

Techno-economic Analysis of Glass Industry Waste Heat Recovery Options: Organic Rankine Cycle, Absorption Refrigeration System and Drying Technology

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Master's Dissertation

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Abstract

Glass container manufacturing is energy-intensive and remains a relevant source of industrial CO₂ emissions. This dissertation, conducted at BA Glass (Avintes, Portugal), evaluates three waste-heat recovery (WHR) pathways that repurpose furnace exhaust heat: a thermal sludge-drying line (direct rotary drum dryer), an organic Rankine cycle (ORC) for power generation, and a single-effect H₂O–LiBr absorption refrigeration system (ARS) for space/process cooling. In parallel, a Python decision-support tool with a GUI was developed to automate the thermodynamic and techno-economic assessments.

The study combines site data from a recent energy audit, bench-scale drying experiments to characterize sludge, and steady-state models for the dryer, ORC, and ARS using CoolProp properties and first-principles mass/energy balances. Economics are compared via net present value, internal rate of return, payback period, and levelized costs, using plant tariffs and reference cost correlations.

With conservative constraints to avoid acid-dew-point condensation, the recoverable heat from Furnace A is estimated at 1.7 MW when cooling the flue gas to 120 °C. Wet sludge after screw-press dewatering averaged 65.25 % moisture, while a representative dry target was 12.33 %. The dryer’s thermal load to meet current sludge throughput is small, making the TDS technically straightforward but economically weak at present production rates (low savings compared to CAPEX/OPEX). The ORC is technically feasible at the available source temperature, with a modeled subcritical cycle efficiency of nearly 16 %. The single-effect H₂O–LiBr ARS is likewise feasible, presenting a COP of nearly 0.75 at typical generator/absorber/condenser approaches, and can offset part of the plant’s cooling electricity. Under current site conditions, the power and cooling options rank ahead of sludge drying on value creation, although final project selection is sensitive to vendor pricing, seasonal cooling-water temperatures, and control/maintenance strategies for fouling and corrosion.

The accompanying Python tool encapsulates the methodology, enabling rapid scenario analyses and reuse at other furnaces/sites. This tool was developed with user-friendliness in mind, such that most input data is pre-set at common values. Thus, for a simple analysis, the user needs only to input the remaining data, and a techno-economic analysis of the three scenarios is produced automatically.

Keywords: waste-heat recovery; glass industry; organic Rankine cycle; absorption refrigeration; rotary drum dryer; techno-economic analysis; energy efficiency; Python GUI tool.

Resumo

Análise Técnico-económica de Opções de Recuperação de Calor Residual na Indústria do Vidro: Ciclo Orgânico de Rankine, Sistema de Refrigeração por Absorção e Tecnologia de Secagem

A produção de embalagens de vidro é intensiva em energia e continua a ser uma fonte relevante de emissões industriais de CO₂. Esta dissertação, realizada na BA Glass (Avintes, Portugal), avalia três vias de recuperação de calor residual que reaproveitam o calor dos gases de exaustão do forno: uma linha térmica de secagem de lammas (secador rotativo de tambor de contacto direto), um Ciclo Orgânico de Rankine (ORC) para geração elétrica e um sistema de refrigeração por absorção H₂O–LiBr de efeito simples (ARS) para arrefecimento de espaços/processos. Em paralelo, foi desenvolvida uma ferramenta de apoio à decisão em Python, com interface gráfica, para automatizar as avaliações termodinâmicas e tecno-económicas destas três vias.

O estudo combina dados de campo de uma auditoria energética recente, ensaios de secagem em bancada para caracterização das lammas e modelos em regime permanente para o secador, ORC e ARS, utilizando propriedades do CoolProp e balanços de massa/energia de primeiros princípios. A comparação económica é feita via valor atual líquido, taxa interna de rentabilidade, período de retorno e custos nivelados, usando tarifas reais da unidade e correlações de custo de referência.

Com restrições conservadoras para evitar condensação abaixo do ponto de orvalho ácido, o calor recuperável do Forno A é estimado em 1,7 MW ao arrefecer os gases de exaustão até 120 °C. A lama, após desaguamento por desidratação em prensa de parafuso, apresentou em média 65,25 % de humidade, enquanto a referência para o produto seco foi 12,33 %. A carga térmica do secador para a produção atual de lammas é reduzida, tornando o sistema de secagem tecnicamente simples mas economicamente pouco viável aos níveis de produção presentes (poupanças baixas face aos custos). O ORC é tecnicamente viável à temperatura da fonte disponível, com uma eficiência modelada do ciclo subcrítico próxima de 16 %. O ARS H₂O–LiBr de efeito simples é igualmente viável, apresentando um COP de aproximadamente 0.75 com aproximações térmicas típicas no gerador/absorvedor/condensador, e pode compensar parte do consumo elétrico de arrefecimento da fábrica. Nas condições atuais do local, as opções de potência e de frio surgem à frente da secagem de lammas em termos de criação de valor, embora a seleção final seja sensível a preços de fornecedores, variações sazonais da temperatura da água de arrefecimento e estratégias de controlo/manutenção para incrustações e corrosão.

A ferramenta em Python encapsula a metodologia, permitindo análises rápidas de cenários e a sua reutilização noutros fornos/instalações. Foi concebida com foco na usabilidade: a maioria dos campos vem pré-preenchidos com valores comuns. Assim, para uma análise simples, o utilizador apenas introduz os restantes dados e desta forma obtém automaticamente a avaliação tecno-económica dos três cenários.

Palavras-chave: recuperação de calor residual; indústria do vidro; ciclo orgânico de Rankine; chillers de absorção; secador rotativo de tambor; análise tecno-económica; eficiência energética; ferramenta Python com GUI.

UN Sustainable Development Goals

The United Nations created the Sustainable Development Goals (SDGs) to provide a universal framework to promote prosperity while protecting the planet. This dissertation contributes to several SDGs by recovering and reusing waste heat from glass furnaces, improving energy efficiency, fostering industrial retrofits, and advancing circular use of materials.

The specific SDGs addressed in this work are:

- **SDG 7:** Affordable and Clean Energy
- **SDG 9:** Industry, Innovation and Infrastructure
- **SDG 12:** Responsible Consumption and Production
- **SDG 13:** Climate Action

SDG	Target	Contribution
7	7.3	Waste-heat recovery (WHR) via ORC and ARS reduces purchased electricity per tonne of glass; the thermal dryer (TDS) uses recovered heat instead of primary fuels (Sections 6.3, 6.4, 6.5).
9	9.4	Industrial retrofit of Furnace A exhaust path with robust heat exchangers and WH-to-use technologies; deployment of a Python decision-support tool (Chapter 5) to accelerate innovation and replication.
12	12.2, 12.5	Circularity: dried sludge is reinserted into the batch, displacing virgin sand and reducing off-site handling (Sections 3.2, 6.3).
13	13.2	Integration of WHR into site planning reduces Scope-2 emissions by decreasing grid demand (site effect depends on the grid factor; replication has larger benefits)(Chapter 7).

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"It does not matter how slowly you go as long as you do not stop."

Confucius

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Acronyms and Symbols

ACH	Air changes per hour
ACM	Air changes per minute
ARC	Absorption refrigeration cycle
ARS	Absorption refrigeration system
BA	BA Glass B.V.
CAPEX	Capital expenditure
CFD	Computational fluid dynamics
COP	Coefficient of performance
CR	Circulation ratio
DR	Drying rate
EU	European Union
ESP	Electrostatic precipitator
FC	Forced convection
FEUP	Faculty of Engineering of the University of Porto
GHG	Greenhouse gas
GUI	Graphical user interface
GWP	Global warming potential
HE	Heat exchanger
HPHE	Heat pipe heat exchanger
HVAC	Heating, ventilation and air conditioning
HT	High temperature
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
IRR	Internal rate of return
IS	Individual section
IWTP	Industrial wastewater treatment plant
LCOC	Levelized cost of cooling
LCOE	Levelized cost of electricity
LT	Low temperature
M&A	Mergers and acquisitions
MC	Moisture content
MT	Medium temperature
NC	Natural convection

NPV	Net present value
OPEX	Operating expenditure
ORC	Organic Rankine cycle
PBP	Payback period
RDD	Rotary drum dryer
RH	Relative humidity
RQ	Research question
RM	Raw materials
SHX	Solution heat exchanger
SO	Specific objective
STHE	Shell and tube heat exchanger
TD	Thermal drying
TDS	Thermal drying system
toe	Tonne of oil equivalent
TS	Total solids
UI	User interface
WF	Working fluid
WH	Waste heat
WHR	Waste heat recovery

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Chapter 1

Introduction

The present dissertation was developed within the scope of the Master’s Degree in Mechanical Engineering, specialized in Fluids and Energy, at the Faculty of Engineering of the University of Porto (FEUP). It was developed in a business context, in the glass package manufacturing company BA Glass B.V., in their industrial complex in Avintes, Porto, Portugal. The thesis explores ways to convert furnace waste heat into value, evaluating three options: a thermal dryer for industrial sludge, an organic Rankine cycle (ORC) to generate electricity, and a water–lithium bromide absorption refrigeration system. In order to disseminate the results of this work and replicate these in further use cases, the methodology developed has been implemented as a Python tool that automates the techno-economic evaluation of waste heat streams for other glass industries.

The thesis is structured in several chapters, with the first chapter presenting the motivation and the scope of the dissertation work, especially as it relates to BA Glass. A succinct history and description of BA Glass is given to frame the work and the main motivation. This chapter also introduces the main research questions, the objectives, and identifies the methodology employed in the development of this work. Finally, this chapter ends with a short description of each chapter in the present work, to briefly present the structure of the document.

1.1 Framework and motivation

Sustainability is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” (United Nations, 2025). Sustainability is understood to include three pillars: social, economic, and environmental (Purvis et al., 2019). Given the focus on the industrial setting, and the potential valorization of waste heat, the environmental pillar of sustainability is particularly relevant for this thesis. This pillar includes concepts such as mitigation of climate change (Butler, 2018), the sustainable use of natural resources, and circular economy (NREP, 2025).

Considering the durability and recyclability of glass, it has been perceived as a more sustainable alternative to plastic packaging, due to its infinite recyclability, while also potentially avoiding

the microplastics pollution and toxicity issues of single use plastics (Baek et al., 2025). Additionally, there are economic and marketing incentives for food or beverage companies to use glass packaging for their products, as consumers attach a perception of superior quality to products in glass containers (Balzarotti et al., 2015).

However, this material is not without its drawbacks. The glass packaging (e.g., bottles, jars) production process is very energy-intensive and, as such, currently emits more greenhouse gases (GHG) than the plastic alternatives, on average (Meng et al., 2024). In recent years, this downside has been mitigated as the energy mix has contained increasingly more renewable energy and as industrial glass furnaces have used increasingly more electricity, slowly replacing natural gas as the main energy source (Gielen et al., 2019). Additionally, the sustainability of use of glass for food and beverages packaging is also closely tied to the extended use and effective recycling practices.

The work carried out within this thesis supports BA Glass's sustainability goals by exploring solutions for using waste heat from the production process, in order to reduce energy consumption and enhance the process energy efficiency. Namely, the thesis explores the use of waste heat recovery (WHR) in three different systems: a thermal dryer powered by waste heat to dry industrial sludge, an organic Rankine cycle (ORC) for electricity generation, and an absorption refrigeration system (ARS) as a cooling mechanism. In addition, in the case of the dryer, the dried sludge can be used as a raw material. Thus, this use of the waste heat could be implemented within a general strategy to promote a more circular, closed-loop process, improving the sustainability and resource efficiency of the production process.

1.2 Energy Use in the Glass Industry

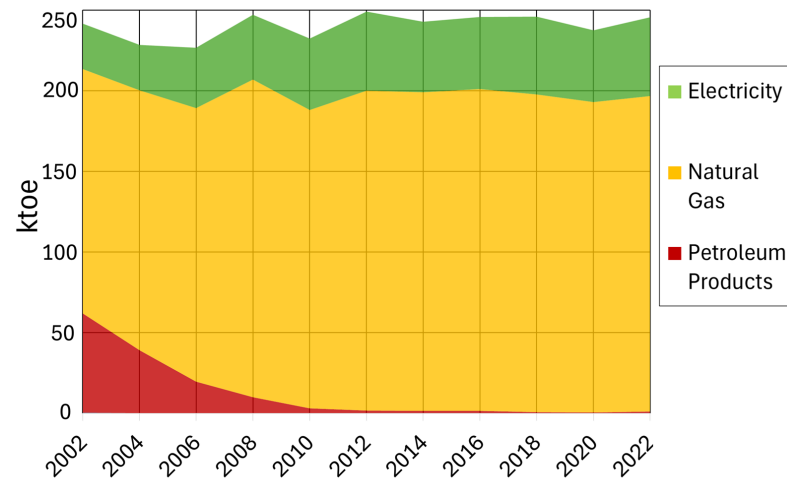
Glass is a highly energy-intensive industry, primarily due to the high energy demand of the industrial furnace used to melt the raw materials and cullet (Martini et al., 2021).

In the hollow glass production process (see Section 3.1), the industrial furnaces represent about 80 % of the total energy demand, due to the energy required to heat and melt the raw materials and glass cullet (Martini et al., 2021; Papadogeorgos and Schure, 2019). Thus, interventions such as the use of regenerative furnaces, or batch and cullet preheating, are increasingly important, as they reduce the energy consumption of the furnace (Cantini et al., 2022).

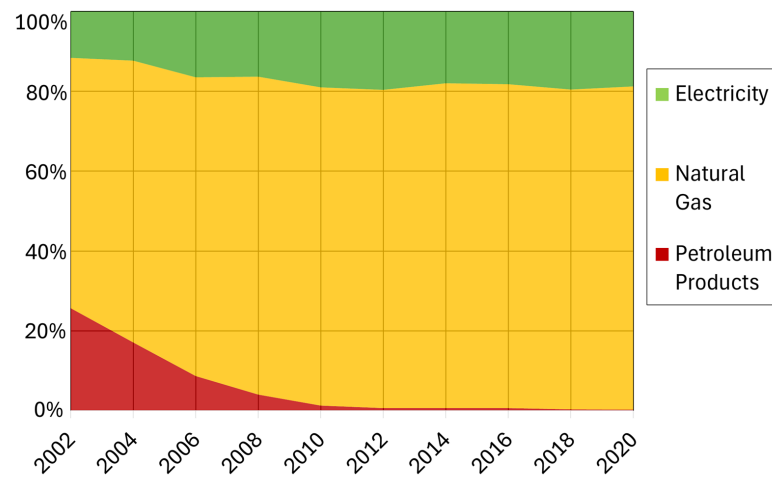
In Portugal, the glass industry is still significantly dependent on fossil fuels, namely on natural gas which constitutes the main source of energy used in the furnaces. Thus, the final energy consumption in the glass industry is primarily sourced from natural gas.

In Portugal, in 2022, the glass industry accounted for a total final energy consumption of 245.65 ktoe (equivalent to 2 856.9 GWh or 10.28 PJ), which represents 5.53 % of the manufacturing industry's energy consumption, 5.03 % of the industry's energy consumption, and also 1.48 % of the total final energy consumption. (DGEG, 2023). The main source is natural gas (195.64 ktoe / 79.6 %), followed by electricity (48.87 ktoe / 19.9 %) and petroleum products (1.09 ktoe / 0.5 %). The recent evolution of the energy mix of the Portuguese glass industry is shown in Figure

1.1. Accordingly, the variation in total energy consumption is nearly negligible. Furthermore, from 2002-2012, the relative weight of petroleum products dropped from 25.5 % to almost 0 %, while that of electricity increased from 11.6 % to 19.6 %, but from 2012-2022 the relative shares of the energy sources have remained essentially constant (DGEG, 2025).



(a) Absolute chart.



(b) Relative chart.

Figure 1.1: Absolute and relative evolution of energy sources for the Portuguese glass industry (Data from DGEG (2025)).

Figure 1.2 shows the evolution of the relative final energy consumption in the glass industry in 2002-2022, with respect to the energy consumption of the manufacturing industry and the total final energy consumption in Portugal. With this graph and the knowledge that energy use in the glass industry remained relatively constant (from Figure 1.1.a), it becomes clear that both the manufacturing industry and the country as a whole decreased their energy use in recent years, while the glass industry was unable to do the same (DGEG, 2025).

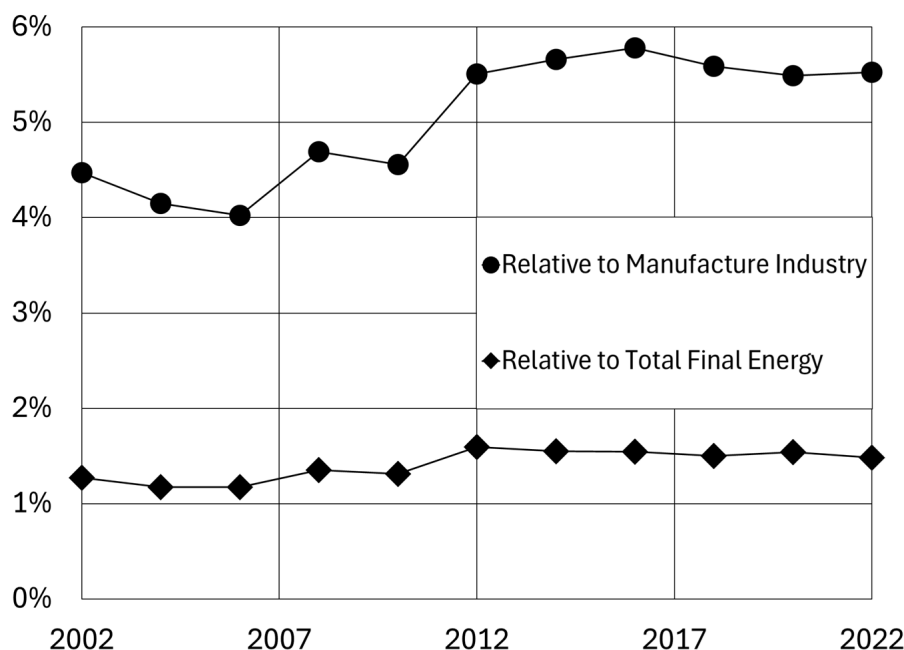


Figure 1.2: Evolution of the glass industry's final energy use, relative to the Portuguese manufacturing industry and to Portugal as a whole (Data from DGEG (2025)).

The glass industry has significant GHG emissions, since it is a highly energy-intensive industry for which the primary source of energy is natural gas. In fact, in Portugal, the glass industry produced 157.54 thousand tonnes of CO₂ emissions, in 2022. In Figure 1.3, the evolution of this value is shown in recent years. Notably, little variation can be seen and, in fact, the 2022 CO₂ emissions are 0.6 % higher than they were in 2018 (Eurostat, 2024).

The observed trends in energy consumption and GHG emissions of the glass industry, showing little change within the last 20 years, can be traced back to three main barriers to the decarbonization of the glass industry, namely:

- **Lack of economic alternative energy sources:** Although electric boosting arc furnaces are a common implementation that substitutes part of the natural gas consumption with electricity, the transition to electricity or hydrogen as a fuel source necessitates an increase in their cost competitiveness (Seo et al., 2020; Zier et al., 2021; Colangelo, 2024);
- **Technical limitations:** Further research and technological advancements have to be conducted in order to design electricity or hydrogen powered industrial furnaces that remain economically viable (Colangelo, 2024);
- **Recycling limitations:** The use of cullet as a raw material reduces energy consumption, as cullet requires less energy than virgin materials to melt. However, the availability and quality of cullet are limiting factors, and virgin materials are often cheaper than cullet (von Koeller et al., 2021).

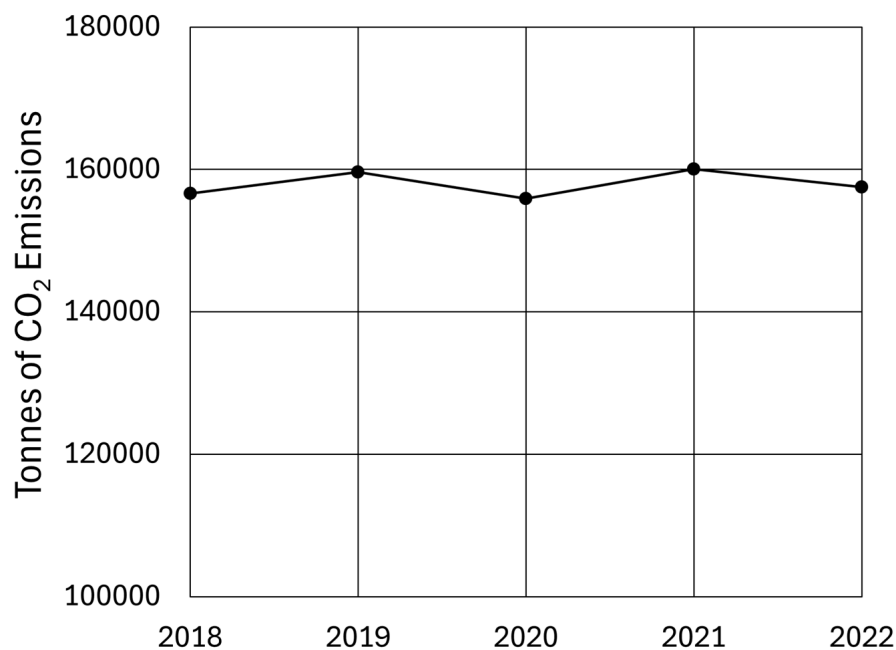


Figure 1.3: Evolution of the Portuguese glass industry's CO₂ emissions (Data from Eurostat (2024)).

1.3 BA Glass

In 1912, BA Glass was incorporated by business partners Raúl da Silva Barbosa and Domingos de Almeida. Initially, the company was called Barbosa & Almeida, a namesake to its founders, and the origin of the name BA Glass. It did not originally manufacture glass packaging, but rather focused on the redistribution of glass bottles, imported from Germany and provided from Seixal, Portugal. The company later began its industrial production activity in 1928, with the acquisition of a factory in Campanhã, Portugal. Later, in 1969, the company began operating the Avintes industrial unit (with two regenerative furnaces), where this dissertation was developed.

From 1993 to 1995, BA Glass merged with CIVE, a company with a three-furnace industrial complex in Marinha Grande. This M&A process marked the beginning of a steady expansion period for the company, which has yet to stop. Indeed, it soon expanded production to include Spain, as in 1998, BA constructed a one-furnace factory in Villafranca de los Barros, and, in 1999, it acquired Vidriera Leonesa, S.A., a company with a two-furnace industrial unit in León.

Continuing its expansion, in 2008 BA acquired the Sotancro group, with an industrial complex in Venda Nova (Portugal), and also Vidriera del Atlántico, S.A., a company with a factory in Xinzo de Limia (Spain). The latter would later be shut down, thus it is no longer in operation.

In 2012, BA began production outside the Iberian Peninsula, with the acquisition of 80 % of the Warta Glass Group, a Polish group headquartered in Poznan, with two factories, in Sieraków and Jedlice, each with two furnaces. This deal was completed shortly before the company's 100th birthday (Alves, 2012).

2016 was a year of significant M&A activity for BA, with three major acquisitions: 25 % of

the third largest glass manufacturer in the United States (at the time) - Anchor Glass, 100 % of the share capital of HNG Global GmbH, a company with a one-furnace factory located in Gardelegen, Germany, and also 100 % of Yioula Glass, a company with four industrial sites - in Athens, Greece; in Sofia, Bulgaria; in Plovdiv, Bulgaria; and in Bucharest, Romania. The transaction with Yioula would only be completed by 2017 (BA Glass, B.V., 2016). BA Glass began production outside of Europe in 2023, with the acquisition of a 60 % equity stake in the Mexican glass packaging producer Vidrio Formas, in Lerma de Villada, Mexico. Finally, in 2024, BA acquired CP Glass, a Polish company with an industrial unit in Orzesze. A summarized timeline of BA's history, with a focus on M&A activities, can be seen in Figure 1.4 (BA Glass, B.V., 2023, 2024).

1912	1947	1969		1993	1998	1999
Incorporation of Barbosa & Almeida	Introduction of Automatic Technology	Start of Operation at Avintes Industrial Unit		Acquisition of CIVE <i>Marinha Grande Industrial Unit</i>	<i>Start of Operation at Villafranca de los Barros Industrial Unit</i>	Acquisition of Vidriera Leonesa <i>León Industrial Unit</i>
2008	2012	2016	2017		2023	2024
Acquisition of Sotancro <i>Venda Nova Industrial Unit</i>	Acquisition of Warta <i>Sieraków and Jedlice Industrial Units</i>	Acquisition of HNG Global <i>Gardelegen Industrial Unit</i>	Acquisition of Youla <i>Athens, Sofia, Plovdiv and Bucharest Industrial Units</i>		Acquisition of Vidrio Formas <i>Lerma de Villada Industrial Units</i>	Acquisition of CP Glass <i>Orzesze Industrial Unit</i>

Figure 1.4: BA Glass history timeline (Source: BA Glass, B.V. (2024)).

BA Glass issued its first stock in 1975, and the company's stock began being publicly traded in the stock market. Nowadays, BA is a private company, thus it is no longer listed in the stock market, and it is owned by Fim do Dia, SGPS, S.A. (47.4 %), Teak Capital, S.A. (26.3 %), and Tangor Capital, S.A. (26.3 %) (BA Glass, B.V., 2024).

Currently, BA Glass is one of the largest glass container producers in the world. In fact, in 2024, it registered a turnover of 1 532.1 M€, over 11 billion bottles and jars produced, and 4,869 employees worldwide. It operates 13 glass plants in Portugal (3), Spain (2), Germany (1), Poland (3), Bulgaria (2), Romania (1), and Mexico (1), along with 5 cullet treatment stations (i.e., glass recycling plants) in Portugal (1), Spain (1), the United Kingdom (2) and Mexico (1) (BA Glass, B.V., 2024).

BA Glass has been recognized for the fifth consecutive year as the most sustainable company in the glass industry by World Finance Magazine. In line with their sustainability objectives, 100 % of the electricity BA Glass uses is sourced from renewable sources. The Avintes unit of BA Glass, where this dissertation was developed, is no exception. In Avintes, the total electricity

consumption in 2024 was 90 667 MWh. This unit operates 3 regenerative industrial glass furnaces, with a total of 10 production lines.

This project was carried out in the Mechanical Maintenance Department of BA Glass's Avintes plant. The department oversees a broad scope of responsibilities, handling all non-electrical issues except those related to storage silos, glass furnaces, IS machines, annealing lehrs, or automatic inspection machines, which are typically managed by other specialized departments.

1.4 Scope and Objectives

Initially, the company proposed conducting a study of two previously identified issues: improving the thermal comfort of the shop floor through passive solutions and identifying a waste heat recovery system for sludge drying. An initial analysis of the thermal comfort issue identified several possible passive solutions, including natural ventilation, radiant heat control, and clothing changes. From these options, natural ventilation was the only viable solution given the Avintes site characteristics. An initial literature search identified computational fluid dynamics (CFD) as the only suitable method to accurately model natural ventilation systems in the Avintes site, given the extremely high thermal load (around 10 MW). However, given the modeling requirements of a complex environment such as the Avintes site, this would be infeasible within the timeline of the dissertation. Thus, the initial scope of the dissertation was reformulated to merge the two initial requests, focusing the thesis work on the analysis of waste heat recovery (WHR) and use options that included the use waste heat for drying sludge, for production of cold via absorption chillers - which could be used also to improve thermal comfort at the level of the shop floor -, and for production of electricity via an organic Rankine cycle (ORC).

Once the techno-economic analysis of all three WHR options was completed, the objectives of the thesis were once again expanded to include the development of a computational tool, in Python programming language, which should be capable of automating the processes and calculations performed in this study to be used by other glass production companies with similar technical characteristics.

1.4.1 Waste Heat Recovery

The flue gases from the natural gas combustion reaction in the furnaces represent a potential waste heat source, even after being substantially cooled in the furnace regenerator. Indeed, the Avintes unit has two chimneys, one of which serves Furnace A, which has a waste heat potential of approximately 1 697 kW. Using this gas as a waste heat source would align with BA Glass's sustainability objectives, and it would also represent potential financial savings.

Sludge Drying Mechanism

In BA Glass's industrial complex in Avintes, water is used to lubricate and cool several components of the IS machines (molding machines), as well as the gob (molten glass drop) itself. The

used water is then transported to an industrial wastewater treatment plant (IWTP), to be treated and purified. This process produces sludge, which the company desires to use as raw material by reinserting it into the furnaces. However, even after being processed in a screw press dewatering mechanism, the sludge still has a moisture content that is too high for it to be reinserted into the furnace.

Therefore, the present dissertation aims to study and perform a techno-economic assessment for a sludge drying system, which should use the waste heat from the flue gases of the industrial glass furnace as an energy source, improving the energy efficiency of the glass container manufacturing plant.

Organic Rankine Cycle

Furthermore, WHR alternatives should also be analyzed to fully determine the potential of the waste heat source. Namely, a techno-economic analysis is also performed on an ORC, a common waste-heat-to-power technology. This would allow the conversion of flue gas waste heat into useful electrical power.

Absorption Refrigeration System

Another WHR alternative for which a techno-economic analysis is performed is an ARS, a system commonly utilized to transform waste heat into useful cooling.

1.4.2 Python Tool

The last objective of the present dissertation was the development of a Python program capable of automating the process and methodology employed in the techno-economic assessment of the previous three WHR options. In other words, the tool should be able to take user inputs related to flue gas (waste heat) characterization, cooling needs, sludge drying needs, among others, and output a techno-economic analysis of a drying system, an ORC, and an ARS powered by the available waste heat.

Furthermore, this tool should be as user-friendly as possible, such that the user should not require extensive knowledge or experience in the engineering of drying systems or thermodynamic cycles to operate it. To this end, the tool should feature a graphical user interface (GUI) which should make the tool's utilization process evident. This way, any person with access to the relevant data would be able to quickly obtain a techno-economic assessment of the WHR options for the available waste heat.

1.4.3 General and specific objectives

Within the revised the scope of the analysis the following objectives were defined for this thesis:

General objective. Determine how the available furnace waste heat at BA Glass (Avintes) can be valorized in a cost-effective way under plant constraints.

Specific objectives.

SO1: Quantify technically recoverable waste heat. Establish the recoverable thermal power and temperature window while maintaining a safe flue-gas outlet temperature (at or above 120 °C).

SO2: Evaluate alternative uses of the waste heat on a common techno-economic basis. Model and compare three pathways using site data and consistent economic metrics:

- a) A thermal sludge-drying line sized to reach the target moisture content for reinsertion;
- b) A single-effect H₂O–LiBr absorption refrigeration system (ARS) to provide cooling that can also improve thermal comfort;
- c) A subcritical organic Rankine cycle (ORC) for on-site power generation.

Report performance and economics (e.g., NPV, IRR, PBP, and levelized costs) to identify the most cost-effective option(s).

SO3: Generalize the methodology in a reusable software tool. Package the models, assumptions and calculations into a user-friendly Python GUI application so that similar plants can rapidly assess WHR options with their own inputs.

1.5 Research Questions

Given the thesis objectives, the development of the work in this dissertation was guided by the following research questions (RQs):

RQ1: Technical WH potential: What is the technically recoverable waste heat from Furnace A while maintaining the flue-gas outlet from the WHR heat exchanger at or above 120 °C?

RQ2: Dryer feasibility: For the measured sludge properties and throughput, what dryer operating conditions and thermal load are required to reach the target moisture content, and is the project economically viable (NPV, IRR, PBP)?

RQ3: ORC performance: What net power and efficiency can an ORC deliver from the same source, what are the corresponding CAPEX/OPEX and LCOE, and is this project economically feasible?

RQ4: ARS performance: What cooling capacity and COP can a single-effect H₂O–LiBr ARS provide while powered by the available waste heat, what fraction of current cooling electricity can it displace, what is the LCOC, and is this project economically feasible?

RQ5: Methodology portability: To what extent can the applied methodology be encapsulated in a user-friendly software tool and applied to other furnaces/sites with minimal re-work, and what are the associated inputs/outputs?

1.6 Dissertation Plan and Implementation Timeline

The first couple of weeks of the internship were used to get to know the Avintes plant's departments and what their respective functions are. In doing so, a deeper understanding of the hollow glass production process is attained, as well as the knowledge of what department or person is to be contacted, should assistance be required for any obstacle to the project.

An initial identification of the feasible technical solutions for thermal comfort improvement was carried out. Due to time constraints and the complexity of the modeling, a revised scope of analysis was agreed with the company. The sludge drying mechanism with waste heat recovery then became the primary objective. Shortly thereafter, testing was performed at INEGI to characterize the sludge produced in Avintes, in May. Once this objective was completed, the goals of also studying an ORC and an ARS were added, at the beginning of June, to expand the scope of the techno-economic analysis.

In mid-July, once these last goals were achieved, the objective of programming a Python tool to automate the process of assessing WHR options was added. It was completed in late August, as was the writing of this thesis.

1.7 Document Structure

This dissertation is structured as follows:

- **Chapter 1:** An introduction to the document, where the context, framework, objectives, research questions and methodology of the project are briefly described. The document's structure and the company in which the project was developed, as well as the glass industry as a whole, are also presented;
- **Chapter 2:** Existing literature is reviewed as to characterize the state-of-the-art of engineering solutions for waste heat recovery, drying technologies, ORCs, and ARSs. This section also reviews existing literature for energy use in the glass industry, with a focus on potential waste heat sources;
- **Chapter 3:** The problem this dissertation aims to ameliorate is described in detail, including waste heat characterization, and sludge production and drying in the Avintes unit. Furthermore, a general overview of the hollow glass manufacturing industrial process is exposed, as to contextualize the rest of this chapter;
- **Chapter 4:** This chapter describes the methodology employed in solving the problem at hand and developing the present dissertation. This includes assigning the values for each required input, detailing the equations used for calculations, and the experiments that were carried out during this project. This aims to assure replicability and transparency;
- **Chapter 5:** This section is dedicated to detailing the objectives, methods, and dependencies applied in the development of the decision-support tool, in the Python programming

language. It also displays the layout of the GUI, thereby demonstrating the user experience with the program;

- **Chapter 6:** This section of the document is used to present the results obtained once the methodology previously presented was applied. Furthermore, the results should be validated once obtained, e.g., by comparison with available references in literature;
- **Chapter 7:** Finally, this chapter concludes the present dissertation with a discussion of the presented work. This includes interpreting the results obtained, answering the research questions, evaluating the limitations with the presented methods, and discussing future works that could build on the obtained results.

Chapter 2

Literature Review

This chapter summarizes the state-of-the-art of the aspects analyzed in this dissertation according to the scope, objectives and research questions presented in Chapter 1. Namely, the literature review starts with an analysis of the sources of waste heat in the glass industry, followed by the technologies and methods through which waste heat is recovered, and the potential uses of the recovered heat - including industrial sludge drying technologies, organic Rankine cycles, and absorption refrigeration systems.

2.1 Waste Heat

Waste heat (WH) is defined as the thermal energy that is generated in processes, that does not serve any practical use, and is instead dissipated to the environment. Common sources of WH include combustion processes and heat that is dispersed by industrial processes, products or equipment to the environment through convection, conduction and radiation. As such, one of the main sources of WH is industrial processes (Jouhara et al., 2018).

Waste heat recovery (WHR) is the practice of capturing and reusing waste heat, that is, heat that would otherwise be lost to the environment with no added value. WHR does not require the energy to be reused within the same process, and can also be considered to generate power, cold or as a direct heat source (Jouhara et al., 2023). In the context of climate change, the potential of WHR applications to reduce total greenhouse gas emissions is straightforward, because a successful implementation of any WHR technology inherently leads to an increase in the energy efficiency of the process, all else being equal, usually leading to a reduction in GHG emissions (Oh et al., 2024).

Exergy is the maximum amount of useful work that can be extracted from a system as it comes into thermodynamic equilibrium with its environment (Park et al., 2014). The concept of exergy is helpful when determining the maximum potential useful work that can be extracted from a WH source. Through this analysis, one finds that the thermodynamic potential of a heat source decreases as its temperature approaches ambient temperature. For example, considering two heat sources at 500 °C and 50 °C, in the former, 61.4 % of the total energy can be converted to useful

work, compared to only 7.7 % for the latter. To calculate these values, one must refer to Carnot's theorem, as per Equation 2.1, where η_{Carnot} [-] is the Carnot efficiency, and T_C [K] and T_H [K] are the cold and hot temperatures, respectively. In these calculations, an ambient temperature of 25 °C (T_C) and a reversible process with Carnot efficiency were assumed. Note that the Carnot efficiency is a theoretical maximum, and thus, in practice, the real process efficiency will be lower (Panayiotou et al., 2017; Shang et al., 2014).

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} \quad (2.1)$$

Since a difference in WH temperature corresponds to a difference in exergy, as well as differences in applicable WHR technologies, and in WHR economic viability, it is common to categorize WH sources based on their temperature, according to Table 2.1 (Panayiotou et al., 2017; Lin et al., 2022; Jouhara et al., 2018). This facilitates the choice of an appropriate WHR technology for each case, and provides a simplified estimate for the WHR potential for a given WH source (Jouhara et al., 2018). Nevertheless, this practice is not universal, as some sources choose 400 °C as the temperature cutoff between the medium and high temperature ranges, instead of 300 °C (Forman et al., 2016).

Temperature Category	Temperature Range
High Temperature (HT)	>300 °C
Medium Temperature (MT)	100–300 °C
Low Temperature (LT)	<100 °C

Table 2.1: Categorization of waste heat sources by temperature.

In addition to categorizing WH sources based on their temperature, another important distinction is whether the origin of WH is an exhaust and/or effluent, or other types of losses. Exhaust and effluent losses, in this context, are defined as the thermal energy carried by flue gases and by coolants (e.g., water or air), respectively (Forman et al., 2016). This distinction is relevant because, due to technical limitations, only the WH in exhaust and effluent losses is feasible for recovery, and as such the other losses should not be regarded when implementing WHR technologies. In other words, one should only consider WH carried by a fluid (gas or liquid) as a viable WH source (Lin et al., 2022).

2.1.1 Waste Heat Potential

WHR has the potential to significantly reduce total energy consumption. This is evident in the fact that more than two thirds of the total global primary energy consumption is lost without serving any practical use, and as such is waste heat (Forman et al., 2016). In fact, in Figure 2.1, a diagram for the world energy use in 2012 is displayed, and it can be seen that 340 512 PJ were rejected with no practical use, out of the total 474 171 PJ used worldwide, which accounts for 71.8 % of the total energy use. It can be seen that the largest producer of WH is electricity generation, followed by the sectors in the displayed order (Forman et al., 2016).

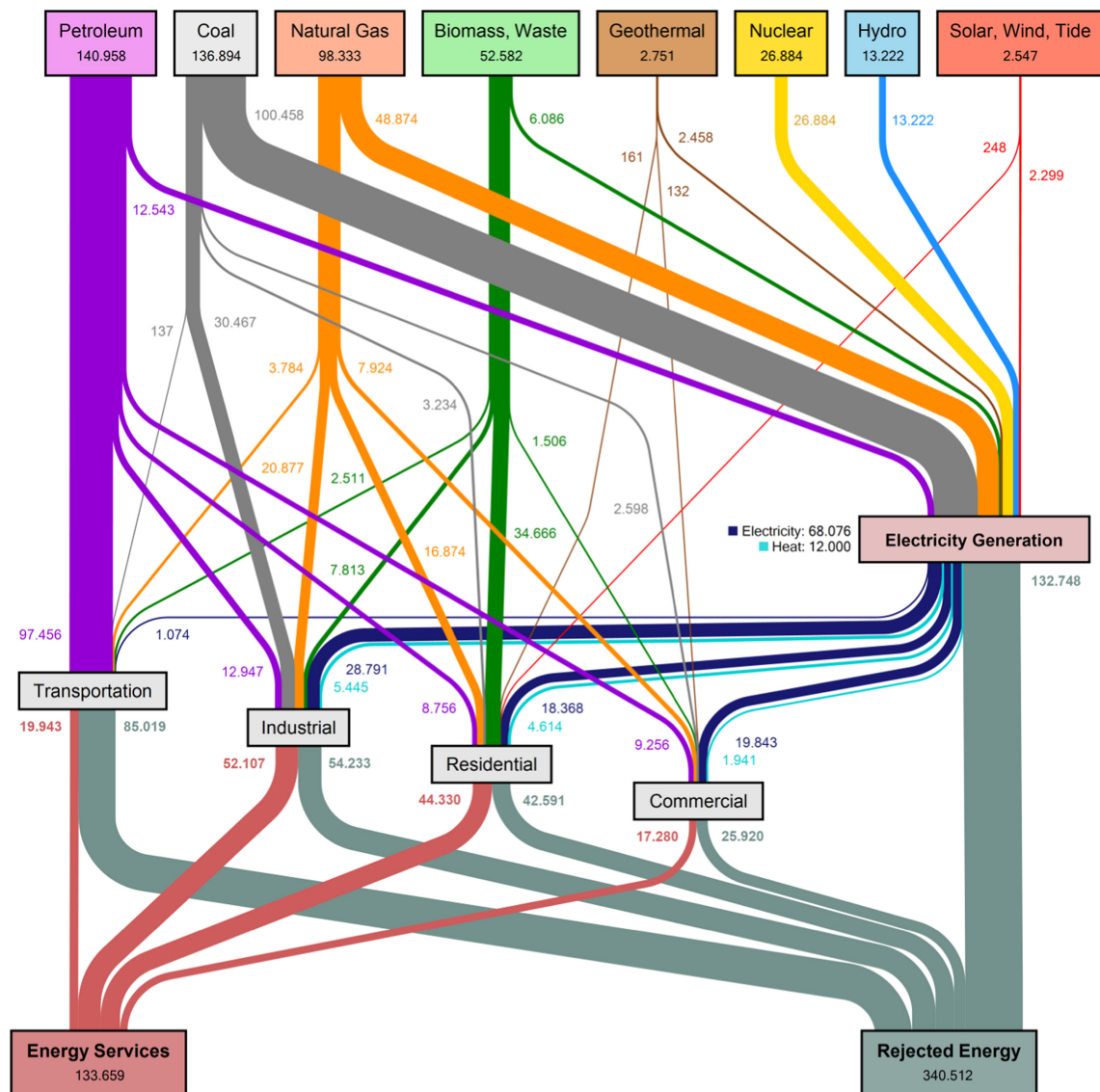


Figure 2.1: Diagram of 2012 world energy use, in PJ (Source: Forman et al. (2016)).

In order to better understand the potential for WHR in the 341 EJ of total waste heat in 2012, it is useful to divide this value in exhaust and/or effluent losses, and other losses. Furthermore, categorizing the WH that is viable to recover based on the respective temperature is also useful, as mentioned above. For this, one can observe Figure 2.2 for a diagram in which such distinctions are made. There, one can understand that 51.8 % of total energy use is lost in the form of exhaust and effluent losses, which represents a vast potential for WHR. This energy is then categorized by temperature into HT (20.6 %), MT (16.0 %), and LT (63.3 %). This means 10.7 %, 8.3 %, and 32.8 % of the total world energy use in 2012 was dissipated in the form of HT, MT and LT exhaust and effluent WH, respectively.

These values highlight one of the key barriers to WHR. Even though low temperature (below 100 °C) WH represents the majority of total energy dispersed in the form of exhaust and effluent WH, technological progress still has to be made to improve the efficiency and economic

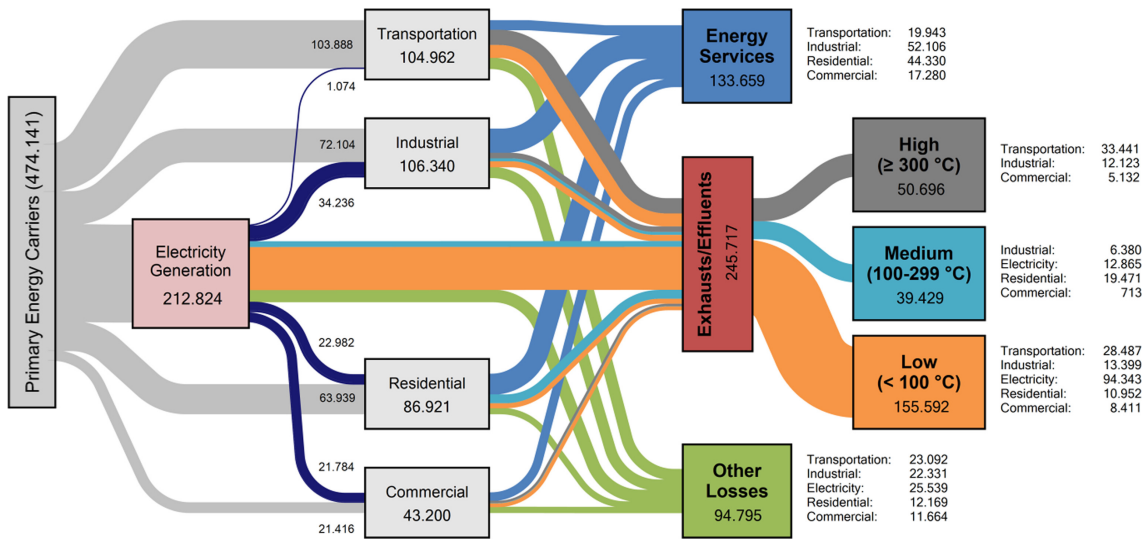


Figure 2.2: Diagram of 2012 world waste heat distribution, in PJ (Source: Forman et al. (2016)).

viability of LT WHR. Specifically, advancements in the selection of working mediums, thermodynamic optimization from the system level, and technical readiness for commercial applications are promising future developments for LT WHR. Keep in mind, the Carnot efficiency (20 % for a source at 100°C , considering an ambient at 25°C) is a physical limitation that cannot be exceeded, despite any future technological advancements. Thus, only if the desired WHR output is not work (e.g., heat) can the efficiency of a LT WHR application exceed 20 %. Nevertheless, technology for LT WHR have been developed, including the heat pump technology and the WH to refrigeration technology (Lin et al., 2022).

Figure 2.3 displays the relative amount each temperature category of WH (LT, MT or HT) for each sector of energy consumption. There, one can see that despite being the biggest producer of WH (as per Figure 2.1), electricity generation has an 88 % share of LT WH, meaning its potential for WHR is limited. Furthermore, the transportation sector appears to have great WHR potential as 54 % of the 85 EJ of WH created by this sector in 2012 were in the form of HT WH. However, technical limitations are a key challenge to WHR in the transportation sector (Forman et al., 2016).

Carnot's efficiency was applied based on the temperature of the heat sources in each sector, as per Equation 2.1, and the results are visible in Figure 2.4. There, it can be seen that the transportation sector has the biggest exergy potential of the analyzed sectors, followed by industry. It should be noted that, in practice, industry is better suited for WHR than transportation, due to the inherent technical limitations of the sector. Furthermore, it can be noticed that electricity generation has the lowest relative Carnot potential (5 %). This is due to the fact that WH in this sector is primarily low temperature, as shown in Figure 2.3.

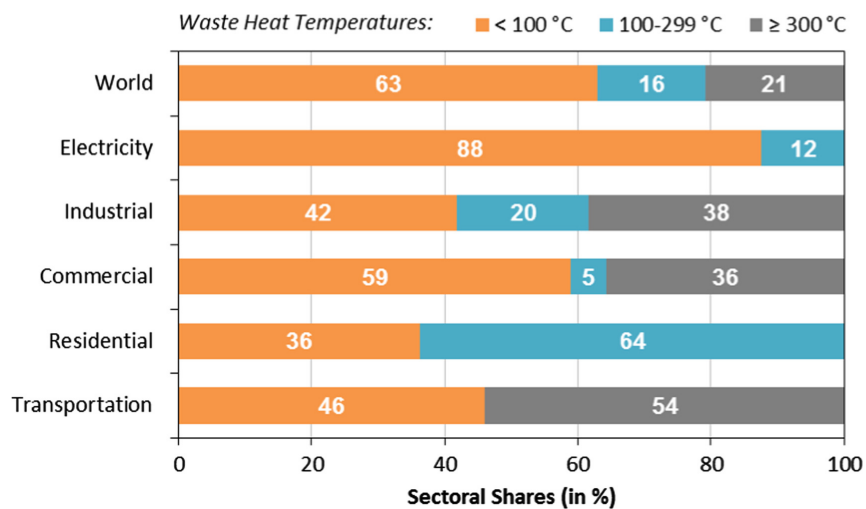


Figure 2.3: 2012 world waste heat generation by sector and temperature (Source: Forman et al. (2016)).

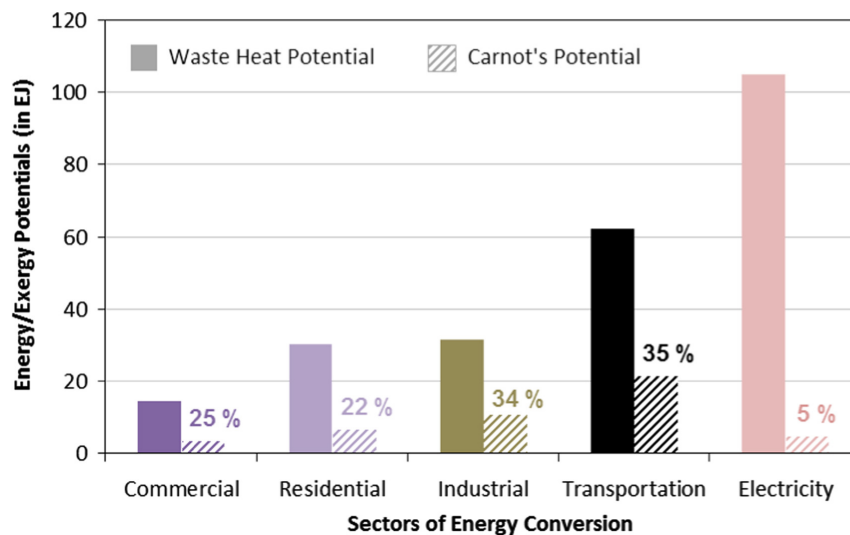


Figure 2.4: 2012 world waste heat potential and Carnot potential by sector (Source: Forman et al. (2016)).

2.1.2 Waste Heat in the Glass Industry

When looking into waste heat recovery (WHR) methods for industrial processes, the identification of waste heat sources is an important aspect in order to achieve optimum results and efficiency. As mentioned above, the glass industry is very energy-intensive, particularly due to the energy demand of the furnace, which accounts for 60-90 % of the total plant energy consumption. Estimates of this exact value may vary, but most lie somewhere in the range of 75-85 %. In Table 2.2, the relative energy consumption of each section in the glass container production process (see Section 3.1) is detailed (Martini et al., 2021; Papadogeorgos and Schure, 2019; Furszyfer Del Rio et al., 2022; Johnson et al., 2008; Lu et al., 2016; Saha et al., 2020; Su et al., 2021).

The furnace represents the majority of the energy consumption, and it mostly uses thermal

Section	Energy Consumption
Batch preparation	1.0–1.5 %
Melting & fining	75–80 %
Refining & conditioning	6–7 %
Forming & moulding	5–6 %
Annealing	4–5 %
Surface treatment	0.3–0.8 %

Table 2.2: Energy consumption distribution across manufacturing sections in the glass container industry (Data from Papadogeorgos and Schure (2019)).

energy. Thus, it comes as no surprise that 80 % of the energy consumed in the hollow glass production process is thermal energy. This is one of the main reasons why the glass industry produces a considerable amount of waste heat. Indeed, studies have estimated that 20-50 % of the energy input in the glass industry is lost in the form of waste heat (Su et al., 2021). Aside from the glass furnaces, sources of waste heat include, for example, thermal energy in the glass packages, annealing lehr structural losses, and friction in the mechanical systems (e.g., in the IS machines or conveyor belts).

Industrial Glass Furnace Waste Heat

The furnace itself is the main source of waste heat in the hollow glass production process, due to the extreme temperatures achieved within them. The flue gases from the natural gas combustion reaction need to be removed from the furnace, and these gases are at temperatures in the range of 1600 °C (Pereira et al., 2025). Usually, about 50 % of the energy input of the furnace is disseminated through exhaust gases and structural losses (depending on furnace insulation, sealing and waste heat utilization). This represents about 40 % of the total energy input in the production process (Papadogeorgos and Schure, 2019).

In particular, the flue gases account for 25-30 % of the total energy input of the industrial furnace, and, as such, 20-24 % of the total energy input of the production process (Dolianitis et al., 2016; Jost et al., 2025). Thus, the furnace's flue gases stand out as one of the best sources of waste heat in the glass industry, not only because they represent a considerable amount of the total energy input, but also because this waste heat is relatively easy to capture and utilize, especially when compared to other waste heat sources in this industry, such as the structural losses of the furnace or the thermal energy in the glass product (Jost et al., 2025; Zier et al., 2021). Indeed, in practice, waste heat carried by a fluid heat carrier (gas or liquid) is the easiest to recover, due to limitations in available WHR technologies (Lin et al., 2022).

Currently, recovering the waste heat from the flue gases is a common practice in the glass industry, usually in the form of regenerative furnaces, which use the thermal energy in the flue gases to preheat the combustion oxidizer (air) before it is introduced into the furnace. Indeed, there are four main types of industrial glass furnaces (regenerative, recuperative, oxy-fuel, electric), but regenerative furnaces account for about 75 % of the container glass industry, and are also the type

of furnace utilized in the Avintes unit of BA Glass, so they are the most relevant type for this study (Colangelo, 2024; Zier et al., 2021).

A diagram of the functioning principle of the regenerator of an end-fired regenerative industrial glass furnace, like those in the Avintes factory, can be seen in Figure 2.5. The two chambers constitute the regenerator. One of these chambers removes the exhaust gases, heating or "charging" said chamber as the flue gases cool, while the other supplies the combustion oxidizer, cooling or "discharging" the chamber as the oxidizer heats up. Thus, the functioning principle of this device exploits thermal inertia. The combustion of natural gas only occurs on the side of the furnace which is being supplied with the oxidizer. However, to maintain a homogeneous temperature profile inside the furnace and to enhance the regenerator efficiency, the regenerator chambers operate on a cycle, such that, each 20-30 minutes, the combustion stops on one side and begins in the other. Also, in this moment, the purpose of the chambers are swapped, such that the one that previously removed the flue gases now supplies the oxidizer, and vice-versa. These two cyclical states of functioning that the furnace has are represented by Figures 2.5.a) and 2.5.b) (Pereira et al., 2025; Zier et al., 2021; Danieli et al., 2019).

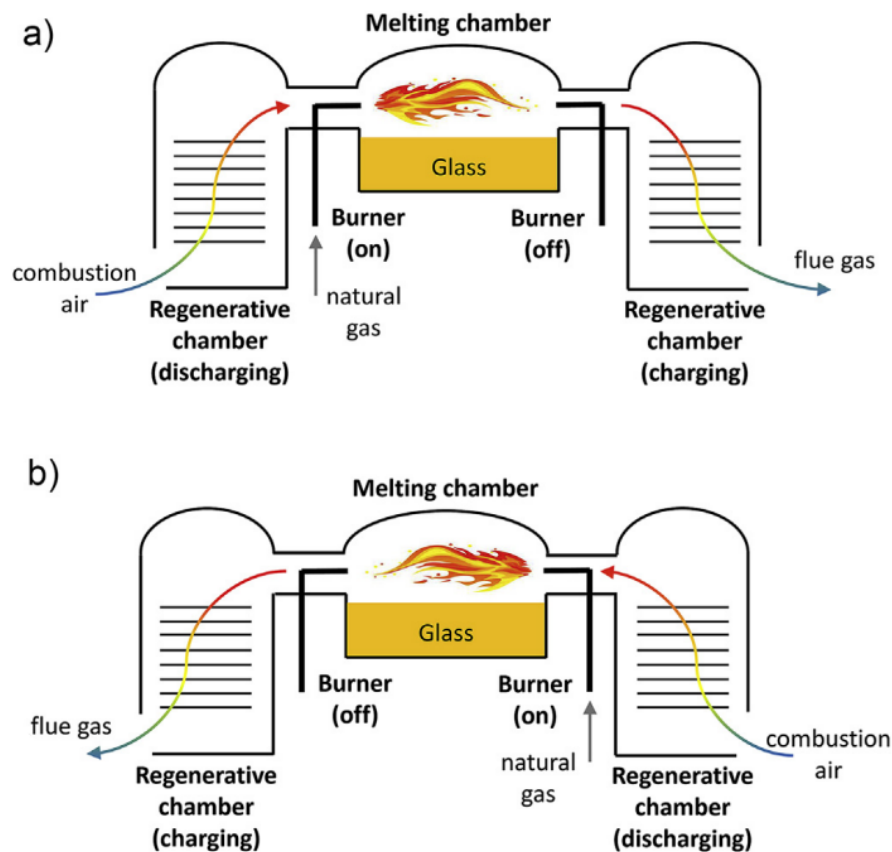


Figure 2.5: Regenerative industrial glass furnace functioning principle (Source: Danieli et al. (2019)).

These regenerators achieve efficiencies of 60-65 %, such that the combustion air is heated

from the outdoor air temperature to about 1300 °C, while the flue gases are cooled from 1600 °C to 500 °C, approximately. This results in a very significant recovery of the waste heat, as 30-35 % of the energy input is from the heat recovery, and therefore regenerative furnaces represent energy savings of 30-35 % when compared to their non-regenerative counterparts. A Sankey diagram for the energy flow in an end-fired regenerative container glass furnace can be observed in Figure 2.6. It is relevant to observe that in this case, the flue gases still represent a strong potential for waste heat recovery, even after being cooled in the regenerator, as they account for 22.5 % of the energy introduced into the furnace (disregarding the energy input of the regenerator) (Pereira et al., 2025; Zier et al., 2021; Dolianitis et al., 2016).

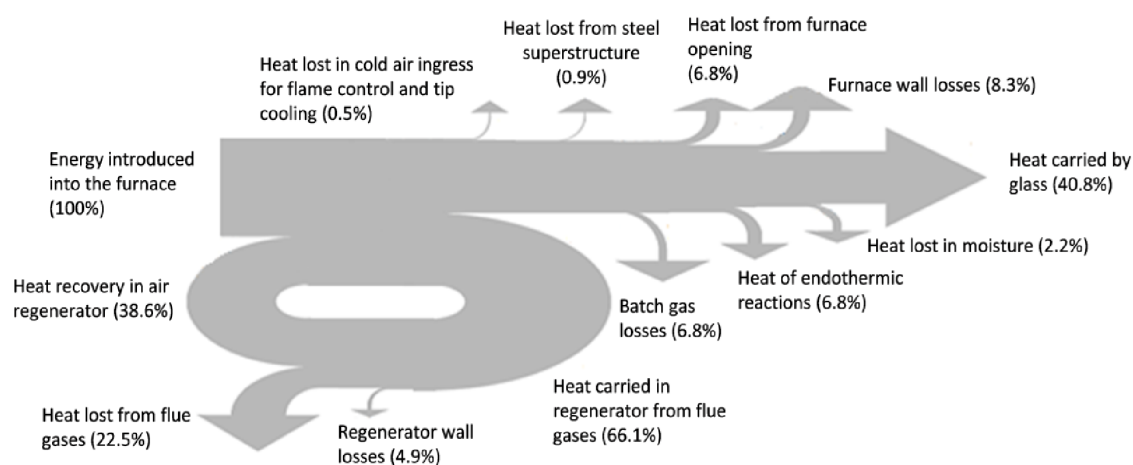


Figure 2.6: End-fired regenerative industrial glass furnace energy flow diagram (Source: Dolianitis et al. (2016)).

2.2 Heat Exchangers for Waste Heat Recovery

After identifying the potential sources of waste heat, it is important to identify and study waste heat recovery (WHR) technologies. Heat exchangers are the most important equipment in WHR systems (Farhat et al., 2022). However, WHR technologies include not only heat exchangers, but also the systems that transform or use said heat, such as thermodynamic cycles (e.g., Rankine cycle) or thermal dryers, respectively (Jouhara et al., 2018).

A heat exchanger (HE) is a device which transfers heat between two or more process fluids. These can vary in many ways, including geometry and efficiency (Farhat et al., 2022). However, most HEs are only suitable for a specific range of applications, namely based on temperature range, physical state of working fluids (liquid or gas), and whether or not cross-contamination is acceptable (Jouhara et al., 2018). For the project at hand, the WH source is in the medium temperature range (272 °C - see Section 4.2), and a HE with no cross-contamination is required, because the exhaust gases contain hazardous chemicals which legally can not be released at a low

altitude. Therefore, a few of the most common HEs used for WHR are discarded immediately, and will no longer be considered in this section.

The most commonly used HEs in industry are the shell and tube heat exchanger (STHE) and the plate heat exchanger (Pourhoseini et al., 2023). However, for this study, plate HEs are discarded as their main benefit is compactness and efficiency, which are largely irrelevant for this project, and because they present temperature and pressure limitations, and fouling and clogging challenges, which makes them overall less robust and suitable for harsh industrial environments with corrosive and particulate exhausts, much like the glass industry (Mota et al., 2015; Annadurai et al., 2024; Anand Seamless Tubes, 2025). The types of HE that shall be considered are, therefore, STHEs and heat pipe HEs (Jouhara et al., 2018).

2.2.1 Shell and Tube Heat Exchanger

Figure 2.7 is a diagram displaying the functioning principle that shell and tube heat exchangers (STHE) are based on. It can be observed that the design is rather simple, as its primary components are the shell, which is a thick pipe that one of the working fluids circulates freely through, and the tubes, which are a bundle of narrower pipes placed within the shell, in which the other working fluid flows (Arveng Training & Engineering, 2015). Therefore, the tube walls serve as the heat exchange surface, and transfer heat from one of the fluids to the other. Thus, this is an indirect type of heat exchanger, as there is no contact between the heat source and heat sink. The fluids can have a parallel flow or a counter flow configuration. Typical values for overall heat transfer coefficient and efficiency range from $100\text{--}1\,000\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ and 60–90 %, respectively (VRcooler, 2024).

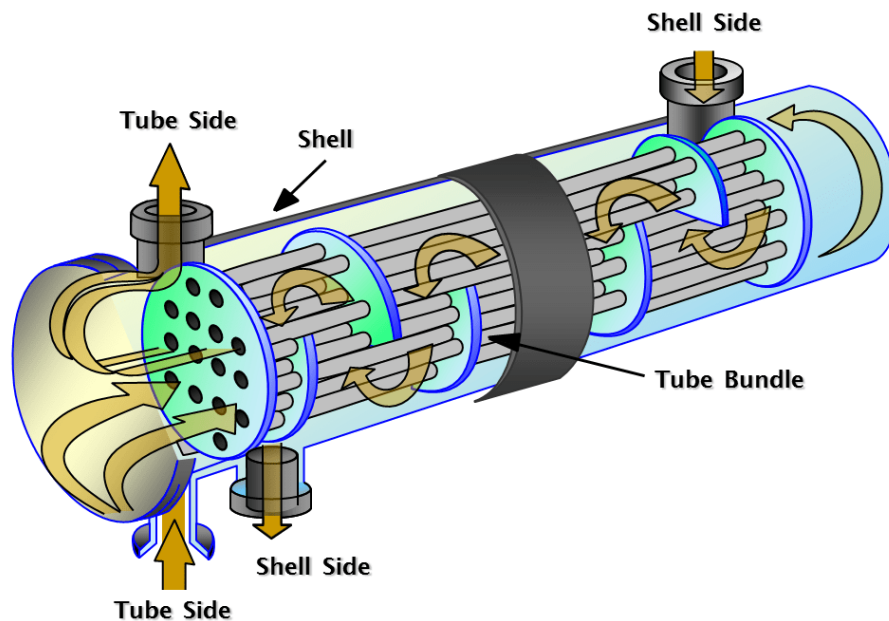


Figure 2.7: Shell and tube heat exchanger diagram. (Source: Arveng Training & Engineering (2015)).

Besides the shell and the tubes themselves, these HEs must have a front-end and rear-end head, on either side, to accommodate the input and output for both the shell side and tube side flows. Furthermore, baffles are a common addition, disrupting the shell side flow in order to increase heat transfer efficiency, as per Figure 2.7. This simple design makes the STHE attractive in many applications because it is overall robust and cost-effective. Therefore, the most widespread and versatile type of HE is the STHE (Couper et al., 2012).

When compared to other HEs, the main advantages of STHes are a long service life, reliability, resistance to scale (mineral deposits) formation, control of the associated pressure drop, resistance to thermal stress, versatility, wide choice of material to suit the application, and ease of maintenance access (Edreis and Petrov, 2020; Arveng Training & Engineering, 2015). On the other hand, downsides for STHE include a vulnerability to fouling which creates a requirement for regular maintenance and cleaning, large dimensions, and heavy weight (VRcooler, 2024; Edreis and Petrov, 2020). Therefore, it is essential to consider the aggressiveness of the environment and working fluids when choosing the material for the STHE, to reduce the formation of corrosion, blockages, fouling and scale (Edreis and Petrov, 2020).

2.2.2 Heat Pipe Heat Exchanger

A heat pipe heat exchanger (HPHE) is a passive (no moving parts) thermal transfer device which functions based on vapor diffusion and phase-change materials, such that the heat absorbed and discharged by the working fluid is latent instead of sensible (Jouhara et al., 2018). They display higher effective thermal conductivity than other traditional heat exchangers, with heat transfer coefficients in the range of $1\,000\text{--}100\,000\text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, and thermal conductivities in the range of $5\,000\text{--}200\,000\text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, and an efficiency in the range of 45–55 % (Farhat et al., 2022; Jouhara et al., 2018; Brough and Jouhara, 2020).

HPHEs consist of one or several independent mounted heat pipes, configured to suit the specific application. Usually, these are mounted in a staggered or inline array, and the heat exchanger can contain a number of passes or baffles (Jouhara et al., 2023). The heat pipes themselves can be divided into three sections (evaporator, adiabatic, condenser) and function based on the following working principle: as thermal energy is absorbed on the evaporator section (hot end) of the heat pipe, the working fluid near the surface evaporates, and the generated vapor pressure drives the resulting vapor to the condenser section (cold end), where it releases the latent heat of vaporization, which condenses the fluid back to a liquid, that is then driven back to the evaporator section, and the cycle repeats itself (Oyedepo and Fakeye, 2021; Jouhara et al., 2018). Figure 2.8 shows a diagram detailing a heat pipe and HPHE.

Among the benefits of HPHEs are the high thermal conductivity, ability to transfer heat over long distances effectively, and incorporated passive operation, which results in lower operating costs, lower maintenance and a longer life than other conventional heat exchange technologies. However, HPHE installations must be studied and designed based on the specific application to achieve optimum performance, including choice of pipe material, working fluid and possibly wick type. These are best utilized in medium-high temperature applications (Jouhara et al., 2018).

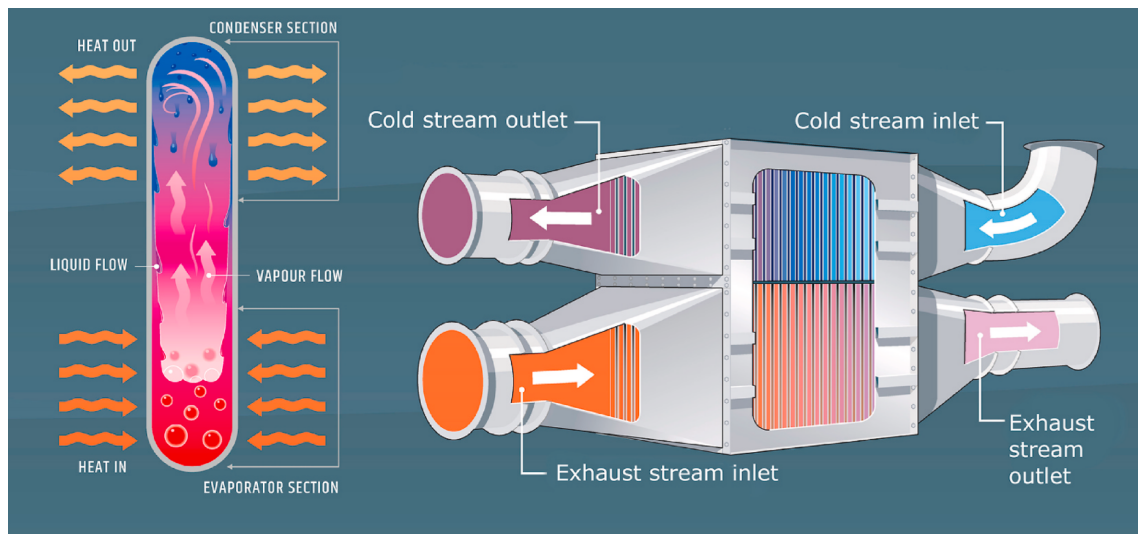


Figure 2.8: Heat Pipe and HPHE diagram. (Source: Jouhara et al. (2023)).

Furthermore, since the heat absorbed by the heat pipe is latent, the outer temperature of the heat pipe is uniform, which reduces fouling when compared to STHs (Jouhara et al., 2021). Oyedepo and Fakeye (2021) claim that the HPHE is the best choice for heat recovery from exhaust gases in a furnace stack, citing virtually no cross-contamination, compactness, lack of moving parts, relative economy, and reliability as the main advantages of this system.

2.3 Industrial Sludge Drying Technologies

One of the objectives of this project is to analyze a solution for the drying of industrial sludge, so it is relevant to identify and study available state-of-the-art industrial sludge drying and dewatering technologies. Chang et al. (2023) categorized these technologies as mechanical dewatering, mechanical dewatering after anaerobic digestion, deep dewatering, bio-drying and thermal drying, and these categories have an average solids content of 24.7 %, 28.7 %, 37.6 %, 59.9 %, and 89.6 % of the total mass in their respective outputs, respectively. Immediately, these figures confirm that all drying mechanism categories, aside from thermal drying, are unsuitable for this project, as the desired solids content in the drying mechanism output is around 88 % (see Section 6.1). Thus, even though thermal drying technologies have the highest power consumption per input mass of all categories, they are the only thermal drying systems that shall be analyzed in this section, due to their capability of achieving lower moisture content in the final product, which is a requirement for this project (Chang et al., 2023).

Thermal drying (TD) technologies generally fall into three categories: solar, direct / convective, and indirect / conductive. Solar dryers use sunlight to evaporate the moisture in the product, so they are not relevant to this project. The difference between direct and indirect thermal dryers lies in the means of heat transfer. Indeed, while direct dryers use a flow of hot gas (usually air) to transfer heat directly to the product through convection, indirect dryers use a heated surface to

transfer heat through conduction instead (Cambi, 2024). Relative to indirect dryers, the main disadvantages of direct dryers are a longer drying time, unpleasant odors, gaseous emissions, possible entrainment of fine materials in the process gas, and a looser control of the processing environment and final product humidity. On the other hand, the advantages of direct dryers include lower financial costs, easier manipulation, less required maintenance, and efficiency. Direct and indirect dryers have specific energy consumptions of 700-1 400 kWh/t and 800-955 kWh/t, and specific drying rates of $0.2\text{--}30\text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ and $7\text{--}35\text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, respectively (Wang et al., 2021; Le Capitaine and Carlson, 2024; Kurt, 2014; Camera et al., 2021). Thus, the advantages of direct dryers outweigh those of the indirect counterpart, considering the objectives of this project. Therefore, indirect dryers shall be disregarded, and direct thermal dryers are the only type of dryer considered from this point forward.

It is important to understand the physical processes and phenomena that reduce sludge moisture content in TD technologies, in order to effectively implement them. The drying of sludge involves complex heat and mass transfer processes. As hot air contacts the sludge surface, heat is transferred via convection and radiation, causing surface moisture to evaporate. The rest of the sludge also rises in temperature by heat conduction inward. Internally, water migrates from the core to the surface due to diffusion, originated by moisture gradients. Thus, while convection is the primary mode of heat transfer in this process, conduction and radiation also play a vital role (Ling et al., 2022).

Sludge drying rate increases as temperature and/or air velocity increases, and as relative humidity and/or sludge particle size decreases. At higher temperatures, the air has increased ability to absorb humidity just as the sludge itself shows lower resistance in releasing moisture. At higher air velocities, evaporation is promoted, not only due to lower vapor pressure at the surface, but also because of an increase in the heat and mass transfer coefficients, due to the thinner boundary layer. At lower relative humidity, the sludge-air humidity gradient is greater, which is a driving force for moisture transfer (Zheng et al., 2021; Ling et al., 2022). In fact, Zheng et al. (2021) conducted a study which concluded that, for the thermal drying of sludge, the sensitivity indicators of temperature, air velocity, and relative humidity on the drying time were 0.470, 0.232 and 0.025, respectively.

Figure 2.9 shows the four stages that a sludge drying process generally goes through. In the first two stages, unbound water is removed, as opposed to bound water in the latter two. The first two stages are, in chronological order, the preheating stage, where the drying rate increases as the temperature of the sludge rises, and the constant drying rate stage, where an equilibrium is reached as the temperature of the sludge surface rises to the wet bulb temperature, which causes the heat transfer to be almost entirely latent, for the evaporation of water. Then, the first decelerating drying rate stage occurs, when the lower moisture content in the sludge lowers the diffusion rate of inside moisture such that it can no longer keep up with the evaporation rate of moisture, which makes sensible heat transfer return and thus sludge surface temperature exceeds wet bulb temperature. Finally, the second decelerating drying rate stage occurs, where the diffusion resistance is greater than the water evaporation resistance, and the mass transfer between the hot air and the sludge is

nearly at equilibrium (Ling et al., 2022).

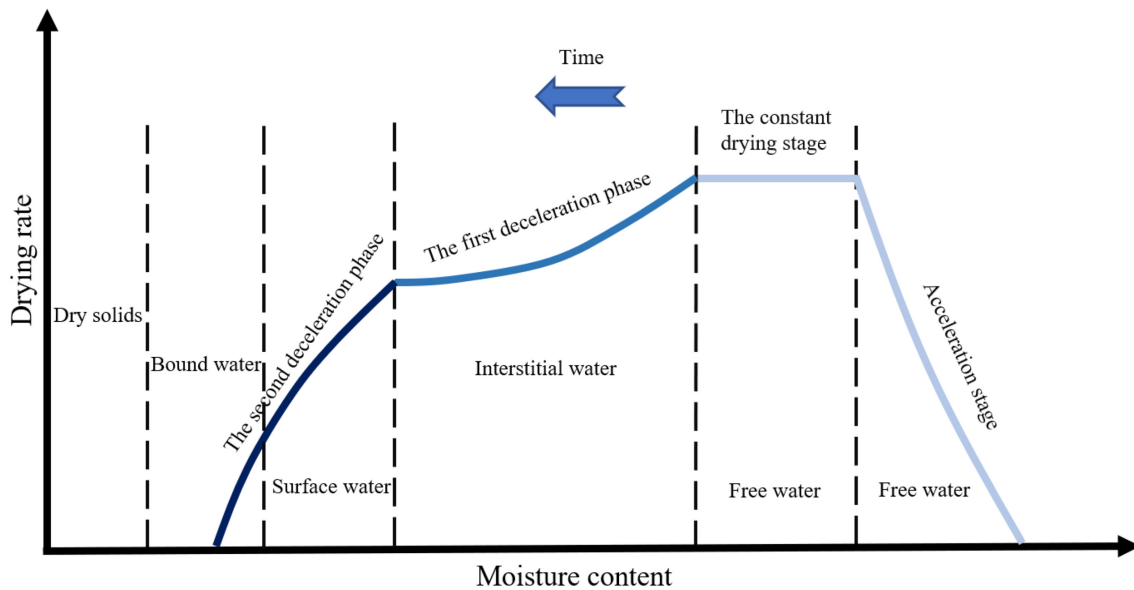


Figure 2.9: Diagram of sludge drying rate as a function of moisture content. (Source: Ling et al. (2022)).

Industrial thermal drying (TD) technologies include rotary drum dryer (RDD), fluidized bed dryer, belt dryer, flash / pneumatic dryer, spray dryer, and paddle dryer, among many others. However, among them, the rotary drum dryer stands out as the best choice for this project. This is because they are robust, simple, and flexible, so they have lower maintenance costs and greater capacity than any type of dryer. Also, they are less sensitive to particle size and can accept a wider range of gas temperatures. These characteristics, among others, make them the most used for drying aggregates (e.g., sand) and other granular, lumpy, sludge-like materials (Burlacu et al., 2022; Poós, 2022; Donoso-García et al., 2024; Del Giudice et al., 2019).

2.3.1 Rotary Drum Dryer

The rotary drum dryer (RDD) typically features a long cylindrical shell (drum) that is partially enclosed and slightly inclined relative to the horizontal, into which wet sludge is introduced at the higher end, as per Figure 2.10. On the inner surface of the drum, there are blades that help move and mix the material to be dried. Due to the inclination and rotation of the cylinder, as well as the direction in which the hot gas is blown, the sludge slowly flows to the other end of the cylinder, where it exits dry. Although they occupy a large amount of space, these dryers feature simple construction and maintenance, making them suitable solutions for large-scale sludge drying. However, they are less cost-effective for small-scale sludge drying (FEECO, 2025).

There are several types of direct contact RDDs, which can be characterized according to the direction of sludge movement in relation to the direction of the hot gas flow: co-current and counter-current. Co-current dryers, as seen in Figure 2.10, are the most common and are also the most suitable for drying materials that cannot withstand high temperatures, as is the case

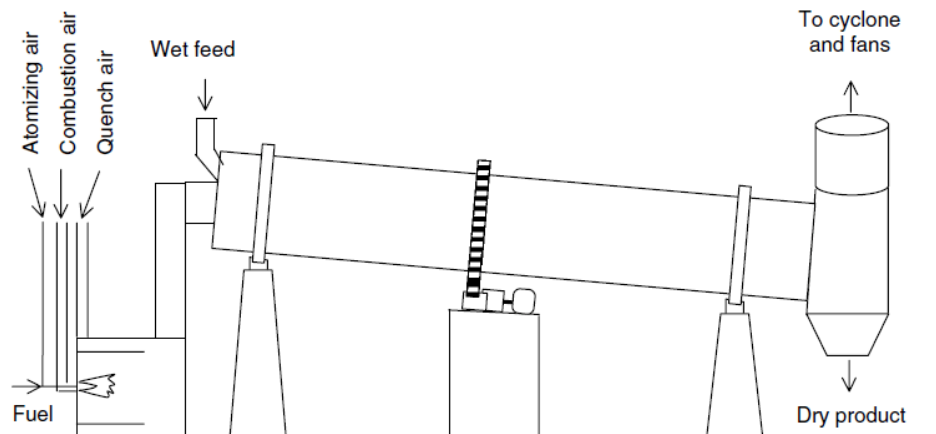


Figure 2.10: Diagram of a rotary drum dryer. (Source: Patel and Bade (2019)).

under study (see Section 6.1). The heating medium (air) exits cooled at the same end as the dried sludge. Since there is contact between the medium and the sludge, the cooled medium is mixed with evaporated water from the sludge and with dry sludge particles. For this reason, the medium cannot be directly reused and must be filtered to remove the dry particles and water vapor (FEECO, 2025).

In these dryers, the temperature of the hot gas at the cylinder inlet is usually quite high, leading to rapid evaporation of the moisture in the sludge. The initial heat transfer rate is very high, so the gas cools down quickly, preventing excessive heating of the material and the cylinder (Xiao et al., 2020; FEECO, 2025). When the material to be dried has a moisture content above 30 %, it may enter a "sticky phase", making it difficult to transport it along the cylinder, which hinders the drying process (Xiao et al., 2020). Generally, the initial moisture content, the desired final moisture content, and the characteristics of the material to be dried influence the design of the dryer and its operating parameters, such as the length and diameter of the rotary cylinder, the blade geometry, the heating medium and its temperature, and the drying time (Le Capitaine and Carlson, 2021).

2.4 Organic Rankine Cycle

The Rankine cycle is a thermodynamic cycle which receives heat energy and converts it into mechanical energy, and it is the simplest vapor power cycle, consisting of only four components. These can be classified as steam Rankine cycles or organic Rankine cycles (ORCs), based on whether the working fluid is water or an organic working fluid, respectively. As a consequence of the different working fluids in these cycles, ORCs are able to operate using lower temperature heat sources than steam Rankine cycles. This makes the ORC an attractive choice for WHR in lower grade heat sources, even though ORC cycles are generally less efficient than steam Rankine cycles (Kasaeian et al., 2022).

The functioning principle of an ORC can be observed in Figure 2.11, which includes both a schematic and a T - s (Temperature-entropy) diagram of the cycle. As can be observed, the low-temperature, low-pressure saturated liquid (state 1) is compressed in a pump. The resulting high-pressure liquid (state 2) is directed to a heat exchanger (evaporator), where heat is transferred to the fluid by the heat source until the fluid is in a state of saturated vapor or superheated vapor (state 3). Then, a turbine / expander decreases the pressure of the fluid, producing mechanical work in the process (often this mechanical work is converted to electricity using a generator). Finally, the low-pressure gas (state 4) passes through a second heat exchanger (condenser), where it releases heat to a heat sink until it becomes a saturated liquid, and the cycle repeats itself (Jiménez-García et al., 2023).

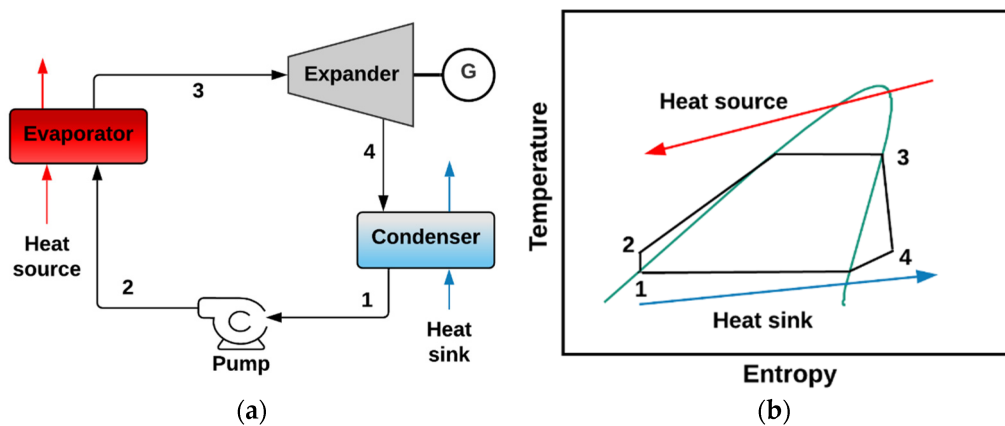


Figure 2.11: ORC (a) Schematic; (b) T - s diagram (Source: Jiménez-García et al. (2023)).

The choice of working fluid is a key aspect of ORC design, as it largely governs the feasible temperature levels, heat-exchanger design (pinch/glide), expander selection, safety, and environmental performance of ORCs. Reviews consistently group fluids by the slope of the saturated-vapor line in the T - s plane: dry and isentropic fluids (e.g., R245fa, R1233zd(E), light hydrocarbons) have positive and vertical slopes, respectively, and avoid two-phase conditions at turbine exit, whereas wet fluids have negative slopes and tend to require superheating to prevent blade erosion (Bao and Zhao, 2013; Chen et al., 2010). Environmental constraints have driven a shift away from high-GWP hydrofluorocarbons (e.g., R245fa) toward low-GWP hydrofluoroolefins (e.g., R1233zd(E), R1234ze(Z)) and hydrocarbons. Furthermore, experiments in WHR test rigs and engine applications show R1233zd(E) delivering comparable or slightly higher thermal efficiency than R245fa under similar conditions, while offering significantly lower GWP (Eyerer et al., 2016; Yang et al., 2024).

ORCs are considered one of the best waste heat-to-power systems, with relevance in WHR in the glass industry. Indeed, Danieli et al. (2019) conducted a study regarding WHR using the flue gas from industrial glass furnaces, in which the techno-economic performance of four waste heat-to-power systems were evaluated, namely an ORC, two configurations of supercritical CO_2 Brayton-Joule cycle, and a regenerative air Brayton-Joule cycle. The results showed that the ORC

was the best choice for small furnaces, but the air Brayton-Joule cycle was slightly more competitive in medium sized furnaces, as it displayed a 4.5 year PBP, while the ORC needed 4.7 years. Furthermore, ORC systems average cycle thermal efficiencies of 15-19 % for WH temperatures of $\sim 270^\circ\text{C}$ (Colonna et al., 2015).

2.5 Absorption Refrigeration System

Absorption refrigeration systems are mechanisms that operate based on the absorption refrigeration cycle (ARC). This cycle is powered by heat and operates to produce useful cooling. Thus, it is similar to a vapor-compression refrigeration cycle, but the work input (energy source) of that cycle is replaced by heat input, and thus the mechanical compressor is replaced by a thermal compressor, as in Figure 2.12. Although vapor-compression systems boast a larger coefficient of performance (COP) than ARS (around 3.5 compared to 0.7, respectively), the latter are relevant and usually more economic when waste heat is utilized as a heat source, as in these cases the energy input of the ARS is essentially free (El-Shafie et al., 2021; Alghamdi and Krarti, 2025). Therefore, ARS are most commonly used in WHR applications, and are among the most widely used waste-heat-to-cold technologies (Liang et al., 2024).

Figure 2.12 displays a schematic containing the basic components of an ARC. It consists of four heat exchangers (condenser, evaporator, absorber, generator), two expansion valves and a pump. Also, it operates using two working fluids instead of one: an absorbent and a refrigerant. When these are mixed, it is called a solution. The strong solution has a higher refrigerant concentration than the weak solution (Khalil and Mohammad, 2024; Tawalbeh et al., 2020).

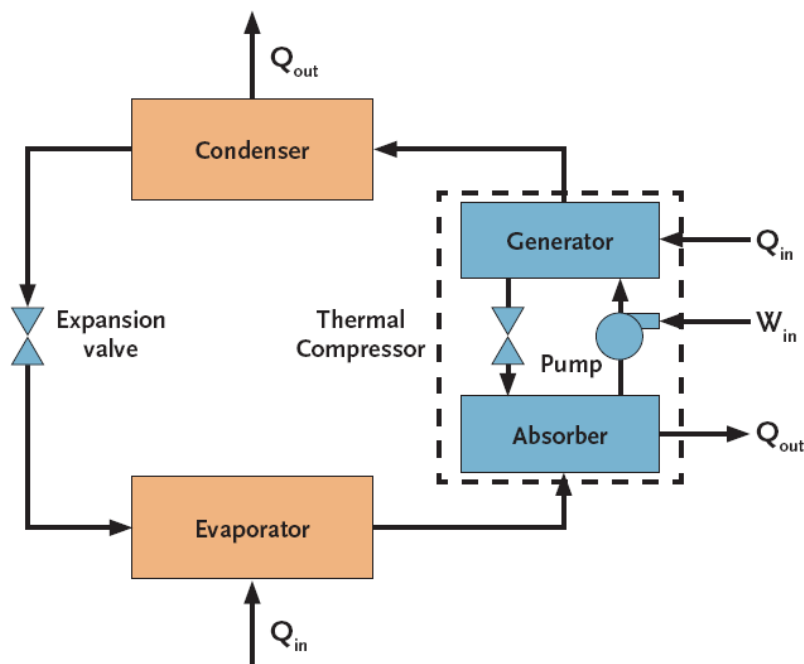


Figure 2.12: ARC Schematic (Source: Welch (2009)).

As can be seen in Figure 2.12, the working principle of the cycle is as follows: in the generator, heat is transferred from the heat source to the strong solution, causing an endothermic reaction that separates pure refrigerant vapor from the solution. This high-pressure high-temperature vapor flows to the condenser, where it is cooled and condensed (usually by cooling water), and then to the expansion valve, where its pressure is reduced. The resulting low-pressure low-temperature liquid refrigerant is heated and evaporated in the evaporator, absorbing heat (usually from chilled water) and producing the useful cooling output of the system. Consequently, the refrigerant flows to the absorber, where it is absorbed by the weak solution in an exothermic reaction. Thus, the absorber needs to release this heat (usually to cooling water). The resulting strong solution is pumped to increase its pressure, and returns to the generator, where the cycle repeats. In the solution side of the cycle, the weak solution resulting from the desorption in the generator is depressurized in an expansion valve before returning to the absorber, where it absorbs refrigerant (Ren et al., 2019; Wang et al., 2024).

The most commonly used working fluid pairs in ARS are water-lithium bromide (H_2O -LiBr) and ammonia-water (NH_3 - H_2O), for refrigerants and absorbents, respectively. The main advantages of the former pair are that it boasts a higher COP and, thus, cooling capacity, by approximately 33 % (abu Shaban et al., 2024), that the fluids are less corrosive and hazardous to human health (Siller et al., 2010; Moser et al., 2011), and that the ARC is less complex as it does not need a rectifier (Ren et al., 2019). On the other hand, the main advantages of the NH_3 - H_2O pair are that the refrigerant has a lower condensation temperature, so the evaporator and, therefore, the chilled water, can operate at a lower temperature (Tawalbeh et al., 2020), and that it does not feature the crystallization problem of H_2O -LiBr systems (Ren et al., 2019).

These characteristics of the working fluid pairs make H_2O -LiBr the most predominant choice for systems that do not require cooling at very low ($< 5\text{ }^\circ\text{C}$) cooling, such as cooling for HVAC applications (Cefarin, 2015; Lima et al., 2020; Stoyanov et al., 2024). Therefore, that is the only working pair that shall be considered for ARS, as this project is not interested in analyzing other cooling applications.

Chapter 3

Problem Description

This chapter describes in detail the scope of the analysis carried out in this dissertation, namely, the actual setting and physical systems involved. For this purpose, the glass packaging production process in the Avintes plant of BA Glass is presented in detail. Other relevant adjacent processes are also described, including the production and treatment of industrial sludge, and the exhaust system that will be the main source of waste heat analyzed throughout this dissertation.

3.1 Glass Packaging Production Process

The production process begins with the reception of raw materials (RM) at the facility, which are then stored in specific silos. All RM transport and storage systems are carried out using pneumatic systems and open belt conveyors. After being introduced into the silos, which are equipped with bag filters, the dosing and mixing process takes place, which is fully automated.

Recycled glass (cullet) is then added to the composition, before being transported to the silos that feed the furnaces. The glass cullet at the facility is of internal origin, from rejects that occur during the manufacturing process, and of external origin, already duly treated. This external cullet is initially deposited in bulk and then transported by a loader to the hopper, followed by a bucket, to 3 storage silos with a capacity of 150 tons each. The total storage capacity, in silos and bulk cullet, is 1950 tons.

The glass composition enters the furnaces through the kiln mouths, located laterally, passing through the “melting zone” where the mass is melted at a temperature of approximately 1550 °C. After melting, and still in the furnace, the mass is homogenized and refined in the “tuning zone”.

The molten mass passes to the working zone through the throat of the furnace and flows through channels heated by natural gas (feeders), which feed the molding machines. These have a gob-cutting device, which directs the glass gobs to the various sections of the molding machines (IS machines – individual section machines). The drop falls into a first mold and the container is formed in a second mold after blowing compressed air.

Furnace A is associated with 4 molding lines, Furnace B with 3 molding lines, and Furnace C with 3 molding lines. All lines, fed by their respective feeders, consist of IS machines and

an annealing lehr (furnace used for the annealing of glass). At any given moment, the plant can produce at most 3 different colors of glass, and 10 different final products, since there are a total of 3 furnaces and 10 molding lines. For this project, only the stack carrying the flue gases of Furnace A is being considered for waste heat recovery, as per BA's request.

Upon exiting the IS machines and on the molding machine conveyor, the glass containers undergo a hot surface treatment at a temperature ranging from approximately 550 °C to 650 °C before entering the annealing lehr. This process occurs as the containers pass through a canopy (tunnel) where, through evaporation, the components of the applied product come into contact with the exterior surface of the glass, forming a protective film aimed at improving its physical-mechanical properties.

The product then proceeds to the annealing lehrs to relieve internal stresses resulting from the previous stages, bringing the glass containers to a uniform temperature (with a maximum temperature of 560 °C), followed by controlled cooling (molecular stabilization).

Upon exiting the annealing lehr, the glass containers undergo a cold surface treatment, in which a diluted polyethylene emulsion is sprayed onto them. This treatment is designed to improve their performance on the production line by reducing the coefficient of friction.

After the cold surface treatment, the products move on to a line where natural and/or automatic inspection is carried out to reject non-compliant products. The characteristics analyzed include height, diameter, closure, micro-cracks, verticality, and the presence of impurities. All rejected materials are recycled in the form of cullet.

After passing the quality control process, the products proceed to palletization. Each line is equipped with automatic palletizers for forming pallets, which are subsequently wrapped in plastic and shrink-wrapped before being sent to the shipping warehouse. The movement of the palletizers to the shrink-wrapping machines is controlled by an automated system. There is also a re-selection line consisting of an inspection line for non-compliant bottles.

A simplified scheme portraying the production process of glass packaging can be seen in Figure 3.1, where the main source of waste heat (the furnace exhaust) is visualized.

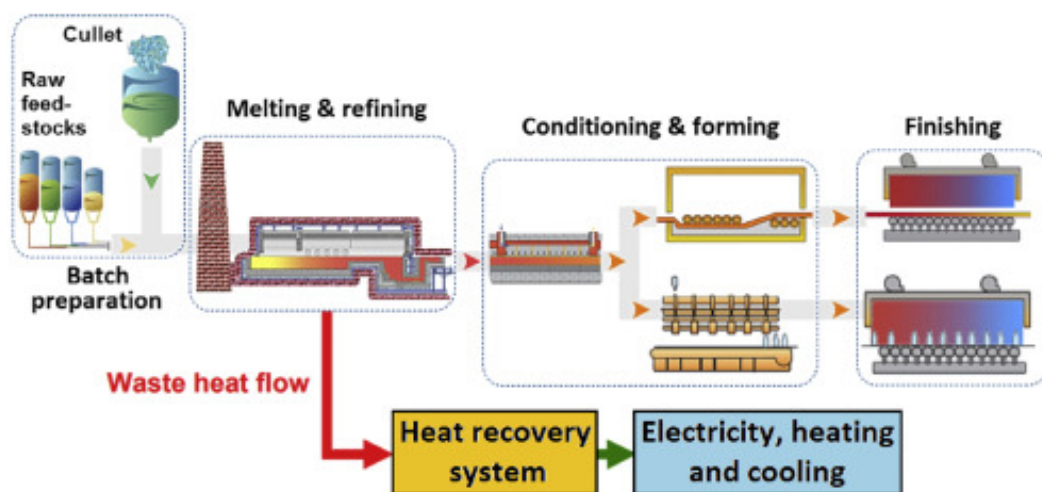


Figure 3.1: Glass packaging production process, simplified. Source: Redko et al. (2020).

3.2 Industrial Sludge Drying Problem

In the Avintes plant of BA Glass, all devices and machines that require cooling (e.g., the industrial glass furnaces) are air-cooled by fans. However, there is one exception to this generalization, which is the IS machines. In these machines, water is used to cool and also lubricate the gob-cutting device, as well as the channels that guide the gob itself to each of the sections of the IS machine. Furthermore, the water also serves the purpose of cooling the gob (i.e., the molten glass drop) itself, to control the viscosity of the gob and to lower the heat load to the components of the IS machine.

For this purpose, the plant has a closed-loop water piping system. This system allows for the used water to be reused without requiring additional treatment. However, this system is limited in its flow capacity. It can fully meet the water demands of the entire plant while it is in steady-state conditions, but not when maintenance is being performed in any of the 10 IS machines. During IS machine maintenance, the gob is rejected through a rejection chute, to later be recycled as cullet. To prevent the molten glass from solidifying in the rejection chute, and to lower the heat load to the chute itself, the chute requires a substantially higher flow of water to cool and lubricate, when compared to the normal functioning of the IS machines. Thus, the closed-loop water piping system cannot meet the plant's water demand when IS machine maintenance is occurring.

When the closed-loop system's flow capacity is exceeded, the plant uses water from the Douro river piping system. This system captures water from the Douro river, which is about 400 meters East of the unit, as can be seen in the top-right corner of Figure 3.2. After completing its cooling and lubricating purpose, the water from the Douro river piping system needs to be treated before being released once again to the Douro river, as to avoid polluting it. For this objective, the plant has an industrial wastewater treatment plant (IWTP). The work cycle of the IWTP produces an industrial sludge that is chemically composed of water and the RM composite that was absorbed in the IS machines, for the most part (i.e., disregarding possible contamination). Therefore, in the Avintes unit, the sludge production rate is directly proportional to the Douro river piping system water consumption, which itself is directly proportional to the maintenance time of the IS machines. Thus, the sludge production rate is not constant year-round.

Due to of the chemical composition of the sludge, its intended end use is for it to be reinserted into the industrial furnaces as RM. However, this is currently not feasible, as the elevated moisture content in the industrial sludge is associated with a viscous consistency, which in turn causes the sludge to get stuck and block the pneumatic systems and open belt conveyors of the RM transport and storage systems.

In order to reduce the moisture content in the sludge, the Avintes plant already possesses and utilizes a drying system for the dewatering of the industrial sludge. It is a mechanical drying system, specifically a screw press dewatering system. A schematic detailing the functioning principle of this type of mechanical press can be seen in Figure 3.3. In a screw press, wet sludge is inserted at the lower end. From there, a rotating screw conveyor, based on the functioning principle of the Archimedes' screw, transports the sludge through a narrowing channel, such that the altitude in-



Figure 3.2: Aerial view of the Avintes industrial unit of BA Glass.

creases and the cross-sectional area decreases as the sludge progresses through the system. During this process, water is squeezed out through screens or perforated casing, which leaves behind drier material. The initial section of the mechanism, right after the feed inlet, is called the thickening zone, and is where low pressure and large openings in the screen remove the free water in the sludge. The following section is the dewatering zone, where high pressure and small openings in the screen remove the bound water in the sludge.

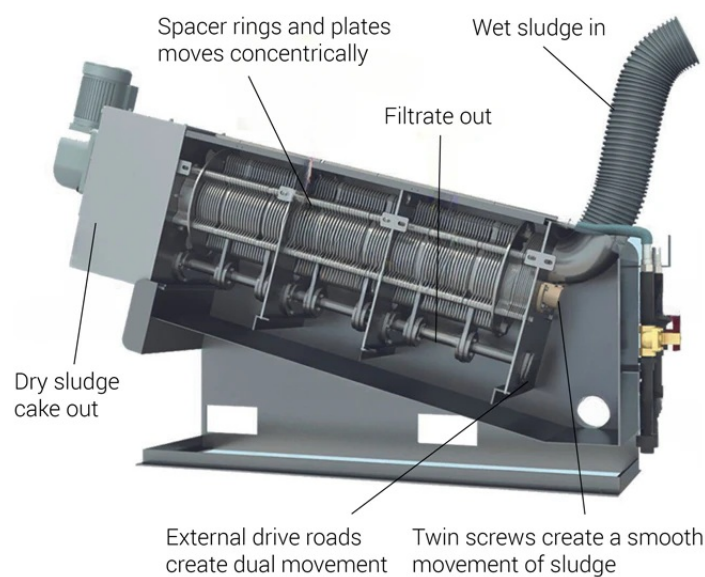


Figure 3.3: Schematic of a screw press dewatering system. Source: CWT (2025).

However, in practice, the industrial sludge has a moisture content of around 65.25 % at the screw press output (see Section 6.1), which is still too high for it to be reinserted into the furnace without causing problems. Currently, after passing through the mechanical dryer, the industrial sludge is left to dry naturally (i.e., it is simply exposed to ambient air) in a tank. However, this technique is extremely ineffective, especially in the winter, in which the northern Portuguese climate features unfavorable conditions for natural drying: cold temperatures, high humidity, and high precipitation. Since this is not enough to obtain a moisture content low enough for the sludge to be reinserted into the furnace, excess sludge has to be removed from the facility, at a financial cost to the company.

This project aims to minimize this problem, and ensure a low moisture content in the sludge, such that it will not cause problems as it is reinserted into the furnace, and no sludge has to be removed from the plant. For this purpose, the project aims to implement another drying system, particularly, a thermal drying system. Since the project intends to complement the currently utilized screw press instead of replacing it entirely, the term "wet sludge" shall be used to refer to sludge as the output of the screw press, instead of the output of the IWTP.

3.3 Furnace A Exhaust System

As per BA's request, in order to accomplish their sustainability objectives, this system should use waste heat recovered from the exhaust of Furnace A, which consists of flue gases from the natural gas combustion that occurs within Furnace A in order to heat and melt the raw materials and cullet. Furnace A operates under steady-state conditions, but there are instantaneous changes to these conditions whenever the glass pull rate is altered, which in turn occurs due to a change in the final manufactured product. Since Furnace A accounts for 4 production lines, these changes occur about once every other day. Furthermore, since Furnace A is regenerative, the flue gas temperature constantly oscillates with the frequency of the regenerator chamber changes (Danieli et al., 2019). Consequently, the flue gases are not at perfectly constant temperature, pressure and flow rate. These exhaust gases also contain particles and problematic substances, which leads to fouling, deposits and blockages. The inconsistent characteristics of the flue gas, together with its fouling-causing particulates, make it a rough stream for WHR, requiring a robust heat exchanger and consistent maintenance. Nevertheless, utilizing this source of energy would make the plant more energy-efficient and thus more sustainable. Therefore, the ductwork carrying the flue gases to the stack is analyzed, as this is the optimal location for implementing a waste heat recovery system (Jouhara et al., 2025).

The atmosphere inside the combustion chamber has a temperature of around 1600 °C, which corresponds to the temperature of the flue gases as they exit the combustion chamber. However, because Furnace A is a regenerative industrial glass furnace (see Section 2.1.2), after exiting the combustion chamber, the flue gases pass through the furnace regenerator, where thermal energy contained within the gas is captured and used to preheat the combustion oxidizer (air) that will

then enter the furnace. This process causes a drop in the temperature of the exhaust gases to about 500 °C, which significantly reduces their potential for waste heat recovery.

After passing through the regenerators, the flue gases are directed into the exhaust ductwork. On either side of the lower end of the Furnace A regenerator there are exhaust ducts to remove the flue gases. At any given time, only one of these is operational, due to the functioning principle of the regenerator, in which both sides of the regenerator periodically switch which gas they carry, between the combustion air and the flue gases. Both of these ducts then converge into a single duct, which then transitions from indoor to outdoor pathways. Once outside, the flue gases enter an electrostatic precipitator (ESP) which removes particles from the flue gas, in order to prevent fouling and blocking from occurring within the ductwork and stack. It is worth noting that the temperature of the flue gas in the ESP is limited to protect it from degradation. To this end, the exhaust is mixed with ambient air before the filter's inlet, to lower the gas temperature.

From the ESP, the flue gases pass through a fan which ensures a sufficient and stable airflow rate, and compensates for the pressure drop due to the ductwork pathways. Then, the ductwork is directed to the industrial stack, which is 50 m tall and with an internal diameter of 2.43 m. The height of the stack is required by Portuguese legislation, as the flue gases contain hazardous pollutants which could negatively impact human health if released at a lower altitude. The most abundant undesirable substances in the flue gases are NO_x , SO_x , CO_2 and the aforementioned particles (although most are captured in the ESP). Figure 3.4 shows the outdoor section of the ductwork, from the entry into the ESP until the stack entry. The main path of the exhaust gases, as just described, can also be seen in the 3D schematic of Figure 3.5.(a), where the yellow path represents active exhaust flow, and the blue path is inactive.

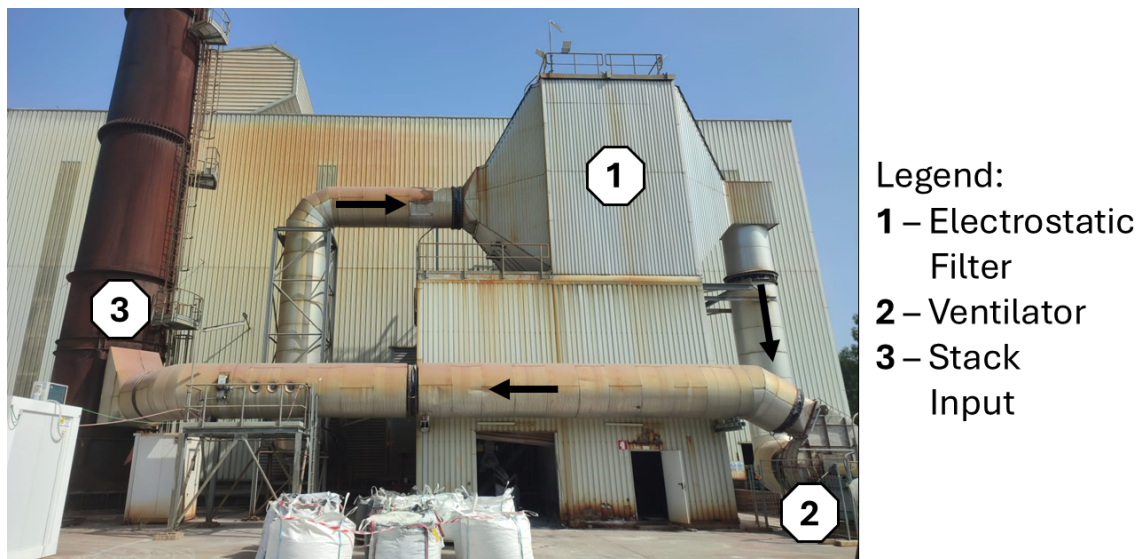


Figure 3.4: Outdoor section of the Furnace A exhaust ductwork. Arrows denote airflow direction.

Alternatively, the exhaust airflow can follow a different path to the stack. Indeed, there exists a bypass to the presented ductwork, which carries the flue gases directly from the furnace regenerator to the stack via subterranean ducts, as per Figure 3.5.(b). Usually, this bypass is only used

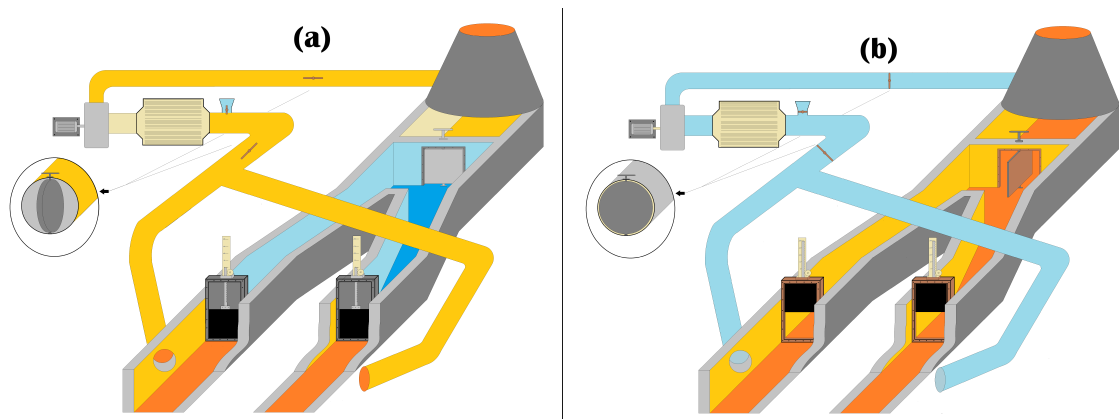


Figure 3.5: Schematic of Furnace A exhaust ductwork's (a) main pathway; (b) bypass to stack. Intellectual property of BA Glass.

for maintenance on the electrostatic filter, the fan, or the ductwork. This is because the particles present in the flue gas originate fouling and blockages in the ducts and stack if the ESP is bypassed. Also, Portuguese legislation limits the number of hours per year that the bypass can be in use for, to regulate pollutants. Notably, this bypass presents itself as a very helpful tool for this project, as otherwise the steady-state operation of the furnace would represent a major challenge in the implementation of a waste heat recovery system in the ductwork, due to the high temperature of the flue gases, as well as the fact that they cannot legally be released at a low altitude.

Chapter 4

Methodology

This chapter describes the methods and procedures used to characterize the available waste heat, and the evaluation of the different options for waste heat use. The methods presented here and implemented throughout the remainder of the dissertation are a direct result of the state of the art presented in Chapter 2. In the case of the use of the waste heat for sludge drying, a detailed description of the processes and laboratory setting that was implemented to characterize the sludge is also provided in this section. The mathematical formulation behind all the techno-economic calculations is also provided and serves as the basis of the tool which is presented in Chapter 5.

4.1 Sludge Characterization

The characterization of the sludge that is to be dried by this project's TDS is important, as it allows for an estimate of the necessary heat requirement and also because the composition of the sludge must be taken into account when selecting an appropriate drying technology. In addition, determining the moisture content at the inlet and outlet of the TDS is paramount. Therefore, an experiment was conducted to assess relevant sludge characteristics, namely total solids (TS) content after the mechanical press, desired TS content, density, and the sludge drying curve.

Many photographs were captured along the experiments to better display the process that was applied. However, they were deemed superfluous to the core text of the present work and thus included in Appendix A.

4.1.1 Equipment

The description and technical specifications of the utilized equipment is important in order to assure reliable and reproducible results. Particularly, the most important pieces of laboratory equipment to describe technically are the furnaces, the scale, and the power meter. Furthermore, images of some of the key pieces of equipment (furnaces and trays) can be seen in Section A.1 of Appendix A. The utilized equipment is described as follows, with spatial measurements in length x height x width:

- **Forced convection laboratory oven:** *BINDER* FD115 forced convection (FC) laboratory drying oven, 2003 model. This unit operates between ambient temperature and 300°C, with maximum electrical capacity of 220 V, 7.5 A, and 1.65 kW. External dimensions are 834 x 680 x 697 mm, and internal dimensions are 600 x 480 x 400 mm, corresponding to an internal volume of 115.2 L. The oven uses a FC system, and the air change rate of this system is deemed relevant to this project, but information was unavailable. Therefore, a short laboratory experiment, that can be seen in Appendix B, was conducted in order to determine this value. The result obtained is 143 ACH (air changes per hour) or 2.39 ACM (air changes per minute), which corresponds to a volumetric airflow rate of 16.5 m³/h or 4.58 L/s. The power meter was used to determine that the FC system draws 55.0 W of power;
- **Laboratory muffle furnace:** *Nabertherm* L 9/11 laboratory muffle furnace, 2020 model. It has no FC mechanism, and thus operates under natural convection (NC). This unit has a mass of 35 kg, and operates between ambient temperature and 1100°C, with maximum electrical capacity of 240 V, 13.8 A, and 3.3 kW. External dimensions are 415 x 455 x 515 mm, and internal dimensions are 235 x 240 x 170 mm, corresponding to an internal volume of 9.6 L;
- **Precision scale:** *Kern & Sohn* EW6000-1M precision scale. Minimum and maximum capacity of 5 g and 6000 g, respectively. Resolution, verification scale interval, and reproducibility of 0.1 g, 1 g, and 0.1 g, respectively. Stabilization time of 2 seconds. Linearity of ± 0.3 g;
- **Power meter:** *Orno* WAT-419 power meter. Maximum electrical capacity at 230 V, 16 A, and 3.68 kW. Accuracy of ± 8 %;
- **Steel tray:** A steel kitchen tray, with a mass of 264.2 g and internal dimensions of 348 x 47 x 221 mm;
- **Glass tray:** A glass kitchen tray, with a mass of 888.2 g and internal dimensions of 207 x 44 x 207 mm;
- **Plastic beaker:** A laboratory plastic beaker, with a mass of 32.6 g, maximum capacity of 250 mL, and resolution of 5 ml.

Furthermore, utilized equipments that do not require a detailed description include a large wooden spoon, two stainless steel spoons, plastic gloves, oven mitts, a plastic bucket, plastic sample bags, plastic wrap, and duct tape.

4.1.2 Procedure

As the first step of the experiment, samples were obtained for laboratory testing. Four samples of wet sludge were obtained at the output of the mechanical screw press. In addition, one dry sample,

i.e., with acceptable moisture content, was also obtained. Each sample weighed around 2.5 kg, and they were placed in a plastic bag and sealed with duct tape, to prevent any variation in the moisture content of the samples during transportation, as per Figure A.4 of Appendix A.3. In this Figure, the difference in MC between wet and dry sludge samples is immediately apparent due to the color of the sludge, as they are white and brown, respectively.

The four wet samples were obtained manually with a small shovel from a non-homogenized tank, at the output of the mechanical screw press, in Avintes. Thus, in order to ensure that the initial moisture content is the same in each test, all four wet samples were placed in a plastic bucket, and mixed with a spoon, as per Figure A.5 of Appendix A.3. In between test runs, the bucket was sealed with a film of plastic wrap and duct tape, to ensure no variation of the moisture content of the mix. Despite being stored in a sealed container, the wet sludge underwent physical separation over time, leading to the formation of a drier layer at the surface, while free liquid accumulated at the base, suggesting gravitational settling and internal moisture migration. Thus, the bucket had to be mixed again every time a new sample was taken from it for testing, to ensure homogeneity.

The testing of the samples was performed in Porto, at the Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), in the combustion laboratory. The experiments were performed under the guidance of INEGI engineers Vítor Ferreira and G  ssika Morgado. The main pieces of equipment from INEGI that were used in this project were two laboratory furnaces and a precision scale.

Density Test

A sample of wet sludge was tested in order to calculate its apparent density. Thus, 250 mL of the sample were placed in a plastic beaker, and the consequential difference in mass was measured, as per Figure A.6 of Appendix A.3. Therefore, apparent density is used in this context instead of density, as this methodology can not guarantee the absence of air pockets within the measured sample, which may skew the results. Equation 4.1 was then used to calculate the apparent density of the substance, in which ρ [kg/m³], m [kg], and V [m³] are the apparent density, mass, and apparent volume of the substance, respectively.

$$\rho = \frac{m}{V} \quad (4.1)$$

Drying Tests

Then, tests were conducted to determine the drying rate at different controlled temperatures, and to obtain the moisture content in the obtained samples. These tests mainly consisted of using either of the laboratory furnaces to heat and dry the sludge, while the precision scale was used to periodically measure the mass of the sample, as to track its drying rate.

First, a test was conducted using the dry sample to determine its TS content, as this information is important when designing an appropriate drying mechanism. Only the FC furnace was used, as

for this case, characterizing the effect of convection type on the drying rate is superfluous. A steel tray containing 1 kg of sludge was placed in the furnace, preheated to 200 °C. After a short period, visible smoke was observed emanating from the chamber, prompting removal of the sample. The dry sample, initially light gray, had turned black in color. The darkening of the material and the release of smoke suggest thermal degradation of organic components, likely through pyrolysis or partial combustion. These observations indicate that the sludge contains volatile or thermally unstable constituents that begin to decompose at relatively low temperatures. However, when the procedure was repeated at 120 °C, degradation of the sample did not occur. The sample was in the furnace for over 72 hours, to ensure that there would be no further mass variation and that the TS content was approximately 100 %, at the end of the procedure. Thus, the data from this test run was considered and used in Equation 4.2 to calculate the initial moisture content (MC) of the sample, where MC [-] is the moisture content of the sample in the wet state, and m_{wet} [kg] and m_{dry} [kg] are the mass of the sample in the wet and dry state, respectively (Król et al., 2019).

$$MC = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \quad (4.2)$$

Drying tests were also conducted on the wet samples of sludge. In these tests, the desired information was not only the initial MC in the samples (calculated using Equation 4.2), but also the drying curve (i.e., graph of mass over time) of the substance, and the specific energy consumption of the drying process. Also, a graph of the drying rate (DR) as a function of MC is desired, and DR is calculated between two data points according to Equation 4.3, where m_1 [kg], m_2 [kg], and t_1 [s], t_2 [s] are the mass and time of two consecutive data points (mass measurements), and the corresponding MC is the average of the MCs of these two data points.

$$DR = \frac{m_1 - m_2}{t_2 - t_1} \quad (4.3)$$

Furthermore, these drying tests also aim to characterize the effect that furnace temperature and convection type (natural or forced) have on sludge drying rates. To achieve these goals, wet samples were tested at each of the four defined temperatures, in each of the two furnaces (natural and forced convection), for a total of eight test runs. The temperatures used in the tests were 50 °C, 100 °C, 150 °C and 200 °C. These values were selected because the sludge experiences thermal degradation at high temperatures, so testing at higher temperatures is irrelevant to this project. Intervals of 50 °C between testing temperatures were deemed as sufficient for characterizing the effect of temperature on drying rate.

Test runs on the FC oven used 1 kg of wet sludge in the steel tray. However, the muffle furnace has smaller interior dimensions, such that the steel tray does not fit in it. Thus, the glass tray was used to contain the wet sludge in the muffle furnace tests. Because of the smaller dimensions of the glass tray, these tests only used 0.5 kg samples, so that the sludge depth is roughly consistent across all tests (around 2 cm), to ensure comparable results. Also, only the tests in the FC furnace registered the consumed electricity, through the use of the power meter.

Aside from the aforementioned differences, all tests followed the same process. The furnace

was preheated to the desired temperature, and the sample was then placed within. Then, using the precision scale, mass measurements were taken periodically to track the progressive mass loss of the sample. Since the first few hours of the tests demonstrated the most significant mass loss rate, measurements were taken every 30 min during this period, with some measurements taken outside this window due to logistical constraints in accessing the equipment used in the tests. Each test concluded when the periodic mass measurements and revealed a negligible mass loss rate (less than 0.2 g/h).

4.2 Waste Heat Characterization

The first practical step in the solution of the project is to characterize the potential of the waste heat source to be used. This is important as it allows for an estimate of the recovered waste heat of the project and because flue gas characterization (e.g., temperature, chemical composition) is paramount to properly design a system with a heat exchanger. As mentioned above, the flue gases from the combustion reaction inside the industrial glass furnaces are considered the best source of waste heat in the glass industry. This is due to the significant amount of thermal energy stored within the gas, as well as the low degree of difficulty in harnessing said thermal energy, since it is bound to a fluid (Forman et al., 2016).

Portuguese legislation states that any energy-intensive building or plant that has an energy consumption equal to or greater than 500 toe/year must perform energy audits periodically, to control and characterize aspects such as GHG emissions (SGCIE, 2025). Therefore, the Avintes plant had recently performed an energy audit, in December of 2024. Thus, the corresponding data was requested to the appropriate department (Batch & furnace department), and was analyzed for this project. The information obtained only refers to Furnace A and its respective stack and flue gases, as all other information is superfluous to this project.

During sampling, Furnace A operated nearly at full capacity. In fact, it produced 444 tons/day, when its maximum capacity is of 450 tons/day, corresponding to 98.7 % of the maximum capacity, and incorporating 78.6 % cullet into the raw materials for the produced glass. Although these values may vary due to changes in the final product being produced, the furnace constantly operates at nearly full capacity. The exhaust properties that were obtained during the audit can be seen in Table 4.1.

Notably, Table 4.1 states that the temperature of the exhaust in the stack is around 272 °C, which is lower than literature suggests for the exhaust of a regenerative furnace. This is expected because (i) ambient dilution air is normally injected upstream of the electrostatic precipitator (ESP) to protect it, and (ii) additional heat losses occur along the downstream duct and tall stack to the sampling plane. Although the dilution damper is closed during energy audits (so the reported composition is on an undiluted basis), it is usually closed only a few hours beforehand. Since the ESP and ductwork have substantial thermal mass, their walls remain cooled for some time, which biases the measured stack temperature low even after dilution stops. Upstream recovery points

Parameter	Value
Ambient Temperature	17.3 °C
Ambient Pressure	100.2 kPa
Effluent Temperature	272.2 ± 6.3 °C
Absolute Pressure	99.9 ± 1.2 kPa
Moist Molecular Mass	28.2 ± 0.1 g/mol
Flow Velocity	3.5 ± 1.2 m/s
Actual Flow Rate	58293 ± 20074 m ³ /h
Dry Volumetric Flow Rate	25173 ± 8686 m ³ /h
O ₂	8.7 ± 0.6 % vol
CO ₂	7.0 ± 0.4 % vol
Humidity	12.6 ± 0.8 % vol

Table 4.1: Furnace A energy audit: exhaust results.

therefore exhibit higher gas temperatures. Nevertheless, per BA's request, the 272 °C value in Table 4.1 is adopted as a conservative assumption for this study.

To calculate the available power in the exhaust stream, Equation 4.4 should be used, where $\dot{Q}_{\text{flue}}$ [W] is the heat content in the exhaust, $\dot{V}$ [m³/s] is the volumetric exhaust flowrate, ρ [kg/m³] is the density of the flue gas, and Δh [J/kg] is the difference in specific enthalpy between the WHR system inlet (h_{in} [J/kg]) and the WHR system outlet (h_{out} [J/kg]) (Jouhara et al., 2018).

$$\dot{Q}_{\text{flue}} = \dot{V} \cdot \rho \cdot \Delta h \quad (4.4)$$

The actual flow rate ($\dot{V}$) is obtained directly from Table 4.1. Also, for the WHR system, condensation within the heat exchanger is undesirable as it promotes fouling and corrosion due to the composition of the exhaust gases, so maintaining a flue gas temperature of at least 120 °C is recommended. Thus, this is the value that will be used as the outlet temperature of the WHR system (T_{out} [K]) (Teng et al., 2022). To obtain the exhaust density, Equation 4.5 is utilized, under the assumption of an ideal gas, where R (8.314 J·mol⁻¹·K⁻¹) is the ideal gas constant, and M [kg/mol], p [Pa], and T [K] are the molar mass, pressure, and temperature of the gas, respectively (Rapp-Kindner et al., 2024). Note that the gas pressure and temperature are available in Table 4.1.

$$\rho = \frac{M \cdot p}{R \cdot T} \quad (4.5)$$

Since the exhaust is a composite gas, Equation 4.6 is used to obtain the respective molar mass, represented by $\bar{M}$ [kg/mol], where χ_i [-] and M_i [kg/mol] are the molar fraction and molar mass of component i , respectively (Lower, 2019).

$$\bar{M} = \sum_i \chi_i \cdot M_i \quad (4.6)$$

Similarly, Equation 4.7 is used to calculate the specific enthalpy at the inlet and outlet of the system, where $\bar{h}$ [J/kg] is the specific enthalpy of the composite gas, and w_i [-] and h_i [J/kg] are

the mass fraction and specific enthalpy of each substance i present in the gas.

For enhanced precision in the results, the CoolProp 6.8.1 library is used to calculate the specific enthalpy of the exhaust at the inlet and outlet of the WHR system. This software can calculate the properties of the most common fluids once its state is defined. In this case, the state of the exhaust is defined by its temperature and pressure, which are known, both for the inlet and outlet of the system. Since each pure substance in the exhaust is analyzed individually, as per Equation 4.7, CoolProp can be used to determine h_i . Equation 4.8 can then be used to determine the variation in specific enthalpy of the flue gas.

$$\bar{h} = \sum_i w_i \cdot h_i \quad (4.7)$$

$$\Delta h = \bar{h}_{in} - \bar{h}_{out} \quad (4.8)$$

To calculate the molar and mass fraction of each substance present in the gas, first it was assumed that the gas was composed entirely of O₂, CO₂, H₂O, and N₂. This is a reasonable simplification, as aside from these four chemicals, the highest mass fraction is around 0.05 %, corresponding to NO₂. Then, the molar fraction of H₂O was obtained directly from Table 4.1 ("Humidity"), and the molar fraction values for O₂ and CO₂ had to be adjusted, as the registered measurements considered a dry basis. The conversion from dry basis molar fraction, χ_{dry} [-], to wet basis molar fraction, χ_{wet} [-], is performed according to Equation 4.9, where χ_{H_2O} [-] is the molar fraction of water, or humidity. The remaining molar fraction was assumed to be composed entirely of N₂.

$$\chi_{wet} = \chi_{dry} \cdot (1 - \chi_{H_2O}) \quad (4.9)$$

Mass fraction for each component is then obtained according to Equation 4.10, where $\bar{M}$ [kg/mol] is the molar mass of the mixture, and w_i [-], χ_i [-], and M_i [kg/mol] are the mass fraction, molar fraction, and molar mass of component i , respectively.

$$w_i = \frac{\chi_i \cdot M_i}{\bar{M}} \quad (4.10)$$

The listed equations are, therefore, sufficient to calculate the available power in the exhaust stream for a waste heat recovery system.

4.3 Thermal Drying System

The model of the thermal drying system (TDS) is visible in Figure 4.1, and mainly consists of a co-current rotary drum dryer (RDD) coupled with a heat exchanger (HE) to heat the drying medium using flue gas heat. In this case, it is a direct RDD, so the drying medium is air. An intermediate HE could also be applied to improve the control of flue gas and drying air temperature, such that the flue gas would transfer its heat to a thermal oil in the first HE, and the thermal oil would

then transfer heat to ambient air for the drying process. The screw pump (screw press dewatering system) is already in use by the company, as per Section 3.2. Furthermore, a cyclone is usually implemented in these systems, to remove particulates present in the outlet air of the RDD (El-Qanni et al., 2022).

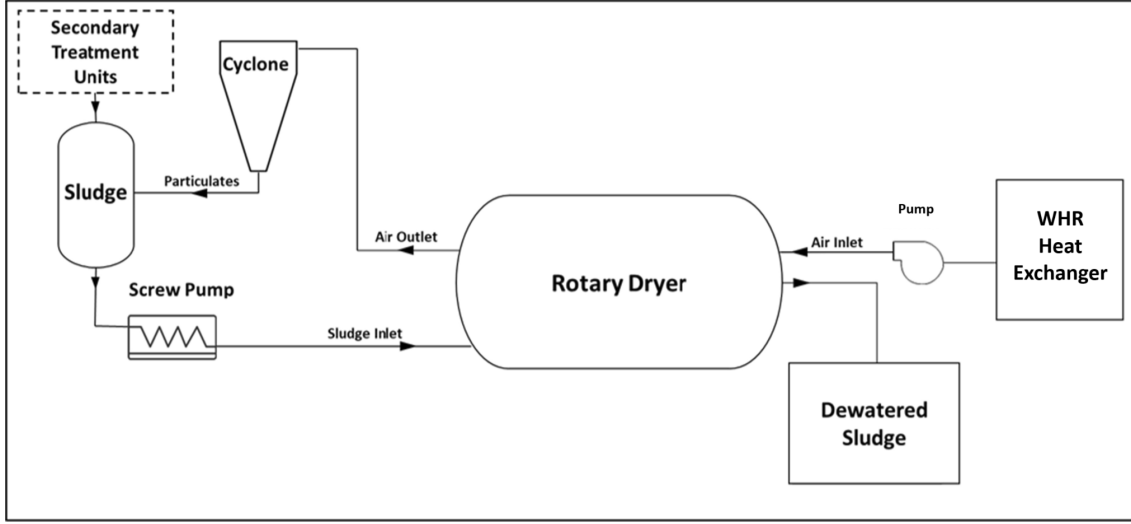


Figure 4.1: TDS schematic. Adapted from: El-Qanni et al. (2022).

The calculations performed in the modeling of this system are based on the following assumptions: (i) the system operates in steady-state conditions; (ii) the components and the pipelines that connect them do not experience heat and/or pressure loss; (iii) the specific heat capacity of liquid water, water vapor, and air does not vary with temperature, and their values are $Cp_w = 4184$, $Cp_v = 1880$, and $Cp_{air} = 1005$ [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$], respectively; (iv) the specific heat capacity of the dry solids in the sludge does not vary with temperature; (v) the psychrometric states and thermodynamic properties of humid air are defined using the CoolProp 6.8.1 library.

4.3.1 Input Data

To process the modeling of this system, the required input data is as follows:

- Sludge inlet mass flow rate, $\dot{m}_{s,in}$ [ton/day];
- Dry solids specific heat capacity, Cp_{ds} [$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$];
- Moisture content of inlet and outlet sludge, MC_{in} and MC_{out} [-];
- Temperature of inlet and outlet sludge, $T_{s,in}$ and $T_{s,out}$ [K], respectively;
- Temperature of inlet and outlet air, $T_{air,in}$ and $T_{air,out}$ [K], respectively;
- Ambient air relative humidity, RH_{air} [-].

As mentioned in Section 3.2, the sludge production rate of the Avintes unit is not constant. However, the water consumption is registered, which is directly proportional to the mass of sludge

produced. Therefore, to determine the sludge mass flow rate, the sludge mass produced over the course of two weeks was measured, and a correlation was formed with the flow of water consumed over those two weeks. This correlation, which is around 1.16 kg of sludge per m³ of water, was then used to extrapolate the data and estimate the sludge production over the last year, which would be around 40.78 tons. This corresponds to an average sludge mass production rate of around 0.1117 ton/day ($\dot{m}_{s,in}$).

Also mentioned in Section 3.2 is the fact that most of the dry solids present in the sludge is yellow sand, the most abundant RM in use by BA. Therefore, the specific heat capacity of dry solids is assumed to be the same as that of yellow sand, or around 830 J·kg⁻¹·K⁻¹ ($C_{p_{ds}}$) (Essa et al., 2022).

As per Section 6.1, the MC of inlet and outlet sludge are 65.25 % and 12.33 % (MC_{in} and MC_{out}), respectively. Furthermore, there is no sludge preheating system in place, so the sludge inlet temperature is considered to be ambient temperature, or 25 °C ($T_{s,in}$). As for the outlet temperature, 100 °C ($T_{s,out}$) was assumed, as this is the boiling point of water (El-Qanni et al., 2022).

As demonstrated in Section 4.1.2, the air temperature has to be carefully selected to avoid thermal degradation of the dry solids in the sludge. However, since this is a co-current thermal dryer, the highest (inlet) air temperature contacts the sludge while it has plenty of humidity, which helps avoid thermal degradation, even at high temperatures (El-Qanni et al., 2022). Therefore, the inlet and outlet air temperatures were selected at 200 °C and 80 °C ($T_{air,in}$ and $T_{air,out}$), respectively. Finally, ambient air RH is set as the year-round average in Porto, at a value of 77 % (RH_{air}).

4.3.2 Mass and Energy Balances

The basis of the system's model is the water mass and energy balances performed on the dryer, which can be seen in Equations 4.11 and 4.12, respectively, where $\dot{m}_{da}$ [kg_{da}/s] is the mass flow of dry air through the dryer, $\dot{m}_{ds}$ [kg_{ds}/s] is the mass flow of dry solids through the dryer, W_{in} and W_{out} [kg/kg_{da}] are the absolute humidity of the inlet and outlet air, respectively, X_{in} and X_{out} [kg/kg_{ds}] are the absolute humidity of the inlet and outlet sludge, respectively, $h_{air,in}$ and $h_{air,out}$ [J/kg_{da}] are the specific enthalpy of the inlet and outlet air, respectively, and $h_{s,in}$ and $h_{s,out}$ [J/kg_{ds}] are the specific enthalpy of the inlet and outlet sludge, respectively (El-Qanni et al., 2022).

$$\dot{m}_{da} \times (W_{out} - W_{in}) = \dot{m}_{ds} \times (X_{in} - X_{out}) \quad (4.11)$$

$$\dot{m}_{da} \times (h_{air,out} - h_{air,in}) = \dot{m}_{ds} \times (h_{s,in} - h_{s,out}) \quad (4.12)$$

The absolute humidity of the inlet air (W_{in}) is obtained based on its psychrometric properties using CoolProp, since they are defined based on ambient temperature, ambient pressure, and relative humidity (RH_{air}).

The absolute humidity of inlet and outlet sludge can be obtained based on the sludge's inlet and outlet moisture content, respectively, as can be seen in Equation 4.13.

$$X = \frac{MC}{1 - MC} \quad (4.13)$$

Equation 4.14 can be used to calculate the dry solids mass flow rate of the system, $\dot{m}_{ds}$ [kg_{ds}/s]. This equation considers $m_{s,in}$ in ton/day, which originates the factor of 86.4.

$$\dot{m}_{ds} = \frac{\dot{m}_{s,in} \times (1 - MC_{in})}{86.4} \quad (4.14)$$

The variation in specific enthalpy of the sludge, between the inlet and outlet states, is given by Equation 4.15

$$h_{s,in} - h_{s,out} = (Cp_{ds} + Cp_w \cdot X_{in}) \cdot T_{s,in} - (Cp_{ds} + Cp_w \cdot X_{out}) \cdot T_{s,out} \quad (4.15)$$

The enthalpy of inlet and outlet air can be computed using Equation 4.16, considering their respective temperature and absolute humidity, and where $\Delta H_{fg} = 2260000$ [J/kg] is the latent heat of vaporization of water (El-Qanni et al., 2022).

$$h_{air} = (Cp_{air} + Cp_v \cdot W) \cdot T_{air} + W \cdot \Delta H_{fg} \quad (4.16)$$

Applying the water mass balance (Equation 4.11) and energy balance (Equation 4.12) to the dryer and substituting the above constitutive relations yields a closed-form expression for W_{out} , shown in Equation 4.17.

$$W_{out} = \frac{\frac{W_{in}}{X_{in} - X_{out}} + \frac{h_{air,in} - Cp_{air} T_{air,out}}{h_{s,out} - h_{s,in}}}{\frac{1}{X_{in} - X_{out}} + \frac{Cp_v T_{air,out} + \Delta H_{fg}}{h_{s,out} - h_{s,in}}} \quad (4.17)$$

Once W_{out} is known, the dry-air mass flow follows directly from the water balance, as in Equation 4.18.

$$\dot{m}_{da} = \dot{m}_{ds} \frac{X_{in} - X_{out}}{W_{out} - W_{in}} \quad (4.18)$$

4.3.3 Main Outputs

The main desired output of the model is to determine the heat load necessary to dry the sludge to the desired moisture content. The overall thermal load on the dryer, $\dot{Q}_{total}$ [W] (evaporation and sensible heating inside the drum, plus sensible heating of the retained sludge phase) is modeled as in Equation 4.19, where f [-] is a design allowance factor (here $f = 1.08$ is considered, per El-Qanni et al. (2022)) accounting for auxiliary losses and model simplifications, and T_{wb} [K] is a characteristic wet-bulb temperature inside the dryer, evaluated at the mean state of the process air, using CoolProp, as in Equation 4.20 (El-Qanni et al., 2022).

$$\dot{Q}_{\text{total}} = f \left[\dot{m}_{\text{ds}} (X_{\text{in}} - X_{\text{out}}) \left(\Delta H_{\text{fg}} + C p_w (T_{\text{wb}} - T_{\text{s,in}}) + C p_v (T_{\text{air,out}} - T_{\text{wb}}) \right) + \dot{m}_{\text{ds}} (C p_{\text{ds}} + X_{\text{out}} C p_w) (T_{\text{s,out}} - T_{\text{s,in}}) \right] \quad (4.19)$$

$$T_{\text{wb}} = \text{Twb} \left(\frac{T_{\text{air,in}} + T_{\text{air,out}}}{2}, P_{\text{amb}}, \frac{W_{\text{in}} + W_{\text{out}}}{2} \right). \quad (4.20)$$

The overall thermal load should then be compared to the available flue gas heat, to assess whether or not the available WH is sufficient to satisfy the system's thermal load. If it isn't, the system should then be downsized to use the entirety of the available WH, and to only dry a fraction of the sludge flow rate. The aforementioned equations, with the input data, are sufficient to characterize the thermal drying system.

4.4 Organic Rankine Cycle

The ORC to be modeled is based on the schematic and T - s diagram presented in Figure 4.2. In this schematic, the flue gases or thermal oil are directed through a set of heat exchangers that heat the working fluid, namely the preheater, evaporator, and superheater (PH, EV, and SH, respectively). The produced superheated live vapor (state 1) is expanded in a turbine (T) to produce mechanical work that is converted to electricity in a generator (G). Then, the resulting low-pressure vapor (state 2) passes through two heat exchangers, the vapor condenser (VC) and the condenser (C), where it releases heat to the cooling water until it achieves a saturated liquid state (state 4). A pump then transforms this low-pressure saturated liquid into high-pressure liquid (state 5), which then flows through the set of heating heat exchangers, and the cycle continues.

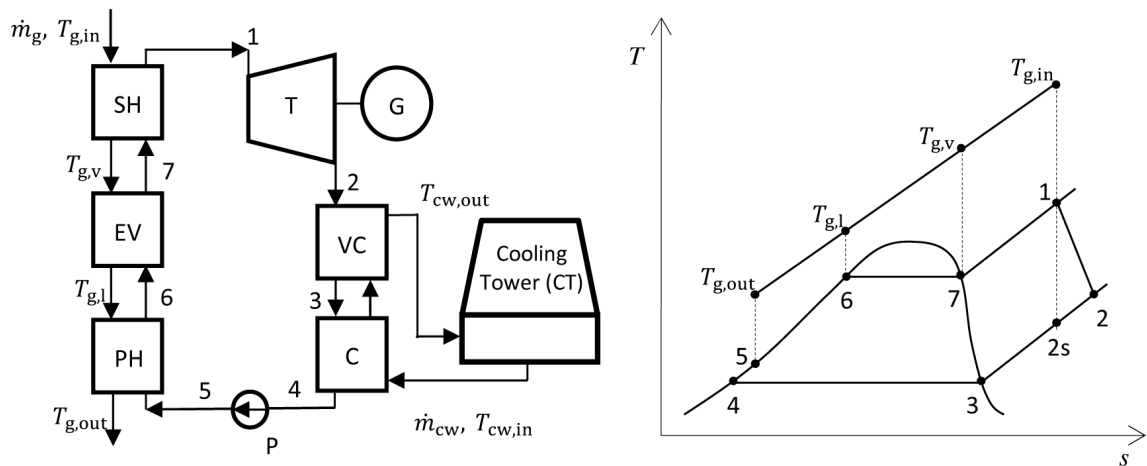


Figure 4.2: ORC schematic and T - s diagram. Source: Hribernik and Hribernik (2021).

The thermodynamic characterization of the ORC in this study was carried out based on the following simplifying assumptions: (i) all parts function in steady-state circumstances; (ii) the components and the pipelines that connect them will not experience heat and/or pressure loss; (iii) the working fluid is saturated at the condenser exit; (iv) the CoolProp 6.8.1 library is used to calculate the streams' thermodynamic characteristics. Under these conditions, the procedure outlined below enables the estimation of all relevant thermodynamic parameters, component work, and cycle efficiency.

4.4.1 Input Data

The input parameters for the model are:

- Heat input, $\dot{Q}_{\text{flue}}$ [W];
- Working fluid selection;
- Evaporation temperature, T_{evap} [K];
- Condensation temperature, T_{cond} [K];
- Degrees of superheat, SH [K];
- Isentropic efficiencies of the turbine (η_t [-]) and pump (η_p [-]), and the mechanical-to-electrical efficiency of the generator (η_g [-]).

Working fluid selection and evaporation temperature are inherently linked through the pinch point in the evaporator, which is defined as the minimum temperature difference between the heat source and the working fluid. Appropriate selection of working fluid should tailor the evaporation profile to more closely match the heat source, reducing irreversibilities and improving efficiency (Linke et al., 2015). However, in this preliminary techno-economic analysis, a detailed pinch point analysis is beyond the scope of the project. Instead, an ORC model was found in literature with a similar heat source temperature (270 °C). Thus, toluene was selected as the working fluid of this project, set to an evaporator temperature of 250 °C (T_{evap}), and considering 5 °C of superheating at the turbine inlet (SH) (Borsukiewicz-Gozdur, 2013; Jiménez-García et al., 2023).

The heat input to the system is as was calculated in Section 4.2 using Equation 4.4, i.e., it is equivalent to the entirety of the available WH. Condensation temperature is usually set as low as possible to improve cycle efficiency. However, practical limitations (e.g., the temperature of the cooling water) usually enforce a minimum temperature, such that condenser temperatures usually fall within the 30-50 °C range (Malwe et al., 2025). Considering toluene as the working fluid, there is an additional practical limitation, because the saturation pressure of toluene at 40 °C is around 8 kPa, meaning the low pressure side of the ORC would have to operate at a deep vacuum, which could be challenging. Instead, condenser temperature is set at 100 °C (T_{cond}), such that the condenser pressure is near atmospheric pressure (74.2 kPa) (Dambrosio et al., 2019).

The efficiencies of ORC components were set as standard values in literature. Namely, the isentropic efficiencies of the turbine and pump considered are 80 % and 75 % (η_t and η_p), respectively. Furthermore, the mechanical-to-electrical efficiency of the generator was set at 98 % (η_g) (Auld et al., 2013; Khosravi et al., 2025)

4.4.2 Thermodynamic States

The high and low pressure values of the cycle (p_{high} [Pa] and p_{low} [Pa], respectively) are obtained directly from the saturation properties of the chosen working fluid, as well as the evaporation and condensation temperatures, respectively, as per Equations 4.22 and 4.21, where $p_{\text{sat}}(T)$ is the saturation pressure of the working fluid at temperature T [K].

$$p_{\text{high}} = p_{\text{sat}}(T_{\text{evap}}) \quad (4.21)$$

$$p_{\text{low}} = p_{\text{sat}}(T_{\text{cond}}) \quad (4.22)$$

To obtain the live vapor temperature (state 1), T_{live} [K], Equation 4.23 is used.

$$T_{\text{live}} = T_{\text{evap}} + SH \quad (4.23)$$

Using the aforementioned CoolProp library, and with p_{low} , p_{high} , T_{live} , T_{evap} , and T_{cond} , defined, the thermodynamic properties (including specific enthalpy, h [J/kg], and specific entropy, s [J/kg]) can be determined for all characteristic states of the cycle, as the temperature and pressure is defined at all these states, with the exception of the states at the turbine exit and pump exit (states 2 and 5, respectively).

The turbine exit properties are determined using the pressure and enthalpy at state 2. The enthalpy of state 2 is obtained as per the turbine isentropic efficiency definition, presented in Equation 4.24, where h_1 [J/kg] is the turbine inlet enthalpy, h_2 [J/kg] is the actual outlet enthalpy, and h_{2s} [J/kg] is the outlet enthalpy for an isentropic expansion from p_{high} to p_{low} , which corresponds to the enthalpy of the working fluid with pressure p_{low} and specific entropy s_1 .

$$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (4.24)$$

Similarly, the pump exit properties are determined from the pressure and enthalpy at state 5. In this case, the enthalpy of state 5 is obtained through the pump isentropic efficiency definition, as in Equation 4.25, where h_4 [J/kg] is the pump inlet enthalpy, h_5 [J/kg] is the actual outlet enthalpy, and h_{5s} [J/kg] is the outlet enthalpy for an isentropic compression from p_{low} to p_{high} , which corresponds to the enthalpy of the working fluid with pressure p_{high} and specific entropy s_4 .

$$\eta_p = \frac{h_{5s} - h_4}{h_5 - h_4} \quad (4.25)$$

Using these equations, all states of the ORC are well defined, and the thermodynamic properties can be determined for all characteristic states of the cycle.

4.4.3 Main Outputs

After the thermodynamic properties of the cycle are defined, calculations are made to obtain the main results and outputs of the model. The working fluid mass flow rate, $\dot{m}$ [kg/s], is calculated from the energy balance in the heating heat exchangers (PH, EV, and SH), as presented in Equation 4.26.

$$\dot{m} = \frac{\dot{Q}_{in}}{h_1 - h_5} \quad (4.26)$$

The turbine work output, W_t [W], and the pump work input, W_p [W], are given by Equations 4.27 and 4.28, respectively. These work values are proportional to the working fluid mass flow rate, $\dot{m}$ [kg/s], and the respective enthalpy variation, $(h_1 - h_2)$ [J/kg] and $(h_5 - h_4)$ [J/kg], for the turbine and pump, respectively (Mokarram et al., 2023).

$$W_t = \dot{m}(h_1 - h_2) \quad (4.27)$$

$$W_p = \dot{m}(h_5 - h_4) \quad (4.28)$$

Finally, the cycle thermal efficiency, η_{ORC} [-], is calculated as the ratio between electricity output and heat input, $\dot{Q}_{evap}$ [W], as per Equation 4.29. Electricity output, P_{ORC} [W], is defined as net work output multiplied by the generator efficiency, as per Equation 4.30.

$$\eta_{ORC} = \frac{P_{ORC}}{\dot{Q}_{evap}}. \quad (4.29)$$

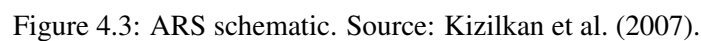
$$P_{ORC} = (W_t - W_p) \cdot \eta_g \quad (4.30)$$

This methodology enables a complete thermodynamic characterization of the ORC, providing all relevant state properties and performance indicators for subsequent analysis.

4.5 Absorption Refrigeration System

The single-effect water-lithium bromide (H₂O-LiBr) absorption refrigeration system (ARS) modeled is displayed on the schematic of Figure 4.3. The installation comprises two coupled internal circuits: the refrigerant loop (states 7–10) and the solution loop (states 1–6).

On the solution side, low-pressure strong solution leaves the absorber at state 1 and is pressurized by the solution pump to state 2. It is then preheated in the counter-current solution heat exchanger (SHX), reaching state 3 before entering the generator. In the generator, heat is provided by the flue gas or thermal oil to the solution (Q_G), which drives desorption: high-pressure refrigerant vapor is released to state 7 while high-pressure weak solution exits at state 4. The hot weak



On the refrigerant side, the desorbed high-pressure vapor (state 7) is condensed in the condenser, rejecting heat (Q_C) to the cooling water and leaving as saturated liquid at state 8. This liquid is expanded isenthalpically across the refrigerant expansion valve to the low-pressure level, then enters the evaporator. There, it absorbs the cooling duty (Q_E) from the chilled-water stream, exiting as saturated vapor at state 10. The vapor is absorbed into the low-pressure weak solution within the absorber, where the exothermic absorption releases heat (Q_A) to the absorber cooling circuit and regenerates the strong solution at state 1, closing the solution loop.

The thermodynamic characterization of the ARS in this study was carried out based on the following assumptions: (i) all parts function in steady-state circumstances; (ii) no pressure losses in components or interconnecting piping; (iii) the refrigerant (H_2O) is saturated at the condenser and evaporator exits; (iv) the refrigerant (H_2O) is superheated at the generator exit; (v) the solution (H_2O -LiBr) is saturated at the absorber and generator exits; (vi) pump work is negligible; (vii) the pump, the solution expansion valve and the refrigerant expansion valve are isenthalpic and adiabatic; (viii) the CoolProp 6.8.1 library is used to calculate the pure streams' (H_2O) thermodynamic characteristics, while the thermodynamic characteristics of solution streams (H_2O -LiBr) are calculated using empirical correlations. Under these conditions, the following methodology is able to fully characterize thermodynamic states, component work, and cycle efficiency (Kaushik and Arora, 2009).

4.5.1 Input Data

The required inputs are:

- Available flue gas heat rate, $\dot{Q}_{\text{flue}}$ [W];
- Target component temperatures, T_g , T_a , T_c and T_e [K], for the generator, absorber, condenser, and evaporator, respectively;
- Solution heat exchanger (SHX) effectiveness ε_{SHX} [-];
- Current cooling requirement $\dot{Q}_{\text{need}}$ [W].

The available flue gas heat rate ($\dot{Q}_{\text{flue}}$) is as was calculated in Section 4.2 using Equation 4.4. Component temperatures are obtained reference temperatures for H₂O-LiBr ARC. Namely, the temperatures in the generator, absorber, condenser and evaporator (T_g , T_a , T_c and T_e) are 90 °C, 40 °C, 40 °C and 7 °C. Similarly to the condenser in the ORC model, the absorber and condenser temperatures in this model are limited by the minimum cooling medium (usually water) temperature (Khalil and Mohammad, 2024). SHX efficiency is set at 80 % (ε_{SHX}), again from reference values obtained from literature (Olympios et al., 2022). Finally, the current cooling requirement, i.e., the minimum thermal power output of the system to satisfy the cooling needs, was obtained by requesting the total installed space cooling power in the Avintes plant to the appropriate department (Electrical maintenance department). This value is around 1186.64 kW ($\dot{Q}_{\text{need}}$).

4.5.2 Thermodynamic States

The ARS pressure levels follow from the saturation properties of the refrigerant (water), as well as the evaporator and condenser temperatures, as per Equation 4.31.

$$p_{\text{low}} = p_{\text{sat}}^{\text{H}_2\text{O}}(T_e), \quad p_{\text{high}} = p_{\text{sat}}^{\text{H}_2\text{O}}(T_c) \quad (4.31)$$

Empirical correlations are used to determine the weak- and strong-solution LiBr mass fractions (X_{ws} [-] and X_{ss} [-], respectively), based on the temperatures of the cycle. These formulae can be seen in Equation 4.32, considering temperatures in °C (Ren et al., 2019).

$$X_{\text{ws}} = \frac{T_g - 0.845 T_c + 35.6}{0.538 T_c + 48.3}, \quad X_{\text{ss}} = \frac{T_a - 0.845 T_e + 35.6}{0.538 T_e + 48.3} \quad (4.32)$$

The circulation ratio (CR [-]) is then defined as the ratio between the mass flow rates of strong solution and refrigerant ($\dot{m}_{\text{ss}}$ [kg/s] and $\dot{m}_r$ [kg/s], respectively). It is calculated based on the weak- and strong-solution LiBr mass fractions, as in Equation 4.33 (Ren et al., 2019).

$$CR = \frac{\dot{m}_{\text{ss}}}{\dot{m}_r} = \frac{X_{\text{ss}}}{X_{\text{ss}} - X_{\text{ws}}} \quad (4.33)$$

Applying a mass balance on either the generator or the absorber reveals how the weak solution mass flow rate ($\dot{m}_{\text{ws}}$ [kg/s]) relates to the other mass flow rates of the system, as can be seen in Equation 4.34.

$$\dot{m}_{ws} = \dot{m}_{ss} - \dot{m}_r \quad (4.34)$$

The temperature of state 9 (T_9 [K]) is defined using its pressure and enthalpy (equal to the enthalpy of state 8) and CoolProp. Furthermore, because the SHX is adiabatic and the hot-side heat-capacitance rate is always smaller ($\dot{m}_4 c_p < \dot{m}_3 c_p$), the temperature of the weak solution at the SHX outlet (T_5 [K]) can be determined by Equation 4.35 (Tawalbeh et al., 2020).

$$T_5 = T_4 + (T_2 - T_4) \cdot \varepsilon_{SHX} \quad (4.35)$$

Since the H_2O -LiBr solution is liquid, it is assumed that a variation of the solution's pressure causes only a negligible change in its temperature and enthalpy. Also, pump work is considered negligible. Thus, the temperature and enthalpy is considered the same at states 1 and 2, and at states 5 and 6. At this stage, the temperature and pressure is known for all states, except state 3.

Refrigerant-state specific enthalpy is computed using the respective state's pressure and temperature, and CoolProp. Solution-state specific enthalpies are calculated via an empirical correlation calibrated for H_2O -LiBr. This correlation is presented in Equations 4.36-4.39, considering solution temperature in Celsius (T), and solution LiBr mass concentration in percentage (X). Note that these equations are presented with the constants truncated for visual clarity (Faruque, 2020).

$$R_A(X) = -2024.3 + 163.31X - 4.8816X^2 + 0.063030X^3 - 2.91371 \cdot 10^{-4} \cdot X^4 \quad (4.36)$$

$$R_B(X) = 18.283 - 1.1692X + 0.032480X^2 - 4.0342 \cdot 10^{-4} \cdot X^3 + 1.8521 \cdot 10^{-6} \cdot X^4 \quad (4.37)$$

$$R_C(X) = -0.03701 + 0.002888X - 8.131 \cdot 10^{-5} \cdot X^2 + 9.912 \cdot 10^{-7} \cdot X^3 - 4.444 \cdot 10^{-9} \cdot X^4 \quad (4.38)$$

Then the solution enthalpy, $h_{sol}(X, T)$ [kJ/kg], is

$$h_{sol}(X, T) = R_A(X) + T \cdot R_B(X) + T^2 \cdot R_C(X) \quad (4.39)$$

Finally, because the SHX is adiabatic, an energy balance across the SHX enables the thermodynamic characterization of state 3 through Equation 4.40.

$$h_3 = h_2 + (h_4 - h_5) \frac{\dot{m}_{ws}}{\dot{m}_{ss}} = h_2 + (h_4 - h_5) \frac{CR - 1}{CR} \quad (4.40)$$

The corresponding strong-solution temperature at the SHX outlet, T_3 , is obtained by solving the scalar equation presented in Equation 4.41. This process is performed iteratively, according to Equation 4.42, initialized by $T_3^{(0)} = T_a + (T_g - T_a) \varepsilon_{SHX}$ and terminated when $|h_3 - h_{sol}(X_{ss}, T_3^{(k)})| < 10^{-1}$ J/kg.

$$h_{sol}(X_{ss}, T_3) = h_3 \quad (4.41)$$

$$T_3^{(k+1)} = T_3^{(k)} + \frac{h_3 - h_{\text{sol}}(X_{\text{ss}}, T_3^{(k)})}{3000} \quad (4.42)$$

Using these equations, all thermodynamic states of the ARS to be modeled are defined.

4.5.3 Main Outputs

Once the thermodynamic states of the ARC are defined, calculations are performed, according to the following methodology, to obtain the main results and outputs of the model. First, the coefficient of performance (COP) of the designed cycle must be obtained to properly size the system. Since pump work is negligible and both throttling valves are isenthalpic ($h_9 = h_8$ and $h_6 = h_5$), no mechanical work terms appear. The coefficient of performance (COP [-]) is then obtained by Equation 4.43, where $\dot{Q}_E$ [W] and $\dot{Q}_G$ [W] are the heat load to the evaporator and generator, respectively.

$$\text{COP} = \frac{\dot{Q}_E}{\dot{Q}_G} \quad (4.43)$$

The formulae for the heat load to the evaporator and generator are obtained when an energy balance is applied to each component, as per Equations 4.44 and 4.45, respectively.

$$\dot{Q}_E = \dot{m}_r \cdot (h_{10} - h_9) \quad (4.44)$$

$$\dot{Q}_G = \dot{m}_{\text{ws}} h_4 + \dot{m}_r h_7 - \dot{m}_{\text{ss}} h_3 \quad (4.45)$$

Since the mass flow rates of the ARS are not yet defined, Equations 4.33, 4.34, 4.43, 4.44 and 4.45 can be used to obtain Equation 4.46, which allows the calculation of the COP without defined mass flow rates.

$$\text{COP} = \frac{\dot{Q}_E}{\dot{Q}_G} = \frac{h_{10} - h_9}{(CR - 1) \cdot h_4 + h_7 - CR \cdot h_3} \quad (4.46)$$

To avoid excessive spending on the ARS (CAPEX and OPEX), the system should be sized to the user's needs. If the ARS's cooling capacity exceeds the required cooling capacity (taken as an input) when it accepts the entirety of the available flue gas waste heat load, then the system's power is reduced to meet the user needs without exceeding them, according to the following methodology. To this end, the system is scaled so that the generator heat load intake of the ARS is the minimum value between the available flue gas heat and the heat rate needed to meet the cooling demand, as per Equation 4.47.

$$\dot{Q}_G = \min\left(\dot{Q}_{\text{flue}}, \frac{\dot{Q}_{\text{need}}}{\text{COP}}\right) \quad (4.47)$$

Once the generator heat load is properly sized, the mass flow rates of the system can be calculated using Equations 4.33, 4.34, and 4.45, which become Equation 4.48.

$$\dot{m}_r = \frac{\dot{Q}_G}{h_7 + (CR - 1)h_4 - CRh_3}, \quad \dot{m}_{ss} = CR\dot{m}_r, \quad \dot{m}_{ws} = \dot{m}_{ss} - \dot{m}_r \quad (4.48)$$

Finally, the heat duties of the remaining components, the evaporator, condenser and absorber, can be calculated using Equations 4.44, 4.49, and 4.50, respectively.

$$\dot{Q}_C = \dot{m}_r \cdot (h_7 - h_8) \quad (4.49)$$

$$\dot{Q}_A = \dot{m}_{ws}h_5 + \dot{m}_r h_{10} - \dot{m}_{ss}h_2 \quad (4.50)$$

This methodology enables not only a complete thermodynamic characterization of the cycle, but also provides relevant performance indicators for subsequent analysis.

4.6 Economic Analysis

Projects in a for-profit corporation like BA Glass need to be economically evaluated, to assess the potential profitability of the investment. For this purpose, an economic model of the project at hand was developed to calculate important financial metrics, namely the net present value (NPV), the internal rate of return (IRR) and the payback period (PBP).

4.6.1 Financial Metrics

The NPV is a way of measuring the present value of an asset that has cashflow, through the sum of the present value of all the future cash flows associated with that asset. It can be calculated with Equation 4.51, where CF_t [€] is the cashflow in period t , r [-] is the periodic discount rate, and n [-] is the number of periods in the lifetime of the project. Usually, each period corresponds to a year (Zhao, 2023; Cotter, 2023).

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+r)^t} \quad (4.51)$$

The IRR is a financial metric used in investment appraisal to estimate the profitability of potential projects. It represents the discount rate that makes the NPV of the project equal to zero. In other words, IRR is the break-even cost of capital: if the required rate of return is below the IRR, the project is considered financially attractive; if it is above, the project may not be worthwhile. The IRR is widely used in capital budgeting because it translates the value of an investment into a single percentage rate, which is easy to compare across different opportunities. It can be calculated with Equation 4.52, where IRR [-] is the internal rate of return (Brealey et al., 2025).

$$\sum_{t=0}^n \frac{CF_t}{(1+IRR)^t} = 0 \quad (4.52)$$

The PBP determines the amount of time required to recoup the initial funding of a determined investment. This point in time is also known as the break-even point. The formula for calculating the PBP can be seen in Equation 4.53. From this, it can be observed that the PBP is a less reliable metric than the NPV in that it does not account for the time value of money or cashflows after the break-even point. Furthermore, the NPV assesses investments in terms of capital value, which enables it to compare two projects against each other. The same can not be said about the PBP (Zhao, 2023; Cotter, 2023).

$$\text{PBP} = \text{Years before break-even} + \frac{\text{Unrecovered cost at start of year}}{\text{Cash flow during the year}} \quad (4.53)$$

Therefore, to calculate these financial metrics, the initial investment (or CAPEX), the operating expenses (or OPEX), and the economic benefits (or savings) have to be characterized for each of the three WHR options. While the economic benefits are easily calculated for each case, CAPEX and OPEX values are often undisclosed or even closely guarded by the system's manufacturers. Therefore, the correlations available in literature are scarce, and only a rough estimate can be obtained.

4.6.2 Input Data

For all three systems, CAPEX and OPEX are evaluated as a function of a characteristic value of the respective system. However, to calculate the economic benefits of each project, additional input data is required. The required inputs are as follows:

- Annual discount rate, r [-];
- Annual average inflation rate [-];
- Yearly operating hours, $YearlyHours$ [h/yr];
- Electricity cost, $ElectricityPrice$ [€/kWh];
- Current cooling system electricity consumption, $YearlyCoolingLoad$ [kWh/yr];
- Wet sludge disposal cost, $WSDC$ [€/ton];
- Dry solids value, DSV [€/ton].

The discount rate is used for calculating the NPV of all investments, and its value is set as 8 % (r), as that is a reference value for corporate finance (Schmidt, 2025). The inflation rate is set as 2 %, and is used to calculate the value of future cash flows (Srinivasan, 2025). The yearly operating hours are useful to determine the output of each system, and is defined as 8700 h/yr ($YearlyHours$) per BA's request. This value is within the expected range as the glass industry operates on a continuous basis, with production maintained day and night throughout the year.

The price that BA pays for electricity is very relevant in calculating the savings associated with the ORC and the ARS, as the former produces electricity directly, while the latter produces cooling, displacing the electricity consumption that would occur in conventional cooling

systems. This value is hard to define as electricity markets are volatile. Thus, the electricity consumption of Avintes in 2024 was analyzed, and the average cost of electricity was 0.108 €/kWh (*ElectricityPrice*), which is the value adopted for the electricity cost in the economic model.

For the ARS, determining the amount of electricity consumption displaced by the system is paramount for an economic analysis. However, these are considered non-essential consumptions by BA, and thus these values are not tracked. Therefore, an estimate was requested from the appropriate department in Avintes (Electrical maintenance department), which stated that roughly 80 % of the installed cooling power is in constant operation (24/7) year-round (e.g., furnace control rooms, electrical switchgear rooms), while the remaining 20 % is in constant operation in the summer only (e.g., office spaces). A conservative estimate for the cooling electricity consumption was made, by considering only the 80 % of cooling that operates year-round. To this end, the COP values of all installed cooling devices were obtained (when unavailable, COP = 3.5 was assumed). Then, Equation 4.54 was used, where $\sum_i \frac{P_i}{COP_i}$ [kW] is the sum of the power consumption of all space cooling devices in Avintes. The resulting cooling load is 2 552 449 kWh/yr (*YearlyCoolingLoad*). Note that this equation considers 8766 annual operating hours (365.25 days), as the cooling systems run independently of the furnaces.

$$YearlyCoolingLoad = 0.8 \times 8766 \times \sum_i \frac{P_i}{COP_i} \quad (4.54)$$

For the TDS, the value of drying sludge is related to the value of the sludge once its dried. The dry solids in the sludge are meant to be repurposed as RM, specifically, they are to substitute yellow sand in the composition. Thus, the average price paid for yellow sand in Avintes was calculated and defined as the value of dry solids, at a value of 12.35 €/ton (*DSV*). Furthermore, the value of drying sludge is also related to the avoided cost of removing the wet sludge from the facility. Currently, excess sludge is removed from BA in bulk containers that contain other excesses. Thus, the average price per ton associated with these containers was calculated, considering the dataset of all 160 shipments that occurred between January 2024 and May 2025, and that value, 35.19 €/ton (*WSDC*), was attributed to the wet sludge disposal cost.

Furthermore, each of the WHR scenarios require an input value for the expected lifetime of the system, to calculate metrics such as the NPV, IRR, LCOE or LCOC. These values were obtained from literature, and correspond to 20 years, 25 years, and 15 years, for ORC, ARS, and TDS scenarios, respectively (Valencia Ochoa et al., 2020; Selvaraj and Victor, 2021; Kovalev et al., 2025)

4.6.3 Thermal Drying System

Positive Cash Flows

Equation 4.55 is used to calculate the positive cashflow associated with the cost of removal of the wet sludge from the facility that is displaced with this project, where $CF_{Disposal}$ [€/yr] is the yearly

cashflow due to transportation savings, $\dot{m}_{ds}$ [kg_{ds}/s] is the dry solids throughput of the system, and X_{in} [kg/kg_{ds}] is the absolute humidity of the wet sludge.

$$CF_{Disposal} = WSDC \times (\dot{m}_{ds} \times (1 + X_{in}) \times YearlyHours \times 3.6) \quad (4.55)$$

Furthermore, the dried sludge represents additional savings in that it is then reintroduced into the glass furnace as a substitute to yellow sand. To quantify these savings, Equation 4.56 is used, where CF_{RM} [€/yr] is the yearly cashflow due to RM savings.

$$CF_{RM} = DSV \times (\dot{m}_{ds} \times YearlyHours \times 3.6) \quad (4.56)$$

TDS Costs

There are very few correlations in literature regarding TDS CAPEX and OPEX correlations. However, U.S. EPA (2006) cited a price correlation with the dryer's dry throughput in ton/day. For example, it stated that a 20 ton/day dryer would cost about 3.6 M\$, while a 100 ton/day dryer would cost about 11 M\$. The data from this source was adjusted for inflation, the currency was converted to euro, and the units used were changed from ton/day to kg/s of dry feed. The data was then fit to a power curve using Excel. The dry throughput of the system, $\dot{m}_{dry}$ [kg/s] is calculated with Equation 4.57. The resulting CAPEX of the system, $CAPEX_{TDS}$ [€] is then calculated according to Equation 4.58. GEI Consultants (2024) claim an average value for rotary drum dryer OPEX, $OPEX_{TDS}$ [€/yr], disregarding thermal energy costs, is 2 % of the corresponding CAPEX, thus this value is calculated using Equation 4.59.

$$\dot{m}_{dry} = \dot{m}_{ds} \cdot (1 + X_{out}) \quad (4.57)$$

$$CAPEX_{TDS} = 13\,450\,008 \times \dot{m}_{dry}^{0.694} \quad (4.58)$$

$$OPEX_{TDS} = 0.02 \times CAPEX_{TDS} \quad (4.59)$$

4.6.4 Organic Rankine Cycle

ORC Positive Cash Flows

The useful output of the ORC system is the electricity it generates. Therefore, the economic benefits in this case are equivalent to the market value of the electricity produced by the ORC, if that electricity is consumed (as it displaces electricity that would otherwise be bought from the grid) or sold to the grid. The savings associated with the ORC system can, therefore, be calculated with Equation 4.60, where $CF_{Electricity}$ [€/yr] is the yearly cashflow due to the electricity generated by the system, and P_{ORC} [W] is the net ORC electrical power (as in Equation 4.30).

$$CF_{Electricity} = \frac{P_{ORC}}{1000} \times YearlyHours \times ElectricityPrice \quad (4.60)$$

ORC System Costs

Calculating the CAPEX and OPEX of an ORC with only the system's characteristics is difficult as these vary in a case by case basis, and because available resources in literature are scarce. Kumar et al. (2023) published a study in which a techno-economic analysis of WHR solutions is performed. To this end, they developed a correlation for estimating the CAPEX and OPEX of ORC systems based on the available waste heat rate. These formulae have been adjusted for inflation (according to INE (2024)) and to use the system's output power, instead of input. The resulting equations are available in Equations 4.61 and 4.62, where $CAPEX_{ORC}$ [€] and $OPEX_{ORC}$ [€/yr] are the CAPEX and OPEX of the ORC.

$$CAPEX_{ORC} = 286.1734 \times P_{ORC}^{0.6662} \quad (4.61)$$

$$OPEX_{ORC} = P_{ORC} \times (0.0227 + 2 \times 10^{-6} \times YearlyHours) \quad (4.62)$$

Levelized Cost of Electricity

Besides the NPV, IRR and PBP, an extra financial metric is determined for this project, a common indicator for the economic viability of systems that generate electricity. The levelized cost of energy (LCOE) is a widely used metric to evaluate and compare the cost-effectiveness of different energy generation technologies. It represents the average cost per unit of electricity generated over the lifetime of a project, discounted to present value. It is particularly useful because it allows different energy projects, regardless of scale or technology, to be compared on a consistent basis. The LCOE [€/kWh] can be calculated with Equation 4.63, where C_t [€] are the costs associated with the system's CAPEX and OPEX in period t , and E_t [kWh] is the electricity generated by the project in period t (IEA, 2020).

$$LCOE = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{E_t}{(1+r)^t}} \quad (4.63)$$

4.6.5 Absorption Refrigeration System

ARS Positive Cash Flows

The useful output of the ARS is the cooling power it produces. However, usually, excess cooling produced can not be sold to the grid. It is also important to adequately characterize the value of the produced cooling. The value of cooling is not the cost of the thermal energy accepted by the ARS, but instead the cost of producing the same useful cooling load with an alternative refrigeration system. This is relevant because the most common alternative to the ARS (for HVAC)

would be a vapor-compression refrigeration system, which has a much higher COP than the ARS ($COP_{VC} \approx 3.5$, $COP_{ARS} \approx 0.7$) (Alghamdi and Krarti, 2025).

Equation 4.64 is used to calculate the positive yearly cashflows of the system, $CF_{Cooling}$ [€/yr], if the system's power is reduced to meet the user needs without exceeding them, as per Section 4.5. However, if instead the available flue gas heat rate is not enough for the ARS's power to meet BA's needs, Equation 4.65 is used instead, where $\dot{Q}_{flue}$ [W] is the heat content in the exhaust (Equation 4.4), COP [-] is the COP of the ARS (Equation 4.46), and $\dot{Q}_{need}$ [W] is the current cooling requirement. This equation assumes that the fraction of the necessary cooling load satisfied by the ARS (kWh/yr) is equal to the fraction of the cooling capacity satisfied by the ARS (kW). This is a worst-case-scenario assumption, as it assumes the cooling system is operating at maximum capacity every time it is used.

$$CF_{Cooling} = YearlyCoolingLoad \times ElectricityPrice \quad (4.64)$$

$$CF_{Cooling} = YearlyCoolingLoad \times ElectricityPrice \times \frac{\dot{Q}_{flue} \times COP}{\dot{Q}_{need}} \quad (4.65)$$

ARS Costs

Much like the other industrial technologies discussed, CAPEX and OPEX data for ARS are limited. U.S. Department of Energy (2017) gave typical values for these systems, both for CAPEX and OPEX. Importantly, these costs include not only the equipment cost, but also the construction and installation costs. This data set was then adjusted for inflation, the currency was converted to euros, the power unit was converted from refrigeration tons to S.I. units, and Excel was used to fit a power function to the data set. For CAPEX, the formula can be seen in Equation 4.66, where $CAPEX_{ARS}$ [€] is the CAPEX cost of the system and $\dot{Q}_E$ [W] is the useful output power of the ARS. This formula has an R^2 value (coefficient of determination) of 0.98, which indicates a good fit of the formula to the dataset. For yearly OPEX, the formula obtained an R^2 value of 0.96, which also shows an adequate fit. This formula can be seen in Equation 4.67, where $OPEX_{ARS}$ [€/yr] are the yearly OPEX costs of the system, and $CoolingProduced$ [kWh/yr] is the yearly cooling output of the system. However, the latter is scarcely readily available information to companies, and so Equation 4.68 is used if the system's power is reduced to meet the user needs. In case the available WH is not enough to meet BA's needs, Equation 4.69 is used instead, where the factor of 3.5 represents the average COP of a conventional vapor-compression refrigeration system (Alghamdi and Krarti, 2025).

$$CAPEX_{ARS} = 133.398 \times \dot{Q}_E^{0.648} \quad (4.66)$$

$$OPEX_{ARS} = 2.314664 \times \dot{Q}_E^{-0.576} \times CoolingProduced \quad (4.67)$$

$$OPEX_{ARS} = 2.314664 \times \dot{Q}_E^{-0.576} \times \text{YearlyCoolingLoad} \times 3.5 \quad (4.68)$$

$$OPEX_{ARS} = 2.314664 \times \dot{Q}_E^{-0.576} \times \text{YearlyCoolingLoad} \times 3.5 \times \frac{\dot{Q}_{\text{flue}} \times COP}{\dot{Q}_{\text{need}}} \quad (4.69)$$

Levelized Cost of Cooling

Similar to how the LCOE calculated in Section 4.6.4 provides the average cost per unit of electricity of the project, in the case of the ARS, it is useful to determine the levelized cost of cooling (LCOC), which represents the average cost per unit of cooling over the project's lifetime. Similar to LCOE in the energy sector, LCOC aggregates all relevant costs discounted to present value and divided by the total useful cooling delivered. LCOC [€/kWh] can be calculated with Equation 4.70, where C_t [€] are the costs associated with the system's CAPEX and OPEX in period t , and Q_t [kWh] is the useful cooling produced by the project in period t (Phelan et al., 2024).

$$LCOC = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{Q_t}{(1+r)^t}} \quad (4.70)$$

Chapter 5

Python Tool

This section describes the implementation of the decision-support tool based on the thermodynamic and economic formulations presented in Chapter 4 (Sections 4.2–4.5). The focus of this chapter is the tool architecture, the user-interface (UI) design, data flow, and validation. The real-case assessment of the feasibility of the three WHR technologies was initially performed using the Excel software through the direct implementation of the methods described in Chapter 4. The Excel outputs were then used as the basis for validation of the results obtained with the Python tool.

5.1 Objectives and Scope

The tool was designed to facilitate and automate the techno-economic analysis of the three WHR options (ORC, ARS, TDS), by taking user inputs and calculating the system properties and important financial metrics for each case. A simple and user-friendly user interface (UI) was developed, which does not require extensive engineering knowledge from users. The implementation of the tool uses Python 3 with the following dependencies:

- **Tkinter** for the GUI (layout, forms, dialogs, and pop-up windows);
- **CoolProp** for thermophysical and psychrometric properties;
- **NumPy** and **NumPy Financial** for numeric utilities and financial computations.

The program follows a simple model–view–controller pattern:

1. **View (UI):** a Tkinter form with a short introductory text, five input sections (flue gas, ORC, ARS, TDS, financial), a read-only panel displaying the main results, and a row of action buttons that open dedicated pop-up windows.
2. **Controller:** a single orchestration routine `run_calculation()` that (a) extracts and validates inputs, (b) calls the toggled scenario blocks, (c) aggregates results, and (d) updates the UI. This routine was intentionally kept minimally invasive, modifying only the logic strictly necessary for the new features.

3. **Model:** self-contained computational blocks for ORC, ARS, and Dryer that compute states and key outputs using the equations detailed earlier in this chapter.

The tool also handles errors via try/except blocks and shows informative messages in the results panel. Furthermore, it does not require external web services, ensuring full offline reproducibility. According to the methodology section, the tool is set up with the modeling assumptions presented earlier (steady-state operation, no pressure losses, etc.). The results should therefore be interpreted within those bounds.

5.2 User Interface Design

To achieve the objective of user-friendliness, the GUI layout was developed to be simple, compact, flexible and easy to use. Thus, as the majority of the layout consists of input fields for the variables used in the calculations, most of these fields are filled out by default with reference values, when applicable, which the user can later change to fit the particular case under analysis. To enhance visual clarity, the remaining input fields have their labels highlighted through the use of bold text, and are placed at the top of their respective sections, to communicate to the user that an input is required. Furthermore, even though the calculations use S.I. units, the input fields use the most commonly used units (e.g., Celsius instead of Kelvin for temperature inputs). The tool then converts these to the appropriate units to perform the analysis in the back end.

For added flexibility, the user is presented with a checkbox above each of the three WHR scenarios, to give the option to disable the techno-economic analysis for one or more of WHR and use scenarios. For each disabled section, the inputs are ignored and calculations are not performed, such that input fields can be left blank without disrupting the program.

As mentioned, CAPEX and OPEX estimates for industrial systems can be inaccurate. Thus, each WHR scenario has a checkbox that allows the user to input their own CAPEX and OPEX data directly. This results in a more accurate economic analysis, especially if the costs are the ones given directly by the technology providers.

The results of the calculations are more focused towards the economic analysis, rather than the technical. To this end, once the calculations are performed, the tool presents a menu with different options to visualize the results that are shown as pop-up windows. These display either a table of the financial metrics of each project, a bar graph comparing a financial metric among all projects, or a table with the thermodynamic properties of each state in the ORC or the ARC.

Considering the objectives of this project, the tool was designed as follows:

Introduction. A static text banner at the top explains the tool's purpose and a short "how to use" guide. This is important to assure the program is user-friendly. A representation of this section in the user interface is shown in Figure 5.1.

Flue gas inputs. Immediately after the introductory text, the user is presented with the flue gas inputs section, as these input fields are required in all configurations, including when some WHR

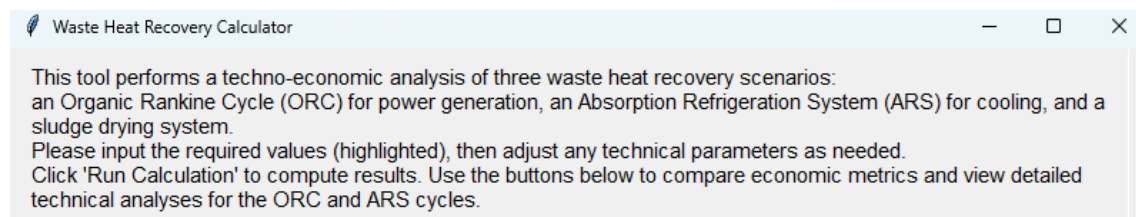


Figure 5.1: Python tool introductory text.

scenarios are disabled. The exhaust information is crucial to assess the available WH, and varies case by case. Therefore, few input fields in this section have a value by default. These are the flue gas pressure, which is assumed to be ambient pressure, and flue gas outlet temperature, which is assumed to be 120 °C to avoid condensation in the heat exchanger. This section is visible in Figure 5.2.

 A screenshot of the "Flue Gas Inputs" section of the software. It contains several input fields with labels: "Flue Gas Inlet Temperature (°C):", "Flue Gas Flow Rate (m³/h):", "O₂ (dry basis) in flue gas (% vol):", "CO₂ (dry basis) in flue gas (% vol):", "Humidity in flue gas (% vol):", "Flue Gas Pressure (kPa):" (with a value of 101.325), and "Flue Gas Outlet Temperature (°C):" (with a value of 120).
Figure 5.2: Python tool *Flue Gas Inputs* section.

ORC inputs. The tool then presents the user with the ORC inputs section. As mentioned, this contains a checkbox to enable or disable this scenario entirely (enabled by default) and a checkbox to be enabled if the user wishes to input CAPEX and OPEX data directly (disabled by default). These features function in the exact same manner for all three WHR scenarios. In this section, there are no mandatory input fields, as all of them have preset values. This is because all of the inputs pertain to the technical aspects of the cycle. This section is visible in Figure 5.3.(a). Furthermore, to make this section more user-friendly, the working fluid selection is a drop-down menu containing 5 common ORC working fluids, and when a new fluid is selected, the evaporator temperature is automatically adjusted to a reference value in literature for that specific fluid. These fluids are R245fa, R123, R1233zd(E), n-Pentane, and Toluene, and their reference evaporator temperatures are 122 °C, 125 °C, 135 °C, 161 °C, and 250 °C, respectively (Zhang et al., 2019; Mariani et al., 2024; Nusiaputra et al., 2015; Borsukiewicz-Gozdur, 2013). The drop-down menu is visible in Figure 5.3.(b). The remaining input fields have the same values that were used in the real-case analysis, with the exception of the condenser temperature, which is set at 40 °C by default (Malwe et al., 2025).

ARS inputs. This section relates to the necessary inputs for the ARS calculations. As mentioned, it also features the option to disable this section, and the option for the user to input

(a) Default View:

- ☒ Include ORC (Organic Rankine Cycle)
- ORC Inputs:
 - Working Fluid: R1233zd(E)
 - Evaporator Temperature (°C): 135
 - Condenser Temperature (°C): 40
 - Superheat Degrees (°C): 9
 - Turbine Isentropic Efficiency (0–1): 0.8
 - Pump Isentropic Efficiency (0–1): 0.75
 - Generator Efficiency (0–1): 0.98
 - ORC System Lifetime (years): 20
 - ☐ Input CAPEX/OPEX data
 - ORC CAPEX (€):
 - ORC OPEX (€/year):

(b) Drop-down Menu Open:

- ☒ Include ORC (Organic Rankine Cycle)
- ORC Inputs:
 - Working Fluid: R1233zd(E) (selected from dropdown)
 - Evaporator Temperature (°C): R245fa
 - Condenser Temperature (°C): R123
 - Superheat Degrees (°C): R1233zd(E)
 - Superheat Degrees (°C): n-Pentane
 - Superheat Degrees (°C): Toluene
 - Turbine Isentropic Efficiency (0–1): 0.8
 - Pump Isentropic Efficiency (0–1): 0.75
 - Generator Efficiency (0–1): 0.98
 - ORC System Lifetime (years): 20
 - ☐ Input CAPEX/OPEX data
 - ORC CAPEX (€):
 - ORC OPEX (€/year):

Figure 5.3: Python tool *ORC Inputs* section (a) default view; (b) with the drop-down menu open.

CAPEX and OPEX values, rather than use the estimates. The only necessary (blank by default) inputs here are the required cooling capacity, which is used to size the ARS appropriately, and the current cooling electricity consumption, which is used in determining the economic benefits of the system. The remaining input data are preset with the values used for the real-case analysis. This section is displayed in Figure 5.4.

☒ Include ARS (Absorption Refrigeration System)

ARS Inputs:

- Required Cooling Capacity (kW):
- Cooling Electricity Consumption (MWh/year):
- Generator Temperature (°C): 90
- Absorber Temperature (°C): 40
- Condenser Temperature (°C): 40
- Evaporator Temperature (°C): 7
- Solution HX Efficiency (0–1): 0.7
- ARS System Lifetime (years): 25
- ☐ Input CAPEX/OPEX data
- ARS CAPEX (€):
- ARS OPEX (€/year):

Figure 5.4: Python tool *ARS Inputs* section.

Dryer inputs. Then, the inputs of the last WHR scenario are presented. Again, this section can be disabled, and costs can be input manually. Here, the values that have no value by default, and thus need user input, are the sludge throughput / sludge production rate, used to size the system appropriately, and the disposal cost of the wet sludge and the added value of the dry sludge, which are used in assessing the economics of this project. The remaining inputs are as they were in the real-case analysis, with the exception of sludge inlet and outlet moisture content, which were

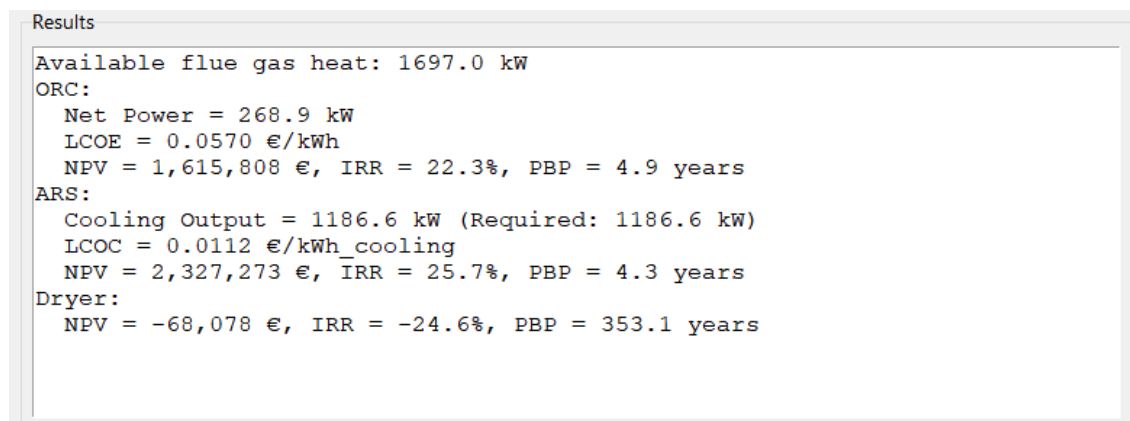
changed to reference values in literature, 70 % and 10 %, respectively (Chang et al., 2023). This section is presented in Figure 5.5.

Figure 5.5: Python tool *Dryer Inputs* section.

General economic inputs. Finally, there is an input section regarding data that is used for the economic analysis of all projects. This section is placed last because all values are filled by default, and thus require no user input. This section can be seen in Figure 5.6, and the input fields are the discount rate, inflation rate, yearly operating hours, and the cost of electricity, which are all preset with the values used in the real-case analysis.

Figure 5.6: Python tool *General Economic Inputs* section.

Results. After the 5 input sections of the program, a text box presents the main results of the calculation, for each case. This text box can be seen in Figure 5.7, with results displayed. The values in this section are updated each time the *Run Calculation* button is used.

Figure 5.7: Python tool *Results* section.

Button row. At the very bottom of the program, a horizontal row containing 8 buttons allows the user to interact with the program, as in Figure 5.8. The *Run Calculation* button is the most important of them, as pressing this button prompts the `run_calculation()` routine, which gathers the inputs, calculates the techno-economic analysis for each case, and updates the GUI to present the results.

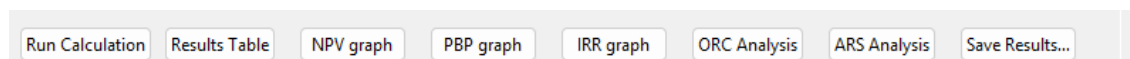


Figure 5.8: Python tool button row.

Next is the *Results Table* button, that opens a pop-up window containing a table where the NPV, IRR, and PBP of each analyzed scenario is presented, to ease the comparison of these metric among the presented scenarios. It can be seen in Figure 5.9.

NPV, PBP, and IRR by Scenario			
Scenario	NPV (€)	PBP (years)	IRR (%)
ORC	1,615,808	4.9	22.3%
ARS	2,327,273	4.3	25.7%
Dryer	-68,078	353.1	-24.6%

Close

Figure 5.9: Python tool *Results Table* pop-up window.

The following 3 buttons have similar functionalities, as the *NPV Graph*, *PBP Graph*, or *IRR*

Graph buttons each launch a pop-up window containing a bar chart where, for every WHR scenario, the NPV, PBP, or IRR is presented, respectively. In Figure 5.10, an NPV chart of the three scenarios is presented.

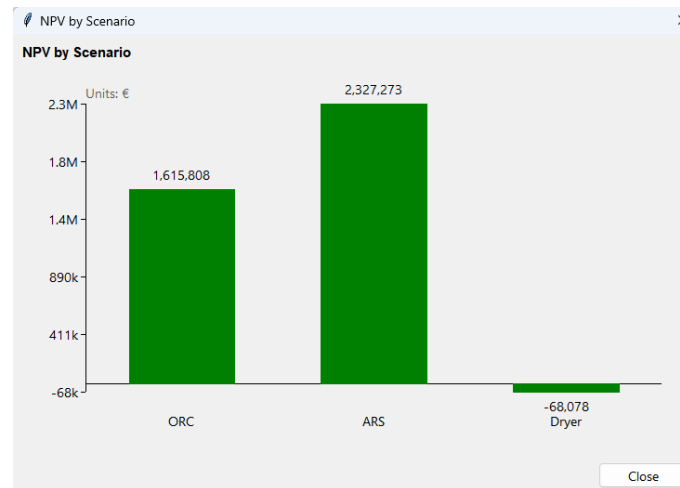


Figure 5.10: Python tool *NPV Graph* pop-up window.

The *ORC Analysis* and *ARS Analysis* buttons present a pop-up window containing the thermodynamic characterization (temperature, pressure, and enthalpy) of each state in the respective cycle, along with a diagram of the cycle for improved readability. Additionally, the absorber concentration in the solutions are also presented, in the case of the ARS. All pop-ups are implemented with Tkinter `Toplevel` windows. Charts are rendered without external plotting dependencies, using Tkinter canvas primitives to maintain the minimal stack. Figure 5.11 displays the ARS case.

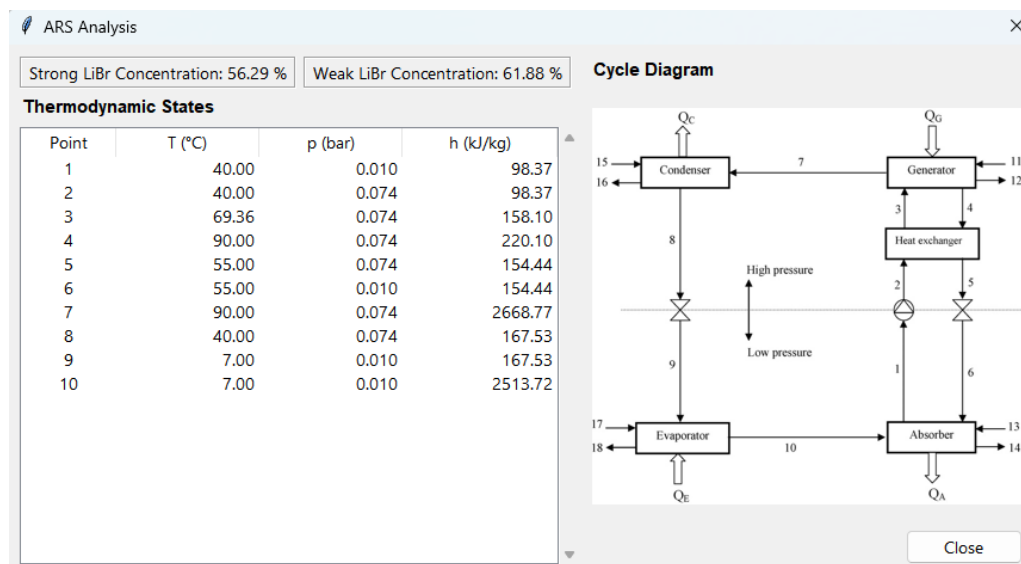


Figure 5.11: Python tool *ARS Analysis* pop-up window.

Finally, the *Save Results...* button allows the user to export and preserve the obtained results,

which improves the traceability, reproducibility, and collaboration potential of this tool. Furthermore, it allows for the comparison of results between different sets of input data.

5.3 Computation Methodology

As mentioned, the program runs the calculation when the *Run Calculation* button is pressed, which triggers the `run_calculation()` function. When this function is called:

1. Flue-gas inputs are parsed and validated. Then, the available heat rate is computed using CoolProp-based mixture enthalpies (methodology from Section 4.2);
2. General economic inputs are parsed and validated;
3. The system checks for thermal infeasibility. This occurs when the temperature of the flue gas is lower than the live vapor temperature in the ORC, if it is lower than the generator temperature in the ARS, or if it is lower than the air inlet temperature in the dryer (note that these conditions are only verified if the respective WHR case is enabled). If thermal infeasibility occurs, a warning pop-up will appear to the user, and the calculation proceeds;
4. If the ORC analysis is enabled, its inputs are parsed and validated. Then, the methodology from Sections 4.4 and 4.6.4 is used to perform the techno-economic analysis of the system;
5. Similar to the ORC, if the ARS analysis is enabled, its inputs are parsed and validated, and the subsequent techno-economic analysis is performed using the methodology in Sections 4.5 and 4.6.5;
6. The dryer inputs are parsed and validated, and the system is analyzed using the methods described in Sections 4.3 and 4.6.3, if the dryer section is enabled;
7. Finally, the results are saved for later use, as these values will be needed to perform the function of any button (except the *Run Calculation* button). Also, the results panel is updated with the calculated results.

The current version of the tool provides a practical and user friendly implementation of the methodology set out in Chapter 4, which can be used by any glass industry similar to BA Glass, to analyse the feasibility of using the process WH in the three WHR scenarios analysed.

Chapter 6

Results

This chapter presents the results of the analysis of the waste heat recovery and use in three different scenarios: sludge drying, ORC and ARS, for the glass production unit of BA Glass located in Avintes. This includes the sludge drying experiments, the entirety of the real-case WHR analysis - starting with the sludge characterization, followed by the calculation of the available WH, and, finally, the techno-economic evaluation of the different WHR and use options. The results are a direct output of the implementation of the methods described in Chapter 4.

6.1 Sludge Characterization

6.1.1 Drying Rate Experiments

The eight drying tests performed on the wet sludge provided different initial moisture content results. These results can be seen in Table 6.1. The results show that the effect of convection on final MC is minimal, and the difference in the results may not be meaningful. On the other hand, the effect of temperature is apparent: drying tests at higher temperatures have a lower final mass, resulting in a higher initial MC as per Equation 4.2. This is particularly noticeable in the tests at 200 °C, where the sample began emanating dark smoke. This suggests that the lower final mass in these tests is not due to a more complete evaporation of the water content in the sample, but instead due to thermal degradation of components in the sample, in line with the observations made in Section 4.1.2. Furthermore, the lower initial MC in the tests at 50 °C correspond to a higher final mass, suggesting incomplete evaporation of the humidity contained in the sample. Therefore, the value of MC in the wet sludge that was calculated as the average of the four tests at 100 °C or 150 °C. This corresponds to a MC of 65.25 %, and a TS content of 34.75 %.

	50 °C	100 °C	150 °C	200 °C
Natural Convection	63.96 %	65.02 %	65.60 %	71.58 %
Forced Convection	63.82 %	64.10 %	66.27 %	70.30 %

Table 6.1: Initial MC of wet sludge under NC and FC at different temperatures.

The drying curve obtained from the periodic weighing of the sample during the drying tests can be seen in Figure 6.1, for the samples tested at 50 °C, 100 °C, 150 °C, and 200 °C, considering both NC and FC. The figure shows the evolution of MC as a function of time. Notably, the same initial MC of 65.25 % was assumed for all data (as opposed to the results in Table 6.1) to ensure a fair comparison. As expected, this means the trials at high temperatures (150 °C and 200 °C) achieve negative values of MC in the late stages of the tests. The results observed in the graph are as expected: drying rate is proportional to the trial temperature, and is higher when FC is used, relative to NC. It is interesting to note that, considering any case with NC as the baseline, a temperature increase of 50 °C with NC results in a higher drying rate, compared to using FC at the baseline temperature, without exception. This suggests that a temperature increase of 50 °C has a higher effect on drying rate than introducing FC at 143 ACH.

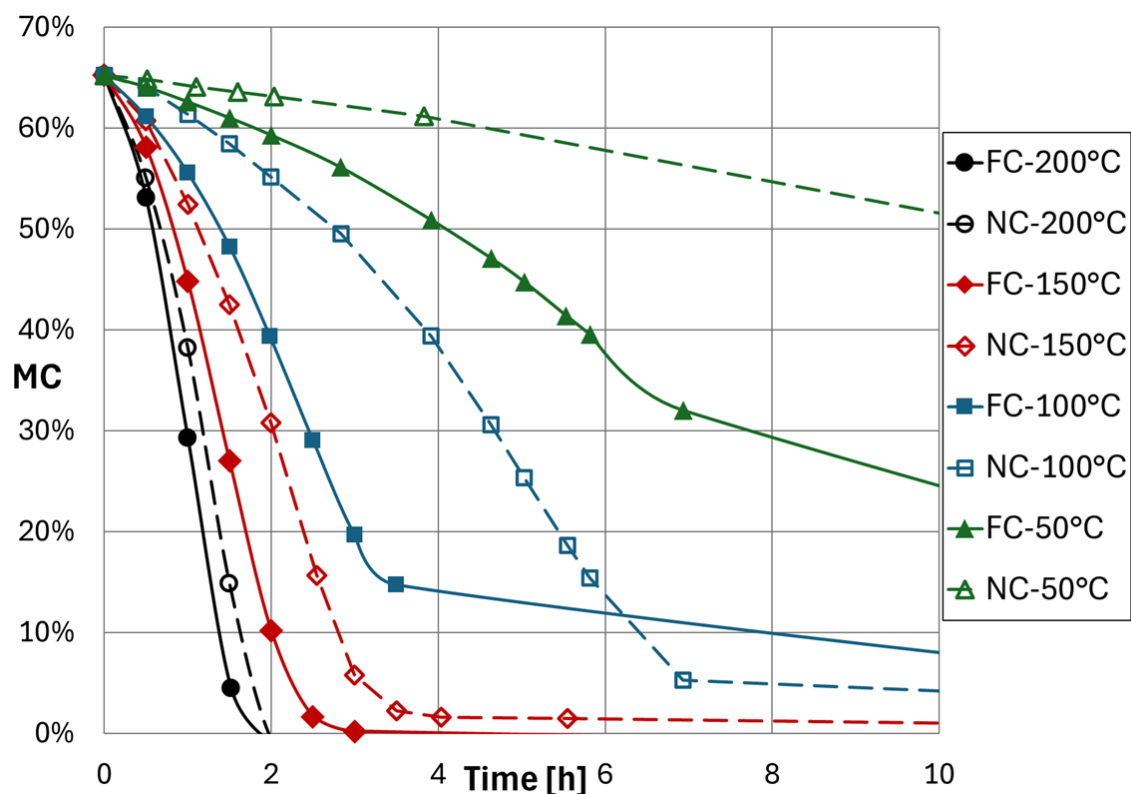


Figure 6.1: Sludge moisture content as a function of time at various temperatures, for NC and FC.

Figure 6.2 shows the change in sludge relative mass as a function of time for the same eight sets of data. Relative mass, as a percentage of the initial mass of each sample, was chosen instead of absolute mass to ensure a fair comparison, since, as mentioned in Section 4.1.2, the samples in the NC muffle furnace had a mass of 500 g, as opposed to the 1000 g samples in the FC oven. Here, the same conclusions that could be drawn from Figure 6.1 are also apparent. Also, in this graph, the period of constant drying rate of each sample is visible, represented by a period where relative mass and time have a linear relationship with a negative slope, shown by a straight line in the graph. Furthermore, the falling drying rate period can also be observed, as the slope of each

dataset decreases until relative mass is approximately constant. These results fall in line with the expected drying rate curve, as per Figure 2.9.

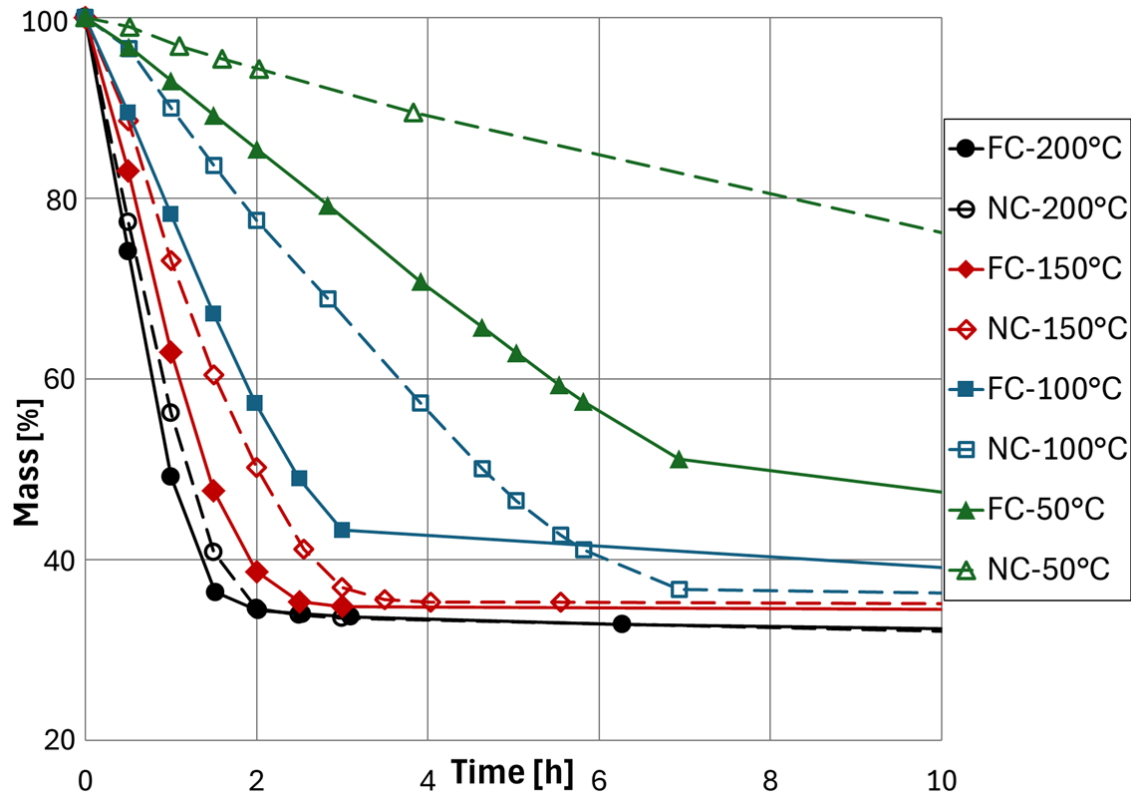


Figure 6.2: Sludge relative mass as a function of time at various temperatures, for NC and FC.

Only the first 10 hours of each trial were considered for the graphs in Figures 6.1 and 6.2, as this was considered the most important period, and to facilitate the interpretation of the figures. The extended versions of the graphs, as well as the raw data obtained, are presented in Appendix C.

Figure 6.3 displays the drying rate (DR) of the sludge as a function of sludge MC, for each of the eight experiments. Notably, the DR was increased by a factor of 2 in the NC cases, to ensure a fair comparison. In this graph, the constant drying rate expected from theory (visible in Figure 2.9) is more apparent in the lower temperature cases. This is likely due to the periodicity of the mass measurements taken during the trials, which was too slow to accurately capture the dynamics of the drying process of the high temperature cases, as these experienced a much higher drying rate, and thus a faster drying process overall.

6.1.2 Other Results

The testing performed on the FC oven used a power meter to track the energy consumption along the drying process. The results show that the power draw of the FC oven was nearly constant during each trial, at a value of approximately 240 W, 535 W, 1 052 W, and 1 150 W, for the trials

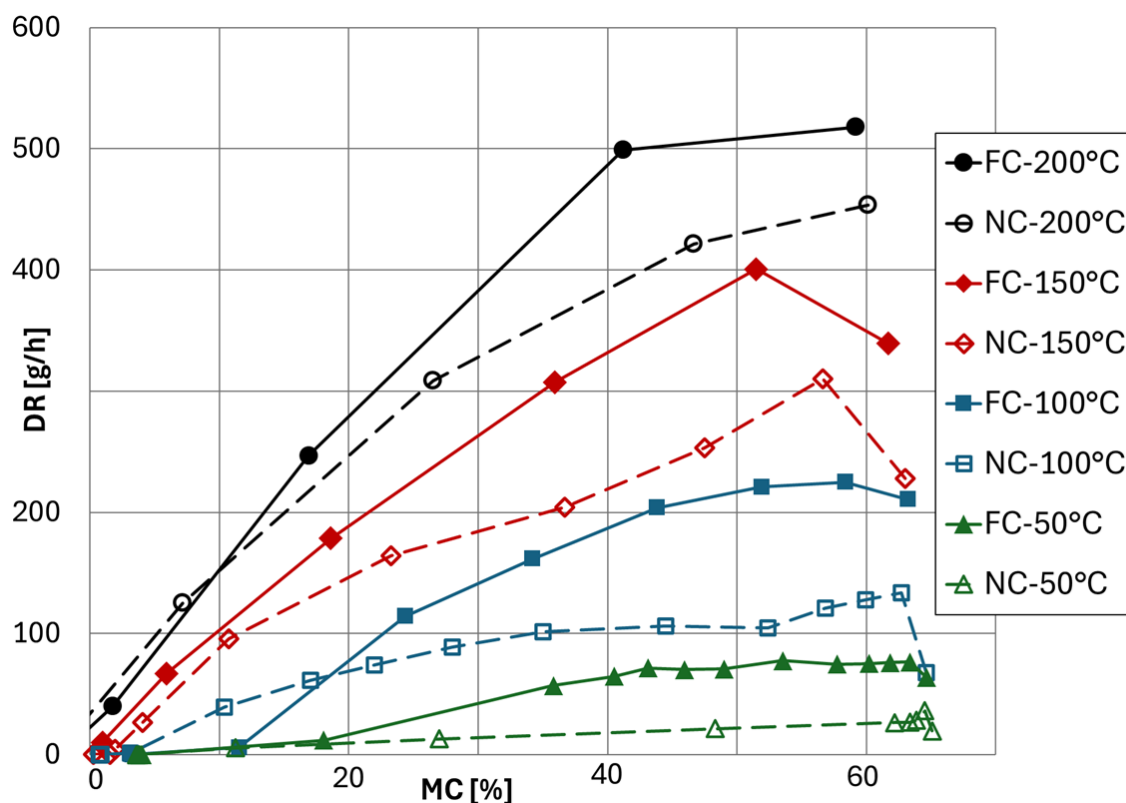


Figure 6.3: Sludge drying rate (DR) as a function of MC at various temperatures, for NC and FC.

performed at 50 °C, 100 °C, 150 °C, and 200 °C, respectively. The resulting graph of electricity consumption (in kWh) as a function of MC can be seen in Figure 6.4. As would be expected, there is a clear trend showing that the total energy consumed to achieve a given MC is lower at higher temperatures. Furthermore, it can be observed that the drying process at 200 °C provided significantly lower specific energy consumption than the other tests. This is expected as this is the highest used temperature, but it should be noted that this result may be skewed due to the fact that, at 200 °C, chemical degradation of the sample was observed. This graph provides a rough estimate for the power draw of the thermal drying system.

The density test performed on the wet sludge sample revealed an apparent density of 1166 kg/m³, as the 250 mL sample had a mass of 291.5 g. This result falls within the expected range, as it is similar to the density of water, the main component of the sample.

The dry sludge sample exam revealed a MC of 12.33 %, which corresponds to a TS content of 87.67 %. This result is important in that it quantifies the desired final humidity. However, it should not be taken at face value, as the sample was described as acceptable by BA, but not necessarily containing the highest acceptable MC for the desired purpose. Indeed, the dry sludge sample exhibited a very solid, hardened state. The material had formed into distinct agglomerates or clumps resembling small rocks. Its color was a very light gray, consistent with the typical appearance of samples following thermal drying in the furnace, as can be seen in Appendix A.3.

These observations indicate that the MC of the dry sample was extremely low. Furthermore,

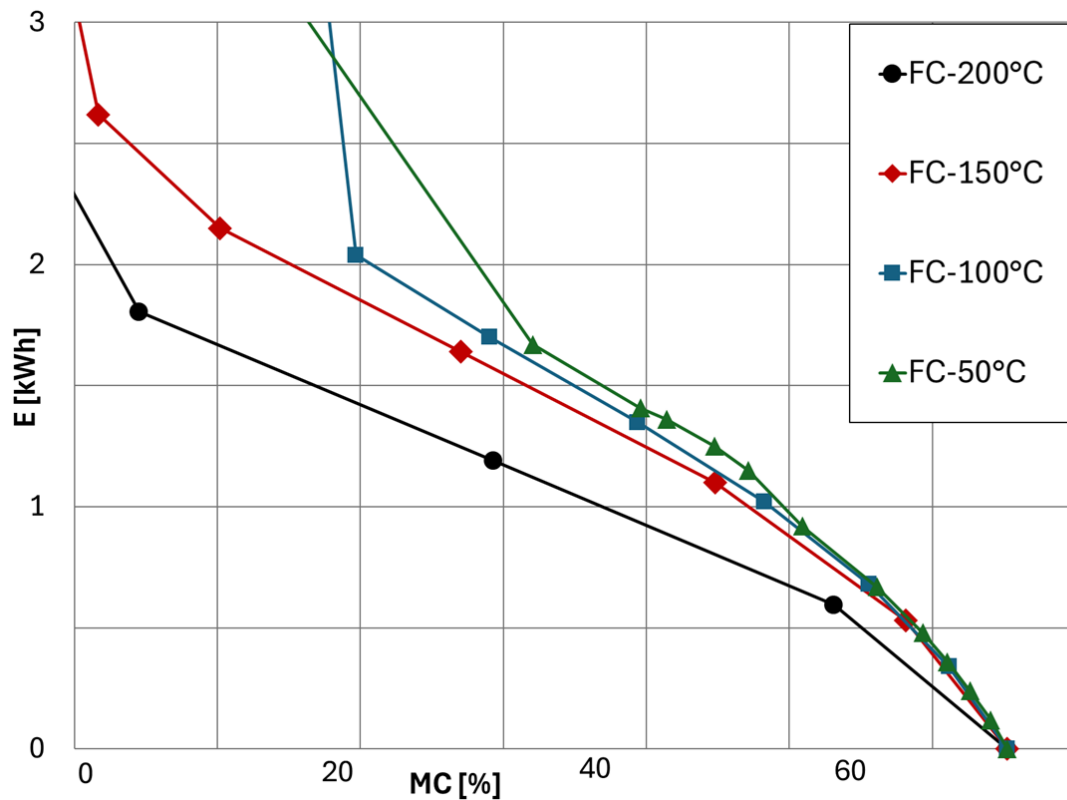


Figure 6.4: Sludge energy consumption as a function of MC at various temperatures, for FC.

it suggests that even samples with higher MC may not have flowability or handling issues in the pneumatic and open belt conveying systems of the RM transport and silage infrastructure. However, to ensure that the sludge is properly dry, the MC of 12.33 % shall be considered for the outlet of the TDS.

6.2 Waste Heat Characterization

The methodology and input data described in Section 4.2 was used to calculate the available waste heat that can be obtained by cooling the Furnace A exhaust to 120 °C. The results obtained are presented in Table 6.2. The resulting available waste heat is approximately 1.7 MW, which presents a strong potential for WHR.

Taking the value of 1.7 MW as the base value for the available waste heat, the methodology described in Chapter 4 was then implemented to calculate the techno-economic viability of the 3 different options for the use of the available waste heat, namely the thermal drying system, the production of power via an ORC system and the production of cold through an ARS system. The results of this analysis are presented in the next three sections.

Parameter	Value
O ₂ Mass Fraction	8.68 %
CO ₂ Mass Fraction	9.60 %
N ₂ Mass Fraction	73.62 %
H ₂ O Mass Fraction	8.10 %
Molar Mass	28.04 g/mol
Density	0.618 kg/m ³
Mass Flow Rate	10.00 kg/s
Enthalpy In	778.1 kJ/kg
Enthalpy Out	608.5 kJ/kg
Available Waste Heat	1 697.0 kW

Table 6.2: Calculated flue gas properties.

6.3 Thermal Drying System

The rotary drum dryer was modeled based on the methodology and input data presented in Sections 4.3 and 4.3. The sludge production rate in Avintes is very low (0.1117 ton/day), such that the waste heat availability results of Section 6.2 confirm that the system can dry the entire sludge throughput with the waste heat, and thus the system does not need to be downsized. In fact, the entire system can be powered with only around 2.1 kW. This means that the power of the heat source is higher by nearly 3 orders of magnitude than the power needed for drying the produced sludge.

6.3.1 Technical Analysis

The results of the technical analysis of the TDS are shown in Table 6.3. As expected, the mass flow rate of dry solids through the system is very low (0.45 g/s), due to a very low sludge throughput. Considering each kilogram of dry solids flowing through the system accounts for 1.737 kilograms of humidity evaporated, the humidity evaporation rate of the system is 0.78 g/s. Furthermore, it can be seen that each kilogram of dry air flowing through the system absorbs 71.4 g of humidity, on average. Since the air mass flow rate of the system is 10.93 g/s, the humidity evaporation rate of the system is 0.78 g/s. Although it may seem redundant to calculate the same metric twice, the fact that the result was the same proves the system's water mass flows are balanced, validating the results.

6.3.2 Economic Analysis

The results of the economic analysis of this WHR system are shown in Table 6.4. The results show that this system is not economically feasible. The main reason for the infeasibility is that the economic benefits it provides are too small, mainly due to the low sludge production rate of the Avintes facility. In fact, the economic benefits are barely enough to offset the estimated OPEX costs of the system. The OPEX is 87.6 % of the total economic benefits, resulting in a yearly cashflow of only 198.28 €.

Parameter	Value
Dry Solids Mass Flow	0.45 g/s
Sludge Inlet Absolute Humidity	1.878 kg H ₂ O/kg dry solids
Sludge Outlet Absolute Humidity	0.141 kg H ₂ O/kg dry solids
Air Inlet Absolute Humidity	15.4 g H ₂ O/kg dry air
Air Outlet Absolute Humidity	86.8 g H ₂ O/kg dry air
Air Outlet Relative Humidity	26.03 %
Air Mass Flow Rate	10.93 g/s
Dryer Heat Input	2.094 kW

Table 6.3: Dryer system technical results.

It is interesting to note that 89.1 % of the economic benefits result from the avoided wet sludge disposal costs, while only 10.9 % are accounted for by the value of dry solids. This is due to the fact that the cost per ton of wet sludge is 2.85 times higher than the value of dry solids. This difference is then amplified as each ton of wet sludge dried by the system only contains 347.5 kg of dry solids.

Parameter	Value
CAPEX	70 019 €
OPEX	1 400.38 €/yr
Wet Sludge Disposal Displaced Costs	1 424.89 €/yr
Dry Solids Value	173.77 €/yr
Total Yearly Benefits	1 598.66 €/yr
Yearly Cashflow	198.28 €/yr
NPV	-68 078 €
IRR	-24.6 %
PBP	353.1 years

Table 6.4: Dryer economic analysis results.

A brief analysis of the techno-economic results shows that this system has negative NPV, corresponding to almost the entirety (97 %) of the corresponding CAPEX. This is supported by the IRR of -24.6 %, meaning the project has overall higher costs than returns. This is also reflected in the amount of time that would be needed to pay back the installation costs, which corresponds to 353.1 years, according to the PBP.

6.4 Organic Rankine Cycle

The model of the ORC using toluene as the working fluid was performed based on the methodology presented in Sections 4.4 and 4.6.4. This system was sized to use the entirety of the available heat from the flue gas, under the assumption that any excess electricity production would be sold to the grid. The results show that this assumption is unnecessary, as all the electricity produced by the ORC system, 2 339 MWh/yr, can be consumed within the BA site. Indeed, the

Avintes plant has a total electricity consumption equivalent to around 90 667 MWh/yr, meaning the implementation of a WHR ORC would satisfy around 2.6 % of the site's electricity needs.

6.4.1 Technical Analysis

Table 6.5 shows the thermodynamic characterization of every state in the ORC, as per Figure 4.2. Therefore, for the evaporator to absorb the available waste heat, the mass flow rate of toluene must be 2.90 kg/s.

Point	T [°C]	p [kPa]	h [kJ/kg]
1	255.0	1 672	566.2
2	177.5	74.2	468.9
3	100.0	74.2	346.5
4	100.0	74.2	-21.0
5	100.8	1 672	-18.3
6	250.0	1 672	321.2
7	250.0	1 672	554.4

Table 6.5: ORC thermodynamic characterization results.

The main technical results of the analysis are presented in Table 6.6. An energy balance can be performed on the ORC to validate the results. The total energy output (in the condenser and turbine) is equal to 1 705 kW, and the total energy input (in the evaporator and pump) is equal to 1 705 kW, confirming the energy flows of the system are balanced. Furthermore, a total cycle efficiency of 15.85 % is in the expected range, considering an ORC (Jiménez-García et al., 2023).

Parameter	Value
Toluene Mass Flow Rate	2.90 kg/s
Condenser Heat Output	1 422.4 kW
Evaporator Heat Input	1 697.0 kW
Turbine Work Output	282.2 kW
Pump Work Input	7.81 kW
ORC Power Output	268.9 kW
ORC Efficiency	15.85 %

Table 6.6: ORC technical analysis results.

6.4.2 Economic Analysis

The economic analysis of the use of the available waste heat to produce electricity via the ORC system shows that this system is viable, as shown in Table 6.7. The economic viability results essentially from the high value of the project's yearly cashflows (241 889 €/yr). The calculated LCOE reveals that the electricity produced by this project will cost 0.057 €/kWh on average, nearly half of the current electricity price. Furthermore, the project's NPV and IRR are 1 615 808 € and 22.3 %, respectively, which indicate the project has strong value creation. Nevertheless, the

system requires an estimated 1 185 327 € as CAPEX, which is a high initial investment. Indeed, this results in a PBP of nearly 5 years, which may not be feasible when analyzed through the scope of corporate finance, as the cutoff for acceptable projects is usually ~ 3 years (Lane and Rosewall, 2015).

Parameter	Value
CAPEX	1 185 327 €
OPEX	10 783 €/yr
Electricity Value	252 672 €/yr
Yearly Cashflow	241 889 €/yr
LCOE	0.0570 €/kWh
NPV	1 615 808 €
IRR	22.3 %
PBP	4.9 years

Table 6.7: ORC economic analysis results.

6.5 Absorption Refrigeration System

The use of the available waste heat to produce cold via an H₂O-LiBr ARS system was modeled based on the methods and equations presented in Sections 4.5 and 4.6.5. The results of the techno-economic analysis of the ARS system are presented in this section.

6.5.1 Technical Analysis

The thermodynamic characterization of the states in the absorption cycle is shown in Figure 6.8, according to Figure 4.3. It should also be noted that the LiBr concentration of the strong solution (states 1, 2, 3) is 56.29 %, while in the weak solution (states 4, 5, 6) it is 61.88 %. These values lie in the expected range, as per the available literature (Osta-Omar and Micallef, 2017).

Point	T [°C]	p [kPa]	h [kJ/kg]
1	40.0	1.002	98.4
2	40.0	7.385	98.4
3	69.4	7.385	158.1
4	90.0	7.385	220.1
5	55.0	7.385	154.4
6	55.0	1.002	154.4
7	90.0	7.385	2 668.8
8	40.0	7.385	167.5
9	7.0	1.002	167.5
10	7.0	1.002	2 513.7

Table 6.8: ARS thermodynamic characterization results.

The main technical results of the analysis are presented in Table 6.9. These values demonstrate that the system was not sized to use the entirety of the flue gas heat, but instead only to meet the required cooling capacity of the Avintes site. Indeed, only 93.4 % of the available WH is being absorbed by the generator, meaning the system would have a cooling output of 1 270.1 kW if sized to consume all available WH. A mass balance can be performed on the system's refrigerant and solutions flows. The sum of the refrigerant and weak solution mass flow rates are equal to the mass flow rate of the strong solution (5.597 kg/s), which indicates the ARS's mass flows are balanced. Similarly, the total heat input to the system (in the generator and evaporator) is equal to the total heat output of the system (in the absorber and condenser), at a value of 2 772.1 kW. The verification of the mass and energy balances of the system validates the results obtained. Furthermore, the ARS has a COP value of nearly 0.75, which corresponds to the expected range for a single-stage absorption cycle (Dilshad et al., 2023).

Parameter	Value
Refrigerant Mass Flow Rate	0.506 kg/s
Weak Solution Mass Flow Rate	5.091 kg/s
Strong Solution Mass Flow Rate	5.597 kg/s
Absorber Heat Output	1 507.1 kW
Condenser Heat Output	1 265.0 kW
Generator Heat Input	1 585.5 kW
Evaporator Heat Input / Cooling Output	1 186.6 kW
Coefficient of Performance (COP)	0.7484

Table 6.9: ARS technical analysis results.

6.5.2 Economic Analysis

Table 6.10 presents the main results of the ARS, which show that the use of waste heat to produce cold with ARS has economic viability. Indeed, the modeled system can fully satisfy the current cooling needs of the Avintes site, effectively displacing an electricity consumption of 2 552.45 MWh/yr, which represents a avoided cost of 275 664 €/yr. This value is much larger than the system's yearly OPEX, resulting in a yearly cashflow of 269 107 €/yr. These savings, coupled with the long lifetime of the ARS, produce an NPV and IRR of 2 327 273 € and 25.7 %, meaning the project generates value. Furthermore, a LCOC of 0.0112 €/kWh_{cool} also represents a profitable investment, as the electrical cost for cooling produced with a common vapor-compression system (COP = 3.5) would be 0.0309 €/kWh_{cool}. This means the cost of cooling with the ARS would be less than 36.3 % of the cost with a vapor-compression system, as this comparison disregarded the CAPEX of the latter. Nevertheless, similarly to the economic analysis of the ORC, this system has a high CAPEX associated with it (1 151 618 €), resulting in a PBP of 4.3 years, which is beyond the usual cutoff for corporate financing projects (~3 years) (Lane and Rosewall, 2015).

Parameter	Value
CAPEX	1 151 618 €
OPEX	6 557 €/yr
Displaced Electricity Costs	275 664 €/yr
Yearly Cashflow	269 107 €/yr
LCOC	0.0112 €/kWh _{cool}
NPV	2 327 273 €
IRR	25.7 %
PBP	4.3 years

Table 6.10: ARS economic analysis results.

6.6 Python Tool

The Python tool was developed as per the presented methodology. The results produced by this tool were cross-validated with the real case analysis performed in Excel, thereby confirming that it produces accurate results. The full source code of this tool is presented in Appendix D.

Chapter 7

Discussion

This chapter presents the main conclusions of the dissertation, assessing the level to which the outcomes of this work meet the proposed objectives and were able to respond to the research questions. Additionally, this chapter also revisits the methodology employed, in light of the obtained results.

7.1 Aims and Scope

As described in Chapter 1, following the adjustment of the main scope, the work carried out in this dissertation was focused on the analysis of the technical and economic potential of waste-heat recovery (WHR) and use at BA Glass–Avintes site, using the flue gas from Furnace A as the energy source. Guided by the research questions in Section 1.5, the work quantified (i) the technically recoverable waste heat while respecting a conservative flue-gas outlet temperature constraint of $\geq 120\text{ }^{\circ}\text{C}$ (to avoid acid–dew corrosion and fouling), (ii) the feasibility of implementing a thermal dryer sized to the measured sludge properties and throughput, and (iii) the techno-economic analysis of the viability of implementing of two additional heat-to-use technologies: an organic Rankine cycle (ORC) for electricity production and a single-effect H_2O –LiBr absorption refrigeration system (ARS) for cooling. A final objective consisted in the implementation of the used methodology into a decision tool with a graphical interface that BA Glass and any other glass container production facility can use for rapid studies and future projects - provided that the production process is similar to the one used as the baseline in this dissertation.

The boundaries of the analysis were adjusted to the case under study. Namely, process integration was limited to Furnace A’s exhaust path upstream of the stack, with the electrostatic filter, bypass operation, stack-height constraints, and local emissions rules treated as hard constraints. Flue-gas cooling across the WHR heat exchanger was capped so that the stack inlet remains above $120\text{ }^{\circ}\text{C}$. Thermodynamic models assumed steady state, no distribution losses, and standard approach temperatures. Property calls rely on CoolProp. And the economic evaluation uses a corporate discount rate and plant-supplied operating hours and energy prices.

The results of this dissertation include a validated flue-gas dataset and recoverable-heat estimate for Furnace A, a lab characterization of the sludge (moisture, density, drying curves under NC/FC at 50–200 °C), steady-state performance models for the dryer, ORC, and ARS, a techno-economic comparison of these systems (NPV, IRR, PBP and levelized costs), and, finally, a Python tool implementing the same methods and assumptions for quick and easy use.

7.2 Answers to the Research Questions

RQ1. *What is the technically recoverable waste heat from Furnace A while maintaining the flue-gas outlet from the WHR heat exchanger at or above 120 °C?*

Answer: The methods employed here, using the 2024 energy audit data and mixture properties, led to the conclusion that the technically recoverable waste heat from Furnace A is an estimated 1.70 MW (see Section 6.2). While these were the input values to use on BA's request, these flue gases can be actually be obtained at higher temperatures if heat recovery is made at a point further upstream, and the exhaust dilution valve is closed (this valve can be closed in steady-state if the WHR system is further upstream than the ESP, as cooling the exhaust for the ESP becomes unnecessary). Furthermore, Furnaces B and C share the same stack, and these flue gases present similar characteristics, except a much higher (~80 %) mass flow rate. These indicate that the WHR potential of the Avintes site may be higher than the one calculated with the initial set of assumptions used in this dissertation. This would certainly influence the techno-economic analysis and may mean that the economic viability, and the payback time, of some of the options may be better than those presented here.

RQ2. *For the measured sludge properties and throughput, what dryer operating conditions and thermal load are required to reach the target moisture content, and is the project economically viable (NPV, IRR, PBP)?*

Answer: The dryer was modeled based on a rotary drum dryer, and used the results of the sludge drying experiments as input. This analysis showed that only 2.1 kW of waste heat are required to dry the 111.7 kg of sludge that the Avintes site produces daily to an acceptable moisture level. This system would require an air mass flow rate of 10.93 g/s to evaporate sufficient moisture from the sludge. The economic analysis of this option showed that it is not economically viable, namely: the NPV, IRR, and PBP were -68 078 €, -24.6 %, and 353 years, respectively. This is mainly due to the very low economic benefits of this project (avoided wet sludge removal costs, and value of dry solids), which amounted to 1 599 €/yr (see Table 6.4). The initial request from BA for analysis of this option may have resulted from an overestimation of the costs associated with the wet sludge transportation. The work carried out in this dissertation was thus able to show that for the relatively small amount of sludge produced at this single site, the current practice is more viable than installing a dedicated dryer powered by WHR.

RQ3. *What net power and efficiency can an ORC deliver from the same source, what are the corresponding CAPEX/OPEX and LCOE, and is this project economically feasible?*

Answer: The use of the waste heat to produce electricity via an ORC system was analyzed according to the methodology presented in Chapter 4, which resulted from the literature review in Chapter 2. The resulting cycle efficiency for the ORC system was 15.85 %, which is at the upper end of the expected range for an ORC. This may be due on the one hand to the simplification assumptions made in the model (e.g., no heat losses in the components), and on the other due to the evaporation temperature at the upper end of the usual ORC evaporation temperature range, which increases efficiency. Therefore, the implementation of the ORC system, considering the available waste heat, can deliver 268.9 kW of electric power. The resulting electricity production accounts for only 2.6 % of the total electricity needs of the Avintes site, and thus there is no excess electricity to sell back to the grid. The economic analysis of this system show that this option is economically viable, as its NPV, IRR, PBP, and LCOE are 1 615 808 €, 22.3 %, 4.9 years, and 0.057 €/kWh respectively (see Section 6.4). Furthermore, the estimated CAPEX and OPEX of the system are 1 185 327 € and 10 783 €/yr, respectively. While the LCOE, NPV and IRR of this project are favorable, the PBP of approximately 5 years is above the 3 year cutoff typically considered for "feasible" investments in private companies.

RQ4. *What cooling capacity and COP can a single-effect H₂O-LiBr ARS provide while powered by the available waste heat, what fraction of current cooling electricity can it displace, what is the LCOC, and is this project economically feasible?*

Answer: The single-effect H₂O-LiBr ARS was chosen to test a solution for cooling using waste heat as this is the most common waste-heat-to-cold system for space cooling. It revealed a COP of 0.7484 (standard for this system) and a cooling output of 1 186.64 kW, meaning it can satisfy the entire space cooling demand of the Avintes site. If the available WH was to be used in its entirety, the cooling output would be 1270.1 kW. It is interesting to consider implementing this scenario and utilizing the excess cooling power to improve thermal comfort on the shopfloor, as per the initial objective of this dissertation, as this would increase CAPEX by only 4.5 % to 1 203 462 €. The economic analysis of this system showed that this project is economically viable, and it is financially the most attractive project of the three analyzed. Indeed, the NPV, IRR, PBP, and LCOC are 2 327 273 €, 25.7 %, 4.3 years, and 0.0112 €/kWh_{cool}, meaning this option outperforms the ORC and the dryer in NPV, IRR and PBP (see Section 6.5).

RQ5. *To what extent can the applied methodology be encapsulated in a user-friendly software tool and applied to other furnaces/sites with minimal re-work, and what are the associated inputs/outputs?*

Answer: The methodology in this dissertation mainly comprises (i) collecting input data; (ii) applying simple algebraic relations and a single iterative equation (Equation 4.42); and

(iii) evaluating thermodynamic properties of the working fluids and humid air via a thermophysical property library. While many inputs can be predefined from reference values, acquiring site-specific data cannot be automated. The rest of the workflow is readily implemented in Python (or other languages) given access to a library such as CoolProp. Therefore, nearly the entire workflow can be encapsulated in a user-friendly tool and ported to other furnaces/sites with minimal re-work, provided site data are available. The computational core (property calls, mass/energy balances, ORC/ARS/TDS models, and finance module) is fully generic. Re-work is typically limited to entering new site inputs, selecting technology options, and optionally tuning cost correlations or limits. The required inputs, i.e., the data with no predefined values, are the flue gas temperature, flow rate and composition, the required cooling capacity, the cooling electricity consumption, the sludge throughput and the value of wet and dry sludge. The main outputs are the full thermodynamic characterization of the ORC and ARS (including efficiency/COP and net power/cooling output), the characterization of the TDS (including required heat duty/air flow and water removed), and relevant financial metrics for all three systems (including NPV, PBP, IRR, and levelized costs).

7.3 Cross-Option Comparison

In light of the results obtained in this dissertation, the ORC and the ARS are the only options with a favorable economic outcome, for the Avintes site and the characteristics of the waste heat available. The ORC valorizes WH directly as electricity with simple operations, but requires careful selection of materials and safeguards for a flammable organic fluid and hot oil circuit if an intermediate loop is used. On the other hand, the ARS valorizes WH indirectly by avoiding the consumption of electricity for cooling. ARS integrates well with existing chilled-water users, but needs LiBr concentration control, LiBr crystallization avoidance, corrosion mitigation, and two heat-rejection duties (absorber and condenser). The dryer, while attractive from a material circularity standpoint (as the sludge is repurposed in the batch), is economically unfeasible.

Figure 7.1 displays a bar chart comparing the main financial metrics for the TDS, ORC and ARS. There, the distinction between the TDS and the other two cases is immediately apparent, as it presents the only negative NPV and IRR values, and its PBP is so large (353 years) that it is not depicted in the graph. Furthermore, it is apparent why the ARS and ORC are economically comparable, even if the ARS is more financially attractive when compared on any of the metrics.

Regarding sustainability, the ORC reduces grid electricity purchases directly, while ARS reduces them indirectly via displaced cooling power. Both of these reduce scope-2 emissions proportionally to the grid factor, but this is negligible since BA uses 100 % renewable electricity. The dryer advances circularity by returning solids to batch, but its absolute GHG benefit is small at current sludge tonnage.

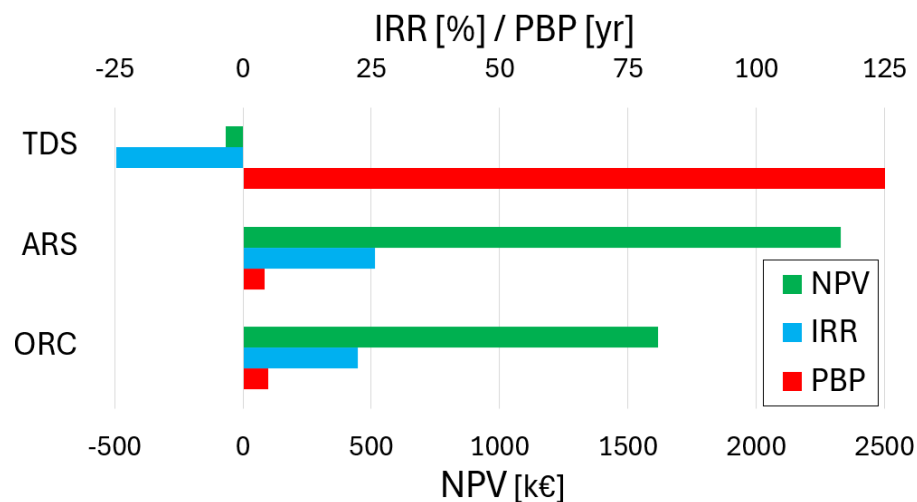


Figure 7.1: Bar chart comparing NPV, IRR and PBP for the studied scenarios.

7.4 Limitations and Future Works

This section of the discussion aims to critically evaluate the limitations of the presented work, and to suggest future works to expand on this report.

7.4.1 Data Quality

The fact that a single campaign was used for the flue gas characterization is arguably the biggest limitation in the methodology employed in this project. The most influential values from this audit are the flow rate of the exhaust, and their temperature, as these cause the biggest variation in the available waste heat. These are also the least reliable values, as the volumetric flow rate measurement has 34.4 % uncertainty (see Table 4.1), and the temperature measurement is subject to the cooling effect of the exhaust dilution, and upstream points could present higher temperatures. Therefore, a multi-season measurement campaign at multiple duct locations, at least 48 h after the dilution duct has been closed, is recommended for future works that desire to obtain more accurate results regarding the available waste heat from the exhaust.

The data that was obtained from the sludge drying tests also has uncertainty due to several factors. These experiments used small, shallow trays in controlled ovens, with limited sampling. Thus, sludge heterogeneity over time was not fully captured, as the sludge may present seasonally higher or lower moisture content at the screw press outlet. Mass measurement periodicity was also not optimal, not fully capturing the dynamics of the sludge drying. The sample had to be removed from the oven for each measurement, meaning more mass measurements could result in inconsistent sludge temperature. Also, while the air velocity and temperature was controlled, the humidity was not, which could have affected the results. Therefore, for future work, further sludge tests should be performed using pilot dryers, where the mass of the sample is continuously measured within the oven. These tests should also be performed with a wider variety of samples, and in an environment with controlled air humidity.

The sludge inlet mass flow rate was determined through indirect measurements carried out over a short sampling time frame. The current space cooling electricity consumption of BA was also a rough estimate based on the size of the installed cooling power and the number of hours that the cooling system is running throughout the year. Also, the cost of electricity to BA is very volatile, especially in a post-pandemic era. Thus, it is suggested that, for future works, one could improve the accuracy of these values by executing longer, more detailed measurement campaigns, and by studying the trends of the European electricity market.

7.4.2 Modeling Assumptions and Simplifications

The thermodynamic modeling of the different systems assumed steady-state operation with no pressure losses in the pipes or components, and negligible heat losses. This may skew the results, resulting in higher COP / efficiencies, and an under-sized HE area. Thus, a future expansion of the present work could increase the modeling accuracy by incorporating pressure-drop models, fouling factors, heat losses, and temperature-dependent properties in the models. Furthermore, in the ARS, assuming negligible pump work similarly skews the results, so this assumption should be discarded in a more accurate model.

The models for the ORC and ARS were further simplified as the ORC did not use a detailed pinch-point analysis, and the ARS did not simulate crystallization margins and off-design maps. These are necessary for the implementation of either of these systems, respectively, but were not included due to the fact that this study is theoretical in nature.

Lastly, the composition of the furnace exhaust was assumed to have the following composition: O_2 , CO_2 , H_2O , and N_2 . This assumption ignores the effect of minor species present in the flue gas, such as SO_2 or NO_2 . This may skew the characterization of the available WH. To improve this, it is again suggested that future works implement a more detailed flue gas measurement campaign.

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Appendix A

Sludge Characterization Experiment Photographs

This appendix is used to display the photographs captured during the sludge drying experiments in INEGI, but that were deemed unnecessary for the main body of text of the present work.

A.1 Equipment

Figures A.1 and A.2 show the main laboratory furnaces used for this experiment: the forced convection oven and the muffle furnace, respectively. In these images, the furnaces are depicted both as closed and as open, displaying the arrangement of the sludge sample inside. Furthermore, Figure A.3 displays both of the trays used in the experiment to contain and transport the sludge samples. The steel tray was used in the FC oven, while the glass tray was used in the muffle furnace.



Figure A.1: *BINDER* FD115 FC oven (a) closed; (b) open, with a sludge sample inside.

A.2 Procedure

Figure A.4 contains two angles displaying the packaging in which the sludge samples were transported from the industrial unit of BA to the laboratory of INEGI. These consist of plastic bags



Figure A.2: Nabertherm L 9/11 muffle furnace (a) closed; (b) open, with a sludge sample inside.



Figure A.3: Steel and glass trays used in the sludge drying experiments.

sealed with duct tape. Furthermore, the different colors immediately distinguish wet from dry samples, as the former are brown, while the latter are white. Figure A.5 displays the plastic bucket containing the four wet sludge samples that were mixed inside it.



Figure A.4: Plastic bags containing the samples for transportation.

Figure A.6 demonstrates the 250 mL plastic beaker filled with wet sludge up to its capacity, being used to measure the mass of this sample.

A.3 Sludge Samples

Figure A.7 displays the wet sludge sample along the drying process using the FC oven at 100 °C. Figure A.8 displays a sample of dry sludge, before the drying test was performed on it (MC of 12.33 %).



Figure A.5: Plastic bucket containing the mix of the four wet sludge samples.



Figure A.6: Plastic beaker measuring the mass of 250 mL of wet sludge.



Figure A.7: Sample photographs along the 100 °C FC experiment. MC are as follows (from left to right, top to bottom): 65.25 %, 61.16 %, 55.57 %, 39.38 %, 29.04 %, and 3.20 %, respectively.



Figure A.8: Dry sludge sample, before the experiment.

Appendix B

Experiment to Determine the Airflow Rate of the Forced Convection Oven

This appendix details the experiment that was carried out in the INEGI facilities to determine the airflow rate of the *BINDER* FD115 FC laboratory drying oven, because this information was not available. The details of this experiment were deemed superfluous to the main text, thus they were included in this appendix.

Measurements

For this experiment, only a few measurements were required. The three internal spatial dimensions were measured, as to calculate the internal volume, as well as the exhaust diameter, as to calculate the area of the cross-section of the exhaust. Also, instantaneous air flow velocity measurements at different points in the cross-section of the end of the exhaust were obtained, as to calculate the exhaust air flow rate.

Therefore, only measurements of length and instantaneous air flow velocity were necessary for the calculations to be performed. For length measurements, a spring-return (retractable) tape measure, with a maximum measuring length of 5 m, was used. The corresponding measurements can be observed in Table B.1. For instantaneous air flow velocity measurements, a hot-wire anemometer was used. The corresponding measurements can be observed in Table B.2. The average of these values was considered for the calculations (2.39 m/s).

Measurement	Value
Interior Length [mm]	600
Interior Height [mm]	480
Interior Width [mm]	400
Exhaust Diameter [mm]	49.4

Table B.1: Length measurements of *BINDER* FD115 FC laboratory drying oven.

Calculations

The internal volume of the oven was calculated at 115.2 liters, as shown in Equation B.1, according to the formula for the volume of a rectangular cuboid. The cross-section area of the exhaust of the oven was calculated at 19.17 cm², as shown in Equation B.2, according to the formula for the area of a circle. Finally, the volumetric airflow rate was calculated at 16.5 m³/h or 4.58 L/s, as shown

Velocity Measurements	Value
Velocity [m/s]	2.39
Velocity [m/s]	2.39
Velocity [m/s]	2.40
Velocity [m/s]	2.42
Velocity [m/s]	2.40
Velocity [m/s]	2.38
Velocity [m/s]	2.36
Velocity [m/s]	2.42
Velocity [m/s]	2.40
Velocity [m/s]	2.36

Table B.2: Instantaneous air flow velocity measurements at oven exhaust.

in Equation B.3, according to the formula for the volumetric flow rate in a duct. To obtain the air change rate, one must simply divide this value by the volume of the oven chamber, and the result is 143 ACH (air changes per hour) or 2.39 ACM (air changes per minute).

$$V = Length \cdot Height \cdot Width = 115.2L \quad (B.1)$$

$$A = \pi \cdot r^2 = 19.17\text{cm}^2 \quad (B.2)$$

$$\dot{V} = v \cdot A = 4.58L/s = 16.5\text{m}^3/h \quad (B.3)$$

Appendix C

Expanded Results of Drying Rate Experiments

This appendix serves the purpose of displaying information, in the form of graphs and raw data, that was obtained during the drying rate experiments performed on the wet sludge samples in INEGI, but was deemed superfluous to the main body of the present work.

C.1 Complete Graphs

Considering the drying rate experiments, the graphs displayed in the core body of the text did not display the entire set of data obtained, as the first 10 hours of each trial were deemed the most relevant. Thus, Figures C.1 and C.2 display the graphs of MC and relative mass over time, respectively, considering the full set of data, with the exception of the trial at 50 °C using NC, as this case lasted until $t = 64$ h, but had a loss of only 0.6 g in the last 24 h, approximately. Thus, the time cutoff for these graphs is at $t = 45$ h.

C.2 Obtained Datasets

In the following tables, the information obtained in the experiments is exposed in tabular form. Tables C.1, C.2, C.3, and C.4 display the data in the NC oven for temperatures of 50 °C, 100 °C, 150 °C, and 200 °C, respectively. Tables C.5, C.6, C.7, and C.8 display the data in the FC oven for temperatures of 50 °C, 100 °C, 150 °C, and 200 °C, respectively.

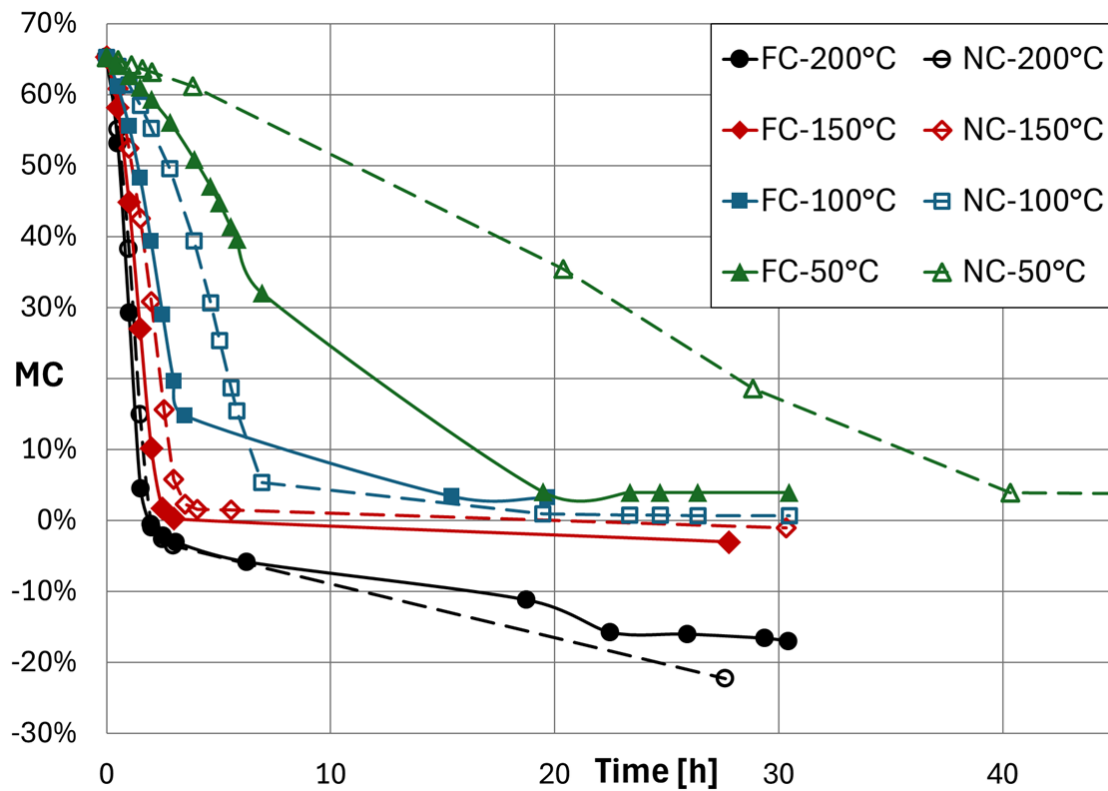


Figure C.1: Sludge moisture content as a function of time at various temperatures, for NC and FC, full dataset.

Time [h]	Mass [g]	MC [%]
0.00	500.0	65.25%
0.52	494.9	64.89%
1.10	484.3	64.12%
1.60	477.2	63.59%
2.03	471.4	63.14%
3.83	447.5	61.17%
20.38	269.0	35.41%
28.83	213.4	18.58%
40.33	180.8	3.90%
51.32	180.3	3.63%
64.43	180.2	3.58%

Table C.1: Drying Data – NC - 50 °C

Time [h]	Mass [g]	MC [%]
0.00	500.0	65.25%
0.51	482.8	64.01%
1.00	450.0	61.39%
1.50	418.1	58.44%
2.00	387.9	55.21%
2.83	344.3	49.54%
3.92	286.8	39.42%
4.63	250.5	30.64%
5.03	232.7	25.33%
5.55	213.6	18.66%
5.82	205.4	15.41%
6.93	183.5	5.31%
19.47	175.4	0.94%
23.35	175.1	0.77%
24.70	175.1	0.77%
26.38	175.0	0.71%
30.47	174.9	0.66%

Table C.2: Drying Data – NC - 100 °C

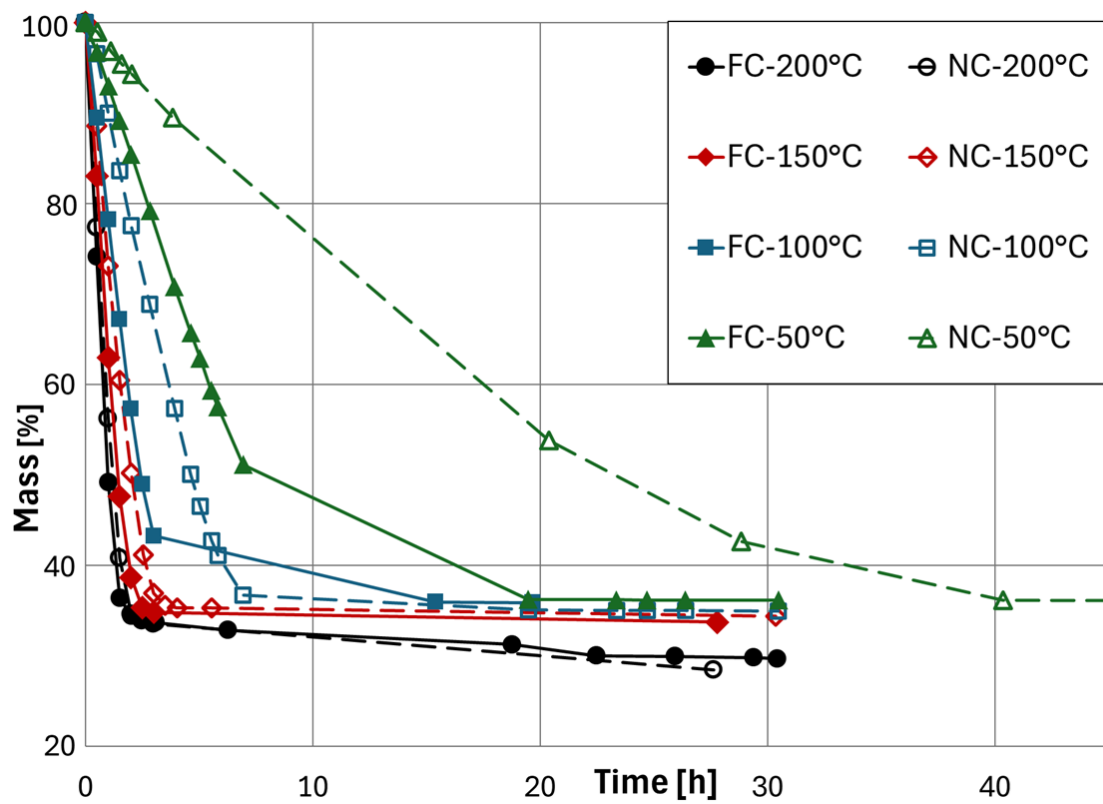


Figure C.2: Sludge relative mass as a function of time at various temperatures, for NC and FC. Full dataset.

Time [h]	Mass [g]	MC [%]
0.00	500.0	65.25%
0.50	443.0	60.78%
1.00	365.5	52.46%
1.50	302.2	42.50%
2.00	251.2	30.83%
2.55	206.0	15.66%
3.00	184.5	5.83%
3.50	177.8	2.28%
4.03	176.6	1.61%
5.55	176.4	1.50%
30.33	172.0	-1.02%

Table C.3: Drying Data – NC - 150 °C

Time [h]	Mass [g]	MC [%]
0.00	500.0	65.25%
0.50	386.6	55.06%
1.00	281.2	38.21%
1.50	204.1	14.87%
2.00	172.8	-0.55%
2.50	169.3	-2.63%
3.00	167.8	-3.55%
27.62	142.1	-22.27%

Table C.4: Drying Data – NC - 200 °C

Time [h]	Mass [g]	MC [%]
0.00	1000.0	65.25%
0.51	967.6	64.09%
1.00	930.0	62.63%
1.50	892.0	61.04%
2.00	854.4	59.33%
2.83	792.2	56.13%
3.92	708.0	50.92%
4.63	657.3	47.13%
5.03	629.2	44.77%
5.53	593.4	41.44%
5.82	575.1	39.58%
6.93	511.4	32.05%
19.47	362.2	4.06%
23.35	361.9	3.98%
24.70	361.8	3.95%
26.38	361.8	3.95%
30.47	361.8	3.95%

Table C.5: Drying Data – FC - 50 °C

Time [h]	Mass [g]	MC [%]
0.00	1000.0	65.25%
0.50	894.6	61.16%
1.00	782.2	55.57%
1.50	671.7	48.27%
1.98	573.2	39.38%
2.50	489.7	29.04%
3.00	432.6	19.67%
3.50	407.6	14.74%
15.40	359.7	3.39%
19.67	359.0	3.20%

Table C.6: Drying Data – FC - 100 °C

Time [h]	Mass [g]	MC [%]
0.00	1000.0	65.25%
0.50	830.3	58.15%
1.00	629.9	44.83%
1.50	476.2	27.03%
2.00	386.9	10.18%
2.50	353.4	1.67%
3.00	348.3	0.23%
27.78	337.3	-3.02%

Table C.7: Drying Data – FC - 150 °C

Time [h]	Mass [g]	MC [%]
0.00	1000.0	65.25%
0.50	741.0	53.10%
1.00	491.5	29.30%
1.52	364.0	4.53%
2.02	344.0	-1.02%
2.53	340.2	-2.15%
3.10	337.1	-3.09%
6.27	328.3	-5.85%
18.75	312.5	-11.20%
22.47	300.2	-15.76%
25.92	299.5	-16.03%
29.38	298.0	-16.61%
30.42	297.0	-17.00%

Table C.8: Drying Data – FC - 200 °C

Appendix D

Python Tool Source Code

This appendix is used to present the entirety of the source code of the Python tool that was developed in this study.

```
1 import tkinter as tk
2 from tkinter import ttk, filedialog, messagebox
3 import numpy as np
4 import numpy_financial as npf
5 import CoolProp.CoolProp as cp
6 from CoolProp.HumidAirProp import HAPropsSI as psy
7 import os, sys
8
9 econ_metrics={}
10 orc_states = {}
11 ars_states = {}
12 ars_conc = {"X_strong": None, "X_weak": None}
13
14 try:
15     from PIL import Image, ImageTk
16     _HAS_PIL = True
17 except Exception:
18     _HAS_PIL = False
19
20
21 # -----
22 # Helper functions
23 # -----
24 def h_solution(X, T):
25     # LiBr solution enthalpy, J/kg, recieving X (mass fraction of LiBr) in kg/kg and T in K.
26     X = 100*X
27     T_C = T - 273.15
28     A = [-2024.33, 163.309, -4.88161, 0.0630295, -0.0002913705]
29     B = [18.2829, -1.1691757, 0.03248041, -0.0004034184, 0.0000018520569]
30     C = [-0.037008214, 0.0028877666, -0.000081313015, 0.00000099116628, -0.0000000044441207]
31     RA = A[0] + A[1]*X + A[2]*X**2 + A[3]*X**3 + A[4]*X**4
32     RB = B[0] + B[1]*X + B[2]*X**2 + B[3]*X**3 + B[4]*X**4
33     RC = C[0] + C[1]*X + C[2]*X**2 + C[3]*X**3 + C[4]*X**4
34     return 1000*(RA + T_C*RB + (T_C**2)*RC)
35
36 def calculate_Q_flue(T_flue_in_C, P_flue_kPa, Vflow_flue_m3ph,
37                     O2_mole_dry_perc, CO2_mole_dry_perc, humidity_mole_perc,
38                     T_flue_out_C):
39     # molar masses (g/mol)
40     mm_N2, mm_O2, mm_H2O, mm_CO2 = 28.0134, 31.9988, 18.0148, 44.011
41     # SI conversions
42     T_flue_in = T_flue_in_C + 273.15
43     T_flue_out = T_flue_out_C + 273.15
44     P_flue = P_flue_kPa * 1000.0
45     Vflow_flue = Vflow_flue_m3ph / 3600.0
46     # compositions
47     N2_mole_dry_perc = 100 - O2_mole_dry_perc - CO2_mole_dry_perc
```

```

48     dry_fraction = 1 - humidity_mole_perc / 100.0
49     O2_mole = O2_mole_dry_perc * dry_fraction / 100.0
50     CO2_mole = CO2_mole_dry_perc * dry_fraction / 100.0
51     N2_mole = N2_mole_dry_perc * dry_fraction / 100.0
52     H2O_mole = humidity_mole_perc / 100.0
53     # effective molar mass (g/mol)
54     mm_flue = O2_mole*mm_O2 + CO2_mole*mm_CO2 + N2_mole*mm_N2 + H2O_mole*mm_H2O
55     # mass fractions
56     O2_mf = O2_mole*mm_O2/mm_flue
57     CO2_mf = CO2_mole*mm_CO2/mm_flue
58     N2_mf = N2_mole*mm_N2/mm_flue
59     H2O_mf = H2O_mole*mm_H2O/mm_flue
60     # density and mass flow
61     rho = P_flue * (mm_flue/1000.0) / (8.314 * T_flue_in)
62     m_dot = rho * Vflow_flue # kg/s
63     # enthalpies (J/kg) at in/out (mass fraction-weighted pure-species enthalpies)
64     h_in = (cp.PropsSI("H", "P", P_flue, "T", T_flue_in, "O2") * O2_mf +
65             cp.PropsSI("H", "P", P_flue, "T", T_flue_in, "CO2") * CO2_mf +
66             cp.PropsSI("H", "P", P_flue, "T", T_flue_in, "H2O") * H2O_mf +
67             cp.PropsSI("H", "P", P_flue, "T", T_flue_in, "N2") * N2_mf)
68     h_out = (cp.PropsSI("H", "P", P_flue, "T", T_flue_out, "O2") * O2_mf +
69             cp.PropsSI("H", "P", P_flue, "T", T_flue_out, "CO2") * CO2_mf +
70             cp.PropsSI("H", "P", P_flue, "T", T_flue_out, "H2O") * H2O_mf +
71             cp.PropsSI("H", "P", P_flue, "T", T_flue_out, "N2") * N2_mf)
72     return m_dot * (h_in - h_out) # W
73
74 def _fmt_currency(x):
75     # € with thousands, no decimals
76     try:
77         if x is None or (isinstance(x, float) and np.isnan(x)):
78             return "--"
79         return f"{x:,.0f}"
80     except Exception:
81         return "--"
82
83 def _fmt_years(x):
84     try:
85         if x is None or (isinstance(x, float) and np.isnan(x)):
86             return "--"
87         if x == float('inf'):
88             return "∞"
89         return f"{x:,.1f}"
90     except Exception:
91         return "--"
92
93 def _fmt_pct(x):
94     try:
95         if x is None or (isinstance(x, float) and np.isnan(x)):
96             return "--"
97         return f"{x*100:.1f}%"
98     except Exception:
99         return "--"
100
101 def _fmt_T(TK):
102     # Treat None/NaN/0 (in your ARS code) as missing
103     try:
104         if TK is None or (isinstance(TK, float) and np.isnan(TK)) or TK <= 1.0:
105             return "--"
106         return f"{TK - 273.15:.2f}" # °C
107     except Exception:
108         return "--"
109
110 def _fmt_p(Pa):
111     try:
112         if Pa is None or (isinstance(Pa, float) and np.isnan(Pa)) or Pa <= 0:
113             return "--"
114         return f"{Pa/1e5:.3f}" # bar
115     except Exception:
116         return "--"

```

```

117
118 def _fmt_h(Jpkg):
119     try:
120         if Jpkg is None or (isinstance(Jpkg, float) and np.isnan(Jpkg)):
121             return "---"
122         return f"{Jpkg/1000.0:.2f}" # kJ/kg
123     except Exception:
124         return "---"
125
126
127 def show_compare_economic_metrics():
128     # Make sure we have something to show
129     if not econ_metrics:
130         messagebox.showinfo("Results Table",
131                             "No results available yet. Please run the calculation first.")
132     return
133
134     # Create popup
135     win = tk.Toplevel(root)
136     win.title("Results Table")
137     win.transient(root)
138     win.grab_set()
139
140     container = ttk.Frame(win, padding=10)
141     container.pack(fill="both", expand=True)
142
143     title_lbl = ttk.Label(container, text="NPV, PBP, and IRR by Scenario",
144                           font=("TkDefaultFont", 11, "bold"))
145     title_lbl.pack(anchor="w", pady=(0, 8))
146
147     # Table
148     cols = ("scenario", "npv", "pbp", "irr")
149     tree = ttk.Treeview(container, columns=cols, show="headings", height=6)
150     tree.heading("scenario", text="Scenario")
151     tree.heading("npv", text="NPV (€)")
152     tree.heading("pbp", text="PBP (years)")
153     tree.heading("irr", text="IRR (%)")
154
155     tree.column("scenario", width=140, anchor="w")
156     tree.column("npv", width=150, anchor="e")
157     tree.column("pbp", width=120, anchor="center")
158     tree.column("irr", width=120, anchor="center")
159
160     # Populate rows
161     order = ["ORC", "ARS", "Dryer"]
162     for key in order:
163         if key in econ_metrics:
164             m = econ_metrics[key]
165             tree.insert("", "end", values=(
166                 key,
167                 _fmt_currency(m.get("npv")),
168                 _fmt_years(m.get("pbp")),
169                 _fmt_pct(m.get("irr")),
170             ))
171
172     tree.pack(fill="both", expand=True)
173
174     # Close button
175     btns = ttk.Frame(container)
176     btns.pack(fill="x", pady=(8, 0))
177     ttk.Button(btns, text="Close", command=win.destroy).pack(side="right")
178
179 def _collect_metric_series(metric):
180     if not isinstance(metric, str):
181         return []
182     series = []
183     order = ["ORC", "ARS", "Dryer"]
184     for name in order:
185         if name in econ_metrics:

```

```

186         series.append((name, econ_metrics[name].get(metric)))
187     return series
188
189 def _open_bar_chart(metric, title, bar_color, value_formatter, value_transform=None,
190 ↪ unit_hint=""):
191     """
192     Draws a popup bar chart for a single metric across scenarios in econ_metrics.
193     - metric: "npv" | "pbp" | "irr"
194     - title: window title
195     - bar_color: e.g., "green", "red", "blue"
196     - value_formatter: function to format labels (_fmt_currency/_fmt_years/_fmt_pct)
197     - value_transform: optional func to transform numeric values for plotting
198                       (e.g., lambda v: v*100 for IRR so bars are in % units)
199     - unit_hint: small y-axis hint (e.g., "C", "years", "%")
200     """
201     if not econ_metrics:
202         messagebox.showinfo(title, "No results available yet. Please run the calculation
203 ↪ first.")
204         return
205
206     series = _collect_metric_series(metric)
207     if not series:
208         messagebox.showinfo(title, "No scenarios to plot. Enable at least one and run
209 ↪ calculations.")
210         return
211
212     # Transform values (if requested) for plotting height, keep originals for labels
213     plot_vals = []
214     for name, v in series:
215         if isinstance(v, (int, float)) and not np.isnan(v):
216             if value_transform:
217                 try:
218                     plot_vals.append((name, value_transform(v)))
219                 except Exception:
220                     plot_vals.append((name, None))
221             else:
222                 plot_vals.append((name, v))
223         else:
224             plot_vals.append((name, v)) # None/inf passes through
225
226     # Determine scale range (handle negative and positive)
227     finite_vals = [v for _, v in plot_vals if isinstance(v, (int, float)) and np.isfinite(v)]
228     if not finite_vals:
229         messagebox.showinfo(title, "All values are non-finite. Nothing to plot.")
230         return
231
232     max_pos = max([0.0] + [v for v in finite_vals if v > 0])
233     min_neg = min([0.0] + [v for v in finite_vals if v < 0])
234
235     # Canvas geometry
236     W, H = 720, 420
237     L, R, T, B = 70, 30, 40, 70 # margins
238     chart_h = H - T - B
239     chart_w = W - L - R
240
241     # Map value -> y pixel
242     span = (max_pos - min_neg) if (max_pos != 0 or min_neg != 0) else 1.0
243     # zero baseline y
244     if min_neg < 0 and max_pos > 0:
245         zero_y = T + (max_pos / span) * chart_h
246     elif max_pos > 0 and min_neg == 0:
247         zero_y = T + chart_h # zero at bottom
248     else:
249         zero_y = T # all negatives, zero at top; bars extend downward
250
251     def y_of(val):
252         if span == 0: return T + chart_h
253         return T + (max_pos - val) * (chart_h / span)

```



```

252     # Popup window
253     win = tk.Toplevel(root)
254     win.title(title)
255     win.transient(root)
256     win.grab_set()
257
258     top = ttk.Frame(win, padding=8)
259     top.pack(fill="both", expand=True)
260
261     ttk.Label(top, text=title, font=("TkDefaultFont", 11, "bold")).pack(anchor="w",
262     ↪ pady=(0,4))
263
264     canvas = tk.Canvas(top, width=W, height=H, highlightthickness=0)
265     canvas.pack(fill="both", expand=True)
266
267     # Axes
268     # Y axis
269     canvas.create_line(L, T, L, H - B) # y-axis
270     # X axis at zero baseline
271     canvas.create_line(L, zero_y, W - R, zero_y)
272
273     # Y ticks (5)
274     ticks = 5
275     for i in range(ticks + 1):
276         v = min_neg + i * (span / ticks)
277         y = y_of(v)
278         canvas.create_line(L - 5, y, L, y)
279         # Tick labels
280         if unit_hint == "%":
281             # show percentage-like tick (no transform for labels; display as raw transformed
282             ↪ units)
283             canvas.create_text(L - 8, y, text=f"{v:.0f}{unit_hint}", anchor="e")
284         elif unit_hint == "years":
285             canvas.create_text(L - 8, y, text=f"{v:.1f}", anchor="e")
286         elif unit_hint == "€":
287             # compact formatting for large € values
288             # use thousands/ millions suffix if helpful
289             if abs(v) >= 1_000_000:
290                 lab = f"{v/1_000_000:.1f}M"
291             elif abs(v) >= 1_000:
292                 lab = f"{v/1_000:.0f}k"
293             else:
294                 lab = f"{v:.0f}"
295             canvas.create_text(L - 8, y, text=lab, anchor="e")
296         else:
297             canvas.create_text(L - 8, y, text=f"{v:.2g}", anchor="e")
298
299     # X labels and bars
300     n = len(series)
301     if n == 0:
302         return
303     gap = chart_w / n
304     bar_w = gap * 0.55
305     left0 = L + gap * 0.225
306
307     for i, ((name, orig_val), (_, v)) in enumerate(zip(series, plot_vals)):
308         cx = left0 + i * gap + bar_w / 2
309         # Label
310         canvas.create_text(cx, H - B + 22, text=name, anchor="n")
311
312         # Skip if None
313         if v is None or (isinstance(v, float) and np.isnan(v)):
314             canvas.create_text(cx, H - B + 40, text="---", fill="gray40", anchor="n")
315             continue
316
317         # Handle inf (e.g., PBP = ∞)
318         if v == float('inf'):
319             # draw a small mark at top/bottom and label ∞
320             y_inf = T if min_neg < 0 else T # pin at top for simplicity

```

```

319         canvas.create_line(cx, zero_y, cx, y_inf, dash=(2, 2))
320         canvas.create_text(cx, T - 10, text="∞", fill="gray25", anchor="s")
321         continue
322
323     # Draw bar from zero_y to y_of(v)
324     yv = y_of(v)
325     x0 = cx - bar_w / 2
326     x1 = cx + bar_w / 2
327     # Determine rect coords respecting direction
328     y0 = min(zero_y, yv)
329     y1 = max(zero_y, yv)
330     # Avoid 0-height invisible rect
331     if abs(y1 - y0) < 1:
332         y1 = y0 + 1
333     canvas.create_rectangle(x0, y0, x1, y1, fill=bar_color, outline=bar_color)
334
335     # Value label (use original value for correct units/format)
336     label = value_formatter(orig_val)
337     # Place label just above bar for positive, below for negative
338     if v >= 0:
339         canvas.create_text(cx, y0 - 6, text=label, anchor="s")
340     else:
341         canvas.create_text(cx, y1 + 6, text=label, anchor="n")
342
343     # Axis unit hint
344     if unit_hint:
345         canvas.create_text(L, T - 12, text=f"Units: {unit_hint}", anchor="w", fill="gray35")
346
347     # Close button
348     btns = ttk.Frame(top)
349     btns.pack(fill="x", pady=(6, 0))
350     ttk.Button(btns, text="Close", command=win.destroy).pack(side="right")
351
352     def show_npv_graph():
353         _open_bar_chart(metric="npv",
354                         title="NPV by Scenario",
355                         bar_color="green",
356                         value_formatter=_fmt_currency,
357                         value_transform=None, # plot in € directly
358                         unit_hint="€")
359
360     def show_pbp_graph():
361         _open_bar_chart(metric="pbp",
362                         title="PBP by Scenario",
363                         bar_color="red",
364                         value_formatter=_fmt_years,
365                         value_transform=None, # years directly
366                         unit_hint="years")
367
368     def show_irr_graph():
369         _open_bar_chart(metric="irr",
370                         title="IRR by Scenario",
371                         bar_color="blue",
372                         value_formatter=_fmt_pct, # labels in %
373                         value_transform=lambda v: v*100, # plot in % heights
374                         unit_hint="%")
375
376     def show_states_window(title, states_dict, diagram_path, img_w=360, img_h=360,
377 ↪ img_col_weight=1, extra_info=None):
378         # Require prior run
379         if not states_dict:
380             messagebox.showinfo(title, "No states found. Please run the calculation first.")
381             return
382
383         win = tk.Toplevel(root)
384         win.title(title)
385         win.transient(root)
386         win.grab_set()

```

```

387 wrapper = ttk.Frame(win, padding=10)
388 wrapper.pack(fill="both", expand=True)
389 wrapper.columnconfigure(0, weight=1)
390 wrapper.columnconfigure(1, weight=img_col_weight)
391 wrapper.rowconfigure(0, weight=1)
392
393 # LEFT: table
394 table_frame = ttk.Frame(wrapper)
395 table_frame.grid(row=0, column=0, sticky="nsew", padx=(0,10))
396
397 if extra_info:
398     info_bar = ttk.Frame(table_frame)
399     info_bar.pack(fill="x", pady=(0,4))
400     # show as compact "badges"
401     for k, v in extra_info.items():
402         lbl = ttk.Label(info_bar, text=f"{k}: {v}",
403                         relief="groove", padding=(6,2))
404         lbl.pack(side="left", padx=(0,6))
405
406 ttk.Label(table_frame, text="Thermodynamic States",
407           font=("TkDefaultFont", 11, "bold")).pack(anchor="w", pady=(0,6))
408
409 cols = ("pt", "T_C", "p_bar", "h_kJkg")
410 tree = ttk.Treeview(table_frame, columns=cols, show="headings", height=16)
411 tree.heading("pt", text="Point"); tree.column("pt", width=60, anchor="center")
412 tree.heading("T_C", text="T (°C)"); tree.column("T_C", width=100, anchor="e")
413 tree.heading("p_bar", text="p (bar)"); tree.column("p_bar", width=100, anchor="e")
414 tree.heading("h_kJkg", text="h (kJ/kg)"); tree.column("h_kJkg", width=110, anchor="e")
415
416 for pt in sorted(states_dict.keys(), key=lambda x: (isinstance(x, str), x)):
417     st = states_dict.get(pt, {})
418     tree.insert("", "end", values=(pt, _fmt_T(st.get("T")), _fmt_p(st.get("p")),
419     ↪ _fmt_h(st.get("h"))))
420
421 ysb = ttk.Scrollbar(table_frame, orient="vertical", command=tree.yview)
422 tree.configure(yscrollcommand=ysb.set)
423 tree.pack(side="left", fill="both", expand=True); ysb.pack(side="right", fill="y")
424
425 # RIGHT: fixed diagram pane
426 img_frame = ttk.Frame(wrapper)
427 img_frame.grid(row=0, column=1, sticky="nsew")
428 ttk.Label(img_frame, text="Cycle Diagram",
429           font=("TkDefaultFont", 11, "bold")).pack(anchor="w", pady=(0,6))
430
431 canvas = tk.Canvas(img_frame, width=img_w, height=img_h, highlightthickness=1,
432 ↪ relief="solid")
433 canvas.pack(fill="both", expand=True)
434
435 # keep a reference to avoid GC
436 canvas._img_ref = None
437 canvas._img_path = diagram_path
438
439 def render_image(_evt=None):
440     path = canvas._img_path
441     if not os.path.exists(path):
442         canvas.delete("all")
443         canvas.create_text(10, 10, anchor="nw",
444             text=f"Diagram not found:\n{path}", fill="red")
445     return
446
447 try:
448     if _HAS_PIL:
449         im = Image.open(path)
450         c_w = max(100, canvas.winfo_width() or 360)
451         c_h = max(100, canvas.winfo_height() or 360)
452         im.thumbnail((c_w, c_h))
453         photo = ImageTk.PhotoImage(im)
454     else:
455         # PNG/GIF only without Pillow; no resize
456         photo = tk.PhotoImage(file=path)

```

```

454         canvas.delete("all")
455         canvas._img_ref = photo
456         w = canvas.winfo_width() or 360
457         h = canvas.winfo_height() or 360
458         canvas.create_image(w//2, h//2, image=photo)
459     except Exception as e:
460         canvas.delete("all")
461         canvas.create_text(10, 10, anchor="nw",
462             text=f"Error loading diagram:\n{e}", fill="red")
463
464     # Initial render + live resize (nice if Pillow is present)
465     canvas.bind("<Configure>", render_image)
466     render_image()
467
468     # Close
469     btn_row = ttk.Frame(img_frame); btn_row.pack(fill="x", pady=(6,0))
470     ttk.Button(btn_row, text="Close", command=win.destroy).pack(side="right")
471
472
473 def show_orc_technical():
474     if not orc_enabled.get():
475         messagebox.showinfo("ORC Analysis", "ORC is disabled.")
476         return
477
478     show_states_window("ORC Analysis", orc_states, ORC_DIAGRAM_PATH,
479         img_w=720, img_h=360, img_col_weight=2)
480
481
482 def show_ars_technical():
483     if not ars_enabled.get():
484         messagebox.showinfo("ARS Analysis", "ARS is disabled.")
485         return
486     xs = ars_conc.get("X_strong")
487     xw = ars_conc.get("X_weak")
488     xs_txt = f"{xs*100:.2f} %" if isinstance(xs, (int,float)) else "--"
489     xw_txt = f"{xw*100:.2f} %" if isinstance(xw, (int,float)) else "--"
490     show_states_window("ARS Analysis", ars_states, ARS_DIAGRAM_PATH, extra_info={
491         "Strong LiBr Concentration": xs_txt, "Weak LiBr Concentration": xw_txt})
492
493
494 def resource_path(*relative):
495     # return absolute path to a bundled resource
496     base = getattr(sys, "_MEIPASS", os.path.abspath("."))
497     return os.path.join(base, *relative)
498
499
500 ORC_DIAGRAM_PATH = resource_path("assets", "orc_diagram.png")
501 ARS_DIAGRAM_PATH = resource_path("assets", "ars_diagram.png")
502
503 # -----
504 # Tkinter base
505 # -----
506 root = tk.Tk()
507 root.title("Waste Heat Recovery Calculator")
508
509 # Canvas + vertical scrollbar
510 outer = tk.Frame(root)
511 outer.pack(fill="both", expand=True)
512 canvas = tk.Canvas(outer, highlightthickness=0)
513 vsb = ttk.Scrollbar(outer, orient="vertical", command=canvas.yview)
514 canvas.configure(yscrollcommand=vsb.set)
515 vsb.pack(side="right", fill="y")
516 canvas.pack(side="left", fill="both", expand=True)
517 content = tk.Frame(canvas)
518 content_id = canvas.create_window((0, 0), window=content, anchor="nw")
519
520 def _on_frame_configure(_e):
521     canvas.configure(scrollregion=canvas.bbox("all"))
522
523 def _on_canvas_configure(e):
524     canvas.itemconfig(content_id, width=e.width)

```

```

522
523 content.bind("<Configure>", _on_frame_configure)
524 canvas.bind("<Configure>", _on_canvas_configure)
525
526 # mouse wheel
527 def _on_mousewheel(event):
528     if event.delta:
529         canvas.yview_scroll(int(-1*(event.delta/120)), "units")
530     else:
531         if event.num == 4: canvas.yview_scroll(-3, "units")
532         elif event.num == 5: canvas.yview_scroll(3, "units")
533 canvas.bind_all("<MouseWheel>", _on_mousewheel)
534 canvas.bind_all("<Button-4>", _on_mousewheel)
535 canvas.bind_all("<Button-5>", _on_mousewheel)
536
537 # Introduction and quick guide
538 intro_text = ("This tool performs a techno-economic analysis of three waste heat recovery
539 ↪ scenarios:\n"
540             "an Organic Rankine Cycle (ORC) for power generation, an Absorption
541             ↪ Refrigeration System (ARS) for cooling, and a sludge drying system.\n"
542             "Please input the required values (highlighted), then adjust any technical
543             ↪ parameters as needed.\n"
544             "Click 'Run Calculation' to compute results. Use the buttons below to compare
545             ↪ economic metrics and view detailed technical analyses for the ORC and ARS
546             ↪ cycles.")
547
548 # Introductory label
549 intro_label = tk.Label(content, text=intro_text, justify="left", wraplength=760,
550 ↪ font=("TkDefaultFont", 11)) # family, size, style
551 intro_label.pack(fill="x", padx=8, pady=8)
552
553 # util
554 def add_row(frame, r, label, width=16, default=""):
555     font_style = ("TkDefaultFont", 10, "bold") if default == '' else ("TkDefaultFont", 10)
556     ttk.Label(frame, text=label, font=font_style).grid(row=r, column=0, sticky="e", padx=4,
557 ↪ pady=2)
558     e = ttk.Entry(frame, width=width)
559     if default != "": e.insert(0, default)
560     e.grid(row=r, column=1, sticky="w", padx=4, pady=2)
561     return e
562
563 def toggle_section(frame, var):
564     state = "normal" if var.get() else "disabled"
565     for w in frame.winfo_children():
566         try: w.configure(state=state)
567         except tk.TclError: pass
568
569 def toggle_override(est_var, capex_entry, opex_entry):
570     state = "normal" if est_var.get() else "disabled"
571     capex_entry.configure(state=state)
572     opex_entry.configure(state=state)
573
574 def warn_thermal_infeasibility(T_flue_in_C,
575                               orc_enabled, T_evap_orc_C, deg_superheat_C,
576                               ars_enabled, T_gen_ars_C,
577                               dt_enabled, T_air_in_C,
578                               parent=None):
579     issues = []
580     # ORC check
581     if orc_enabled and T_flue_in_C < (T_evap_orc_C + deg_superheat_C):
582         issues.append(f"ORC: Flue gas inlet temperature ({T_flue_in_C:.1f} °C) "
583 ↪ f"is below evaporator + superheat ({T_evap_orc_C + deg_superheat_C:.1f}
584 ↪ °C).")
585     # ARS check
586     if ars_enabled and T_flue_in_C < T_gen_ars_C:
587         issues.append(f"ARS: Flue gas inlet temperature ({T_flue_in_C:.1f} °C) "
588 ↪ f"is below generator temperature ({T_gen_ars_C:.1f} °C).")
589     # Dryer check
590     if dt_enabled and T_flue_in_C < T_air_in_C:
591         issues.append(f"Dryer: Flue gas inlet temperature ({T_flue_in_C:.1f} °C) "

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```

583         f"is below inlet air temperature ({T_air_in_C:.1f} °C).")
584
585     if issues:
586         from tkinter import messagebox
587         messagebox.showwarning(
588             "Potential infeasibility",
589             "One or more scenarios may be thermally infeasible:\n\n"
590             + "\n".join(". " + s for s in issues)
591             + "\n\nYou can proceed, but results may be unrealistic."
592         )
593     return False
594 return True
595
596 # -----
597 # Sections & inputs
598 # -----
599
600 # Flue Gas Inputs
601 flue_frame = ttk.LabelFrame(content, text="Flue Gas Inputs")
602 flue_frame.pack(fill="x", padx=8, pady=6)
603
604 T_flue_in_E = add_row(flue_frame, 0, "Flue Gas Inlet Temperature (°C):", default="")
605 Vflow_E = add_row(flue_frame, 1, "Flue Gas Flow Rate (m³/h):", default="")
606 O2_E = add_row(flue_frame, 2, "O₂ (dry basis) in flue gas (% vol):", default="")
607 CO2_E = add_row(flue_frame, 3, "CO₂ (dry basis) in flue gas (% vol):", default="")
608 humidity_E = add_row(flue_frame, 4, "Humidity in flue gas (% vol):", default="")
609 P_flue_E = add_row(flue_frame, 5, "Flue Gas Pressure (kPa):", default="101.325")
610 T_flue_out_E = add_row(flue_frame, 6, "Flue Gas Outlet Temperature (°C):", default="120")
611
612 # Enable/disable tech sections
613 ars_enabled = tk.BooleanVar(value=True)
614 orc_enabled = tk.BooleanVar(value=True)
615 dt_enabled = tk.BooleanVar(value=True)
616
617 # ORC Inputs
618 ttk.Checkbutton(content, text="Include ORC (Organic Rankine Cycle)",
619                 variable=orc_enabled).pack(anchor="w", padx=8)
620 orc_frame = ttk.LabelFrame(content, text="ORC Inputs")
621 orc_frame.pack(fill="x", padx=24, pady=(2, 6))
622
623 # ORC working fluids dropdown
624 ORC_FLUIDS = ["R245fa", "R123", "R1233zd(E)", "n-Pentane", "Toluene"]
625 ttk.Label(orc_frame, text="Working Fluid:").grid(row=0, column=0, sticky="e", padx=4, pady=2)
626 wf_var = tk.StringVar(value="R1233zd(E)")
627 wf_combo = ttk.Combobox(orc_frame, textvariable=wf_var, values=ORC_FLUIDS, state="readonly",
628                          ↪ width=18)
629 wf_combo.grid(row=0, column=1, sticky="w", padx=4, pady=2)
630
631 T_evap_orc_E = add_row(orc_frame, 1, "Evaporator Temperature (°C):", default="0")
632 T_cond_orc_E = add_row(orc_frame, 2, "Condenser Temperature (°C):", default="40")
633 deg_superheat_orc_E = add_row(orc_frame, 3, "Superheat Degrees (°C):", default="5")
634 eta_turb_E = add_row(orc_frame, 4, "Turbine Isentropic Efficiency (0-1):", default="0.8")
635 eta_pump_E = add_row(orc_frame, 5, "Pump Isentropic Efficiency (0-1):", default="0.75")
636 eta_gen_E = add_row(orc_frame, 6, "Generator Efficiency (0-1):", default="0.98")
637 life_orc_E = add_row(orc_frame, 7, "ORC System Lifetime (years):", default="20")
638
639 use_est_orc = tk.BooleanVar(value=False)
640 ttk.Checkbutton(orc_frame, text="Input CAPEX/OPEX data", variable=use_est_orc).grid(row=8,
641 ↪ column=0, columnspan=2, sticky="w", padx=4, pady=(6, 2))
642 orc_capex_E = add_row(orc_frame, 9, "ORC CAPEX (€):", default="")
643 orc_opex_E = add_row(orc_frame, 10, "ORC OPEX (€/year):", default="")
644 orc_capex_E.configure(state="disabled"); orc_opex_E.configure(state="disabled")
645
646 # ARS Inputs
647 ttk.Checkbutton(content, text="Include ARS (Absorption Refrigeration System)",
648                 variable=ars_enabled).pack(anchor="w", padx=8)
649 ars_frame = ttk.LabelFrame(content, text="ARS Inputs")
650 ars_frame.pack(fill="x", padx=24, pady=(2, 6))

```

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650
651 Q_cool_req_E = add_row(ars_frame, 0, "Required Cooling Capacity (kW):", default="")
652 cool_kWh_E = add_row(ars_frame, 1, "Cooling Electricity Consumption (MWh/year):",
    ↪ default="")
653
654 T_gen_ars_E = add_row(ars_frame, 2, "Generator Temperature (°C):", default="90")
655 T_abs_ars_E = add_row(ars_frame, 3, "Absorber Temperature (°C):", default="40")
656 T_cond_ars_E = add_row(ars_frame, 4, "Condenser Temperature (°C):", default="40")
657 T_evap_ars_E = add_row(ars_frame, 5, "Evaporator Temperature (°C):", default="7")
658 eff_SHX_E = add_row(ars_frame, 6, "Solution HX Efficiency (0-1):", default="0.7")
659
660 # ARS economic sizing inputs
661 life_ars_E = add_row(ars_frame, 7, "ARS System Lifetime (years):", default="25")
662
663 use_est_ars = tk.BooleanVar(value=False)
664 ttk.Checkbutton(ars_frame, text="Input CAPEX/OPEX data", variable=use_est_ars).grid(row=8,
    ↪ column=0, columnspan=2, sticky="w", padx=4, pady=(6,2))
665 ars_capex_E = add_row(ars_frame, 9, "ARS CAPEX (€):", default="")
666 ars_opex_E = add_row(ars_frame, 10, "ARS OPEX (€/year):", default="")
667 ars_capex_E.configure(state="disabled"); ars_opex_E.configure(state="disabled")
668
669 # Dryer Inputs
670 ttk.Checkbutton(content, text="Include Drying (Sludge Dryer)",
    ↪ variable=dt_enabled).pack(anchor="w", padx=8)
671 dt_frame = ttk.LabelFrame(content, text="Dryer Inputs")
672 dt_frame.pack(fill="x", padx=24, pady=(2,6))
673
674 ds_flow_E = add_row(dt_frame, 0, "Sludge Throughput (ton/day):", default="")
675 cost_wet_E = add_row(dt_frame, 1, "Wet Sludge Disposal Cost (€/ton):", default="")
676 val_dry_E = add_row(dt_frame, 2, "Dry Sludge Value (€/ton):", default="")
677 T_air_in_E = add_row(dt_frame, 3, "Inlet Air Temperature (°C):", default="200")
678 T_air_out_E = add_row(dt_frame, 4, "Outlet Air Temperature (°C):", default="80")
679 MC_in_dt_E = add_row(dt_frame, 5, "Sludge Inlet Moisture Content (%):", default="70") #cite
    ↪ chang2023
681 MC_out_dt_E = add_row(dt_frame, 6, "Sludge Outlet Moisture Content (%):", default="10")
682 T_air_E = add_row(dt_frame, 7, "Ambient Air Temperature (°C):", default="25")
683 T_sl_in_E = add_row(dt_frame, 8, "Sludge Inlet Temperature (°C):", default="25")
684 T_sl_out_E = add_row(dt_frame, 9, "Sludge Outlet Temperature (°C):", default="100")
685 RH_air_E = add_row(dt_frame, 10, "Ambient Air RH (%):", default="77")
686 Cp_ds_E = add_row(dt_frame, 11, "Dry Solid Specific Heat (kJ/kg·K):", default="0.83")
687 life_dt_E = add_row(dt_frame, 12, "Dryer System Lifetime (years):", default="15")
688
689 use_est_dt = tk.BooleanVar(value=False)
690 ttk.Checkbutton(dt_frame, text="Input CAPEX/OPEX data", variable=use_est_dt).grid(row=14,
    ↪ column=0, columnspan=2, sticky="w", padx=4, pady=(6,2))
691 dt_capex_E = add_row(dt_frame, 15, "Dryer CAPEX (€):", default="")
692 dt_opex_E = add_row(dt_frame, 16, "Dryer OPEX (€/year):", default="")
693 dt_capex_E.configure(state="disabled"); dt_opex_E.configure(state="disabled")
694
695 # Economic Inputs
696 econ_frame = ttk.LabelFrame(content, text="General Economic Inputs")
697 econ_frame.pack(fill="x", padx=8, pady=6)
698 yearly_h_E = add_row(econ_frame, 0, "Operating hours per year:", default="8700")
699 elec_cost_E = add_row(econ_frame, 1, "Electricity cost (€/kWh):", default="0.108")
700 discount_E = add_row(econ_frame, 2, "Discount rate (%):", default="8")
701 inflation_E = add_row(econ_frame, 3, "Interest rate (%):", default="2")
702
703 # Results
704 res_frame = ttk.LabelFrame(content, text="Results")
705 res_frame.pack(fill="x", padx=8, pady=(6,10))
706 result_text = tk.Text(res_frame, height=14, width=100, state="disabled")
707 result_text.pack(fill="x", padx=6, pady=6)
708
709 btn_row = ttk.Frame(content); btn_row.pack(fill="x", padx=8, pady=(0,10))
710 run_btn = ttk.Button(btn_row, text="Run Calculation")
711 run_btn.pack(side="left")
712
713 ttk.Button(btn_row, text="Results Table",
    ↪ command=show_compare_economic_metrics).pack(side="left", padx=8)
714

```

```

715
716 ttk.Button(btn_row, text="NPV Graph", command=show_npv_graph).pack(side="left", padx=8)
717 ttk.Button(btn_row, text="PBP Graph", command=show_pbp_graph).pack(side="left", padx=8)
718 ttk.Button(btn_row, text="IRR Graph", command=show_irr_graph).pack(side="left", padx=8)
719
720 ttk.Button(btn_row, text="ORC Analysis",
721             command=show_orc_technical).pack(side="left", padx=8)
722
723 ttk.Button(btn_row, text="ARS Analysis",
724             command=show_ars_technical).pack(side="left", padx=8)
725
726
727 def save_results():
728     txt = result_text.get("1.0", tk.END).strip()
729     if not txt:
730         messagebox.showinfo("Save Results", "No results to save yet.")
731         return
732     fpath = filedialog.asksaveasfilename(title="Save Results",
733                                         defaultextension=".txt",
734                                         filetypes=[("Text file", "*.txt"), ("All files", "*.*")])
735     if fpath:
736         with open(fpath, "w", encoding="utf-8") as f: f.write(txt)
737         messagebox.showinfo("Save Results", f"Saved to:\n{fpath}")
738     ttk.Button(btn_row, text="Save Results...", command=save_results).pack(side="left", padx=8)
739
740 # react to estimate checkboxes
741 def on_toggle_orc(*_):
742     toggle_override(use_est_orc, orc_capex_E, orc_opex_E)
743 def on_toggle_ars(*_):
744     toggle_override(use_est_ars, ars_capex_E, ars_opex_E)
745 def on_toggle_dt(*_):
746     toggle_override(use_est_dt, dt_capex_E, dt_opex_E)
747 use_est_orc.trace_add("write", on_toggle_orc)
748 use_est_ars.trace_add("write", on_toggle_ars)
749 use_est_dt.trace_add("write", on_toggle_dt)
750 on_toggle_orc(); on_toggle_ars(); on_toggle_dt()
751
752 def on_wf_change(_event=None): # Auto-change T_evap on wf change
753     fluid = wf_var.get()
754     if fluid == "R245fa":
755         T_evap_orc_E.delete(0, tk.END)
756         T_evap_orc_E.insert(0, "122")
757     elif fluid == "R123":
758         T_evap_orc_E.delete(0, tk.END)
759         T_evap_orc_E.insert(0, "125")
760     elif fluid == "R1233zd(E)":
761         T_evap_orc_E.delete(0, tk.END)
762         T_evap_orc_E.insert(0, "135")
763     elif fluid == "n-Pentane":
764         T_evap_orc_E.delete(0, tk.END)
765         T_evap_orc_E.insert(0, "161")
766     elif fluid == "Toluene":
767         T_evap_orc_E.delete(0, tk.END)
768         T_evap_orc_E.insert(0, "250")
769 wf_combo.bind("<<ComboboxSelected>>", on_wf_change)
770 on_wf_change()
771
772 # -----
773 # CORE: run calculations on click
774 # -----
775 def run_calculation():
776     try:
777         global econ_metrics, orc_states, ars_states, ars_conc
778
779         # Read flue inputs
780         T_in = float(T_flue_in_E.get())
781         Vflow = float(Vflow_E.get())
782         O2 = float(O2_E.get())
783         CO2 = float(CO2_E.get())

```



```

784     hum = float(humidity_E.get())
785     PkPa = float(P_flue_E.get())
786     T_out = float(T_flue_out_E.get())
787
788     Q_flue = calculate_Q_flue(T_in, PkPa, Vflow, O2, CO2, hum, T_out) # W
789     Q_flue_kW = Q_flue/1000.0
790
791     # Economic globals
792     yearly_h = float(yearly_h_E.get())
793     elec_cost = float(elec_cost_E.get())
794     discount = float(discount_E.get()) / 100
795     inflation = float(inflation_E.get()) / 100
796
797     # Prepare output & store states for future (not displayed)
798     outputs = [f"Available flue gas heat: {Q_flue_kW:.1f} kW"]
799
800     # --- Block for the warn_thermal_infeasibility function ---
801     if orc_enabled.get():
802         T_evap_C = float(T_evap_orc_E.get())
803         deg_superheat = float(deg_superheat_orc_E.get())
804     else:
805         T_evap_C = 0.0
806         deg_superheat = 0.0
807     if ars_enabled.get():
808         T_gen_ars_C = float(T_gen_ars_E.get())
809     else:
810         T_gen_ars_C = 0.0
811     if dt_enabled.get():
812         T_air_in_C = float(T_air_in_E.get())
813     else:
814         T_air_in_C = 0.0
815
816     warn_thermal_infeasibility(
817         T_flue_in_C=T_in,
818         orc_enabled=bool(orc_enabled.get()),
819         T_evap_orc_C=T_evap_C,
820         deg_superheat_C=deg_superheat,
821         ars_enabled=bool(ars_enabled.get()),
822         T_gen_ars_C=T_gen_ars_C,
823         dt_enabled=bool(dt_enabled.get()),
824         T_air_in_C=T_air_in_C,
825         parent=root
826     )
827
828     # -----
829     # ORC CALCULATION
830     # -----
831     P_out_kW = 0.0
832     LCOE = None
833     npv_orc = irr_orc = pbp_orc = None
834
835     if orc_enabled.get():
836         wf = wf_var.get()
837         T_evap_C = float(T_evap_orc_E.get())
838         T_cond_C = float(T_cond_orc_E.get())
839         deg_superheat = float(deg_superheat_orc_E.get())
840         eff_turb = float(eta_turb_E.get())
841         eff_pump = float(eta_pump_E.get())
842         eff_gen = float(eta_gen_E.get())
843
844         # Thermodynamic points, states 1..7
845         T1 = T_evap_C + 273.15 + deg_superheat
846         T3 = T_cond_C + 273.15
847         T4 = T_cond_C + 273.15
848         T6 = T_evap_C + 273.15
849         T7 = T6
850
851         p_low = cp.PropsSI('P', 'T', T3, 'Q', 0.5, wf)
852         p_high = cp.PropsSI('P', 'T', T6, 'Q', 0.5, wf)

```

```

853     p1 = p_high; p5 = p_high; p6 = p_high; p7 = p_high
854     p2 = p_low; p3 = p_low; p4 = p_low;
855
856     h1 = cp.PropsSI('H', 'T', T1, 'P', p1, wf)
857     s1 = cp.PropsSI('S', 'T', T1, 'P', p1, wf)
858     h2s = cp.PropsSI('H', 'P', p2, 'S', s1, wf)
859     h2 = h1 - eff_turb * (h1 - h2s)
860     h3 = cp.PropsSI('H', 'T', T3, 'Q', 1, wf)
861     h4 = cp.PropsSI('H', 'T', T4, 'Q', 0, wf)
862     s4 = cp.PropsSI('S', 'T', T4, 'Q', 0, wf)
863     h5s = cp.PropsSI('H', 'P', p5, 'S', s4, wf)
864     h5 = h4 + (h5s-h4)/max(eff_pump, 1e-9)
865     h6 = cp.PropsSI('H', 'T', T6, 'Q', 0, wf)
866     h7 = cp.PropsSI('H', 'T', T7, 'Q', 1, wf)
867
868     T2 = cp.PropsSI('T', 'P', p2, 'H', h2, wf)
869     T5 = cp.PropsSI('T', 'P', p5, 'H', h5, wf)
870
871     # Save states for future display
872     orc_states = {
873         1: {"T":T1, "p":p1, "h":h1}, 2: {"T":T2, "p":p2, "h":h2},
874         3: {"T":T3, "p":p3, "h":h3}, 4: {"T":T4, "p":p4, "h":h4},
875         5: {"T":T5, "p":p5, "h":h5}, 6: {"T":T6, "p":p6, "h":h6},
876         7: {"T":T7, "p":p7, "h":h7}
877     }
878
879     # Heat and work specific (J/kg)
880     q_in = h1 - h5
881     w_t = h1 - h2
882     w_p = h5 - h4
883     w_net = w_t - w_p
884
885     m_orc = Q_flue / max(q_in, 1e-9) # kg/s
886     P_out_kW = (m_orc * w_net * eff_gen) / 1000.0
887
888     # --- ORC economics ---
889     if not use_est_orc.get():
890         capex_orc = 28525.24163 * P_out_kW**(0.6662) if P_out_kW>0 else 0.0
891         opex_orc = 22.7 * P_out_kW + 2 * P_out_kW / 1000 * yearly_h
892     else:
893         capex_orc = float(orc_capex_E.get())
894         opex_orc = float(orc_opex_E.get())
895
896     # NPV/IRR/PBP/LCOE
897     costs_sum_orc=capex_orc
898     elec_total_orc=0
899     yearly_rev = yearly_h*P_out_kW*elec_cost
900     npv_orc = -capex_orc; cf=[-capex_orc]
901     for yr in range(1, int(life_orc_E.get())+1):
902         inflow = yearly_rev*((1+inflation)**yr)
903         outflow = opex_orc*((1+inflation)**yr)
904         costs_sum_orc += outflow/((1+discount)**yr)
905         elec_total_orc += yearly_h*P_out_kW/(1+discount)**yr
906         npv_orc += (inflow-outflow)/((1+discount)**yr)
907         cf.append(inflow-outflow)
908     LCOE= costs_sum_orc/elec_total_orc #C/kWh
909     pbp_orc = (capex_orc/(yearly_rev - opex_orc)) if yearly_rev>opex_orc else
910         ↪ float('inf')
911     irr_orc = npf.irr(cf)
912
913     # -----
914     # ARS CALCULATION
915     # -----
916     LCOC = None
917     npv_ars = irr_ars = pbp_ars = None
918     Q_E_ars_kW = 0.0
919     yearly_cooling_savings = 0.0
920

```

```

921     if ars_enabled.get():
922         ars_r = "Water"
923
924         T_g = float(T_gen_ars_E.get()) + 273.15
925         T_a = float(T_abs_ars_E.get()) + 273.15
926         T_c = float(T_cond_ars_E.get()) + 273.15
927         T_e = float(T_evap_ars_E.get()) + 273.15
928         eff_SHX = float(eff_SHX_E.get())
929         T5 = T_g + (T_a - T_g) * eff_SHX
930
931         p_h = cp.PropsSI('P', 'T', T_c, 'Q', 0.5, ars_r)
932         p_l = cp.PropsSI('P', 'T', T_e, 'Q', 0.5, ars_r)
933         X_weak = (T_g - 0.845*T_c + 35.6) / (0.538*T_c + 48.3)
934         X_strong = (T_a - 0.845*T_e + 35.6) / (0.538*T_e + 48.3)
935         ars_conc["X_strong"] = X_strong
936         ars_conc["X_weak"] = X_weak
937         CR = X_weak / (X_weak - X_strong)
938
939         # states/enthalpies
940         h10 = cp.PropsSI('H', 'T', T_e, 'Q', 1, ars_r)
941         h1 = h_solution(X_strong, T_a)
942         h2 = h_solution(X_strong, T_a)
943         h4 = h_solution(X_weak, T_g)
944         h5 = h_solution(X_weak, T5)
945         h7 = cp.PropsSI('H', 'T', T_g, 'P', p_h, ars_r)
946         h8 = cp.PropsSI('H', 'T', T_c, 'Q', 0, ars_r)
947         h9 = h8
948         h6 = h5
949         h3 = h2 + (h4 - h5) * (CR-1) / CR
950         T9 = cp.PropsSI('T', 'H', h9, 'P', p_l, ars_r)
951
952         err = 1
953         k = 0
954         T3 = T_a + (T_g - T_a) * eff_SHX #initial guess
955         while abs(err) > 1e-1:
956             T3 += err / 3000
957             h3_aux = h_solution(X_strong, T3)
958             err = h3 - h3_aux
959             k += 1
960             if k > 1000:
961                 print('ARS: max temperature loops reached on point 3')
962                 break
963
964         ars_states = {
965             1: {"T":T_a, "p":p_l, "h":h1},
966             2: {"T":T_a, "p":p_h, "h":h2},
967             3: {"T":T3, "p":p_h, "h":h3},
968             4: {"T":T_g, "p":p_h, "h":h4},
969             5: {"T":T5, "p":p_h, "h":h5},
970             6: {"T":T5, "p":p_l, "h":h6},
971             7: {"T":T_g, "p":p_h, "h":h7},
972             8: {"T":T_c, "p":p_h, "h":h8},
973             9: {"T":T9, "p":p_l, "h":h9},
974             10: {"T":T_e, "p":p_l, "h":h10}
975         }
976
977         # per-kg refrigerant energy terms
978         # choose Q_in_ars later based on requirement and flue heat
979         def ars_per_Qin(Q_in_ars):
980             # find refrigerant massflow that consumes Q_in_ars
981             m_r = Q_in_ars / (h7 + (CR-1)*h4 - CR*h3)
982             m_ss = CR*m_r
983             m_ws = m_ss - m_r
984             Q_E = m_r*(h10 - h9) # evaporator (cooling), W
985             Q_G = m_ws*h4 + m_r*h7 - m_ss*h3
986             return m_r, m_ss, m_ws, Q_E, Q_G
987
988         # Sizing to required cooling capacity:
989         Q_cool_req = float(Q_cool_req_E.get()) # kW

```

```

990
991 COP = (h10-h9)/((CR-1)*h4+h7-CR*h3) if ((CR-1)*h4+h7-CR*h3) != 0 else 0.0
992
993
994 # Heat required to meet cooling requirement:
995 Q_in_needed_W = (Q_cool_req*1000.0)/COP if COP>0 else np.inf
996 # ARS can only use up to available flue heat:
997 Q_in_ars_W = min(Q_in_needed_W, Q_flue)
998 m_r, m_ss, m_ws, Q_E, Q_G = ars_per_Qin(Q_in_ars_W)
999
1000 Q_E_ars_kW = Q_E/1000.0
1001
1002 # --- ARS economics ---
1003 if Q_in_needed_W <= Q_flue:
1004     yearly_cooling_savings = float(cool_kWh_E.get()) * 1000 * elec_cost
1005 else:
1006     yearly_cooling_savings = float(cool_kWh_E.get()) * 1000 * elec_cost *
1007     ↪ Q_flue/Q_in_needed_W
1008 if not use_est_ars.get():
1009     capex_ars = 11726 * (Q_E_ars_kW ** 0.648)
1010     if Q_in_needed_W <= Q_flue:
1011         opex_ars = 0.0433 * (Q_E_ars_kW ** 0.424) * (float(cool_kWh_E.get()) *
1012         ↪ 1000 * 3.5 / Q_E_ars_kW) # assumed COP = 3.5 (vapor compression)
1013     else:
1014         opex_ars = 0.0433 * (Q_E_ars_kW ** 0.424) * (float(cool_kWh_E.get()) *
1015         ↪ 1000 * 3.5 / Q_E_ars_kW) * Q_flue/Q_in_needed_W # assumed COP = 3.5
1016         ↪ (vapor compression)
1017 else:
1018     capex_ars = float(ars_capex_E.get())
1019     opex_ars = float(ars_opex_E.get())
1020
1021 # NPV/IRR/PBP
1022 costs_sum_ars=capex_ars
1023 cool_total_ars=0
1024 npv_ars = -capex_ars; cf=[-capex_ars]
1025 for yr in range(1, int(life_ars_E.get()+1):
1026     inflow = yearly_cooling_savings*((1+inflation)**yr)
1027     outflow = opex_ars*((1+inflation)**yr)
1028     costs_sum_ars += outflow/((1+discount)**yr)
1029     cool_total_ars += yearly_h*Q_E_ars_kW/(1+discount)**yr
1030     npv_ars += (inflow-outflow)/((1+discount)**yr)
1031     cf.append(inflow-outflow)
1032 LCOC= costs_sum_ars/cool_total_ars #C/kWhcool
1033 pbp_ars = (capex_ars/(yearly_cooling_savings - opex_ars)) if
1034     ↪ yearly_cooling_savings>opex_ars else float('inf')
1035 irr_ars = npf.irr(cf)
1036
1037 # -----
1038 # DRYER CALCULATION
1039 # -----
1040 npv_dt = irr_dt = pbp_dt = None
1041 if dt_enabled.get():
1042     MC_in_dt = float(MC_in_dt_E.get())
1043     MC_out_dt = float(MC_out_dt_E.get())
1044     sludgeflow_tonpday = float(ds_flow_E.get()) # kg_dry/s
1045     T_s_in = float(T_sl_in_E.get()) + 273.15
1046     T_s_out = float(T_sl_out_E.get()) + 273.15
1047     T_air_in = float(T_air_in_E.get()) + 273.15
1048     T_air_out = float(T_air_out_E.get()) + 273.15
1049     T_amb = float(T_air_E.get()) + 273.15
1050     RH_amb = float(RH_air_E.get())/100.0
1051     Cp_ds = float(Cp_ds_E.get())*1000.0 # J/kgK
1052     life_dt = int(life_dt_E.get())
1053     cost_wet = float(cost_wet_E.get())
1054     val_dry = float(val_dry_E.get())
1055     P_amb=101325; L=2260000.0; Cp_water=4184.0; Cp_vapor=1880.0; Cp_air=1005.0
1056
1057 # conversions
1058 X_in_dt = MC_in_dt/(100-MC_in_dt) #kg/kgds

```

```

1054     X_out_dt = MC_out_dt/(100-MC_out_dt) #kg/kgds
1055     ds_flow = sludgeflow_tonpday * (100-MC_in_dt) / 100 * 1000 / 86400 #kgds/s
1056
1057     # ambient humidity ratio
1058     W_air_in = psy('W','T',T_amb,'P',P_amb,'RH',RH_amb) #kg/kgda
1059
1060     # Energy balance
1061     h_sludge_in = (Cp_ds + Cp_water*X_in_dt)*T_s_in
1062     h_sludge_out = (Cp_ds + Cp_water*X_out_dt)*T_s_out
1063     h_air_in = (Cp_air + Cp_vapor*W_air_in)*T_air_in + W_air_in*L
1064
1065     W_air_out = (
1066         W_air_in/(X_in_dt - X_out_dt) + (h_air_in - Cp_air*T_air_out)/(h_sludge_out -
1067             ↪ h_sludge_in)
1068     ) / (
1069         1/(X_in_dt - X_out_dt) + (Cp_vapor*T_air_out + L)/(h_sludge_out -
1070             ↪ h_sludge_in)
1071     )
1072     air_massflow = ds_flow*(X_in_dt - X_out_dt)/(W_air_out - W_air_in)
1073     T_wb = psy('Twb','T',(T_air_in+T_air_out)/2,'P',P_amb,'W',(W_air_in+W_air_out)/2)
1074     Q_total_dt = 1.08*( ds_flow*(X_in_dt-X_out_dt)*(L + Cp_water*(T_wb - T_s_in) +
1075         ↪ Cp_vapor*(T_air_out - T_wb))
1076         + ds_flow*((X_out_dt*Cp_water)+Cp_ds)*(T_s_out - T_s_in) )
1077
1078     # If dryer needs more than available heat, scale down
1079     if Q_total_dt > Q_flue:
1080         scale = Q_flue/Q_total_dt
1081         ds_flow *= scale
1082         air_massflow *= scale
1083         Q_total_dt = Q_flue
1084
1085     # --- Dryer economics ---
1086     if not use_est_dt.get():
1087         capex_dt = 13450008* (ds_flow*(1+X_out_dt)) ** 0.694
1088         opex_dt = 0.02*capex_dt
1089     else:
1090         capex_dt = float(dt_capex_E.get())
1091         opex_dt = float(dt_opex_E.get())
1092
1093     yearly_dry_profit = ((ds_flow*(1+X_in_dt)/1000.0*cost_wet) +
1094         (ds_flow/1000.0*val_dry))*3600*yearly_h
1095
1096     # NPV/IRR/PBP
1097     npv_dt = -capex_dt
1098     cf = [-capex_dt]
1099     for i in range(1, life_dt+1):
1100         inflow = yearly_dry_profit*((1+inflation)**i)
1101         outflow = opex_dt*((1+inflation)**i)
1102         npv_dt += (inflow - outflow)/((1+discount)**i)
1103         cf.append(inflow - outflow)
1104     pbp_dt = (capex_dt/(yearly_dry_profit - opex_dt)) if yearly_dry_profit>opex_dt
1105     ↪ else float('inf')
1106     irr_dt = npf.irr(cf)
1107
1108     # -----
1109     # Build output
1110     # -----
1111
1112     # --- SAVE METRICS FOR THE POPUPS ---
1113     econ_metrics = {}
1114     if orc_enabled.get():
1115         econ_metrics["ORC"] = {
1116             "npv": npv_orc,
1117             "pbp": pbp_orc,
1118             "irr": irr_orc,
1119         }
1120     if ars_enabled.get():
1121         econ_metrics["ARS"] = {

```

```

1119         "npv": npv_ars,
1120         "pbp": pbp_ars,
1121         "irr": irr_ars,
1122     }
1123     if dt_enabled.get():
1124         econ_metrics["Dryer"] = {
1125             "npv": npv_dt,
1126             "pbp": pbp_dt,
1127             "irr": irr_dt,
1128         }
1129
1130     if orc_enabled.get():
1131         outputs.append("ORC:")
1132         outputs.append(f"    Net Power = {P_out_kW:.1f} kW")
1133         if LCOE is not None: outputs.append(f"    LCOE = {LCOE:.4f} €/kWh")
1134         if npv_orc is not None:
1135             outputs.append(f"    NPV = {npv_orc:,.0f} €, IRR = {irr_orc*100:.1f}%, PBP =
                ↳ {pbp_orc:.1f} years")
1136
1137     if ars_enabled.get():
1138         outputs.append("ARS:")
1139         outputs.append(f"    Cooling Output = {Q_E_ars_kW:.1f} kW (Required:
                ↳ {float(Q_cool_req_E.get()):.1f} kW)")
1140         if LCOC is not None: outputs.append(f"    LCOC = {LCOC:.4f} €/kWh_cooling")
1141         if npv_ars is not None:
1142             outputs.append(f"    NPV = {npv_ars:,.0f} €, IRR = {irr_ars*100:.1f}%, PBP =
                ↳ {pbp_ars:.1f} years")
1143
1144     if dt_enabled.get():
1145         outputs.append("Dryer:")
1146         outputs.append(f"    NPV = {npv_dt:,.0f} €, IRR = {irr_dt*100:.1f}%, PBP =
                ↳ {pbp_dt:.1f} years")
1147
1148     # Show results
1149     result_text.configure(state="normal")
1150     result_text.delete("1.0", tk.END)
1151     result_text.insert(tk.END, "\n".join(outputs))
1152     result_text.configure(state="disabled")
1153
1154     except Exception as e:
1155         result_text.configure(state="normal")
1156         result_text.delete("1.0", tk.END)
1157         result_text.insert(tk.END, f"Error: {e}")
1158         result_text.configure(state="disabled")
1159
1160     run_btn.configure(command=run_calculation)
1161
1162     # finalize
1163     root.minsize(800, 600)
1164     root.mainloop()

```