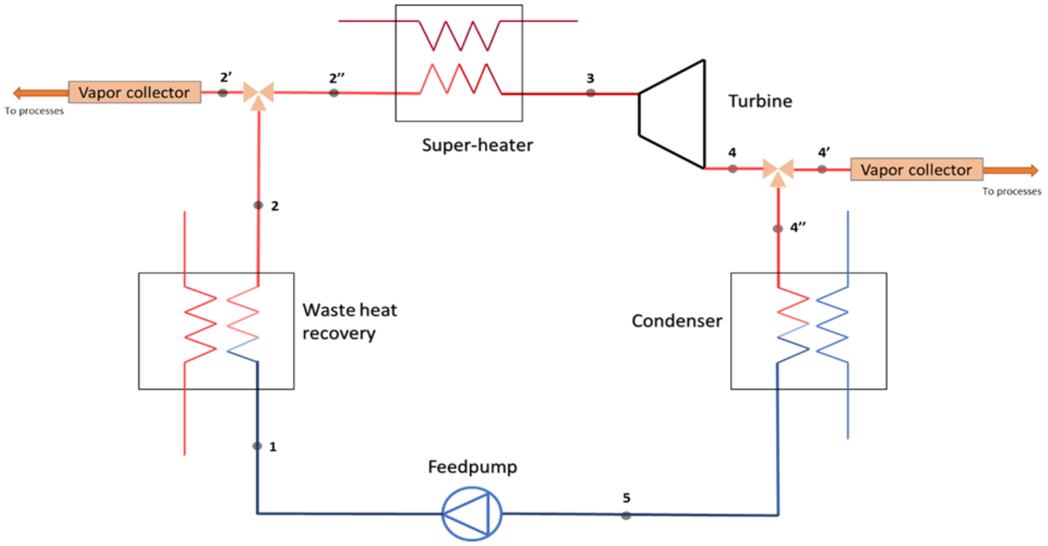


Figure 7: Simplified schematic of the waste heat utilization system that is present at the site

Table 1: Mass flowrate [%] and state of the working fluid in the existing WHR system

Point	Mass flowrate (%)	State
1	100.00%	Saturated liquid
2	100.00%	Saturated vapor
2'	29.82%	Saturated vapor
2"	70.18%	Saturated vapor
3	70.18%	Super-heated vapor
4	70.18%	Saturated vapor
4'	21.93%	Saturated vapor
4"	48.25%	Saturated vapor
5	100.00%	Sub-cooled liquid

Due to the super-heater being fired by natural gas, this system was subject to carbon taxation. This was proving very costly. Thus, the client was presented with few alternatives:

a) Introducing a new, more efficient natural-gas fired super-heater, that would still be subject to the same carbon taxation. However, with this solution the electrical power output of the turbine would be increased (by approximately 7.5%), which would mean that for the same amount of CO2 emissions, more electrical energy would be produced. In other words, the CO2 emissions per kWh of produced electricity would decrease.

b) Introducing a new electric super heater. This would effectively erase the carbon taxation; however, the net electrical power output of the turbine would decrease by approximately 24%.

c) Introducing a new steam turbine that could work with lower quality steam, i.e. saturated or slightly over-heated steam. This would mean a lowered electrical output from the turbine (by approximately 13.5%), but would completely eliminate the gas fired super-heater, and by extension any form of carbon taxation.

The client decided that option c is in their best interest. Hence, the super-heater has been eliminated and a new steam turbine with lower power output has been planned to be ordered.

6.2. Introduction of additional waste heat streams

As a part of a different project, but located on the same industrial site, the client would like to expand and introduce new manufacturing processes. These processes would result with a substantial amount of waste heat that can be recovered and utilized. There are 3 main processes throughout the day, depending on the manufacturing needs. In all 3 processes the waste heat gasses are at similar pressure and temperature levels, but the mass flow rate can vary greatly.

Table 2: Exhaust gasses parameters from the new manufacturing processes

Process	Duration of the day [h]	Temperature [°C]	Mass flow rate [t/h]	Unit flow rate
1	4.5	580	460	1
2	10.5	520	283	0.62
3	9	490	107	0.23

As can be seen from Table 2 the mass flow rate for "Process 3" is less than 25% of the flow rate from "Process 1", which poses a great problem when trying to design a system for waste heat recovery and utilization. This would result with big oscillations in the electrical production, if the waste heat is used to produce electricity. There might be even limitations from the design of the equipment. For example, a conventional steam turbine would have decreased efficiency and its life span might be affected if it is running outside of its nominal working point. Not to mention the additional costs of sizing a system that would be only working at its design point very few hours per day. Hence, the idea of introducing thermal energy storage, that would balance the production of electricity, is justified.

Additionally, for its industrial processes the client is using vapor. The vapor is needed at different pressure levels, hence including thermal energy storage can be beneficial not only for balancing the power output of the new waste heat streams, but also to cater for the already existing demand from the processes. By catering for the production demands, the electrical power output can be indirectly increased.

6.3. System A: Oversizing the steam turbine without any kind of thermal energy storage

The first option that should be analyzed is to see what would happen if all of the recovered energy from the waste streams is sent directly to the turbine. This can be considered as the baseline scenario, upon which the solution with the thermal energy storage will be compared. Of course, there are limitations on what is the minimal acceptable load by the turbine. It is usually in the range of 58-60% of the nominal load. [17] Furthermore, the current trend is to try and lower this level to around 40%. This development has been mostly due to the larger penetration of renewables in the electric grids.

The first step is to analyze the amount of heat that can be recovered from the exhaust gasses. This was done with the help of the Thermoflex software. A visual representation of a HRSG system is shown in the Figure 8. In red is the stream of the exhaust gasses, while in blue the water/steam is represented.

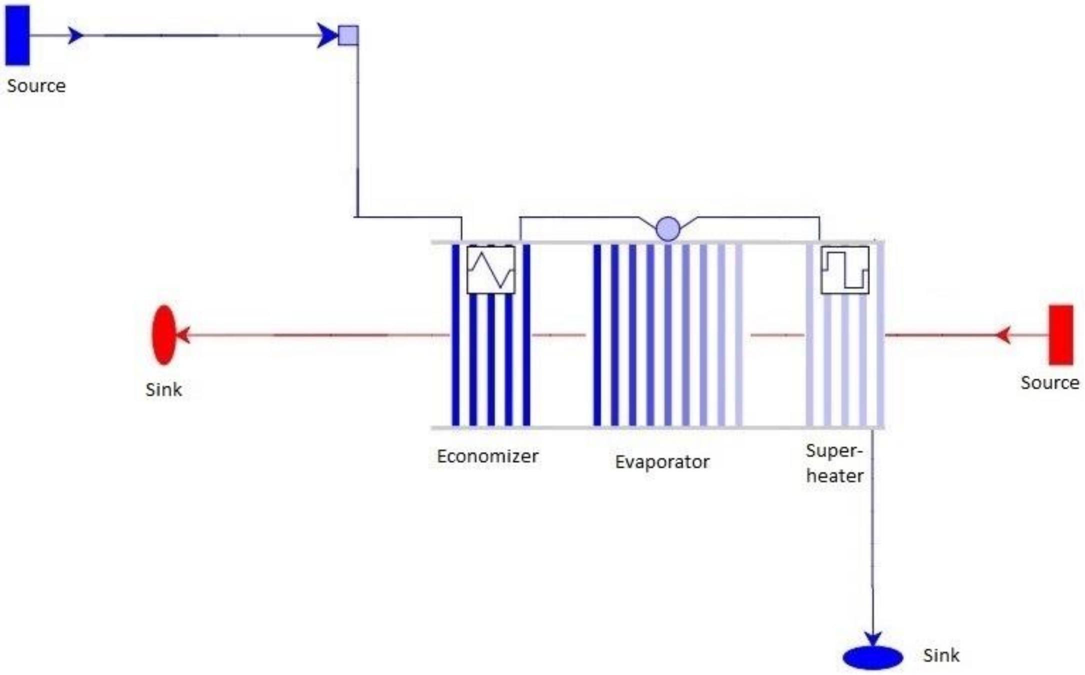


Figure 8: Visual representation of a HRSG system

As can be seen, the HRSG is composed of three components: the economizer, the evaporator and the super-heater. This is a standard engineering practice, when working with latent heat, as it is easier to divide the overall heat balance in three separate balances. The following results were obtained:

Table 3: Vapor conditions at the outlet of HRSG

		Process 1	Process 2	Process 3
Duration	h/day	4.5	10.5	9
Vapor	bar	40	40	40
	°C	400	401	400
	t/h	63	33.4	12.4

As can be seen from the obtained results, the highest mass flow rate is present when recovering energy from Process 1. Hence, this will be chosen as the design point of the HRSG. The temperature and pressure levels are more or less the same, and this has been done on purpose. In the turbine, we would like to have inlet pressure of 40 bars. Thus, the calculations are based on fixing the outlet conditions from the HRSG. Of course, during off-design operation of the turbine the pressure levels may drop.

In Figure 9 the T-Q diagram for the HRSG is given. This diagram is basd on the calculations done for “Process 1”, which is considered to be the design point. With red the exhaust gasses are represented, while in blue the water/steam is represented. The latent heat transfer can clearly be seen in the diagram, due to the isothermal process that occurs in the evaporator. This HRSG will be the basis for all of the subsequent analysis and comparisons.

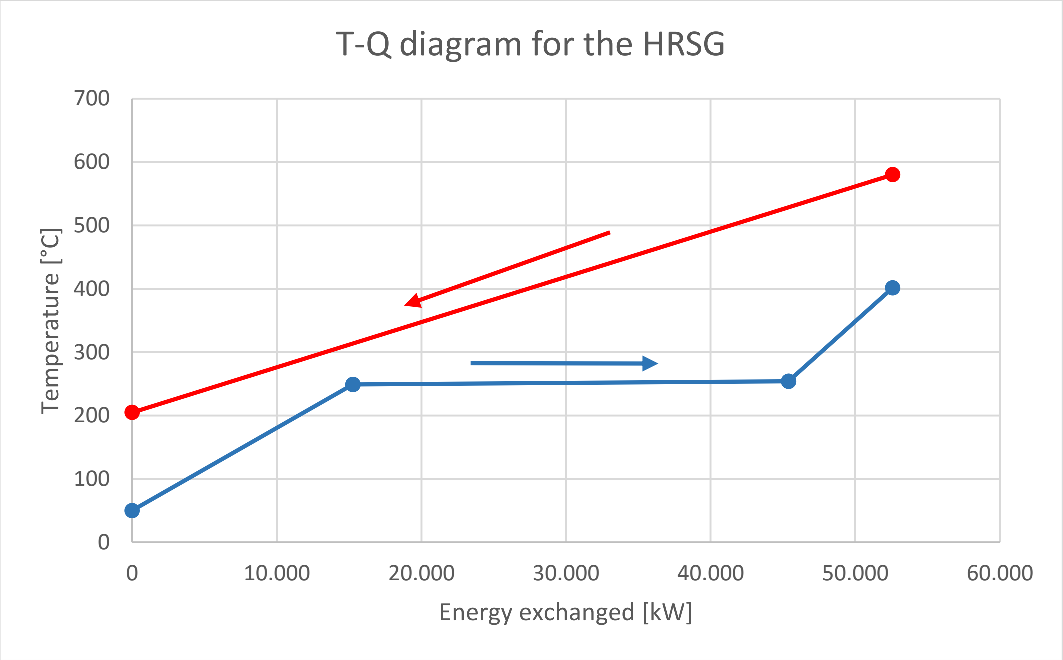


Figure 9: T-Q diagram for the HRSG at design conditions

Using the “Thermoflex” software, the entire system was integrated, and a simulation was done. Detailed schematic of the entire schematic is given in Appendix B. The heat and mass balances can be seen Appendix D. The following results were obtained:

Table 4: Output of the steam turbine without TES

Power output from "Process 1":	**4.5**	**h/day**
Steam turbine gross power:	29,177.00	kW
Parasitic loads (pumps and other auxiliaries):	878.85	kW
Steam turbine net power:	28,298.15	kW
Daily production:	127,341.68	kWh
	127.34	MWh
Power output from "Process 2":	**10.5**	**h/day**
Steam turbine gross power:	21,513.00	kW
Parasitic loads (pumps and other auxiliaries):	733.33	kW
Steam turbine net power:	20,779.67	kW
Daily production:	218,186.54	kWh
	218.19	MWh
Power output from "Process 3":	**9**	**h/day**
Steam turbine gross power:	16,055.00	kW
Parasitic loads (pumps and other auxiliaries):	627.98	kW
Steam turbine net power:	15,427.02	kW
Daily production:	138,843.18	kWh
	138.84	MWh
Total daily production:	484.37	MWh
Total yearly production (assuming 8000 hours):	161,295.67	MWh

Without any kind of thermal energy storage, the net daily production would be **484.37 MWh**. It should be mentioned, that in this case, the design (nominal) point would be based on the energy recovered energy from “Process 1”. As the steam turbine would be produced for those parameters, in all other cases it would work in off-design conditions. Thus, the partial load performance would have to be analyzed, since the power output of the turbine from “Process 3” is only **55%** of the nominal load. Furthermore, the partial load during “Process 2” is **75%** percent of the nominal, meaning that for 19.5hours of the day the turbine would work at partial load. This doesn’t necessarily mean that it would negatively impact the lifespan of the turbine and that it would lead to more frequent maintenance, if taken into account since the beginning of the design phase. However, it is something that should be taken into consideration, when deciding which option is the best.

6.4. Sizing and designing the steam accumulator

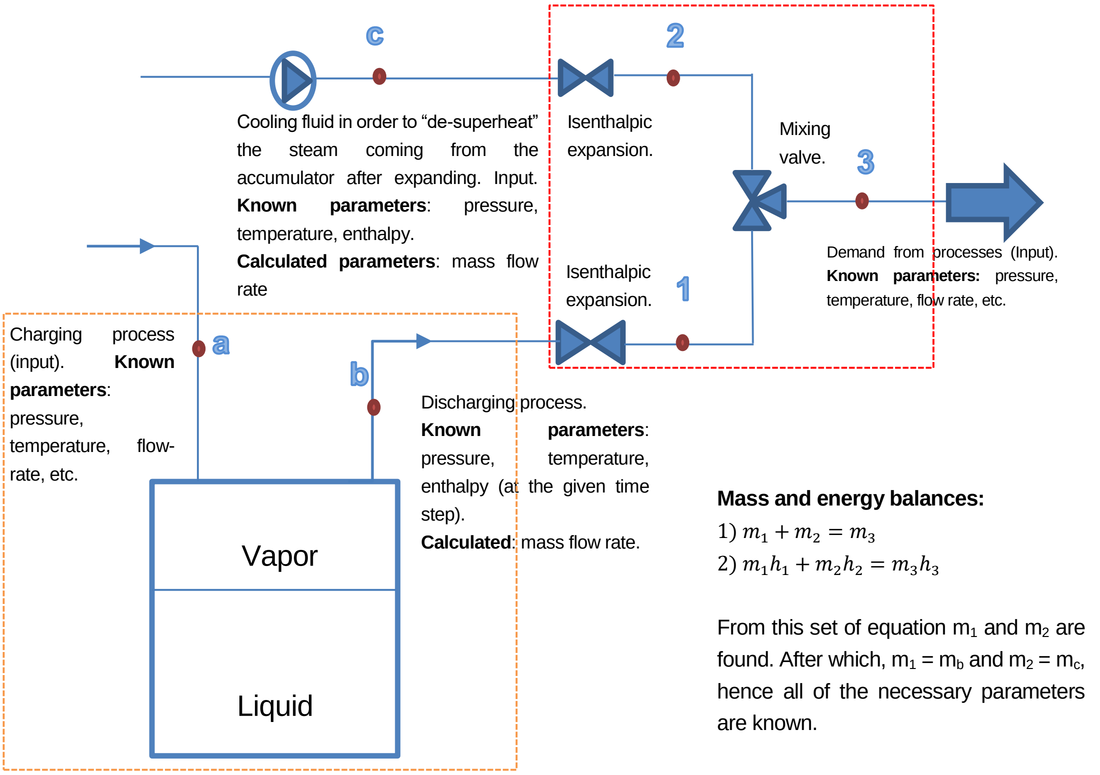
For the needs of sizing and designing the steam accumulator a tool was developed. This tool is composed of a series of mass and energy balances, that have to be coupled in order to create a simulation of the behavior of the accumulator. Since the pressure and temperature of the charging process are known, only the initial conditions are needed to be assumed in order to have a functional model. For the discharging process, it is dependent on the intended use, as the steam accumulator can be used for either satisfying the demand of the manufacturing processes or for balancing the electricity production. In any case, the parameters of the discharging process would also be known. Hence, when knowing the parameters (pressure, temperature, state, mass flow rate) of both the charging and discharging process, all of the required data for a successful simulation is available. Besides the behavior of the system, the physical size of the steam accumulator would be calculated as well. This has big practical implications, as one of the physical constraints in the project is the space that is available at the industrial site.

In Table 5 all of the necessary parameters that are needed for the model of the steam accumulator are given. They are categorized by whether they’re an input (known value), a function of the input value (meaning they can be easily derived depending on the input value) or if they’re the output value (i.e. the value that has to be calculated).

Table 5: Categorization of the parameters of all the streams

	Charging process					Discharging process					Demand from processes					Cooling water				
	P	T	ṁ	h	x	P	T	ṁ	h	x	P	T	ṁ	h	x	P	T	ṁ	h	x
Known (input)	✓	✓	✓			✓	✓			✓	✓	✓	✓		✓	✓	✓			✓
f(input)				✓	✓				✓					✓					✓	
Unknown (output)								✓										✓		

The simulation starts from the initial conditions. Thanks to the initial conditions, the mass of the fluid inside the tank can be calculated as well as the energy contained inside the fluid. When the tank is charging, the mass of the fluid is increased according to the mass flow rate. The energy inside the accumulator is updated thanks to the enthalpy of the charging stream (once the pressure and temperature are known, the enthalpy can be found as well). The values of the mass and energy are updated at every time step. The time step is an initial input. At the same time, the thermal losses to the surroundings are also calculated at each time step. The thermal losses are a function of the temperature difference between the steam accumulator and the surrounding (assumed to be at 25°C), and the thermal conductivity (which is a function of the material – steel in this case). The temperature is also updated at every time step. When discharging is needed, the calculation is a bit different. It starts from the demand of the process. Then the mass flow rate of the cooling water is calculated (the pressure and temperature are known), and finally the needed discharge mass flow rate.



Cooling fluid in order to "de-superheat" the steam coming from the accumulator after expanding. Input. **Known parameters**: pressure, temperature, enthalpy. **Calculated parameters**: mass flow rate

Demand from processes (Input). **Known parameters:** pressure, temperature, flow rate, etc.

Charging process (input). **Known parameters**: pressure, temperature, flow-rate, etc.

Discharging process. **Known parameters**: pressure, temperature, enthalpy (at the given time step). **Calculated**: mass flow rate.

Mass and energy balances:

1) $m_1 + m_2 = m_3$

2) $m_1 h_1 + m_2 h_2 = m_3 h_3$

From this set of equation m_1 and m_2 are found. After which, $m_1 = m_b$ and $m_2 = m_c$, hence all of the necessary parameters are known.

Figure 10: Visual representation of the model for the simulation of the behavior of a steam accumulator

Figure 10 gives a visual representation of the entire model based around the steam accumulator. It is composed of two mass and energy balances. In the figure, their boundaries can be distinguished by the orange and red dotted outlines respectively. The first mass and energy balances (orange outline) are done on the steam accumulator:

$$m_{accumulator}\ [i+1] = \ m_{accumulator}[i] + m_a[i] - m_b[i] \qquad \textit{(Eq. 14)}$$

$$Q_{accumulator}[i+1] = Q_{accumulator}[i] + Q_a[i] - Q_b[i] - Q_{losses}[i] \qquad (Eq.\ 15)$$

Where:

- $m_{accumulator}$ – mass of the accumulator [kg]
- m_a – mass of the charging process (that is entering the steam accumulator) [kg]
- m_b – mass of the discharging process (that is leaving the accumulator) [kg]
- $Q_{accumulator}$ – energy contained inside the steam accumulator [kJ]
- Q_a – energy contained in the charging stream [kJ]
- Q_b – energy that is being “taken away” during the discharging process [kJ]
- Q_{losses} – thermal losses to the surroundings [kJ]

As the tool that was created deals with the temporal evolution of various parameters of the steam accumulator, “[i+1]” and “[i]” represent the future and current time steps respectively. Also, it is important to note that the calculations are being done with discretized values. Hence, the total mass that is being put inside or outside of the tank during a single time step is being considered. Therefore, the model does not work with the mass flow rate. The situation is similar with the energy balances. The energy inside the tank at the first time-step is derived from the initial conditions. After that it is calculated based on the charging process, discharging process and the thermal losses. The energy of the charging process is the mass multiplied by the enthalpy (which is a function of the pressure and temperature). The energy of the discharging process is also equal to the mass multiplied by the enthalpy, however the enthalpy in this case would be a function of the pressure inside the steam accumulator and of quality 1 (meaning saturated vapor).

The second mass and energy balances are done based on the needs for the processes (point 3 and red boundaries in Figure 10). The parameters are known at point 3, however at point 1 and 2 we only know the enthalpies, and not the masses (again, discretized values are used). It is important to underline that after extracting the steam from the steam accumulator, it would have to be expanded to meet the precise requirements of the process. Hence, a certain degree of super-heated steam would be obtained. The industrial processes use latent heat; thus, it is necessary to bring the steam back to saturated vapor conditions. In this particular case, this would be done by extracting water from the feedwater pump. Since the enthalpies are known at all point, only the exact masses have to be calculated. A system of 2 equations with 2 unknowns, will be obtained, which can be easily solved.

$$m_1 + m_2 = m_3 \qquad (Eq.\ 16)$$

$$m_1 \cdot h_1 + m_2 \cdot h_2 = m_3 \cdot h_3 \qquad (Eq.\ 17)$$

6.4.1. Obtained results

Once the tool was completed, it was used to simulate the behavior of the steam accumulator. Furthermore, the appropriate size of the steam accumulator could be chosen. A 3000m^3 steam accumulation system was decided to be suitable for the needs of the system. The initial conditions were as follows:

- Volume of the accumulation system: 3000 m^3
- Liquid level: 90%
- Initial pressure: 22 bar
- Temperature: 212 °C
- Time step: 15 minutes

Furthermore, in order to validate the model, validation-studies were done. Firstly, it was tested if the same (or very similar) results would be obtained with different time steps. In other words, the solution had to be independent of the time step. This was successfully done. Additionally, the individual and global mass balances had to be checked. For example, the difference between energy contained in the fluid at the first and last time-step, had to be equal to the energy that has been gained or lost from the charging, discharging and the thermal losses to environment. Balances like this seem to be a very obvious concept, but are very important to validate the model.

Table 6: Mass energy balances for the steam accumulator

1st day mass & energy balance		**2nd day mass & energy balance**		**3rd day mass & energy balance**	
Mass balance [kg]		**Mass balance [kg]**		**Mass balance [kg]**	
Inlet	96,750.00	Inlet	96,750.00	Inlet	96,750.00
Outlet	-104,206.53	Outlet	-104,202.32	Outlet	-104,198.49
Delta	-7,456.53	Delta	-7,452.32	Delta	-7,448.49
Energy balance [kJ]		**Energy balance [kJ]**		**Energy balance [kJ]**	
Inlet	311,000,232.64	Inlet	311,000,232.64	Inlet	311,000,232.64
Outlet	-311,273,743.38	Outlet	-311,346,754.92	Outlet	-311,419,661.50
Delta	-273,510.74	Delta	-346,522.28	Delta	-419,428.86

In Table 6 the results obtained from the mass and energy balances are given. As can be seen the energy balance is almost perfect. The thermal losses of both discharging processes and losses to the environment are approximately 0.1% higher than the energy that is being supplied while charging the steam accumulator. On the other hand, it is obvious that for the mass balance the situation is a bit different. The mass outlet is noticeable higher that the mass inlet. However, as can be seen in Figure 12, over three days the liquid volume drops less than 1%. In other words, it means that weeks might need to pass before the steam accumulator becomes incapable of supplying the demand of the processes. As this is just a simulation in order to have initial order of magnitude for the size of the accumulator, in reality the operations of the steam accumulator might be very different. It is normal for the steam accumulator to be charged with additional water, or to be discharged in order for some of the excess energy to be dissipated.

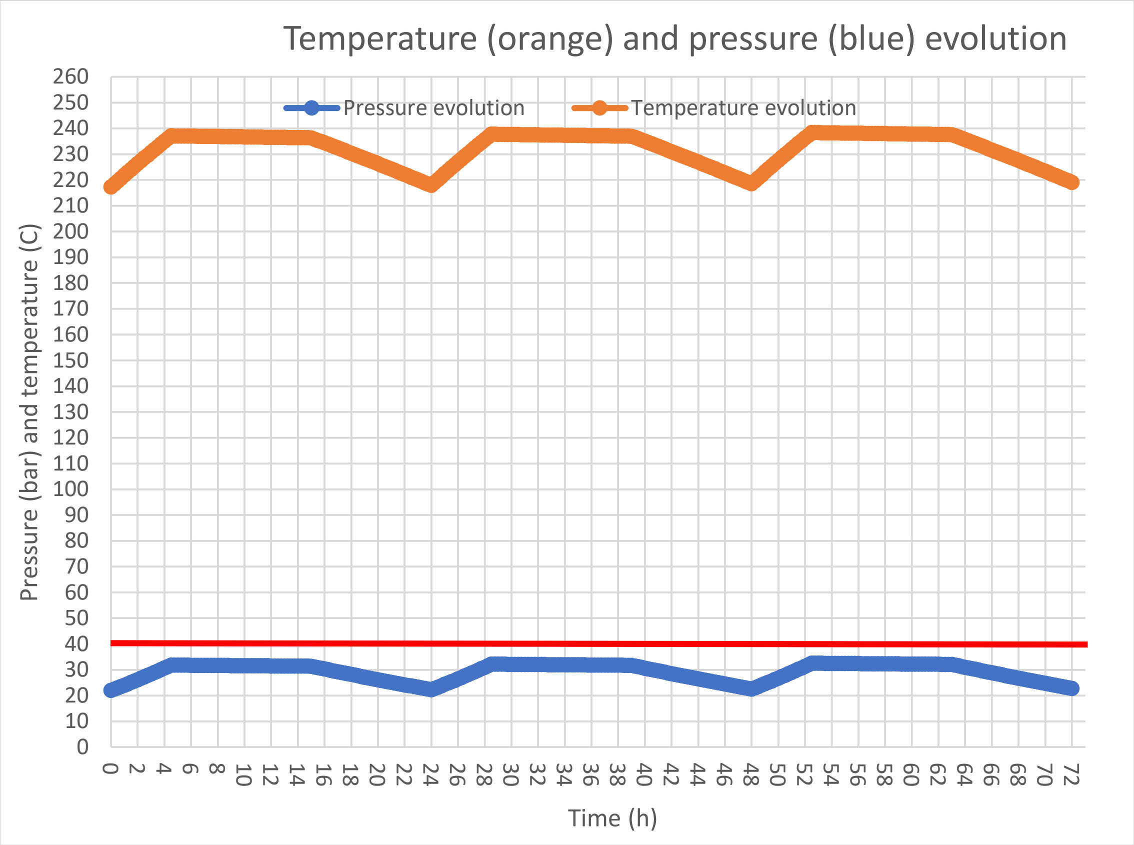


Figure 11:Temperature and pressure evolution of the steam accumulator

In Figure 11 the temperature and pressure evolution are shown. The upper limit for the pressure inside the steam accumulator is 40 bars. If the pressure is higher, than steam obtained from the HRSG won't be able to flow into the steam accumulator. The bottom limit for the pressure is 20 bar plus some safety margin. With the steam accumulation the goal is to satisfy the process needs at 20 bars, hence the bottom limit. The safety margin was decided to be 2 bars. Unlike the pressure, there are not specific limits and constraints for the temperature.

In Figure 12 the evolution of the liquid volume in the accumulator is given. As can be seen, the behavior is very similar to the evolution of the temperature and pressure, in terms of repeatability. It can be seen clearly when the accumulator is charged or discharged.

Figure 13 shows the extrapolation of the maximum and minimum pressure levels. It takes into consideration the maximum pressure and minimum pressure recorded for each day. As the behavior of the accumulator is repeatable, even linear approximations are a good indicator for how the pressure levels will evolve after the three-day simulation period. Both the maximum and minimum pressure experience increase with each subsequent day. At day 11, it is expected for the maximum pressure in the tank to be approximately 36 bar. The pressure inside the tank must be lower than the pressure of the charging fluid. Otherwise, the charging fluid would not be able to enter the tank.

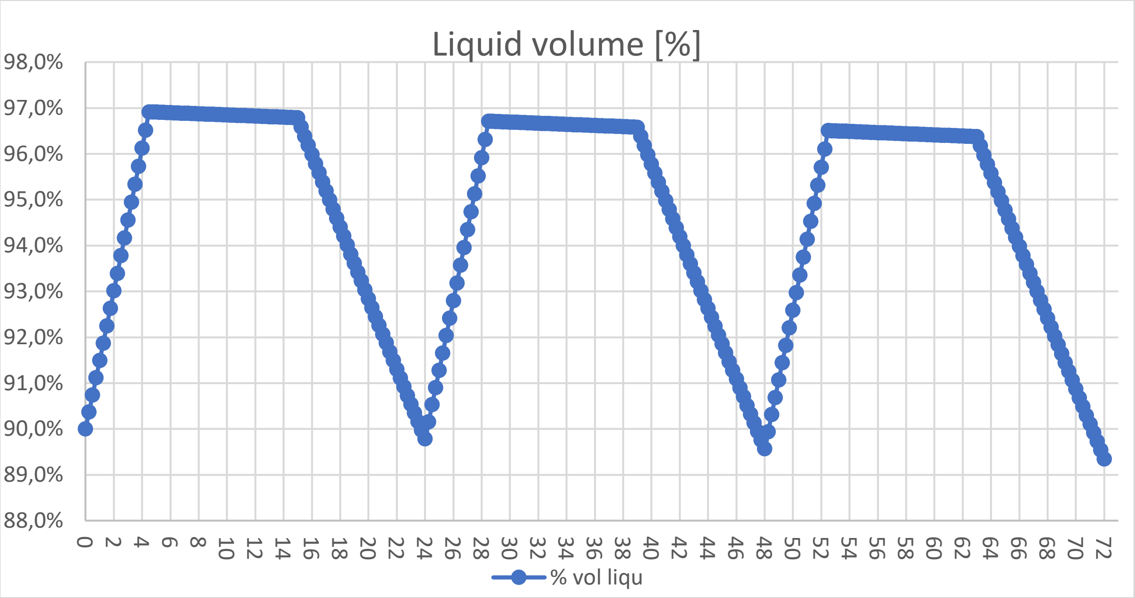


Figure 12: Evolution of the volume of the liquids phase within the steam accumulator

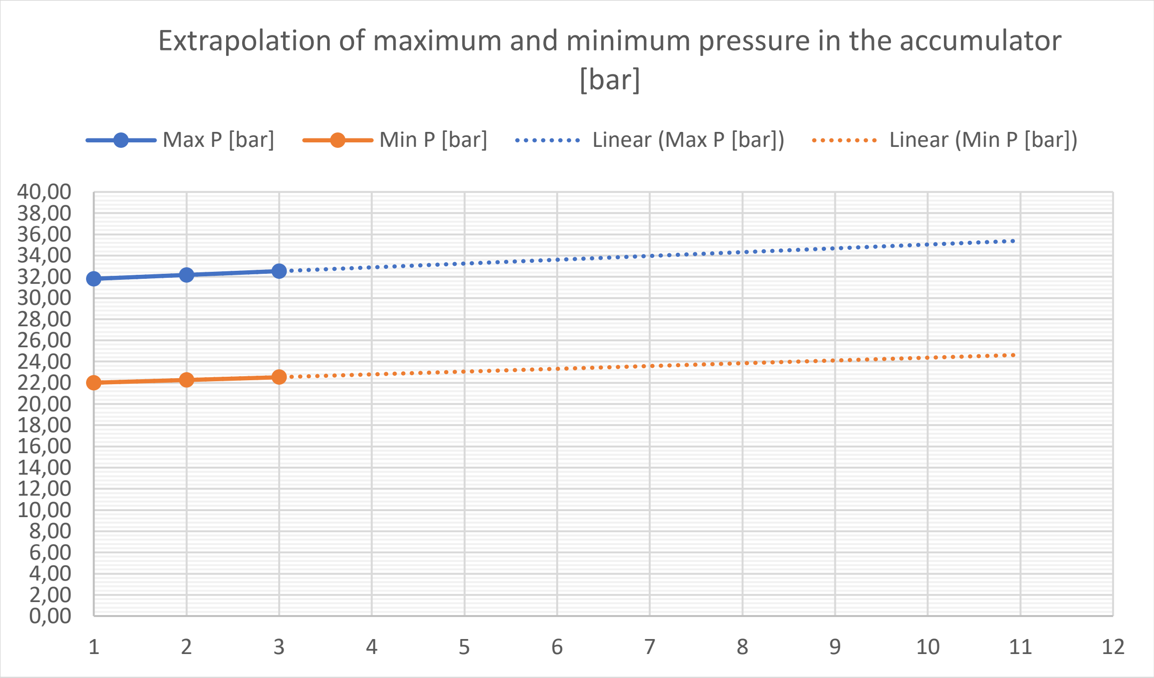


Figure 13: Extrapolation of maximum and minimum pressure

In *Appendix E* more detailed view of the interface of the steam accumulation tool is given. There, the calculations done for each time step can be clearly observed.

6.5. Molten salts storage

Although steam accumulation was chosen as the best solution, molten salts were also analyzed. The molten salt in question, is a binary mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3). The performance of the heat exchanger between the exhaust gasses and the molten salts was analyzed with the help of the “Thermoflex” software. Off-design analysis was not done, as it was clear from the “design-point” analysis that molten salts would not be a feasible solution for this project. In order to be more accurate and confirm the calculations, the open-source “CoolProp” library was also used. [18]

Table 7: Data for the molten salts - exhaust gasses HEX [19]

		T [°C]	h [kJ/kg]	Flowrate [kg/s]	Exchangeable energy [kW]
Exhaust gasses	Inlet	580.00	586.30	127.78	37,464.44
	Outlet	310.00	293.10		
Molten salts	Inlet	300.00	411.74	91.42	
	Outlet	570.00	821.55		

The values in blue are input data, and the values in black are calculated data. The inlet temperature of molten salts was set at 300°C in order to avoid any potential for crystallization of the salts. Although this process starts at 250°C, in CSP plants the minimum temperature is set usually in the range of 290-300°C. The large safety margin is justified, due to the fact that if the salts crystalize at any point in the system, it might lead to a long fixing and maintenance period. For this project, this would be a limitation, since a lot of energy is still left in the exhaust gasses. A 10°C temperature difference was assumed between the two fluids at both inlet and outlet.

The total mass needed can be obtained if the mass flow rate of the molten salts on per hour basis is multiplied with the duration of “Process 1” from the new waste heat streams (Table 7). This would yield a total mass of almost 1.5 million kilograms needed for the molten salts (1,480,982.84kg is the precise value). According to a study done by the National Renewable Energy Laboratory (NREL)[20], the price of molten salts are approximately in the range of $800 to $1000 per ton. Hence, the price of the molten salts would be in the range of $1.2 to $1.5million. For a project of this size, this is not something that can be neglected. Furthermore, the expenses for procuring the storage tanks are not taken into consideration. Hence, from a financial perspective, this solution is far from the best option.

However, the main reason why molten salts are discarded is not financial, but rather thermodynamical and practical. The usual practice with molten salts is to use an intermediary circuit with heat transfer fluid (HTF), usually a thermal oil. This is done in order to “protect” the molten salts from crystalizing. Although there is a safety margin of more than 40°C from the crystalizing temperature, this represents the bulk temperature. However, locally at some point, the temperature might drop to below the liquidus temperature. This is especially true in a heat exchanger, where the cold fluid entering is well below the 250°C liquidus temperature. So, if molten salts are used directly in a heat exchanger for steam generation purposes, where the water would enter at well below 250°C, the risk of crystallization increases. Crystalizing molten salts, can cause real problems and might put the entire system out of operation for a prolonged time. This cannot be allowed, as the primary concern for the client is for his manufacturing processes not to be disturbed in any way. Hence, why intermediary circuit is used. However, this intermediary circuit complexifies the entire system, and the cost for implementation is not negligible. For example, one liter of thermal oil might reach prices of up to 10 €/l. Last but not least, with molten salts at design point conditions roughly 38 MW_t are recovered at nominal conditions, while in the other case, by employing HRSG, 48 MW_t are recovered at nominal conditions.

To conclude, due to thermodynamic and financial reasons, it is rather obvious that molten salts thermal energy storage is not appropriate for this use. It would unnecessarily complexify the system, while also increasing the chances of stopping production.

6.6. System B: Steam turbine with thermal energy storage

By employing thermal energy storage, namely steam accumulation, the aim is to indirectly increase the electrical production, by satisfying the demands for process steam. Furthermore, the goal is to increase the power output of the turbine during the waste heat recovery of "Process 3", since that process takes 9 hours of the day. Hence, even though the power output might decrease during the waste heat recovery of "Process 1", overall an increase in electricity production will occur. Table 8 shows the obtained results for System B.

Table 8: Output of the steam turbine with TES

Power output from "Process 1":	**4.5**	**h/day**
Steam turbine gross power:	23,966.00	kW
Parasitic loads (pumps and other auxiliaries):	746.87	kW
Steam turbine net power:	23,219.13	kW
Daily production:	104,486.09	kWh
	104.49	MWh
Power output from "Process 2":	**10.5**	**h/day**
Steam turbine gross power:	21,950.00	kW
Parasitic loads (pumps and other auxiliaries):	708.69	kW
Steam turbine net power:	21,241.31	kW
Daily production:	223,033.76	kWh
	223.03	MWh
Power output from "Process 3":	**9**	**h/day**
Steam turbine gross power:	19,393.00	kW
Parasitic loads (pumps and other auxiliaries):	647.44	kW
Steam turbine net power:	18,745.56	kW
Daily production:	168,710.04	kWh
	168.71	MWh
Total daily production:	496.23	MWh
Total yearly production (assuming 8000 hours):	165,244.55	MWh

First thing that catches the attention, is that the nominal (maximal) load of the turbine has decreased from **29177 kW** to **23966 kW**. However, the lowest load operation (connected with Process 3 of the additional waste heat streams) has increased from **16055 kW** to **19393 kW**. This would mean that at the lowest partial load, the turbine would work with almost **81%** of the nominal load. This is a big improvement, because in system A, the lowest partial load was only **55%** of the design load. Furthermore, the daily production of electricity has been increased from **484.37 MWh** to **496.23 MWh**. In percentages, that is an increment of **2.45%.** Although this doesn't sound as much, in reality this is not negligible. The best way to visualize where this increment in electricity production comes from, is to look at Figure 14. During the first 4.5 hours of the day System A has considerably higher power output. During the next 10.5 hours System B has slightly higher power output. However, during the last 9 hours of the day System B more than overcomes the deficit from the first part of the day. Hence from a thermodynamic point of view, where the aim is to maximize the production of electricity, while also catering for the demand of process steam, it has been proven that in this case steam accumulation improves the efficiency by permitting the system to work at higher loads, closer to its design point.

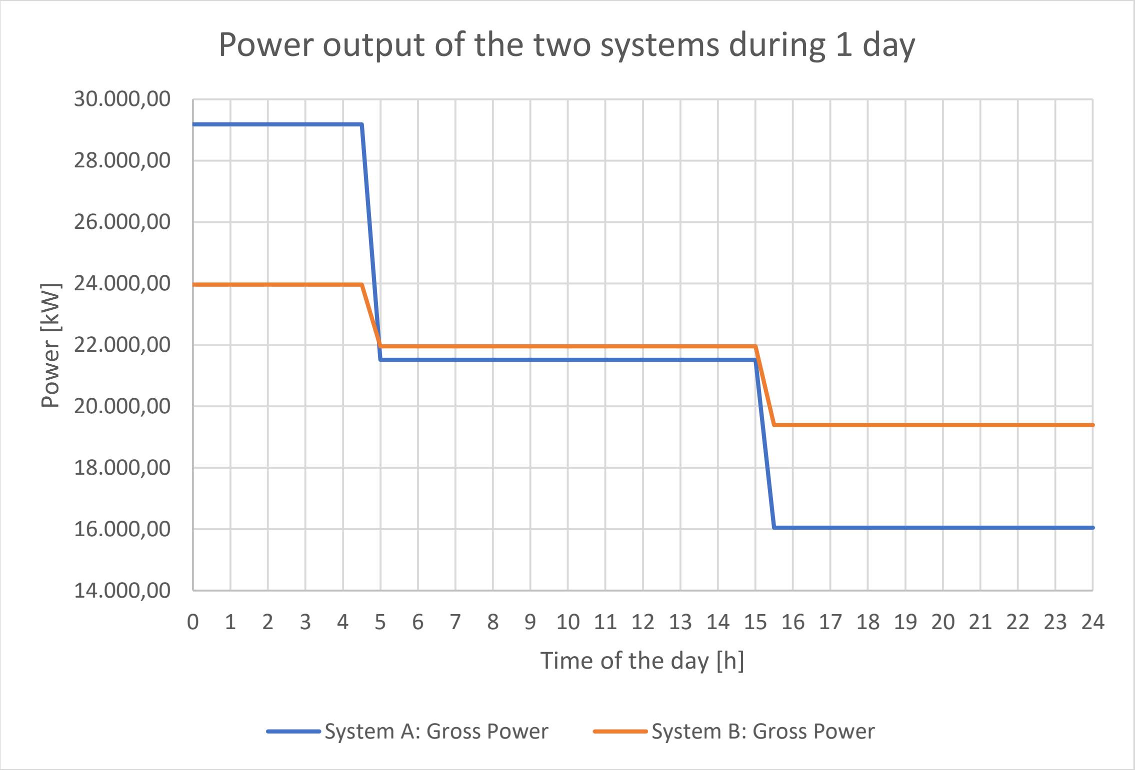


Figure 14: Power output of the two analyzed systems during a single day

From a financial point of view, this topic will be discussed more in depth in one of the following chapters. A detailed schematic of the system, together with the Molier chart are given in Appendix C. The full mass and energy balance is shown in Appendix F.

7. Techno-economic analysis

The basis for techno-economic analysis will be the two systems that have been analyzed in Section 6. The main parameters that would have to be compared are the electrical production, as well as the prices of the equipment. For the generated income on yearly basis, the additional produced electricity from the new WHR system will be taken into consideration. The prices for most of the components are taken from the database of the "Thermoflex" software, while the cost of the steam accumulator is calculated with the help of internal references from Sener. It should be noted that at this point in the development of this project, the prices are only indicative, and shouldn't be taken as a definite proof for the viability of the project.

It is very difficult to predict or to model which way the price of electricity would move. For example, during the Covid pandemic, prices of electricity would go well above 300 EUR/MWh. For example, on EU level, the quarterly average wholesale electricity price in the 3rd quarter of 2022 was highest in Italy and Malta, with prices of 472 and 460 €/MWh respectively. Although Spain had one of the lowest electricity prices on EU level in this period at 146.2 €/MWh, it had a peak of 283 €/MWh in March 2022. This goes to prove that the volatility of the markets was very high, and it was almost impossible to predict the price. For the 3rd quarter of 2022, the Pan-EU average was an enormous 338.6 €/MWh. [21] Although, currently electricity prices are somewhat stabilized, no one can guarantee what will be the price in the future. Hence, a sensitivity analysis will be done, where the impact of different prices of electricity will be analyzed. The sensitivity analysis will be done by comparing the potential income for the WHR system on a 10 year basis. Various values for the electricity prices will be taken into consideration, such as the price before the pandemic, the peak price in Spain during the pandemic and the latest available wholesale price. Although this approach wouldn't give exact and precise predictions, it could be indicative of what can be expected in the future from this system.

Furthermore, other factors, that are out of the control of both Sener or the client, could impact the value of the project, either positively or negatively. For example, a change in legislature, such as an increase in carbon taxes, or subsidies and grants for improving energy efficiency might be available or introduced. These are not taken into consideration.

In Table 9 and Table 10 the cost breakdown for both of the analyzed systems are given. These prices shouldn't be taken very seriously, as they're only indicative. However, they serve their purpose having in mind the current phase of this project. It should be mentioned that "Thermoflex" gives the prices of the components in US dollars. The prices were converted to Euros using the following conversion ratio: 1 USD = 0.91 EUR.

Table 9: System A: Approximative cost for the WHR system without TES

System A: Without Thermal Energy Storage		
Cost Breakdown	**Est. Cost**	
Sum of Costs for Equipment and Components	**14,455,607**	**€**
HRSG Assembly		
Heat Recovery Steam Generator	3,310,915	€
ST Assembly		
Steam turbine	9,112,240	€
Deaerator		
Deaerator	295,653	€
Feedwater Heater (PCE)		
Feedwater Heater	104,553	€
Vapor collectors		
Vapor collectors	266,969	€
Pipe (PCE)		
Pipes	197,208	€
Pump (PCE)		
Pumps	360,542	€
Water-cooled Condenser (PCE)		
Water-cooled Condenser	807,528	€

Table 10: System B: Approximative cost for the WHR system with TES

System B: With Thermal Energy Storage		
Cost Breakdown	**Est. Cost**	
Sum of Costs for Equipment and Components	**16,786,773**	**€**
HRSG Assembly		
Heat Recovery Steam Generator	3,310,932	€
ST Assembly		
Steam Turbine	8,243,119	€
Deaerator		
Deaerator	295,646	€
Feedwater Heater (PCE)		
Feedwater heater	99,695	€
Vapor collectors		
Vapor collectors	247,363	€
Pipe (PCE)		
Pipe	197,208	€
Pump (PCE)		
Pumps	375,093	€
Water-cooled Condenser (PCE)		
Water-cooled Condenser	729,158	€
Steam Accumulator		
Steam accumulator	3,288,560	€

As can be seen, the main difference in the prices of the two systems is the cost of the steam accumulator, which brings the total price of System B to be more than 2M EUR higher than that of System A. It should be mentioned that all of the other components in System B are less expensive than those of System A. This was expected to happen. For example, the steam turbine that would be used for System B has smaller output power than the turbine in System A.

Table 11: Comparison of produced electricity by the old WHR and new proposed options

Electricity production from the old WHR		Electricity production from the new WHR without TES		Electricity production from the new WHR with TES	
111,967,920.00	kWh	161,295,672.87	kWh	165,244,550.04	kWh
		Additional produced electricity		Additional produced electricity	
		49,327,752.87	**kWh**	**53,276,630.04**	**kWh**
		49,327.75	**MWh**	**53,276.63**	**MWh**

Table 11 gives the information for additional produced electricity. As can be seen using TES in the new WHR would result producing additional 53277 MWh, while if the steam turbine is oversized without any type of WHR 49328 MWh of additional electricity will be produced. These values will be the basis for the sensitivity analysis.

The sensitivity analysis will be analyzed with three prices for the electricity:

- 60 €/MWh - representing the price before the pandemic;
- 283 €/MWh – representing the peak price of electricity in Spain during the pandemic;
- 146.2 €/MWh – representing the average price of electricity in Spain during the 3rd quarter of 2022

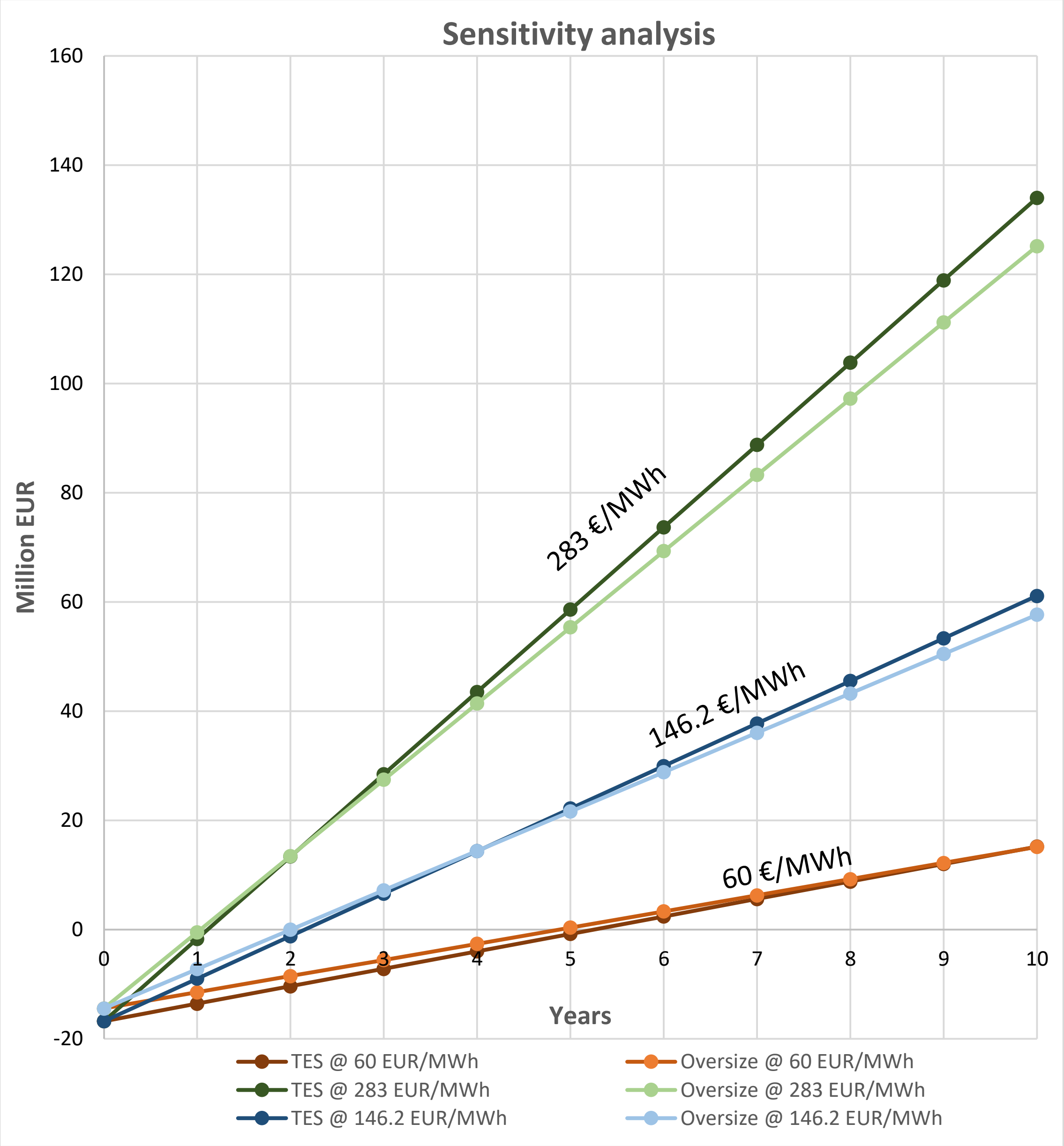


Figure 15: Sensitivity analysis

Figure 15 gives the cashflow for both proposed systems, depending on the price of electricity. As can be seen, all of the curves start from negative values, which are representing the CAPEX cost, i.e. the investment cost. Afterwards, for each subsequent year the additional produced electricity compared to the old WHR system is multiplied with the electricity prices. Operational expenditures (OPEX) are not taken into account, however they can be considered to be more or less equal for both systems.

When the electricity price is 60 €/MWh, both of the systems require around 5 years to break even. To be more specific, the system without thermal energy storage (System A) would require 4.88 years to break even, while the other (System B) will require 5.25 years. In the long term, it seems that system B will bring bigger savings after 10 years. Hence, from a financial point of view, with this price of electricity, there cannot be a clear recommendation which system is better.

When taking into consideration the average wholesale electricity price in Spain during the 3rd quarter of 2022 (146.2 €/MWh), the situation is a bit different. Both systems break even after 2 years. System A (without TES) breaks even after 2 years, while System B breaks even after 2.11 years. In this case, System B would generate more savings after only 4 years, compared to System A. Hence, it is easier to recommend to go with the option of incorporating thermal energy storage.

Finally, when the electricity price is the peak price of 283 €/MWh, it is clear that thermal energy storage should be incorporated into the system. Both systems need around 1 year to break even, with System A (without TES) needing 1.04 years, while System B needs 1.11 years. After little bit more than 2 years, System B starts generating more savings, hence it is more than obvious that higher electricity prices favor the introduction of thermal energy storage.

At the end, it should be noted that inflation wasn't taken into consideration when doing the techno-economic analysis. As this project is at the level of a feasibility study, there is no need to complexify the problem by taking into consideration the inflation. This is justified, as in this analysis there are much bigger uncertainties, such as the actual costs of the components, manpower, operational and maintenance costs, etc. that should be prioritized, because they would increase the accuracy of the study much more compared to introducing the effect of the inflation.

8. Environmental and social impact

8.1. Outlook of the energy consumption by the industry

Industry is one of the 3 biggest consumers of energy globally (the other two being the transport and the household/residential sectors). Ever since the industrial revolution, the growth of industry has been based almost exclusively on higher use of fossil fuels. In other words, the bigger the consumption of fossil fuels, the bigger the industrial activity. Not surprising, this has led to increasing levels of greenhouse gasses emissions that have been accumulating in the atmosphere for more than 2 centuries. Climate change has been accelerated by such activity. Therefore, the need to decouple industrial growth and energy use, as well as decarbonizing the industry is in the focus of the so called “Energy Transition”.

8.1.1. Energy consumption and CO_2 emissions by the industry in EU and globally

One of the biggest challenges humanity is currently facing is how to transition towards self-sustainable societies and limit the carbon footprint. This transition has also been labeled the “Energy Transition”. It implies the necessity to use renewable energy sources as well as low carbon intensity energy sources as a substitute to the fossil fuels. One sector that is a big consumer of energy, and by extension a big greenhouse gas emitter, is the industry. It is responsible for more than one quarter of the final energy consumption in the EU. [22]

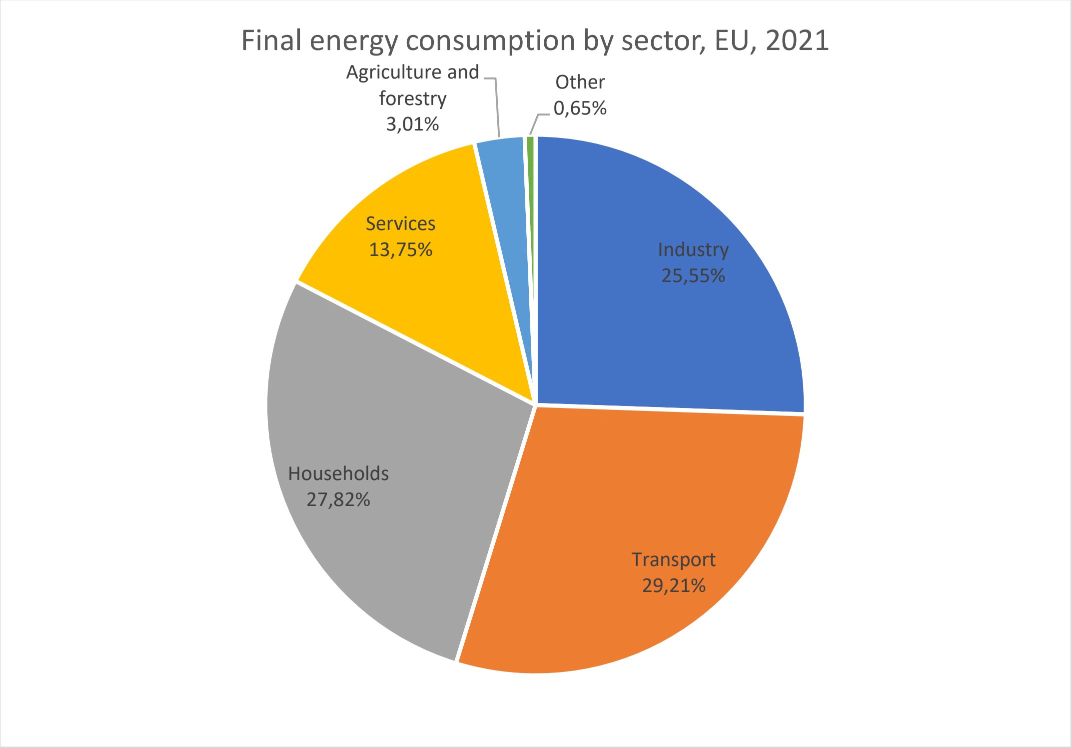


Figure 16: Final energy consumption by sector in the EU, 2021[22]

As can be seen from Figure 16, the three biggest sectors (industry, residential and transport) consume more than 82% of the final energy. Hence, it is obvious why many different pathways towards net-zero CO2 emissions envision decoupling energy consumption and industrial growth. Furthermore, it is also evident that increasing the overall energy efficiency in the industrial sector is needed since this would result with more competitive base cost for the manufacturers, which may lead to bigger profit margins. Additionally, with the carbon tax and the volatility of the prices of fossil fuels (such as natural gas) and electricity, projects that were not economically feasible few years ago, are now becoming very attractive. This is especially true for utilizing low grade waste heat from industrial processes, where until recently it wasn't cost effective to incorporate some form of heat recovery systems. Now, this has changed, and there is industry-wide trend of being as energy efficient as possible. With low fuel prices, this wasn't the case, as it was more convenient to just "throw away" the waste heat.

It should be mentioned that Figure 16 is created based on consumption of energy for "energy use". In other words, it is not taken into consideration the consumption of fossil fuels as a feedstock for industrial process. Hence the real carbon intensity of the industrial sector is much bigger, and decarbonizing the industry shouldn't be only thought of as substituting the energy that is "powering" the sector, but also decarbonizing the feedstock.

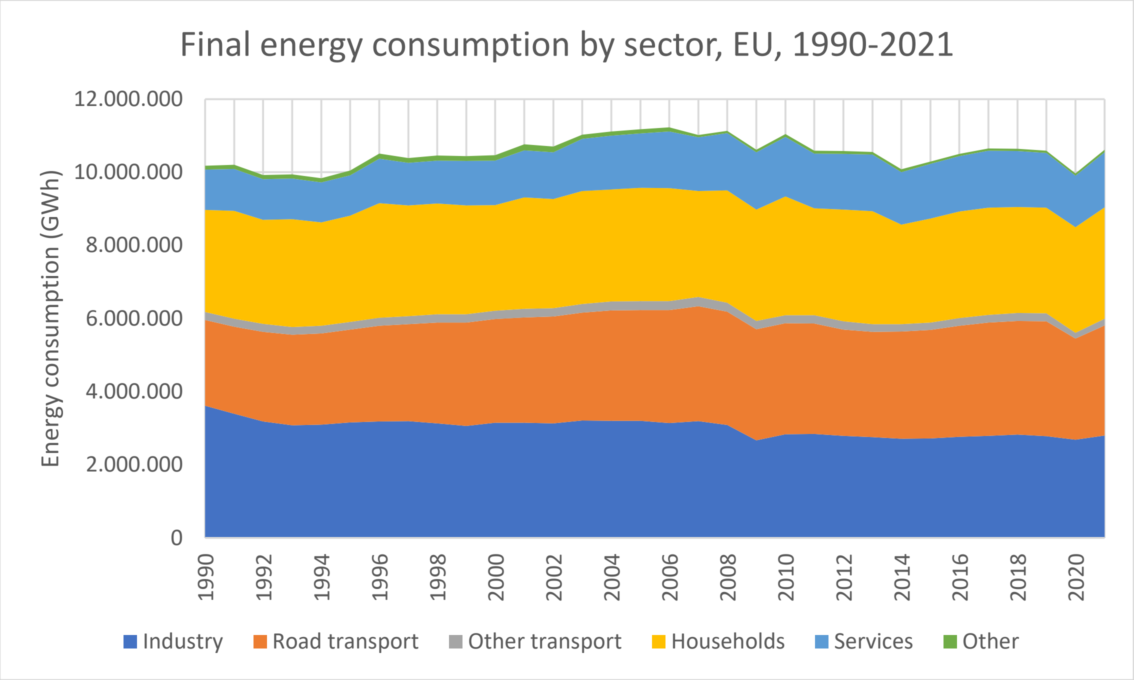


Figure 17: Energy consumption by sector in the period 1990-2021[22]

In Figure 17 the final energy consumption by sector is given, for the time period of 1990-2021. For the industry sector it can be observed that there is a trend of small decline of the final energy consumption. Although this is a good result, in order to reach the goals of the energy transitions, there would have to be even bigger decline in the upcoming years.

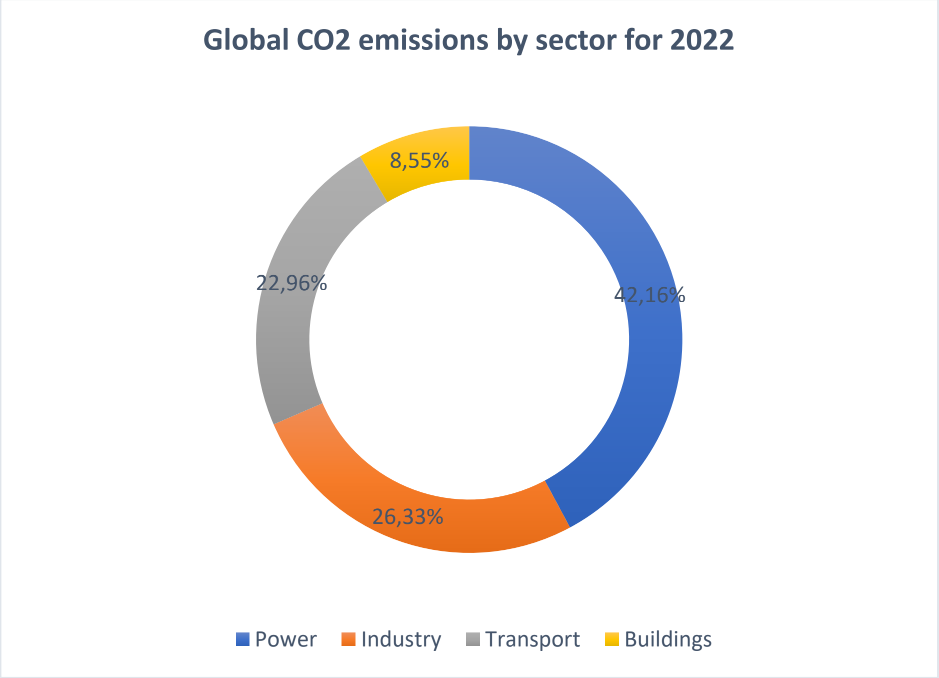


Figure 18: Global CO_2 emissions by sector in 2022 [23]

The CO_2 emissions can be thought of as an extension of energy consumption. Hence, it shouldn't be surprising that the industry sector is responsible for 26.33% of the global CO_2 emissions in 2022, which almost perfectly matches the share of the industry sector for final energy consumption in the EU. Therefore, actions should be taken in order to decarbonize the industry, as without such steps, it is impossible to have anything that resembles a zero-carbon scenario.

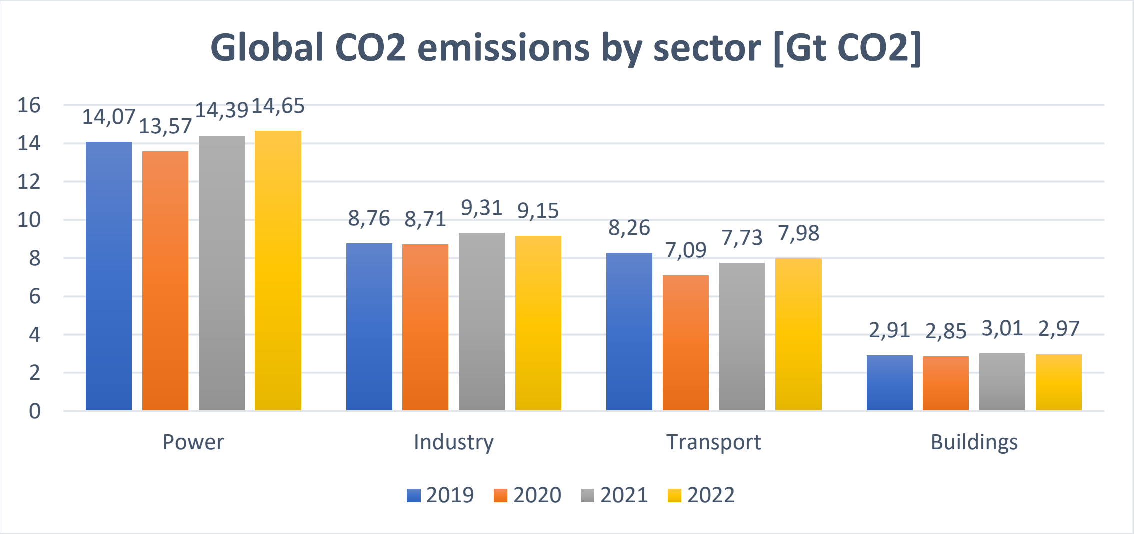


Figure 19: Global CO_2 emissions by sector for the period 2019-2022[23]

It shouldn't be overlooked that the industry seems to be doing the best among the 4 biggest sectors, when it comes to decarbonizing. Analyzing the data in Figure 19 we can see that only the industry, and to a lesser extent the buildings sector, have experienced a decline in CO_2 emissions between 2021 and 2022. Due to the CoVid-19 pandemic, every sector experienced a decrease in CO_2 emissions in 2020 when compared to 2019, however, this was an “artificial” decrease, as it was mainly due to the restriction of movement, which resulted with a lowered industrial activity. Hence, the decrease of CO_2 emissions in the transport sector is not due to the improved practices, but mainly due to sector not recovering completely to pre-pandemic levels. This can be proven by the fact the key markets such as China still had movement restrictions in place, while other big markets such as Russia simply stopped any activity due to the sanctions imposed on them.

8.1.2. Decarbonization

As previously mentioned, industrial decarbonization is an integral part of the various pathways towards net zero. Decarbonization can be thought of as a process, where the current practices and processes in a given sector are adapted to use energy sources that are either renewable or have low carbon intensity.

In the not so distant past, companies didn’t pay much attention towards energy efficiency and improving energy streams, as the price of the fossil fuels were low and the supply secure. However, the landscape has drastically changed since then. The supply isn’t as stable as it once was, due to various reasons that are usually connected with events that cannot be controlled. Furthermore, the price of electricity was also very volatile, especially during the Covid-19 period. Additionally, with the introduction of various forms of carbon taxation, companies were forced into reducing their CO2 footprint, since any use of fossil fuel that wasn’t an absolute must would result with paying taxes that could have been avoided. All of this resulted with the industrial sector heavily investing in improving their already existing sites. Projects that were deemed not to make sense from a financial perspective are now considered a smart investment, as in this way the vulnerability from high energy prices in the future is decreased.

The first thing that comes to mind when industrial decarbonization is mentioned, is using renewable energy sources to power the plants. Certainly, high carbon intensity fuels are being used to cater for the demands of the various processes that are present in different industries. However, one aspect that is often overlooked, is the use of fossil fuels as a feedstock, that will be transformed into a different commodity. This is especially true for the ammonia, cement, ethylene and steel industries. In a report by McKinsey&Company it is estimated that 30% of the total emissions are emissions related to feedstocks. [24]

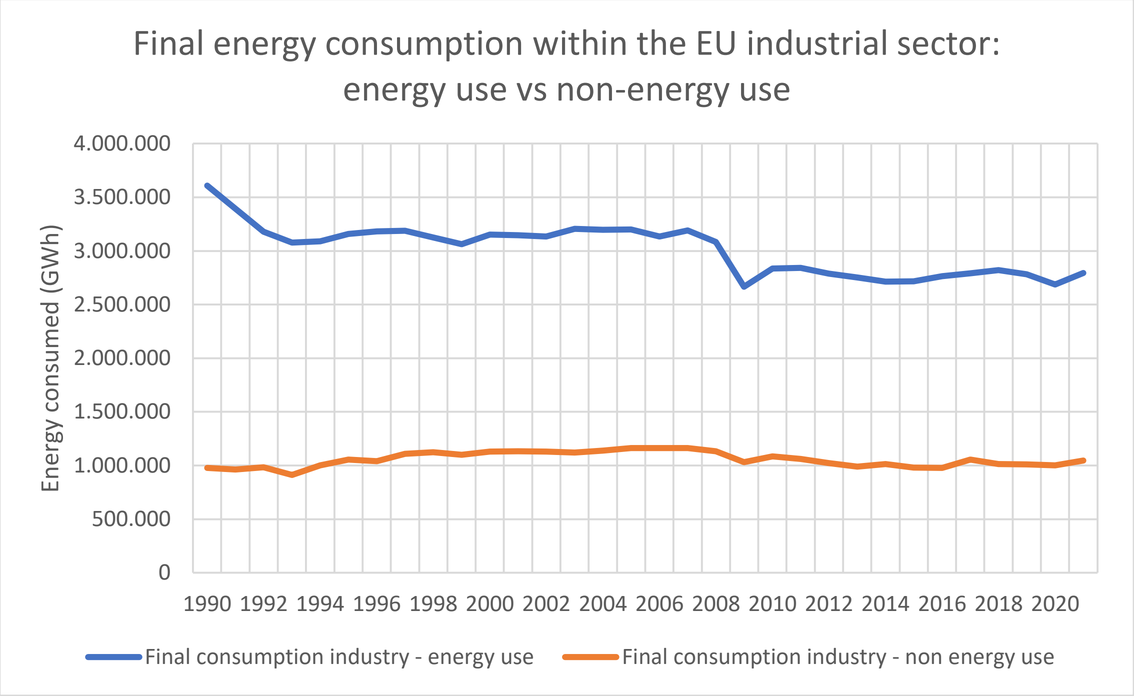


Figure 20: Evolution of the final energy consumption for energy and non-energy use [22]

In Figure 20 the historical evolution of the final energy consumption in the industry in EU is shown. As can be seen, the overall trend for energy use has been decreasing, although there are some local peaks and drops. However, when the energy consumption in 1990 is compared with the energy use in 2021, the decrease in energy use is evident.

When it comes to non-energy use in industry, the peak has been reached in the mid-2000s. Overall, it can be said that the final energy consumption for non-energy use has been somewhat constant. Certainly, the peak has been observed in the mid-2000s, before undergoing a declining trend. However, when comparing the 1990 levels with 2021 levels, we will observe very similar results. Hence, the need for decarbonizing the feedstocks is clear.

8.1.3. Waste heat recovery (WHR)

Waste heat recovery can be thought of as indirect decarbonization. By improving the current practices and processes, less energy in the form of waste heat will be rejected to the environment. Hence, by recovering and utilizing waste heat, a useful form of energy can be obtained. Usually this is in the form of electricity, but there are cases when waste heat has been utilized for district heating.

Improving industrial energy efficiency has been the focus of both academia and legislators. For example, in 2018 the European Union updated it's previous target for industrial energy efficiency, increasing from 27% to 32.5%. [25] Additionally, the EU has kept the possibility of revising and increasing its target by 2023.

Various academic research and papers have tried to analyze the amount of waste heat that is dissipated to the environment and to quantify the potential for electrical production. In the study of Forman et al. [26] it is claimed that worldwide 68PWh were lost as waste heat. A different study, conducted by Bianchi et al. [27] claims that almost 50% of industrial final energy consumption is either lost or is dissipated to the environment as exhaust/effluent. The same paper also claims that with conservative estimation there is potential to exploit 300 TWh/year.

Thus, it is evident that there is a lot of potential for improving industrial energy efficiency by means of waste heat recovery. The most common technologies employed for waste heat recovery have been the Steam (StC) and the Organic Rankine Cycle (ORC). Both of these technologies are very mature, providing stable long-term operations. Both of these technologies employ the same thermodynamic cycle (the Rankine cycle), but are used for different temperature ranges and power outputs. Steam Rankine cycle is a common option for applications characterized by medium-to-large power output (usually in the range of tens to hundreds of MWs), and for high temperature levels (400°C – 700°C). On the other hand, ORC is preferred for smaller systems (from few hundreds kW to tens of MW) and low-to-medium heat source temperatures (from 100°C to 400°C). [28] Another promising technology, that should bridge the gap between ORC and StC, is the supercritical CO_2 Brayton cycle (sCO_2). Although it is a very popular research topic, at the time of writing sCO_2 is not a commercially ready technology.

8.2. Avoided CO_2–eq. emissions

In order to better understand the environmental impact of energy, it has to be quantified in a way. This is done by the so called “carbon dioxide equivalent emissions” or CO_2 – eq for short. In other words, it tries to find the common denominator for all emissions from greenhouse gasses (GHG). The idea behind CO_2–eq. is very similar to “ton of oil equivalent” being used as an energy unit.

When alluding to greenhouse gasses and their CO_2-eq. emissions, we usually refer to the following 6 gasses, that have been covered by the Kyoto Protocol: Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride. [29]

The definition of carbon dioxide equivalent is the amount of CO_2 emissions that would have the same radiative intensity as a certain quantity of a greenhouse gas, or “mix” of greenhouse gasses, multiplied by its respective global warming potential (GWP), to take into account the different lengths of time they remain in the atmosphere. [29]

When assessing the environmental impact of a corporation, product, or just a site, the protocol consists of 3 scopes. The fist scope is the direct scope, and this scope deals with the company's facilities and its energy use, such as the fuel for the company owned vehicles. The second scope deals with the purchased electricity, heating and cooling for its own use. The third and final scope deals with emissions generated due to activities such as business travel, employee commuting, waste generated in operations and so on. The three scopes of accounting for the CO_2–eq. produced by various GHG can best be understood by looking at Figure 21.

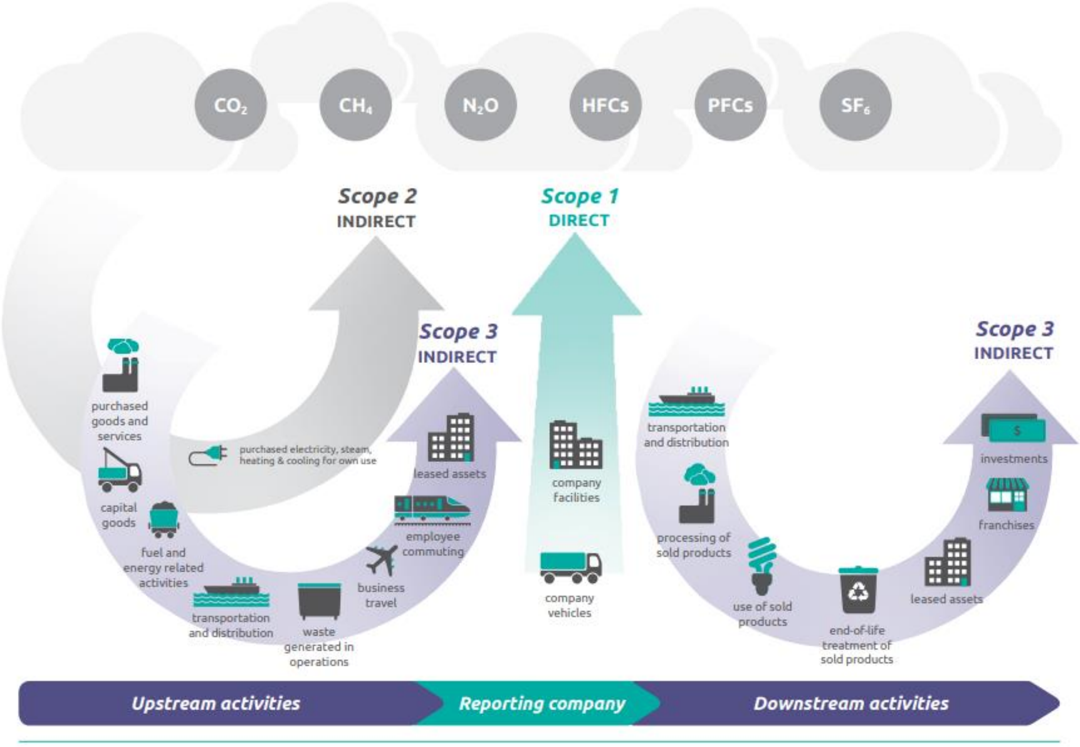


Figure 21: Overview of GHG Protocol scopes and emissions across the value chain[30]

In order to assess the environmental impact of the proposed WHR system, the scope is limited to the analysis of "Scope 2". An assumption will be made that if the energy contained in the exhaust gasses is not recovered by the proposed system, that energy will be simply dissipated to the environment and there wouldn't be any benefit. Thus, this electricity would be essentially carbon free electricity. The electricity that may be produced by the WHR system will be compared with the average emissions of the Spanish utility companies. For the Spanish companies, the average is **162 gCO_2-eq./kWh**. [31]

As mentioned in the previous sections, the total amount of produced electricity on annual basis would be **165,244,550.04 kWh**. However, this value incorporates the electricity produced by the old WHR system. In order to quantify the environmental impact of the expansion of the WHR system, the amount of electricity that could be produced by only the old system (**111,967,920.00 kWh**) should be subtracted. Thus, the expansion of the WHR system would be worth **53,276,630.04 kWh** a year. When multiplying the additional produced electrical energy with the CO_2-eq. emissions per kWh, it would be obtained that more than **8600 tCO_2-eq.** emissions have been avoided.

To put things into perspective, an adult orange tree annually absorbs approximately 50 kg of CO_2. [32] Hence, more than **170,000** adult orange trees would be needed to absorb the aforementioned 8600 tCO_2-eq. With a plantation density of 0.042 trees m^2 [32], a total area of approximately **4.1km^2** would have to be planted with adult orange trees in order to offset the CO_2-eq. emissions that might not have been avoided.

9. Conclusions, future work and recommendations

I. Conclusions

This master thesis aimed to analyze and propose solutions for expanding an already existing waste heat recovery system for an industrial client due to the client expanding their manufacturing capabilities. Hence, additional streams of exhaust gasses would be present. It can be said that an initial feasibility study has been done. This study would conclude if it is worth investing more time for a more detailed analysis. This global objective was successfully met. Expansion of the existing WHR system could yield more than **50,000 MWh** of electricity on a yearly basis. Based on the electricity prices, this expansion of the waste heat recovery could be worth between **3,000,000 €** and **14,150,000 €** on a yearly basis. These are numbers that cannot be ignored, hence it is clear that expanding the WHR system has to be analyzed into more detail.

Due to the new energy source (exhaust gasses) being of oscillating nature, two systems were analyzed for the WHR expansion. System A recovers the energy from the exhaust by means of HRSG and feeds it directly into the network. This approach would result with oversizing of the steam turbine, however during the majority of the day the turbine would have to work at partial load. System B recovers the energy the same way as System A, however it incorporates thermal energy storage, by means of steam accumulation. In this way, the production of electricity is more balanced. It was concluded that System B could produce **2.45%** more electricity than System A, at **16.13%** higher investment cost. It can be concluded that System B is an improvement over System A, however the significantly higher investment cost means that more detailed financial analysis is needed in order to give a clear recommendation for the viability of the project.

To be able to incorporate the thermal energy storage into System B, in-house tool was developed in order to assess the behavior of the steam accumulator. This tool is a series of mass and energy balances, that predicts the time evolution of various parameters. The tool is an important success within the framework of this thesis, as this tool would be helpful for other projects of Sener.

Also, a basic environmental analysis was done, that aimed to quantify how much CO_2-eq. emissions could be avoided, due to the expansion of the WHR system. This was successfully done, and it concluded that approximately **8600 tCO_2-eq** have been avoided as a direct consequence of the expansion of the WHR system. A social impact analysis was conducted by briefly analyzing the current state of industrial decarbonization. It was concluded that industrial decarbonization is a very important pillar for net-zero goals. Although progress has been made through the years, it is clear that much more has to be done, by both decarbonizing the energy sources and the feedstock that are being used in the industry.

II. Future work

As this is an initial feasibility analysis, many things fall outside of the scope of this projects. Hence, in order to continue with the project, lots of other things have to be considered. First of all, a detailed chemical analysis about the new exhaust gasses has to be done. This is very important as the chemical treatment that might be necessary for the exhaust gasses, might allow or disallow the use of ORC system to recover the low-grade heat. The recovery of the low-grade heat might result with additional several hundreds of kilowatts of electrical power. This is far from negligible, especially in light of recent experiences, where price of electricity can go above 300 €/MWh. Furthermore, a study of the electrical consumption of the client site might be interesting. The goal of this study would be to make sure that all of the produced electricity from the WHR system would be used by the client, hence the savings would not be dependent on the electricity market conditions.

As it is expected for this project to be accepted by the client, a more detailed engineering study would have to be done. In this study, suppliers would have to be contacted in order to have a more precise financial analysis. Furthermore, analysis of the behavior of the system during transient conditions, might be worth exploring.

III. Recommendations

This thesis has proved that expanding the waste heat recovery system is justified. However, further, more detailed analysis, into various aspects of the proposed expansion are needed. Contacting suppliers for various components is a must. This not only needed from a financial point of view, but also from technological. It has to be confirmed that the equipment with the desired characteristics can be manufactured and installed. Finally, site visit should be recommended, in order to make sure that the entire system can be physically installed.

10. Acknowledgments

With this thesis, I've completed my master studies, and thus my DENSYS journey comes to an end. It was a great learning experience, that has for sure changed my life and career. In that sense, I would like to thank several people and acknowledge their contribution.

First of all, I would like to thank the DENSYS management team, for trusting in me, as well as selecting me, in a pool of more than 400 applicants. It is an honor, but also a duty to give my best and to justify the trust that has been placed in me. Fabrice Lemoine, Heathcliff Demaie and Samira Menouar, thank you for your all of your advices, hiking trips, suggestions, tips and support, during the entire DENSYS experience, from the visa application up to this thesis.

Afterwards, I would like to thank everyone at SENER, for their great spirits and friendly attitude. You've made me feel as a part of the team from day one. Hopefully this will be a long-lasting relationship. Special thanks goes to Sergio Relloso Lassa, without whom this internship wouldn't have materialized, and who is the best guide of Basque County. My industry mentor, Borja Herazzti Garcia must not be forgotten. He was a great mentor, always available for discussion and possesses great innate ability to transfer his knowledge to others. I have learned a lot during this thesis, and for that I'm truly grateful. Finally, my DENSYS and SENER colleague Nikshan Paudel deserves to be mentioned, as we've spent all of our breaks together, and discussed many different topics, from academic to industrial, and everything in between.

It should not be forgotten the contribution of my academic mentor, Joaquim (Quim) Rigola Serrano. He his contribution was invaluable, but he also was always there to support us, during our stay in Barcelona. He was always willing to help and make our life easier, and for that, this is my modest way of saying thank you.

Last but not least, I have to say huge thank you to my entire family, to all my friends and to my girlfriend for their continuous support. Special thanks to my parents, Magdica and Gjeorgji, for raising me into the man I am today surrounded full of love, as well as always believing in me and supporting me in everything I decide to undertake. My sister Ena, also known as the chief logistic officer, has always been the one whom I can call and talk about anything. Finally, I have to express my gratitude to my girlfriend Monika, who has always been full of support and positive energy, especially in the toughest moments of this journey.

11. Bibliography

[1] Tobias Fleiter, Andrea Herbst, Matthias Rehfeldt, and Marlene Arens, “Industrial Innovation: Pathways to deep decarbonization of Industry. Part 2: Scenario analysis and pathways to deep decarbonization,” ICF Consulting Services Limited and Fraunhofer Institute for Systems and Innovation Research (ISI).

[2] Jeffrey Rissman *et al.*, “Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070.”.

[3] Thomas Hills, Ajay Gambhir, and Paul S. Fennell, “The suitability of different types of industry for inter-site heat integration”.

[4] IRENA, “Innovation Outlook: Thermal Energy Storage.” International Renewable Energy Agency, 2020.

[5] United Nations, “Transforming our World: The 2030 Agenda for Sustainable Development.”

[6] ABB, “Accelerating Ambition; How global industry is speeding up investment in energy efficiency.”

[7] Oihana Casas, “Press release: Gemasolar celebrates its second anniversary with an excellent operational record.”

[8] Solar Millennium AG, “Andasol: The World’s Largest Solar Thermal Power Plant Project Development in Andalucia (Spain),”

[9] Katie Randolph *et al.*, “Hydrogen Production Tech Team Roadmap,” USDRIVE (Driving research and innovation for vehicle efficiency and energy sustainability).

[10] Wolf-Dieter Steinmann and Markus Eck, “Buffer storage for direct steam generation,” *Solar Energy*.

[11] Xiang-yang Zhao, Zhitong Yao, and Jinhui Li, “Study on the Properties and Applications of Molten Salts”.

[12] Samaan Ladkany, William Culbreth, and Nathan Loyd, “Molten Salts and Applications I: Molten Salt History, Types, Thermodynamic and Physical Properties, and Cost.,” *Journal of Energy and Power Engineering 12*, doi: doi: 10.17265/1934-8975/2018.11.001.

[13] Steven Koning, “Molten Salt Systems; other Applications; linkt to Solar Power Plants,” [Online]. Available: www.bertrams-heatec.com

[14] Thomas Bauer, Christian Odenthal, and Alexander Bonk, “Molten Salt Storage for Power Generation”, doi: 10.1002/cite.202000137.

[15] David M. Rasmussen, “Steam-Turbine Fundamentals,”

[16] V. Ganapathy, “Heat-Recovery Steam Generators: Understand the Basics,” *Chemical Engineering Progress*, Aug. 1996.

[17] Wojciech Kosman, Andrzej Rusin, and Piotr Reichel, “Application of an energy storage system with molten salt to a steam turbine cycle to decrease the minimal acceptable load,” Dec. 2022, doi: https://doi.org/10.1016/j.energy.2022.126480.

[18] Ian H. Bell, Jorrit Wronski, Sylvain Quoilin, and Vincent Lemort, “Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp,” *Industrial and Engineering Chemistry Research*, Jan. 2014, doi: https://doi.org/10.1021/ie4033999.

[19] Thermoflow, “Thermoflex.”

[20] Mark Mehos *et al.*, “Concentrating Solar Power Best Practices Study,” NREL, Study, Jun. 2020.

[21] “Quaterly report on European electricity markets; vol.15 issue 3, coveing third quarter of 2022),” European Comission.

[22] EUROSTAT, “Energy Statistics - an overview (Final Energy Consumption).” EUROSTAT. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption

[23] IEA (International Energy Agency), “CO2 Emissions in 2022.” [Online]. Available: https://www.iea.org/reports/co2-emissions-in-2022

[24] Arnout de Pee; Dickon Pinner; Occo Roelofsen; Ken Somers; Eveline Speelman; Maaike Witteveen, “How industry can move toward a low-carbon future?,” McKinsey&Company, Jul. 2018.

[25] *Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018, ammendind Directive 2012/27/EU on energy efficiency*. 2018.

[26] Clemens Forman, Ibrahim Kolawole Muritala, Robert Pardemann, and Bernd Meyer, “Estimating the global waste heat potential,” *Renewable and Sustainable Energy Reviews*, Jan. 2016.

[27] Giuseppe Bianchi *et al.*, “Estimating the waste heat recovery in the European Union Industry”, doi: https://doi.org/10.1007/s40974-019-00132-7.

[28] Dario Alfani, Marco Binotti, Ennio Macchi, Paolo Silva, and Marco Astolfi, “sCO2 power plants for waste heat recovery: design optimization and part-load operation strategies,” *Applied Thermal Engineering*, Apr. 2021.

[29] Oficina Catalana del Canvi Climatic, “Practical Guide for Calculating Greenhouse Gas (GHG) Emissions.” Jan. 03, 2019.

[30] Pankaj Bhatia, Cynthia Cummis, Andrea Brown, David Rich, Laura Draucker, and Holly Lahd, “Corporate Value Chain (Scope 3) Accounting and Reporting Standard.” Greenhouse Gas Protocol.

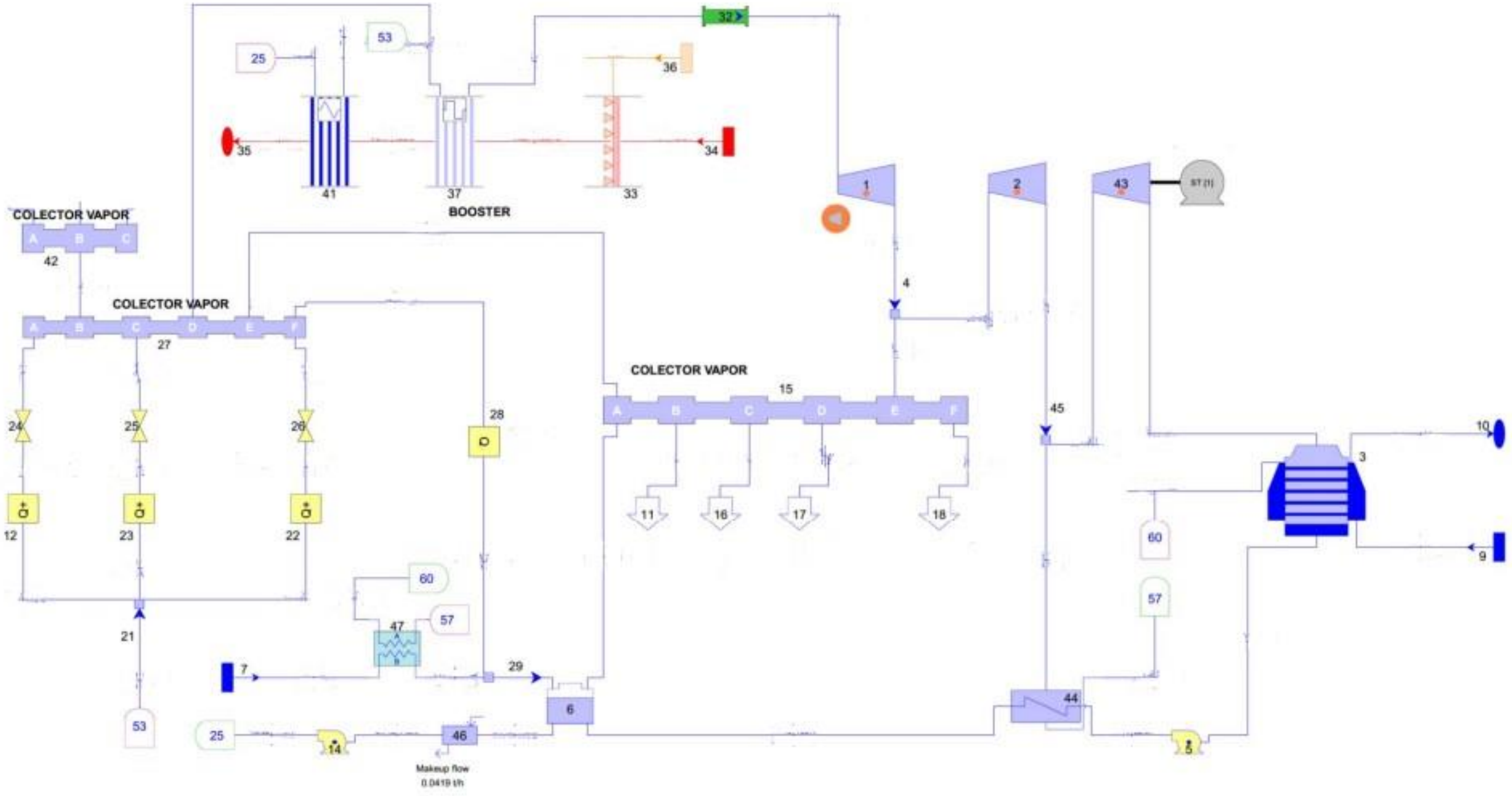
[31] “ANEXO I: Resultados del Etiquetado de Electricidad de las Empresas Comercializadoras Relativos a la Energia Producida en el ano 2022.” Comision Nacional de los Mercados y la Competencia (CNMC).

[32] Cesar Mora, Carlos Alcaraz-Lopez, Maria Iglesias, M.C. Martinez-Ballesta, and

Micaela Carvajal, “Investigation into CO2 absorption of the most representative agricultural crops of the region of Murcia,” Consejo Superior de Investigaciones Cientificas.

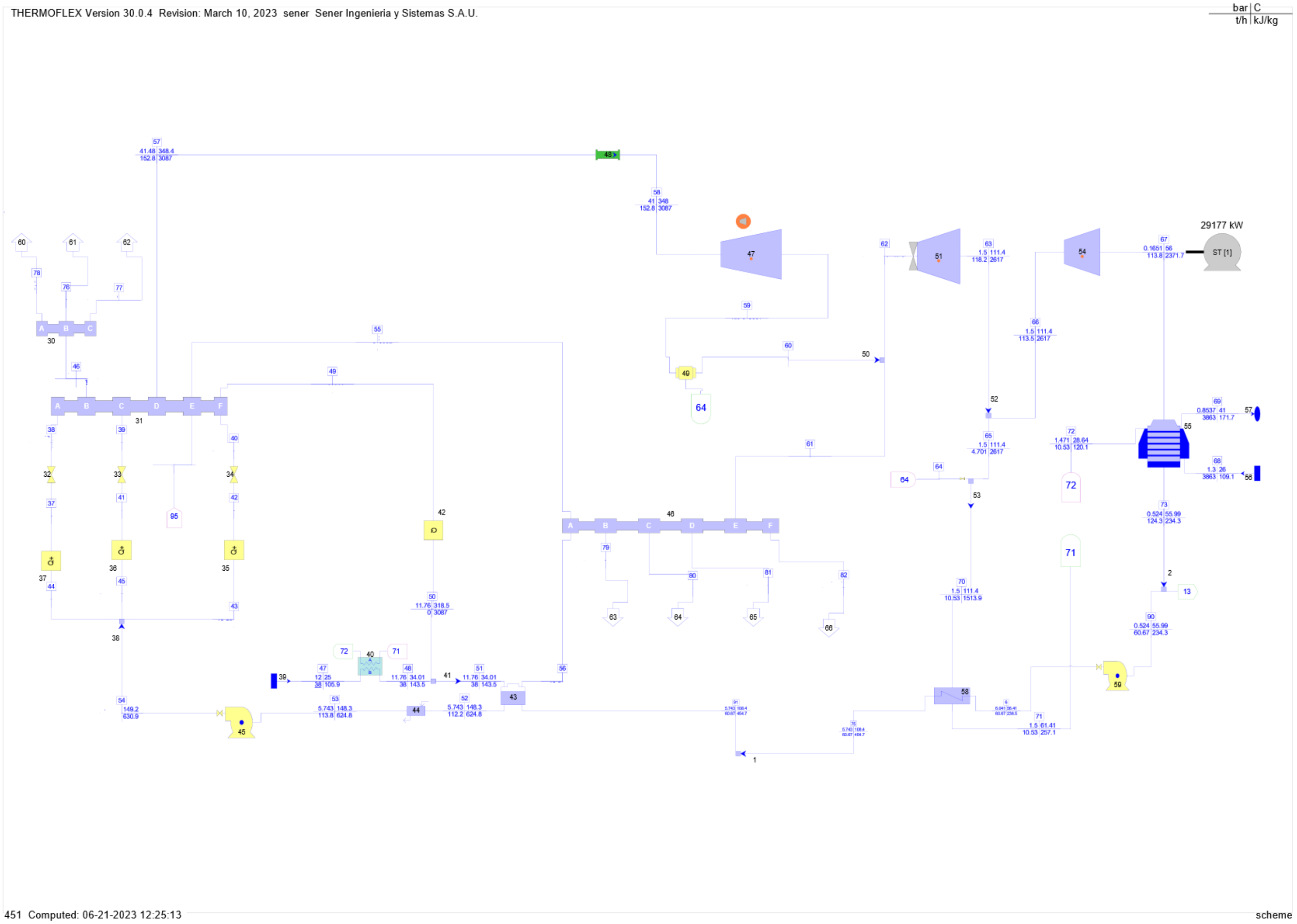
Appendix A

Layout of the old waste heat recovery System.



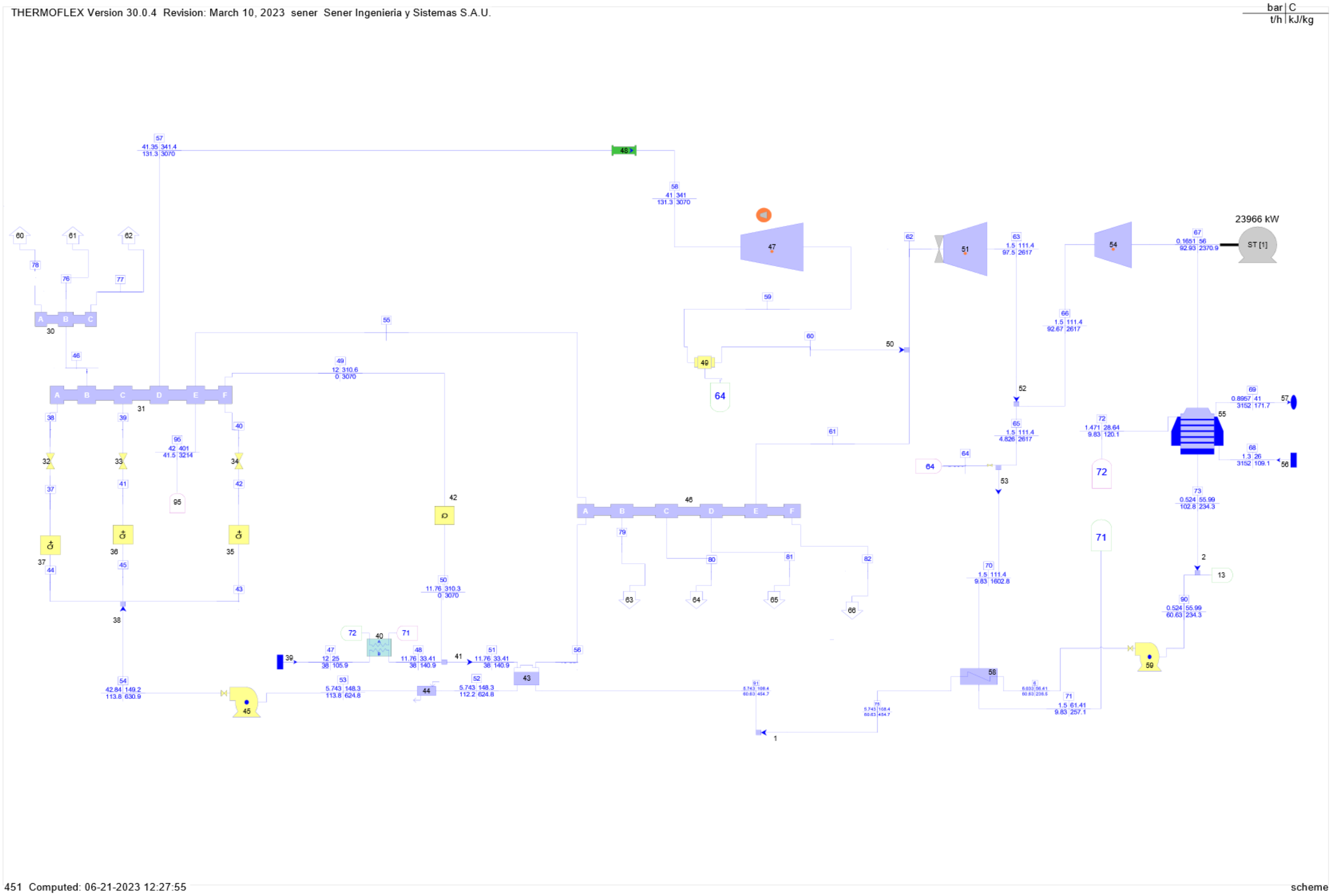
Appendix B

Layout schematic of System A.

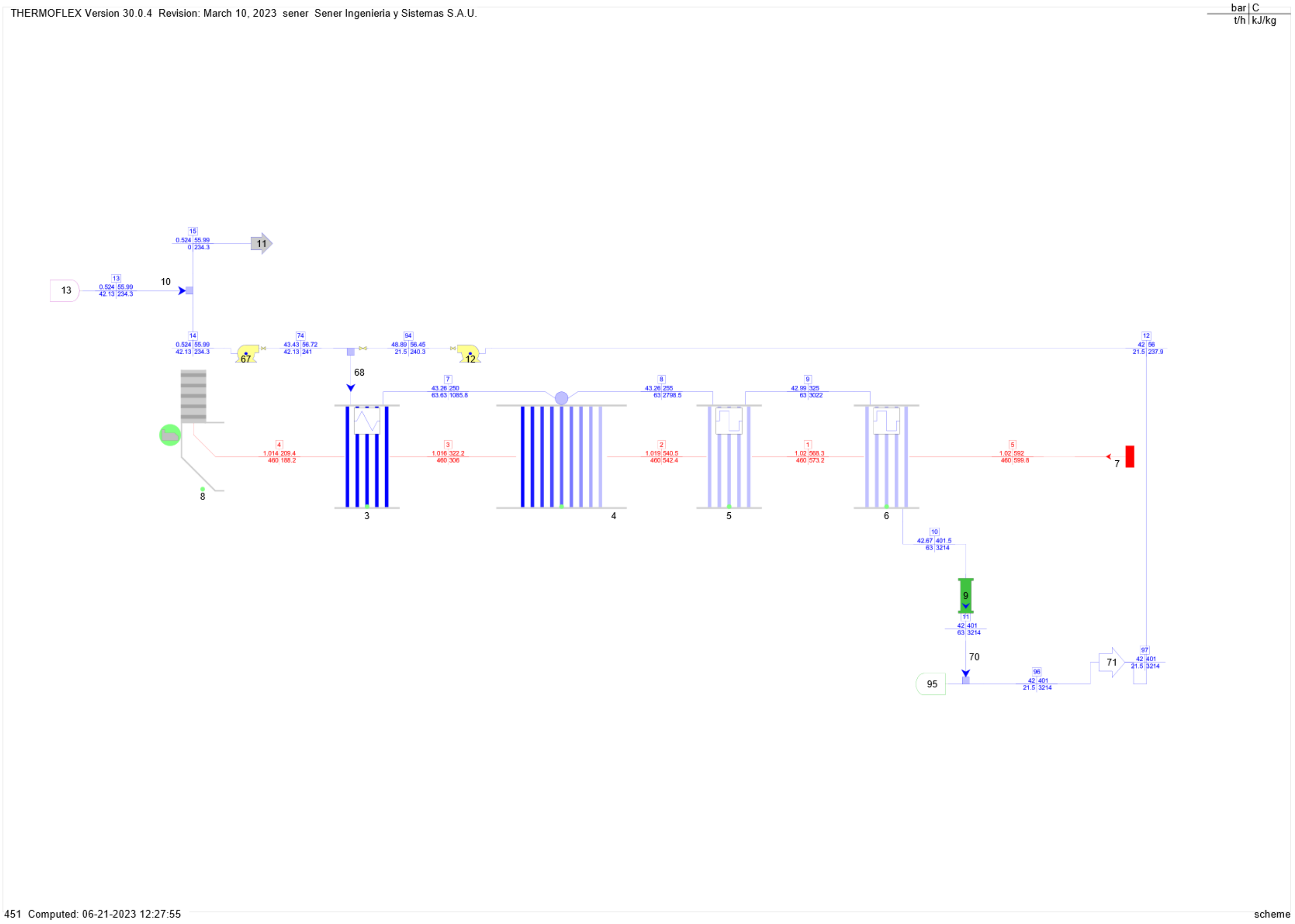


Appendix C

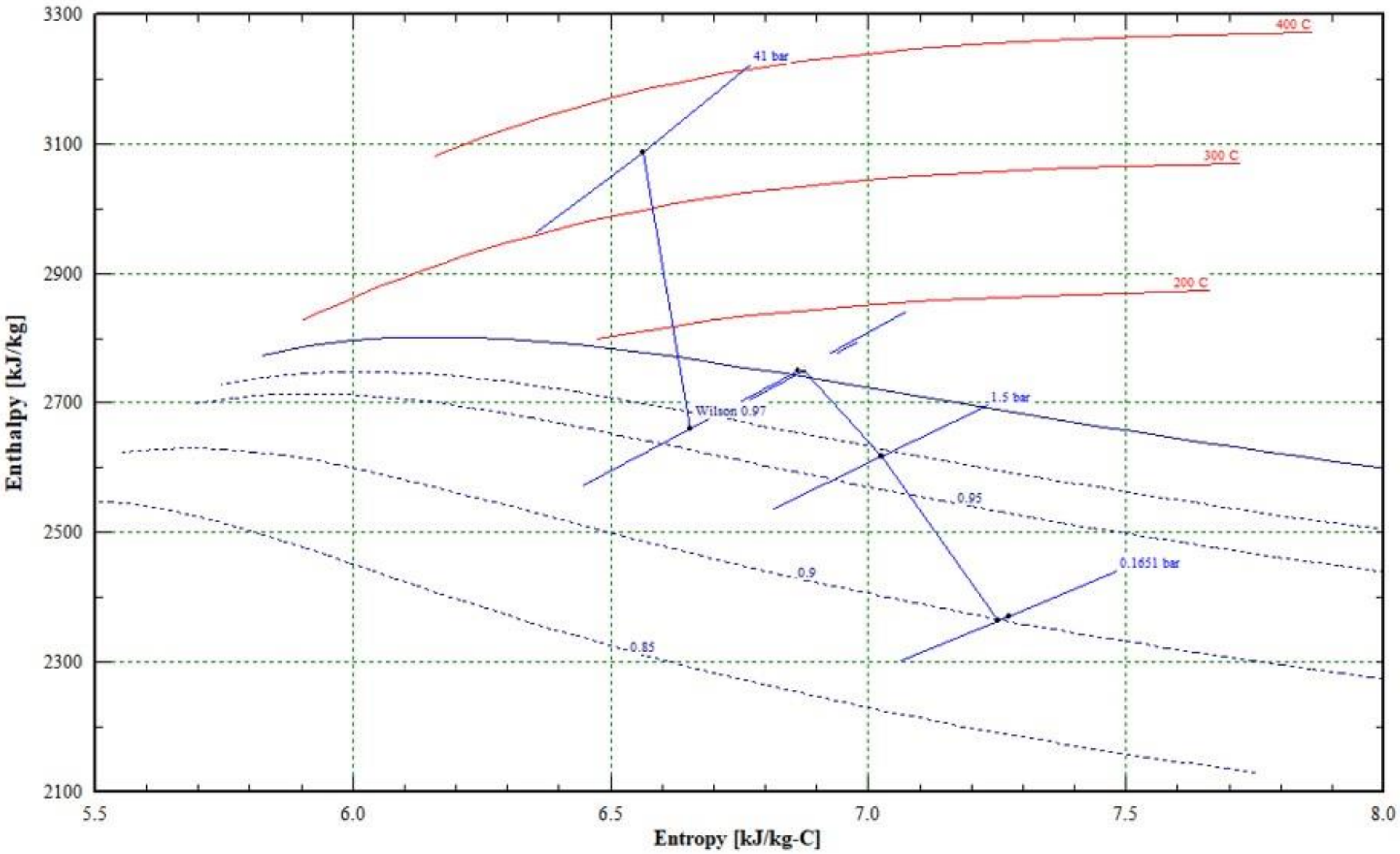
Layout schematic of System B.



Layout of the HRSG System. It is vàlid for both System A and System B.



ST Mollier Chart: ST Assembly [1]



Appendix D

Mass and energy balances for System A.

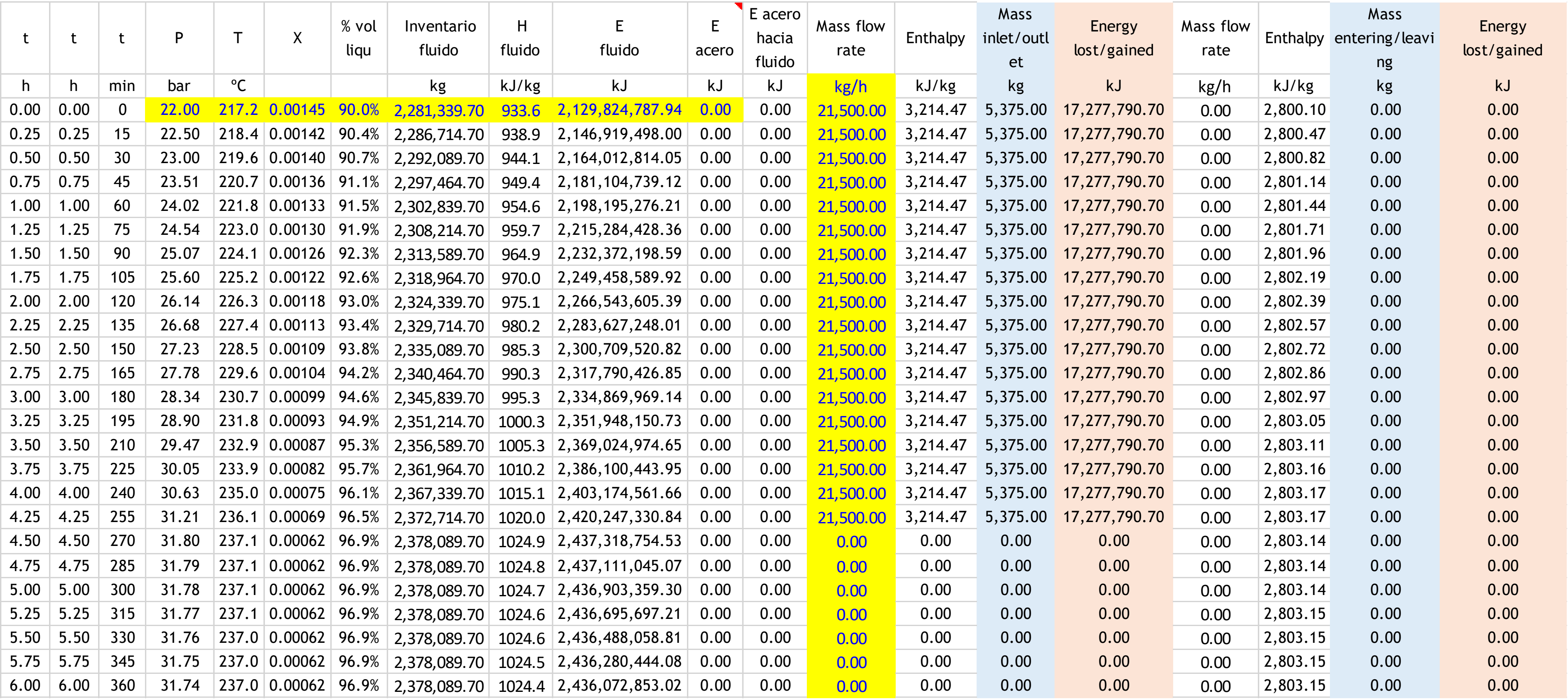
Heat Mass Balance Details				
ENERGY BALANCE				
Zero enthalpy at 77F / 25C with vapor H2O				
Component	**Energy Inflow**	**Energy Outflow**	**In - Out**	**Imbalance**
	kW	**kW**	**kW**	**%**
HRSG Assembly [2] - HRSG: Economiser (PCE) [3]		112		
HRSG Assembly [2] - HRSG: Evaporator (PCE) [4]		-26.69		
Gas/Air Source [7]	76637			
General HX [40]		4.007		
General Process [11]		-0.0002		
Heat Adder [35]	8235			
Heat Adder [36]	5490			
Heat Adder [37]	61669			
Makeup / Blowdown [44]	-839.5			
Process w/ Return [60]		1349.8		
Process w/ Return [61]		1349.8		
Process w/ Return [62]		899.9		
Process w/ Return [63]		761.1		
Process w/ Return [64]		0		
Process w/ Return [65]		0		

Process w/ Return [66]		47.3		
Process w/ Return [71]		0.0002		
Pump (PCE) [45]	195.1			
Pump (PCE) [59]	36.99			
Pump (PCE) [67]	117.7			
ST Assembly [1]: ST Group [47]		18170		
ST Assembly [1]: ST Group [51]	314.3	4343		
ST Assembly [1]: ST Group [54]	17.78	7766		
HRSG Assembly [2] - HRSG: Steel Stack [12]		24055		
HRSG Assembly [2] - HRSG: Superheater (PCE) [5]		29.35		
HRSG Assembly [2] - HRSG: Superheater (PCE) [6]		25.24		
Water Sink [57]		-2549532		
Water Source [39]	-25773			
Water Source [56]	-2616745			
Sums	**-2490644**	**-2490646**	**1.846**	**0**
MASS BALANCE				
Component	**Massflow In**	**Massflow Out**	**In - Out**	**Imbalance**
	t/h	**t/h**	**t/h**	**%**
HRSG Assembly [2] - HRSG: Evaporator (PCE) [4]		0.63		
Gas/Air Source [7]	460			
General Process [11]		0		
Makeup / Blowdown [44]	1.572			
Process w/ Return [60]		9		
Process w/ Return [61]		9		

Process w/ Return [62]		6		
Process w/ Return [63]		14		
Process w/ Return [64]		0		
Process w/ Return [65]		0		
Process w/ Return [66]		0.87		
ST Assembly [1]: ST Group [47]		2.452		
ST Assembly [1]: ST Group [51]	2.095			
ST Assembly [1]: ST Group [54]	0.285			
HRSG Assembly [2] - HRSG: Steel Stack [12]		460		
Water Sink [57]		3863		
Water Source [39]	38			
Water Source [56]	3863			
Sums	**4365**	**4365**		**0**

Appendix E

Microsoft Excel tool simulating the temporal behavior of the steam accumulator.



t	t	t	P	T	X	% vol liqu	Inventario fluido	H fluido	E fluido	E acero	E acero hacia fluido	Mass flow rate	Enthalpy	Mass inlet/outlet	Energy lost/gained	Mass flow rate	Enthalpy	Mass entering/leaving	Energy lost/gained
h	h	min	bar	°C			kg	kJ/kg	kJ	kJ	kJ	kg/h	kJ/kg	kg	kJ	kg/h	kJ/kg	kg	kJ
0.00	0.00	0	22.00	217.2	0.00145	90.0%	2,281,339.70	933.6	2,129,824,787.94	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,800.10	0.00	0.00
0.25	0.25	15	22.50	218.4	0.00142	90.4%	2,286,714.70	938.9	2,146,919,498.00	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,800.47	0.00	0.00
0.50	0.50	30	23.00	219.6	0.00140	90.7%	2,292,089.70	944.1	2,164,012,814.05	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,800.82	0.00	0.00
0.75	0.75	45	23.51	220.7	0.00136	91.1%	2,297,464.70	949.4	2,181,104,739.12	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,801.14	0.00	0.00
1.00	1.00	60	24.02	221.8	0.00133	91.5%	2,302,839.70	954.6	2,198,195,276.21	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,801.44	0.00	0.00
1.25	1.25	75	24.54	223.0	0.00130	91.9%	2,308,214.70	959.7	2,215,284,428.36	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,801.71	0.00	0.00
1.50	1.50	90	25.07	224.1	0.00126	92.3%	2,313,589.70	964.9	2,232,372,198.59	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,801.96	0.00	0.00
1.75	1.75	105	25.60	225.2	0.00122	92.6%	2,318,964.70	970.0	2,249,458,589.92	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.19	0.00	0.00
2.00	2.00	120	26.14	226.3	0.00118	93.0%	2,324,339.70	975.1	2,266,543,605.39	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.39	0.00	0.00
2.25	2.25	135	26.68	227.4	0.00113	93.4%	2,329,714.70	980.2	2,283,627,248.01	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.57	0.00	0.00
2.50	2.50	150	27.23	228.5	0.00109	93.8%	2,335,089.70	985.3	2,300,709,520.82	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.72	0.00	0.00
2.75	2.75	165	27.78	229.6	0.00104	94.2%	2,340,464.70	990.3	2,317,790,426.85	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.86	0.00	0.00
3.00	3.00	180	28.34	230.7	0.00099	94.6%	2,345,839.70	995.3	2,334,869,969.14	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,802.97	0.00	0.00
3.25	3.25	195	28.90	231.8	0.00093	94.9%	2,351,214.70	1000.3	2,351,948,150.73	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,803.05	0.00	0.00
3.50	3.50	210	29.47	232.9	0.00087	95.3%	2,356,589.70	1005.3	2,369,024,974.65	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,803.11	0.00	0.00
3.75	3.75	225	30.05	233.9	0.00082	95.7%	2,361,964.70	1010.2	2,386,100,443.95	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,803.16	0.00	0.00
4.00	4.00	240	30.63	235.0	0.00075	96.1%	2,367,339.70	1015.1	2,403,174,561.66	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,803.17	0.00	0.00
4.25	4.25	255	31.21	236.1	0.00069	96.5%	2,372,714.70	1020.0	2,420,247,330.84	0.00	0.00	21,500.00	3,214.47	5,375.00	17,277,790.70	0.00	2,803.17	0.00	0.00
4.50	4.50	270	31.80	237.1	0.00062	96.9%	2,378,089.70	1024.9	2,437,318,754.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.14	0.00	0.00
4.75	4.75	285	31.79	237.1	0.00062	96.9%	2,378,089.70	1024.8	2,437,111,045.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.14	0.00	0.00
5.00	5.00	300	31.78	237.1	0.00062	96.9%	2,378,089.70	1024.7	2,436,903,359.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.14	0.00	0.00
5.25	5.25	315	31.77	237.1	0.00062	96.9%	2,378,089.70	1024.6	2,436,695,697.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.15	0.00	0.00
5.50	5.50	330	31.76	237.0	0.00062	96.9%	2,378,089.70	1024.6	2,436,488,058.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.15	0.00	0.00
5.75	5.75	345	31.75	237.0	0.00062	96.9%	2,378,089.70	1024.5	2,436,280,444.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.15	0.00	0.00
6.00	6.00	360	31.74	237.0	0.00062	96.9%	2,378,089.70	1024.4	2,436,072,853.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2,803.15	0.00	0.00

Thermal losses			Net mass & energy balance		Demand from processes				Needed output from steam accumulator				After isentalpic expansion (at 20 bar)	
Pérdidas calor (en negativo)	Energy lost	Energy lost	Net mass gained/lost	Net energy gained/lost	Mass flow rate	Enthalpy	Mass needed	Energy needed	Enthalpy	Total Mass outflow	Mass flow rate	Total Energy outflow	Temperature	Quality
kW	kWh	kJ	kg	kJ	kg/h	kJ/kg	kg	kJ	kJ/kg	kg	kg/h	kJ	°C	X
-203.42	-50.86	-183,080.64	5,375.00	17,094,710.06	0.00	2,798.29	0.00	0.00	2,800.10	0.00	0.00	0.00	0.00	0.00
-204.97	-51.24	-184,474.65	5,375.00	17,093,316.05	0.00	2,798.29	0.00	0.00	2,800.47	0.00	0.00	0.00	0.00	0.00
-206.52	-51.63	-185,865.64	5,375.00	17,091,925.06	0.00	2,798.29	0.00	0.00	2,800.82	0.00	0.00	0.00	0.00	0.00
-208.06	-52.01	-187,253.61	5,375.00	17,090,537.10	0.00	2,798.29	0.00	0.00	2,801.14	0.00	0.00	0.00	0.00	0.00
-209.60	-52.40	-188,638.55	5,375.00	17,089,152.15	0.00	2,798.29	0.00	0.00	2,801.44	0.00	0.00	0.00	0.00	0.00
-211.13	-52.78	-190,020.47	5,375.00	17,087,770.23	0.00	2,798.29	0.00	0.00	2,801.71	0.00	0.00	0.00	0.00	0.00
-212.67	-53.17	-191,399.37	5,375.00	17,086,391.33	0.00	2,798.29	0.00	0.00	2,801.96	0.00	0.00	0.00	0.00	0.00
-214.19	-53.55	-192,775.24	5,375.00	17,085,015.46	0.00	2,798.29	0.00	0.00	2,802.19	0.00	0.00	0.00	0.00	0.00
-215.72	-53.93	-194,148.08	5,375.00	17,083,642.62	0.00	2,798.29	0.00	0.00	2,802.39	0.00	0.00	0.00	0.00	0.00
-217.24	-54.31	-195,517.89	5,375.00	17,082,272.81	0.00	2,798.29	0.00	0.00	2,802.57	0.00	0.00	0.00	0.00	0.00
-218.76	-54.69	-196,884.67	5,375.00	17,080,906.03	0.00	2,798.29	0.00	0.00	2,802.72	0.00	0.00	0.00	0.00	0.00
-220.28	-55.07	-198,248.41	5,375.00	17,079,542.29	0.00	2,798.29	0.00	0.00	2,802.86	0.00	0.00	0.00	0.00	0.00
-221.79	-55.45	-199,609.12	5,375.00	17,078,181.59	0.00	2,798.29	0.00	0.00	2,802.97	0.00	0.00	0.00	0.00	0.00
-223.30	-55.82	-200,966.78	5,375.00	17,076,823.92	0.00	2,798.29	0.00	0.00	2,803.05	0.00	0.00	0.00	0.00	0.00
-224.80	-56.20	-202,321.40	5,375.00	17,075,469.30	0.00	2,798.29	0.00	0.00	2,803.11	0.00	0.00	0.00	0.00	0.00
-226.30	-56.58	-203,672.98	5,375.00	17,074,117.72	0.00	2,798.29	0.00	0.00	2,803.16	0.00	0.00	0.00	0.00	0.00
-227.80	-56.95	-205,021.52	5,375.00	17,072,769.18	0.00	2,798.29	0.00	0.00	2,803.17	0.00	0.00	0.00	0.00	0.00
-229.30	-57.32	-206,367.01	5,375.00	17,071,423.69	0.00	2,798.29	0.00	0.00	2,803.17	0.00	0.00	0.00	0.00	0.00
-230.79	-57.70	-207,709.46	0.00	-207,709.46	0.00	2,798.29	0.00	0.00	2,803.14	0.00	0.00	0.00	0.00	0.00
-230.76	-57.69	-207,685.77	0.00	-207,685.77	0.00	2,798.29	0.00	0.00	2,803.14	0.00	0.00	0.00	0.00	0.00
-230.74	-57.68	-207,662.09	0.00	-207,662.09	0.00	2,798.29	0.00	0.00	2,803.14	0.00	0.00	0.00	0.00	0.00
-230.71	-57.68	-207,638.41	0.00	-207,638.41	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.68	-57.67	-207,614.73	0.00	-207,614.73	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.66	-57.66	-207,591.05	0.00	-207,591.05	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.63	-57.66	-207,567.38	0.00	-207,567.38	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.60	-57.65	-207,543.72	0.00	-207,543.72	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.58	-57.64	-207,520.05	0.00	-207,520.05	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.55	-57.64	-207,496.39	0.00	-207,496.39	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00
-230.53	-57.63	-207,472.73	0.00	-207,472.73	0.00	2,798.29	0.00	0.00	2,803.15	0.00	0.00	0.00	0.00	0.00

Needed mass and energy from a source of cooling liquid (usually water)				
Total Mass needed	Mass flow rate needed	Total Energy Output	Energy that can be supplied from the pump	Temperature to processes
kg	kg/h	kJ	kJ	ºC
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00

Appendix F

Mass and energy balances of System B.

Heat Mass Balance Details				
ENERGY BALANCE				
Zero enthalpy at 77F / 25C with vapor H2O				
Component	**Energy Inflow**	**Energy Outflow**	**In - Out**	**Imbalance**
	kW	**kW**	**kW**	**%**
HRSG Assembly [2] - HRSG: Economiser (PCE) [3]		112		
HRSG Assembly [2] - HRSG: Evaporator (PCE) [4]		-26.69		
Gas/Air Source [7]	76637			
General HX [40]		4.007		
General Process [11]		-0.0002		
Heat Adder [35]	8235			
Heat Adder [36]	5490			
Heat Adder [37]	61669			
Makeup / Blowdown [44]	-839.5			
Process w/ Return [60]		1349.8		
Process w/ Return [61]		1349.8		
Process w/ Return [62]		899.9		
Process w/ Return [63]		761.1		
Process w/ Return [64]		0		
Process w/ Return [65]		0		
Process w/ Return [66]		47.3		
Process w/ Return [71]		0.0002		
Pump (PCE) [45]	195.1			
Pump (PCE) [59]	36.99			
Pump (PCE) [67]	117.7			
ST Assembly [1]: ST Group [47]		18170		
ST Assembly [1]: ST Group [51]	314.3	4343		
ST Assembly [1]: ST Group [54]	17.78	7766		
HRSG Assembly [2] - HRSG: Steel Stack [12]		24055		
HRSG Assembly [2] - HRSG: Superheater (PCE) [5]		29.35		
HRSG Assembly [2] - HRSG: Superheater (PCE) [6]		25.24		
Water Sink [57]		-2549532		
Water Source [39]	-25773			
Water Source [56]	-2616745			
Sums	**-2490644**	**-2490646**	**1.846**	**0**

MASS BALANCE				
Component	**Massflow In**	**Massflow Out**	**In - Out**	**Imbalance**
	t/h	**t/h**	**t/h**	**%**
HRSG Assembly [2] - HRSG: Evaporator (PCE) [4]		0.63		
Gas/Air Source [7]	460			
General Process [11]		0		
Makeup / Blowdown [44]	1.572			
Process w/ Return [60]		9		
Process w/ Return [61]		9		
Process w/ Return [62]		6		
Process w/ Return [63]		14		
Process w/ Return [64]		0		
Process w/ Return [65]		0		
Process w/ Return [66]		0.87		
ST Assembly [1]: ST Group [47]		2.452		
ST Assembly [1]: ST Group [51]	2.095			
ST Assembly [1]: ST Group [54]	0.285			
HRSG Assembly [2] - HRSG: Steel Stack [12]		460		
Water Sink [57]		3863		
Water Source [39]	38			
Water Source [56]	3863			
Sums	**4365**	**4365**		**0**