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Electrification and Compliance with the CSRD: Analysis of Sustainable Strategies in Electrical Engineering

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Resumo

A descarbonização dos processos térmicos no sector industrial está a tornar-se cada vez mais relevante à medida que as empresas enfrentam pressões regulamentares e de mercado para reduzir as emissões e cumprir a Diretiva relativa aos relatórios de sustentabilidade das empresas (CSRD). Neste contexto, a eletrificação tem surgido como uma estratégia viável, especialmente em linhas de produção que continuam a depender de combustíveis fósseis para o seu funcionamento. Esta dissertação centra-se na indústria da cortiça e investiga a substituição de equipamentos existentes a gás por alternativas eléctricas. O trabalho foi desenvolvido em estreita colaboração com a Corticeira Amorim e baseia-se em dados reais recolhidos em duas unidades industriais: Socori 2 e Discork. Utilizando uma combinação de análise energética, contabilização de emissões e modelação económica, o estudo avalia a viabilidade técnica, o potencial de poupança e o impacto ambiental de cada solução proposta. Os resultados demonstram que, quando corretamente integradas, as estratégias de eletrificação podem proporcionar ganhos ambientais mensuráveis sem comprometer o desempenho industrial, apoiando simultaneamente a conformidade com as normas emergentes em matéria de relatórios de sustentabilidade.

Palavras-chave: CSRD, Electrificação, Descarbonização, Térmica, Cortiça

Abstract

The decarbonisation of thermal processes in the industrial sector is becoming increasingly relevant as companies face regulatory and market pressure to reduce emissions and comply with the Corporate Sustainability Reporting Directive (CSRD). In this context, electrification has emerged as a viable strategy, especially in production lines that continue to rely on fossil fuels for their functioning. This dissertation focuses on the cork industry and investigates the replacement of existing gas-fired equipment with fully electric alternatives. The work was developed in close collaboration with Corticeira Amorim and is based on real data collected from two industrial units: Socori 2 and Discork. Using a combination of energy analysis, emissions accounting, and economic modelling, the study evaluates the technical feasibility, potential savings, and environmental impact of each proposed solution. The results demonstrate that, when properly integrated, electrification strategies can deliver measurable environmental gains without compromising industrial performance while supporting compliance with emerging sustainability reporting standards.

Keywords: CSRD, Electrification, Decarbonisation, Thermal, Cork

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework to achieve a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

In view of these defined objectives, this work focuses on some of them, namely:

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

SDG 12 Ensure sustainable consumption and production patterns

SDG 13 Take urgent action to combat climate change and its impacts

SDG	**Target**	**Contribution**	**Performance Indicators and Metrics**
9	9.4	Retrofitting industrial processes with electric technologies supports resource use efficiency and the adoption of clean technologies	CO_2 emission per unit of value added, also known as carbon intensity
12	12.6	Promoting sustainability reporting (CSRD compliance) encourages companies to adopt sustainable practices and integrate sustainability into their reporting cycle.	Number of companies publishing sustainability reports
13	13.2	Electrification aligns with climate policies by directly reducing Scope 1 emissions and indirectly Scope 2, supporting national GHG targets and CSRD compliance.	Total greenhouse gas emissions per year

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Miguel Ribeiro

"Sustainability is no longer about doing less harm. It's about doing more good."

Jochen Zeitz

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List of Acronyms

CAPEX	Capital Expenditures
CSRD	Corporate Sustainability Reporting Directive
EFRAG	European Financial Advisory Group
ESG	Environment, Social and Governance
ESRS	European Sustainability Reporting Standards
EU	European Union
GA	Grupo Amorim
GHG	Greenhouse Gas
HAG	Hot Air Generator
IHP	Industrial Heat Pump
LPG	Liquefied Petroleum Gas
NFRD	Non-Financial Reporting Directive
OPEX	Operational Expenditures
PLC	Programmable Logic Controller
PV	Photovoltaic
SDG	Sustainable Development Goals

Chapter 1

Introduction

1.1 Context

This work explores the intersection of sustainability in electrical engineering and compliance with the Corporate Sustainability Reporting Directive (CSRD), which aims to enhance transparency in environmental, sustainability and governance (ESG) issues throughout the European Union. The project focuses on the cork industry, a key sector in Portugal's economy, and the studies conducted are based on the processes adopted by the biggest cork producer in Portugal, Grupo Amorim. GA's activity is already highly decarbonised, since most of the thermal energy is produced first by resources endogenous to its own process (cork powder), then by external biomass (pellets, chips, pine cone bark, olive stones and others) and only then LPG and natural gas appear as fossil fuels, but with very little use in relation to the scale of energy consumption. By electrifying these processes and integrating renewable energy, this study aims to further improve energy efficiency, reduce operating costs and reduce environmental impact.

1.2 Motivation

Growing concerns about climate change and regulatory pressures are driving industries to adopt more sustainable practices. The CSRD emphasizes corporate responsibility and aligns with the EU's carbon neutrality goals. The cork industry, which is already highly sustainable through its use of cork powder and biomass as fuel, as well as renewable energy sources, has the potential to further demonstrate leadership in sustainability. Electrification of fossil fuel-consuming systems not only addresses emissions, but also increases energy efficiency, presenting an opportunity to align with global decarbonisation efforts and meet evolving regulatory requirements.

1.3 Objectives

The main objective of this dissertation is to explore and propose realistic strategies for the electrification of thermal processes in the cork industry, with a particular focus on reducing Scope 1 emissions and supporting alignment with the Corporate Sustainability Reporting Directive (CSRD). The work is developed in close collaboration with Corticeira Amorim and is centred on a set of real industrial use cases, allowing for a practical and realistic approach. This includes: evaluating the feasibility of electrification, understanding the impact these changes have on the Group's energy consumption, estimating operational costs, quantifying emissions reduction and presenting a solution that helps the company to follow the path towards a decarbonised industry.

By analysing different sites and production lines, this study aims to measure the potential benefits of each solution and assess how these interventions may contribute to the companys sustainability objectives. Beyond the technical and economic dimensions, the dissertation also reflects on how electrification can become a strategic tool to support CSRD compliance, decarbonisation goals and the ongoing transformation of industrial energy systems.

In attaining these objectives, the study will seek to contribute to the transition towards even more sustainable energy practices within the cork industry and others.

1.4 Problem definition

Although Corticeira Amorim already relies primarily on renewable energy sources, there are still several thermal processes that rely partially on fossil fuels such as natural gas and liquefied petroleum gas. These fuels are mainly used to support steam generation and hot air production in specific production lines, especially where biomass integration is technically or logistically limited. Despite representing a relatively small fraction of total energy consumption, these systems are responsible for a significant portion of the companys Scope 1 emissions and, therefore, present a clear opportunity for further decarbonisation. With the introduction of the CSRD and the growing pressure to quantify and reduce direct greenhouse gas emissions, the need to rethink these fossil fuel-based systems becomes increasingly relevant. However, any transition must be carefully analysed, not only from an environmental point of view, but also considering energy efficiency, economic viability, and operational compatibility with existing infrastructure. The challenge lies in identifying solutions that are technically feasible, economically justifiable and capable of delivering measurable improvements in sustainability performance, without compromising the reliability or continuity of the industrial processes.

1.5 Dissertation Structure

This dissertation is organised into six main chapters, each building upon the previous to construct a coherent analysis of the electrification potential within the industrial cork sector. In addition to the introduction, this dissertation contains 5 more chapters.

In Chapter 2, the current state of the art is reviewed, covering topics such as energy usage in industry, electrification technologies, regulatory context and sustainability reporting requirements, with a particular focus on the CSRD.

Chapter 3 describes the approach used to evaluate each scenario, including data collection methods and the criteria adopted for technical, economic and environmental analysis. In addition, the major limitations in these various fields are outlined, as far as the implementation of the electrification process is concerned.

Chapter 4 discusses in detail the technical feasibility, economic viability, environmental advantages, and integration challenges of electrification. This chapter provides insight into the actions that can be taken to electrify thermal systems in the cork industry.

Chapter 5 introduces the company that is being studied, Grupo Amorim, focusing on giving an industrial context, along with their strategy to develop into more sustainable practices. In this chapter, a description of its energy use and the impact that thermal processes have on cork production are also discussed to contextualize the selected case studies.

In Chapter 6, each case study is analysed individually, following the methodology stipulated in Chapter 3. The results are discussed in detail, with a breakdown of CAPEX and OPEX considerations, emissions reduction and alignment with sustainability goals.

Finally, the Conclusions chapter presents the main conclusions of the work and suggests future developments that may contribute to the wider decarbonisation of the industrial sector.

Chapter 2

Background and state-of-the-art

Industrial decarbonisation has emerged as a priority in the global effort to reduce greenhouse gas emissions and transition towards more sustainable energy systems. In this context, the electrification of thermal processes seems like a step in the correct direction, particularly when supported by low-carbon electricity sources. This chapter explores the current state of knowledge surrounding industrial electrification, focusing on technological options for generating thermal energy through electric systems, relevant policy and regulatory frameworks, and the practical challenges associated with implementing these solutions in existing industrial facilities. The discussion aims to establish a solid foundation for the case studies developed later in the dissertation, highlighting both the opportunities and limitations that shape the real-world application of electrification strategies in the cork industry and others.

2.1 Electrification and CSRD

The Corporate Sustainability Reporting Directive (CSRD) is an EU regulatory framework that sets very high ambitions in terms of disclosure of environmental, social, and governance (ESG) performance by companies. This directive expands the scope and transparency related to the Non-Financial Reporting Directive (NFRD) [7]. In order to comply with these regulations, industries need to carry out a complete review in terms of energy consumption and greenhouse gas emissions.

Electrification aligns perfectly with CSRD goals by providing measurable reductions in carbon footprint, one of the key metrics in ESG reporting [3]. Of course, electrified systems provide clarity to energy use and resulting emissions, making sustainability reports easier to compile. In addition, in transitioning to electric systems powered by renewables, cork manufacturers also demonstrate leadership in the use of clean energy technologies, and thus improve stakeholder and regulator perception. Electrified systems also improve data accuracy and traceability, both of which are critical in meeting the reporting and auditing standards set by the CSRD.

However, electrification and the replacement of carbon-intensive industrial processes with lower-carbon processes and technologies can also represent a financial risk. The climate transition may require large investments to align with carbon neutrality objectives [5].

Under the CSRD, companies are required to disclose detailed information on their greenhouse gas (GHG) emissions across three distinct scopes, as described in Figure 2.1. Scope 1 refers to direct emissions from sources that are owned or controlled by the company, such as fuel combustion in boilers or industrial equipment. Scope 2 covers indirect emissions associated with the generation of purchased electricity consumed by the company. These first two scopes are typically the most straightforward to quantify and manage. Scope 3, on the other hand, includes all other indirect emissions that occur throughout the value chain, such as those from the production of purchased materials, waste treatment, business travel, or product use [27, p. 28]. While Scope 3 often represents the largest share of total emissions, it is also the most complex to assess.

In the context of this dissertation, the focus is placed primarily on Scope 1 emissions. By electrifying operations that contribute to on-site fuel combustion, such as thermal processes currently reliant on fossil fuels, the company can eliminate one of its main sources of direct greenhouse gas emissions. However, the analysis also considers Scope 2 emissions, given the importance of electricity origin in determining the overall climate impact of electrification strategies.

As mentioned, another component in compliance with the CSRD are Scope 3 emissions, or value-chain-generated emissions. While the cork industry reduces its emissions through the electrification of thermal processes, it also makes the operations of downstream and upstream partners more sustainable. Surplus cork powder, previously used as fuel, for example, could be better channeled within the value chain for an even greater result in sustainability.

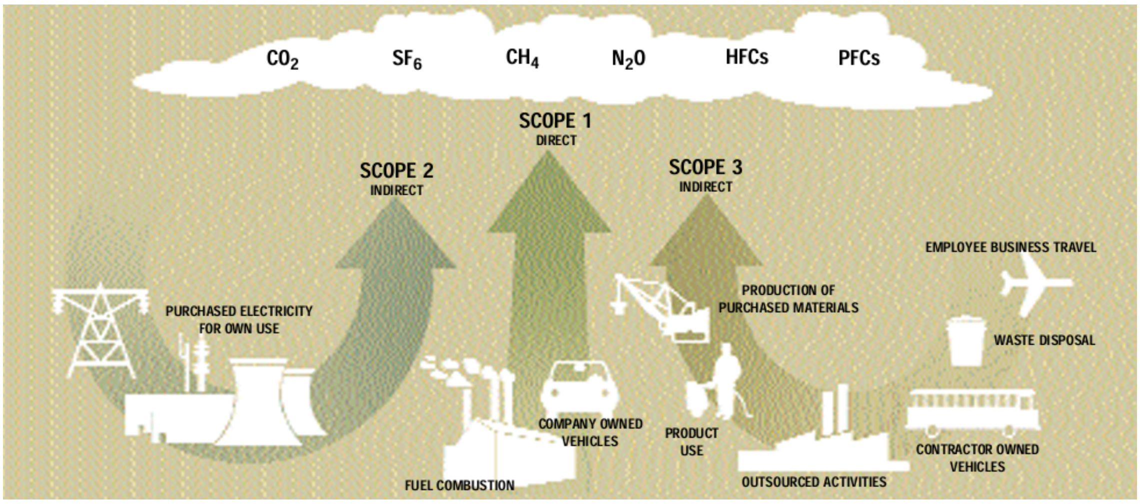

Figure 2.1: Overview of Scopes and Emissions Across a Value-Chain. Source: [27, p. 28]

CSRD Standards The CSRD is made up of standards that ensure a comprehensive approach to sustainability reporting. Developed by the European Financial Advisory Group (EFRAG), European Sustainability Reporting Standards (ESRS) consist of 12 standards divided into two categories: cross-cutting standards and topical standards. Cross-cuting standards (ESRS 1 and ESRS 2) define general reporting principles and fundamental CSRD concepts, while topical standards address Environmental, Social and Governance matters. The latter is composed of 10 standards that provide specific reporting requirements for these areas, and the main target of this work are the standards related to environmental issues.

Table 2.1: Summary of ESRS Standards

Category	**Standard**	**Focus / Key Elements**
Cross-Cutting	ESRS 1: General Requirements	Double materiality, due diligence, value chain, time horizons, sustainability statement structure
Cross-Cutting	ESRS 2: General Disclosures	Governance, strategy, business model, risks, targets, and metrics
Environmental (E1-E5)	ESRS E1: Climate Change	Climate impact, mitigation and adaptation strategies
Environmental (E1-E5)	ESRS E2: Pollution	Pollution sources, reduction measures
Environmental (E1-E5)	ESRS E3: Water & Marine Resources	Water use and protection of marine ecosystems
Environmental (E1-E5)	ESRS E4: Biodiversity & Ecosystems	Biodiversity conservation, restoration efforts
Environmental (E1-E5)	ESRS E5: Resource Use & Circular Economy	Resource efficiency, circular economy principles
Social (S1-S4)	ESRS S1: Own Workforce	Employment, diversity, inclusion, well-being
Social (S1-S4)	ESRS S2: Workers in Value Chain	Labour practices in supply chain
Social (S1-S4)	ESRS S3: Affected Communities	Local community impact
Social (S1-S4)	ESRS S4: Consumers and End-Users	Product safety, consumer rights, satisfaction
Governance (G1)	ESRS G1: Business Conduct	Business strategy, anti-corruption, whistleblower protection

In essence, electrification is not just a technological upgrade, but a strategic response to regulatory demands. It positions the cork industry to meet current expectations while future-proofing operations against evolving sustainability standards, and strengthens its competitive position in an increasingly low-carbon global market.

2.2 Electrification technologies

Electrification technologies are being used as a replacement for traditional thermal processes in the industry, drastically reducing the dependency on fossil fuels for electrical power. The implication of this is that each technology has something unique to offer and has certain specifics that suit different roles in the cork industry.

In this section we will look at some of these technologies and methods in more depth. These will form the basis of the measures adopted to reduce consumption in Corticeira Amorim's thermal processes.

2.2.1 Heat Pumps

Heat pumps utilize source heat to act as an economical means of providing cooling and heating. They are very resourceful, as instead of producing heat, heat is transferred from one source to another and this greatly reduces the amount of energy consumed [22]. In the case of the cork industry, heat pumps can be used to enhance the drying of the product in terms of evenness and accuracy without the high levels of emissions brought about by conventional heating systems. Moreover, heat pumps can also be used in combination with renewable energy sources, which makes them even more attractive for green applications.

Heat pumps are thermodynamic systems that transfer thermal energy from a lower-temperature source to a higher-temperature sink, using external work (typically in the form of electricity) to drive this transfer. The operation of a heat pump is based on the principles of the refrigeration cycle, more specifically a reversed Rankine cycle, and it can be applied for both heating and cooling purposes depending on the configuration and intended application.

At the core of a heat pump system is a closed-loop circuit through which a working fluid, known as the refrigerant, circulates. The cycle begins with the refrigerant in a low-pressure, low-temperature gaseous state, absorbing heat from a heat source (such as ambient air, groundwater, or industrial waste heat) in the evaporator. As the refrigerant evaporates, it draws thermal energy from the surrounding environment. This vapour is then compressed by a mechanical compressor, which significantly increases both its pressure and temperature.

Once compressed, the now high-energy refrigerant enters the condenser, where it releases the absorbed heat to the heat sink (typically water or air to be used in industrial processes or space heating). During this phase, the refrigerant condenses back into a liquid state as it transfers thermal energy to the desired medium. The cycle concludes with the refrigerant passing through an expansion valve, which reduces its pressure and temperature, allowing it to re-enter the evaporator and restart the cycle.

The performance of a heat pump is typically measured by its coefficient of performance (COP), which is defined as the ratio of useful thermal energy delivered to the amount of work input. For heating applications, COP values can range from 2 to 5 or higher, meaning the system can deliver several units of thermal energy for every unit of electrical energy consumed. This makes heat pumps particularly attractive for industrial applications, where they can replace fossil fuel-based heat generation with a more efficient and lower-emission alternative, especially when powered by renewable electricity.

The effectiveness of heat pumps is strongly influenced by the temperature lift required; this means, the difference between the heat source and heat sink temperatures. Industrial heat pumps are increasingly being developed to work in higher temperature ranges, sometimes reaching 160řC or more, making them suitable for medium-temperature processes such as drying, boiling or preheating in manufacturing sectors (including the cork industry). Their integration requires a careful assessment of process heat demands, operating temperatures and potential for heat recovery within the production cycle.

The importance of heat pumps for increasing efficiency and reducing emissions has been growing. The markets are constantly expanding, but in many countries the focus is essentially on the residential sector for regulating room temperature or distributing hot water.

Industrial heat pumps (IHP's), which are increasingly being used, use waste heat from the process as a heat source, promoting it to a higher temperature in such a way that it can be used elsewhere in the process, for heating or preheating. This technology has the advantage of significantly reducing fossil fuel consumption and greenhouse gas emissions, for example in drying, washing, evaporation, distillation, heating and cooling processes in industrial and commercial buildings. Industries that can benefit from implementing heat pumps include food and beverage processing, forestry products, textiles and chemicals [11, p. 88].

Implementing IHP's does, however, present some challenges, such as the lack of refrigerants in the desired temperature range, uncertainty about reliability on the part of potential users and difficulty in integration when having to adapt already existing systems [11, p. 88].

On the other hand, IHP's have very significant advantages when compared to heat pumps for space heating. These advantages include high coefficients of performance (COP), long operating life (sometimes exceeding 20 years) and simultaneous heat demand and waste heat production [11, p. 89].

2.2.1.1 Thermodynamic concepts

Heat pumps use external energy to perform work in order to transfer heat from the source to the destination.

As it can be seen in the image below 2.2, the waste heat source is at a lower thermal level than the level at which it will be used. To do this, work needs to be done to get the heat to a higher temperature so that it can be used elsewhere in the process.

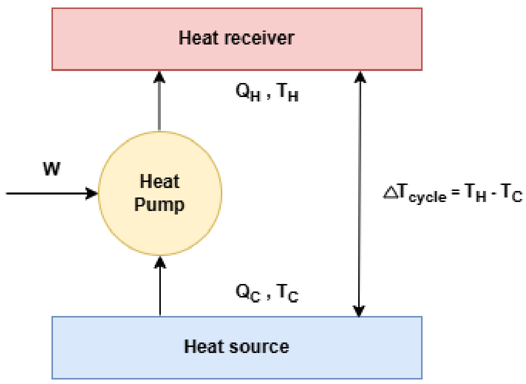

Figure 2.2: Transferring heat from a cold source to a hot source at the cost of work

According to the first law of thermodynamics, the heat transferred Q_H at temperature T_H is related to the heat extracted Q_C at temperature T_C and the work done W.

$$W_S = Q_H - Q_C \tag{2.1}$$

Compression heat pumps can achieve a COP of 6, or more depending on the temperature lift, meaning that 6 kWh of heat can be produced from 1 kWh of electrical energy from a compressor.

$$COP = \frac{Q_H}{W_S} = \frac{T_H}{T_H - T_C} \tag{2.2}$$

There are four main thermodynamic processes for an industrial heat pump: mechanical compression cycle, thermal compression cycle, mechanical vapor recompression (MVR) and thermal vapor recompression (TVR).

2.2.1.2 Mechanical compression cycle

Compression heat pumps can use four different types of compressor: scroll, piston, screw-rotary and centrifugal.

The choice of compressor type is related to the amount of final heat needed. The scroll compressor is used for an output of up to 100 kW, the piston compressor up to 500 kW, the rotary screw compressor up to 5 MW and the centrifugal compressor used in large systems above 2 MW [11, p. 90].

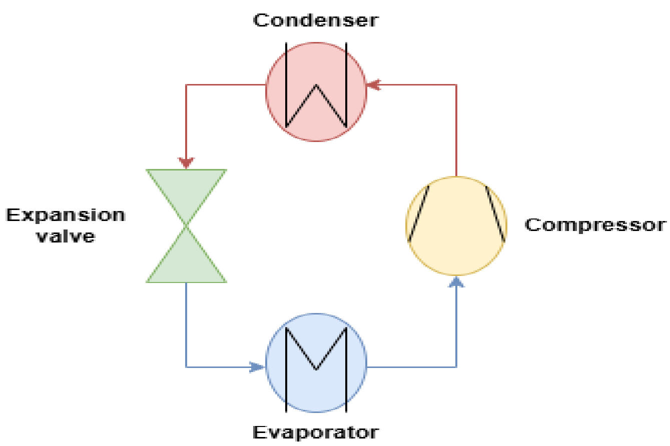

Figure 2.3: Closed mechanical compression cycle

2.2.1.3 Thermal compression cycle

While a mechanical heat pump uses electricity, an absorption heat pump uses thermal energy, as illustrated in Figure 2.4, which can be obtained through steam or the combustion of natural gas. This type of heat pump becomes economically attractive when there is a source of cheap thermal energy at temperatures of 100 C to 200 C, such as geothermal energy, solar energy or surplus heat from cogeneration processes or steam plants. There are two key principles: absorption and evaporation of the refrigerant. It is common to use the Water (absorbent medium) - Ammonia (refrigerant) system [11, p. 91].

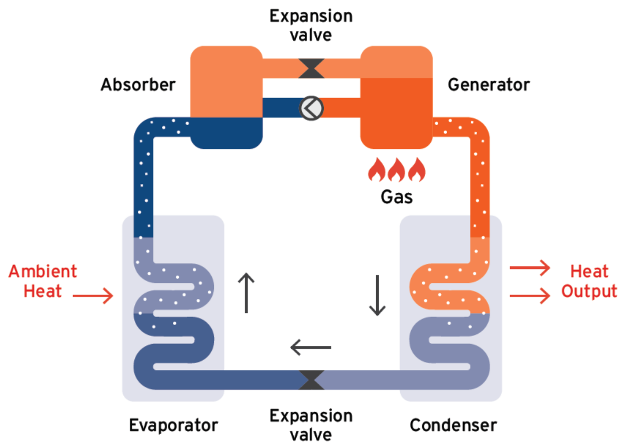

Figure 2.4: Absorption heat pump. Source: [24]

Thermal energy is supplied to the desorber, which causes the refrigerant to evaporate from the absorbing medium. In turn, the absorbent medium is directed to the absorber via a valve. The absorption of the gaseous refrigerant takes place in the absorber, causing heat to be released. The mixture is redirected to the desorber via a pump. In order to increase efficiency, the cold mixture is preheated with the hot mixture.

Due to the use of thermal energy to separate the two components, the gaseous refrigerant enters the condenser. After condensation, heat is released and the liquid refrigerant goes to an expansion valve before entering the evaporator. With the supply of heat, the refrigerant evaporates and goes to the absorber.

There are also absorption-compression heat pumps, Figure 2.5. This type of technology encompasses both absorption and compression processes. The following image shows a simplified diagram of hybrid absorption-compression technology:

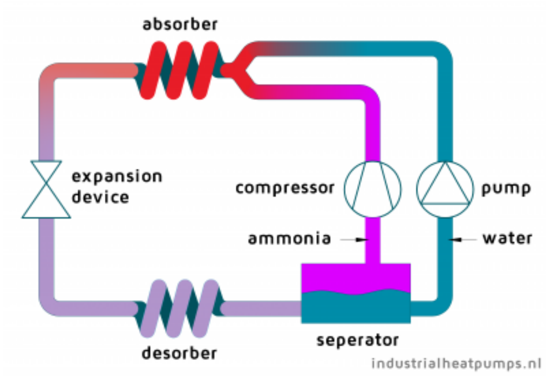

Figure 2.5: Absorption-compression cycle. Source: [14]

The difference between the hybrid cycle and the absorption cycle is that in the hybrid process absorption occurs at high pressure and temperature, and desorption occurs at low pressure and temperature.

2.2.1.4 Mechanical vapor recompression

In this type of technology, low-pressure steam from industrial processes (boilers or evaporators) is compressed and condensed, generating heat at a higher temperature, which can replace an external energy source.

If the vapor is contaminated, an intermediate heat exchanger (boiler) is required. In this case, the system is said to be semi-open. The COP for mechanical vapor recompression plants is between 10 and 30 [11, p. 93]. Mechanical recompression is used in distillation, evaporation and drying operations and to produce steam for a steam distribution network.

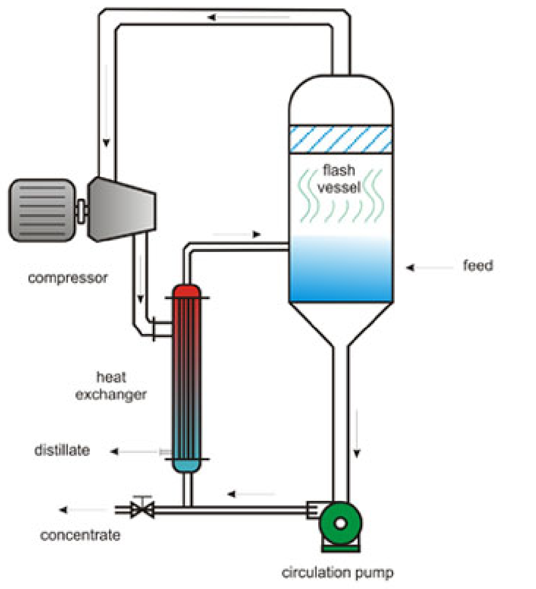

Figure 2.6: Mechanical vapor recompression. Source: [1]

2.2.1.5 Thermal vapor recompression

In this type of technology, the vapor is compressed in an ejector and, unlike mechanical recompression, there is no need to use mechanical energy. It can be used in numerous applications where there is a significant difference between fuel and electricity prices. Like mechanical recompression, it can also be used in evaporation units.

2.2.2 Electric Resistors

Electric resistors are one of the simplest ways of generating heat from electricity. They work on the basis of the Joule effect: when electric current passes through a wire or other conductive material, this material heats up and this thermal energy can then be used directly in the process. This energy can be described by the following equation:

$$E = I^2Rt \quad [\text{J}] \tag{2.3}$$

where E represents the thermal energy released, I the current, R the resistance of the conductor and t the conduction time. This relationship shows how even small variations in current can have a significant impact on the amount of heat generated, which helps explain the efficiency and simplicity of these systems.

It is a direct system with few losses, which is why it is still widely used in industry, especially when precise or local heating is required [6].

In industry, resistors are found in ovens, electric boilers, water heating tanks and even drying systems. They are easy to install, require no major maintenance and, as there is no combustion, there are no local emissions. This can be an important advantage for companies that want to reduce their environmental impact in a relatively simple way.

However, it is not all upside. As the heat is generated directly, there is no utilisation of waste heat or energy recovery, which means that they are less efficient than technologies such as heat pumps. Even so, for processes that do not require very high temperatures and where temperature control and system simplicity are valued, resistors remain a practical and valid solution.

In the case of the cork industry, resistors are especially ideal for smaller operations or those needing steady, high-temperature outputs, such as the agglutination processes used in cork production [21]. They are a straightforward way of replacing fossil fuel systems, and their application can be phased in, which also facilitates industrial adaptation.

2.2.3 Inductive Heating

Inductive heating is a technology that has gained ground in industry, mainly because it is very efficient and allows materials to be heated quickly and precisely [2], without direct contact and without the need for traditional heating elements. The principle is based on the creation of an alternating magnetic field generated by a coil connected to a high-frequency electric current. When a conductive material is placed within this field, electric currents are induced inside it (called Focault currents) which generate heat directly in the material itself due to its electrical resistance.

This phenomenon can be explained by Faraday's law of electromagnetic induction, which states that the voltage induced in a coil is proportional to the variation in magnetic flux:

$$\mathscr{E} = -\frac{d\Phi_B}{dt} \tag{2.4}$$

where $\mathscr{E}$ represents the induced electromotive force and Φ_B is the magnetic flux passing through the coil. The variation of the magnetic field at high frequency induces voltages that cause current to circulate inside the material, resulting in heating due to the Joule effect.

This form of heating is quite different from electric resistors or heat pumps because it does not depend on heat conduction or convection: heat is generated directly inside the part or the conductive fluid. This has some important advantages, such as the fact that very high temperatures can be reached in a short space of time, with great precision in temperature control and the exact location of the heating [10]. In addition, since there is no physical contact with the material to be heated, induction systems tend to degrade less and require less maintenance.

In the case of cork industry, although the direct use of this technology is not yet common, there is potential in processes such as the agglutination of granules or the heating of metal molds on production lines, where localised and controlled heat can be an asset.

2.2.4 Capacitive Heating

Capacitive heating, also known as dielectric heating, is based on applying an alternating electric field to dielectric materials, i.e. electrical insulators such as wood, paper or even cork. This type of heating works by the vibration of the material's polar molecules when exposed to a variable electric field. This vibration generates internal friction, which results in heating [9].

Unlike methods such as induction, the heat here is not generated by electric currents within the material, but by the molecular response to the electric field. It is an especially useful technology for materials that are poor electrical conductors but good insulators, including many natural and composite materials. One of the advantages of capacitive heating is the ability to uniformly heat large volumes of material, even inside it, which is not always the case with resistors or infrared radiation, for example [25].

The power dissipated in this process can be described by:

$$P = 2\pi f \varepsilon_r \varepsilon_0 \tan\delta \cdot E^2 \cdot V \tag{2.5}$$

where P is the dissipated power (W), f the frequency of the electric field (Hz), ε_r the relative permittivity of the material, ε_0 the vacuum permittivity, $\tan\delta$ the dielectric loss factor, E the electric field strength (V/m), and V the volume of the exposed material.

Although still underexplored in the cork industry, it could present a new approach to achieve energy efficiency. The capacitive method has potential, for example, in the heating of agglomerate blocks or in specific drying stages, where volumetric and uniform heating is required, without contact with resistors or hot surfaces.

Comparative Overview After analysing the different electrification technologies - heat pumps, electric resistors, inductive and capacitive heating - it is possible to see that each one has its own characteristics and most suitable applications. Heat pumps stand out for their overall efficiency, especially for heating water or air at moderate temperatures. Electric resistors, on the other hand, are ideal for simple applications requiring precise control, but are less advantageous in processes with large thermal volumes. Induction is effective for rapid, localised heating of metals, and the capacitive method is promising for insulating materials, with potential applications in drying.

These technologies not only reduce the reliance on fossil fuels, but also facilitate a greater integration of renewable energy into industrial operations. Selecting the most appropriate technology for each thermal process will require a careful evaluation of operational requirements, energy costs, and environmental impacts.

Table 2.2: Comparison of Electrification Technologies for Industrial Heating

Technology	**Efficiency**	**Typical Applications**	**Advantages**	**Limitations**
Heat Pumps	High (COP 2–5)	Water or air heating up to ~160C	High efficiency, good for moderate temperatures, renewable integration	Less suitable for high-temperature direct process heat
Electric Resistors	Moderate (close to 100%)	Water tanks, small boilers, dryers	Simple, precise temperature control, low maintenance	Higher operational cost, no heat recovery
Induction Heating	Very high (localized)	Metal heating, molds, food industry	Rapid, contactless heating, accurate	Limited to conductive materials, high-frequency systems required
Capacitive Heating	Moderate to high (volumetric)	Drying of non-conductive materials, wood, composites	Uniform internal heating, non-contact, efficient for insulators	Not suitable for metals, requires specific material properties

2.3 Real applications in industrial environments

Electrification of industrial processes is one of the key strategies toward energy efficiency and carbon emission reduction. There have been important advances in the cork industry, notably the use of by-products from this industry, like cork powder, as biomass for the production of process heat. This minimizes waste and reduces the reliance on fossil fuels, thus reducing the carbon footprint [18].

A close look at the Portuguese cork industry indicates that significant amounts of cork powder are used for process heat to provide a large share of the energy demand of the sector. This approach illustrates that internal biomass resources can be used effectively to meet energy needs [18].

Besides the cork industry, electrification strategies have already been applied to other industries. For example, one Danish pectin production plant studied full electrification of its processes, including heat pumps and mechanical vapor re-compression. The study showed a considerable reduction in energy consumption and greenhouse gas (GHG) emissions, therefore representing a potential benefit that electric-driven technologies could provide to industries [16].

In the chemical industry, the electrification of processes has been investigated as an alternative to conventional thermal power sources. Research indicates that incorporating electrical energy can improve energy efficiency and reduce carbon footprints, particularly when replacing fossil fuel-based systems with electric alternatives such as heat pumps and electric heating methods [17].

These few examples give an idea of the potential benefits that electrification of industrial processes could also bring for the cork industry: higher energy efficiency, lower GHG emissions, and alignment with international goals related to sustainability.

2.4 Conclusions

This chapter compares practical routes to decarbonise thermal demand in the cork industry. Electric boilers offer a low-risk, direct replacement for steam, with predictable efficiency and control, at the expense of higher electricity costs unless paired with PV. Heat pumps are compelling where processes run at medium temperatures ($\leq$ 70–90 C) and with steady duty cycles; high-temperature units ($\approx$ 100–120 C) are promising but less proven for continuous industrial loads. Direct electric heating (resistive/induction) suits fast response and point-of-use heating but requires careful integration to avoid peak demand penalties. Overall, the evidence supports a portfolio approach: prioritise heat pumps where temperatures allow, deploy electric boilers for steam or higher set-points, and leverage PV self-consumption and control strategies to keep OPEX and emissions competitive.

Chapter 3

Methodology

3.1 Data Collection

This study aims to evaluate the feasibility and impact of electrifying thermal processes in the cork industry, focusing on three main pillars: energy efficiency, environmental impact, and economic viability. To address these, both quantitative and qualitative data were collected and analysed.

Quantitative performance indicators On the quantitative side, energy consumption figures, emission indicators, and cost-related metrics were used to compare the current fossil fuel-based systems with the proposed electrified alternatives. Data regarding annual energy use and equivalent CO_2 emissions were obtained from Grupo Amorims internal reports and sustainability publications [5], e+Monitor and Power BI.

Payback periods, operational cost savings and emission reductions were calculated to provide a practical view of each interventions viability. Although some simplifications were necessary, such as using annual averages instead of hourly energy profiles, the methodology aims to strike a balance between analytical consistency and the constraints of real-world data availability.

e+Monitor Developed by EWEN, the e+Monitor platform allows access to high-resolution, real-time data regarding energy consumption in production units. In particular, it enables detailed tracking of electricity, fuel, steam, pressure, and flow rates for thermal equipment. This level of detail helped identify typical energy consumption patterns, peak loads, and process-specific energy profiles, which were essential to estimate the potential impact of electrification in existing systems.

Power BI Power BI used primarily as a visualization and data analysis tool, enables the integration of information from different sources, including spreadsheets, energy reports, and field data, to generate comparative dashboards and facilitate trend analysis. It also helps calculating aggregated energy metrics, such as total annual consumption or cost variation over time, supporting the economic modelling carried out later in the study.

Both tools are essential to bridge the gap between the raw operational data and the analytical structure of the project. They not only improve the accuracy of quantitative input but also provide contextual clarity to qualitative interpretations.

GHG emissions Greenhouse gas estimates were aligned with the definitions of Scope 1 and Scope 2 under the Corporate Sustainability Reporting Directive (CSRD) [8] and fuel consumption data (in mş of natural gas or kg of LPG) was converted into energy using standard calorific values and then into CO_2 emissions using official emission factors. All conversions followed national and EU reference values, as well as conversion factors established by Grupo Amorim itself.

CAPEX and OPEX CAPEX and OPEX estimates for the proposed electric technologies were based on manufacturer quotes, technical datasheets, and existing studies on industrial electrification [4]. When precise financial data were unavailable, assumptions were made based on benchmark values from similar industrial applications.

Qualitative data Qualitative inputs were used to support and contextualize the numerical analysis. These included case studies of electrification in other sectors, such as the food and chemical industries [15], as well as regulatory guidance and informal interviews with technical experts from Grupo Amorim. These sources helped validate technical assumptions and identify potential barriers to implementation.

By combining different types of sources and indicators, this approach provides a robust and well-rounded foundation for evaluating the electrification potential of key thermal processes in the cork industry.

3.2 Cost-benefit Analysis

The electrification of thermal processes in the cork industry involves evaluating capital expenditures (CAPEX) on technologies such as heat pumps and electric steam boilers, while operational expenditures (OPEX) include electricity costs, maintenance, and eventual system optimizations. This transition not only reduces direct greenhouse gas emissions, but also increases energy efficiency and eliminates combustion-related pollutants, particularly when electricity is sourced from renewable systems [26].

From a financial point of view, electric systems tend to have lower ongoing maintenance costs (with reductions of up to 50% when compared to fossil fuel systems) and allow for more precise temperature control, which can contribute to better process stability and product quality [23]. These advantages align directly with the sustainability and efficiency goals outlined in Corticeira Amorims 2024 Sustainability Report, especially regarding the reduction of emissions and the integration of clean energy, in line with the CSRD regulatory framework [5].

The cost-benefit analysis in this study is based on the estimation of energy savings, improvements in operational efficiency, and potential reductions in CO_2 emissions over time. The payback period, calculated as the time needed for energy cost savings to cover the initial investment, was used as a key indicator of economic feasibility. Although the exact payback depends on electricity prices, system efficiency, and possible government incentives or carbon pricing, typical scenarios for industrial-scale applications point to ranges between 5 and 10 years. These values are consistent with case studies from other sectors that have undergone similar transitions.

Additionally, while the direct financial impact remains a critical driver, the analysis also considers intangible benefits, such as reduced regulatory risk, improved environmental image, and long-term alignment with European decarbonisation strategies. In this sense, electrification emerges not only as a technical solution, but also as a strategic investment that supports both the economic and environmental ambitions of the cork industry.

Table 3.1: Main Economic Variables Used in the Cost-Benefit Analysis

Variable	**Description**
CAPEX	Initial investment cost of the electrification equipment (EUR)
OPEX	Annual operational cost, including electricity and maintenance (EUR/year)
Energy Cost	Unit price of electricity or fuel (EUR/kWh)
Efficiency Gain	Percentage improvement in energy conversion efficiency
CO_2 Reduction	Annual reduction in greenhouse gas emissions (kg equivalent CO_2)
Payback Period	Time required to recover the initial investment (years)
Incentives/Subsidies	Public or private support reducing CAPEX or OPEX

3.3 Limitations

The cork industry faces a series of structural, economic, and technical limitations when it comes to the electrification of thermal processes. Despite growing pressure to decarbonize operations, transitioning from fossil fuel-based systems to electric systems still presents several practical obstacles that must be acknowledged within this study.

Technical From a technical perspective, one of the most pressing challenges is the high energy intensity of certain thermal processes, such as steam generation and high-temperature drying. These processes often operate continuously and at significant power levels, placing considerable stress on existing electrical infrastructure. In many industrial facilities, the current grid connection or transformer capacity is insufficient to support full electrification without costly upgrades. In addition, the intermittent nature of renewable energy sources introduces further uncertainty in the reliability of supply, especially in operations that require thermal stability and consistency throughout the production cycle [23, 26].

Economical On the economic front, electric systems often require higher upfront investment than their fossil-fuel counterparts. Although operating costs may decrease over time, the initial CAPEX can be a major barrier, particularly for small to medium-sized companies operating with narrow profit margins. This can make electrification financially unviable without access to subsidies, incentive programs, or favorable financing models [5]. Additionally, electricity prices are subject to greater volatility than fossil fuels in some regions, making long-term planning and risk assessment difficult.

Regulatory Regulatory limitations also play a significant role. While the Corporate Sustainability Reporting Directive (CSRD) sets a clear path for environmental transparency and carbon reduction, the lack of harmonized implementation across EU member states can lead to uncertainty. Different interpretations, timelines, and enforcement strategies complicate the planning of long-term decarbonisation projects and may discourage early adoption [8].

Operational Another relevant barrier is related to workforce readiness. Although electrified systems require less maintenance, they often use more advanced control systems and digital interfaces. However, there is currently a shortage of specialized technicians and electricians trained in these technologies, which could delay or complicate implementation. Preparing the current workforce or recruiting qualified professionals adds another layer of cost and logistical complexity to electrification efforts.

Analytical Finally, it is important to acknowledge limitations in the scope of this study itself. The analysis relies in part on estimated values and general assumptions regarding energy prices, emissions, and system efficiency. Although real operational data were used wherever possible, some simplifications limit the precision of the results. Furthermore, indirect impacts such as changes to production cycles, downtime during equipment replacement, or life-cycle emissions of equipment manufacturing were not fully evaluated and remain areas for future work.

Overcoming these limitations will require not just technological innovation, but also systemic coordination between companies, technology providers, and policy makers. In this sense, electrification must be seen as a gradual transformation, shaped by external support mechanisms, internal planning strategies, and a shared commitment throughout the value chain to accelerate decarbonisation [23].

3.4 Conclusions

The methodological approach in this study combines real operational data with economic and environmental evaluation tools to deliver a practical, decision-oriented analysis of electrification opportunities in the cork industry. Both e+Monitor and Power BI provide reliable insight into consumption patterns and variability, while the cost-benefit framework offers a structured comparison of alternatives in financial and environmental terms (CAPEX/OPEX, avoided fuel use, and CO_2). Inevitably, some simplifications and assumptions are adopted due to data availability and market uncertainty; these are acknowledged through sensitivity checks on key drivers such as energy prices, COP, and PV self-consumption. Even with these limits, the methodology forms a solid

Table 3.2: Main Barriers to Electrification in the Cork Industry

Category	**Limitation**
Technical	High power demand of thermal processes; limited electrical infrastructure; intermittency of renewable energy sources
Economic	High initial investment (CAPEX); electricity price volatility; narrow profit margins in the industry
Regulatory	Inconsistent implementation of CSRD across EU countries; uncertainty in future compliance obligations
Operational	Lack of skilled labour for installation and maintenance; adaptation of production processes; potential downtime during transition
Analytical (Study Scope)	Use of annual averages instead of high-resolution data; simplified economic assumptions; exclusion of life-cycle emissions

basis for assessing real implementation scenarios and aligns results with CSRD-consistent GHG accounting. The next chapter builds on this groundwork to examine the technical, economic, and environmental implications of putting these electrification strategies into practice.

Chapter 4

Implementation Issues

4.1 Technical

The electrification of thermal processes in the cork industry faces numerous technical considerations concerning feasibility and efficiency. First, it is necessary to consider the main electrical systems, such as heat pumps, electric boilers and induction heaters which demand precise infrastructure upgrades. More often than not, retrotting of existing facilities is necessary regarding higher electrical load and compatibility with new advanced technologies [26].

Another critical aspect is process optimization. Electric systems offer superior control over temperature and energy use compared to fossil-fuel systems, enabling more efficient and uniform heat application. Induction heaters offer targeted heating, which minimizes heat losses and improves energy transfer efficiency. On the other hand, heat pumps are better suited for processes that need moderate temperatures, as they're able to capture and reuse heat within the system [23].

The stability and the availability of electricity are also crucial. Electrification can potentially reduce gas emission, on condition that supply is available from dependent and low-carbon sources of electricity. Coordinating renewable energy production (from the photovoltaic project) in companies dealing with cork production is essential to optimize economic and environmental benefits [5].

Lastly, their implementation has to be done in a way that is compatible with the operating systems and processes. Training operators properly and regularly maintaining it is crucial to minimize disruption and maintain efficiency [26].

These technical aspects are the basis for successful electrification, enabling further sustainable and efficient production processes.

4.2 Economical

The economic feasibility of electrificifying thermal processes is a question of balancing high upfront cost with long-term savings. While the capital expenditures (CAPEX) for technologies like heat pumps, electric boilers and induction heaters are normally greater than that required by fossil fuel-based systems, the operational expenditures (OPEX) tend to decrease over the time due to improved energy efficiency, reduced maintenance requirements and lower fuel costs when powered by renewable energy sources [26].

These electric systems, for instance, include electric steam boilers that help minimize maintenance by 50% as compared to conventional systems. Additionally, they eliminate costs associated with combustion emissions, which may be very significant when trying to achieve sustainability requirements as established in the CSRD [5, 23].

Financial incentives, including government subsidies and tax credits for adopting green technologies, can further improve the economic viability of electrification projects. These incentives reduce payback periods, which are typically achievable within 5 to 10 years for industrial systems [26].

Despite initial financial challenges, the economic case for electrification strengthens over time, especially as renewable energy costs continue to fall and regulations increasingly favor sustainable practices.

4.3 Environmental impact

Electrification of thermal processes provides a huge positive impact on the environment since it minimizes GHG emissions and improves energy efficiency. Substitution of fossil-fuel-based systems by electric technologies avoids direct combustion emissions (Scope 1), while the use of renewable electricity reduces indirect emissions (Scope 2). These are in accordance with the current global decarbonisation goals and regulatory frameworks such as the CSRD [5].

Heat pumps, for example, significantly improve energy efficiency by recovering and reusing waste heat, leading to reduced energy consumption and emissions. Induction heating systems also eliminate waste heat through localized, precise heating, further enhancing environmental performance [26].

In addition to reducing greenhouse gas emissions, electrifying these processes also eliminates local air pollutants associated with fossil fuel combustion. This further reduces the industry's environmental footprint, improving public health and compliance with air quality standards.

Finally, electrification linked to renewable sources increases the environmental benefit. The goal is to fit the production schedule of cork factories to periods of peak renewable generation (solar or wind) and thus guarantee close-to-zero operational emissions without giving up cost efficiency.

Despite these advantages, challenges remain, including the carbon intensity of the electricity grid in some regions and the energy demands of retrofitting existing infrastructure. However, long-term electrification offers a pathway for the cork industry to lead in sustainable practices while meeting regulatory and societal demands for greener production processes.

4.4 Integration Challenges

There are many challenges in integrating electrification technologies into the cork industry, ranging from a limiting infrastructure base to operational complexity. For the adoption of heat pumps, electric boilers, and induction systems, for instance, most facilities would have to be retrofitted to bear an increased electrical load. It usually implies a very expensive upgrading of both the electrical and thermal systems, adding to capital expenditure [26].

Additionally, the intermittency of renewable energy sources such as solar and wind complicates the reliability of electrified systems. Cork production processes often demand consistent energy input, making it necessary to either invest in energy storage solutions or align production schedules with renewable energy availability [5]. Grid capacity in certain regions may also be insufficient to support these levels of electrification, therefore requiring further investments in local grid infrastructure.

There is a general lack of familiarity when operating with advanced electric systems. Workers will need training for the operation and maintenance of new technologies, and that could temporarily disrupt production. Also, careful planning and optimization is required to integrate new systems into the workflows without affecting the quality of the product or production timelines [23].

Despite these challenges, the collaboration between industry stakeholders, policymakers, and technology providers can help to smooth them out. Most of these challenges can be minimized through government incentives, green technology subsidies, renewable energy innovation, and storage. Overcoming these integration challenges is the key to realizing the environmental and economic benefits of electrification in the cork industry.

4.5 Conclusions

Electrifying thermal processes in the cork industry is viable, provided that sites undertake targeted upgrades to electrical capacity, controls, and process interfaces. Heat pumps are strongest at moderate temperatures and where heat recovery is possible; electric boilers and induction deliver precise, fast response but can raise peak demand. Financially, higher upfront costs are balanced by lower operating and maintenance expenses and avoided combustion-related costs, with economics further improved by PV self-consumption and available incentives. Environmentally, replacing on-site combustion eliminates Scope 1 emissions and can cut Scope 2 when electricity is low carbon, although grid intensity and retrofit energy needs set practical bounds. The main execution risks are integration-related: grid capacity, renewable variability, storage or scheduling needs, and workforce upskilling. A pragmatic path is to run capacity studies, phase retrofits, train operators, apply demand management, and align production with PV availability.

Chapter 5

Grupo Amorim Industrial Context

5.1 Company Overview

Grupo Amorim is a Portuguese multinational and the global leader in the cork industry, with a history that dates back to 1870. Headquartered in Santa Maria de Lamas, it operates in more than 100 countries and employs thousands of people across various continents. The company is structured into several business units: cork stoppers, floor and wall coverings, insulation cork, and composite cork, each of which specializes in innovative applications of cork for different markets.

In 2024, Corticeira Amorim implemented a new organisational model through the creation of Amorim Cork Solutions business unit, which encompasses all 'non-cork stopper' operations as of 1 January 2025. This restructuring involves the formal merger of Amorim Cork Flooring and Amorim Cork Insulation into Amorim Cork Composites, which will be renamed Amorim Cork Solutions. The other two business units are Amorim Florestal, whose goal is to procure, source, stock and prepare the raw material, being responsible for supplying the other business units, and Amorim Cork, which is the world's largest producer, supplier and distributor of cork stoppers.

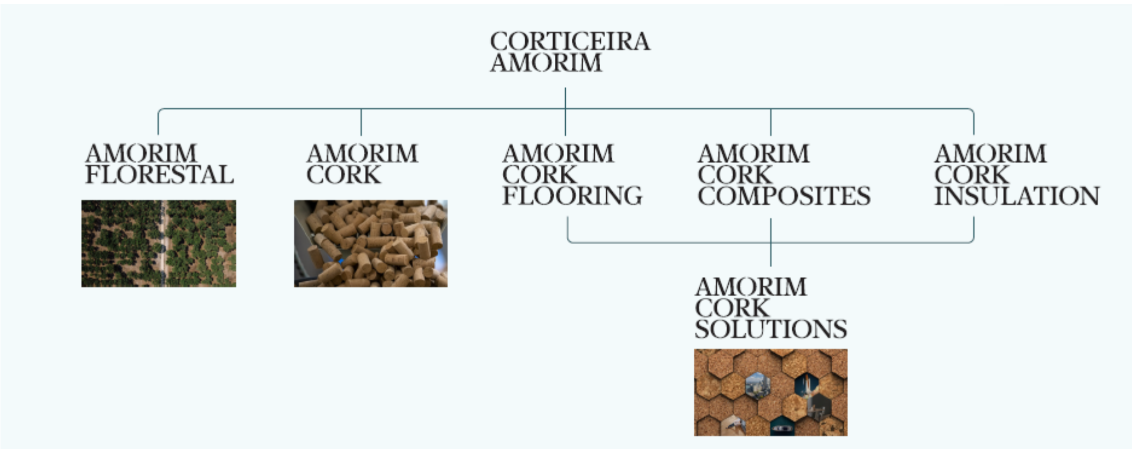

Figure 5.1: Grupo Amorim Business Units. Taken from: [5]

5.2 Industrial Sites and Geographic Footprint

Corticeira Amorim's industrial units are scattered across Portugal, with a higher concentration in the district of Aveiro, in the municipality of Santa Maria da Feira, where the company's operations centre is located. Outside the district of Aveiro, there are some manufacturing units in the Alentejo and Ribatejo regions.

The case studies developed in this dissertation are based on real industrial units belonging to Corticeira Amorim, selected for their representativeness within the groups operations and the availability of reliable data. Each site was chosen not only for its energy profile but also for the presence of thermal processes still reliant on fossil fuels and the potential for meaningful electrification interventions.

Socori 2, located in Rio Meão, is a facility that initially focused on the production of natural cork stoppers. Over time, the site expanded its scope to include granulates, as well as agglomerated and cider stoppers produced through extrusion and moulding methods. The unit later incorporated additional product lines such as discs (now received from external sources), technical 1+1 stoppers, micro-agglomerated stoppers, and champagne corks. This site was selected for the detailed analysis of steam production, as it operates small-scale steam boilers powered by LPG, making it a relevant use case for electric boiler replacement.

Discork, based in Santa Maria de Lamas, presents a different operational profile, with more centralised energy systems and the use of natural gas for steam generation. Its scale and process configuration offer a complementary perspective on electrification, allowing for comparisons in performance and impact relative to Socori 2.

Finally, V&L, a unit located in Valada, was considered for its distinct energy setup and strong integration of renewable sources, including a sizeable photovoltaic installation. While the detailed analysis of this site is still underdeveloped, its inclusion helps extend the applicability of the findings and provides a glimpse into the decarbonisation potential of more advanced energy frameworks.

Together, these locations reflect the geographical and operational diversity of Corticeira Amorims industrial footprint. They also illustrate the various stages of energy transition across different plants, from fossil fuel reliance to partial electrification and renewables integration.

5.3 Sustainability Strategy and Innovation Approach

Sustainability is a fundamental pillar of Grupo Amorims corporate strategy, deeply integrated into both its industrial operations and long-term vision. Rooted in the principles of circular economy, the company is committed to the full use of cork, a 100% natural, renewable, and recyclable material, ensuring that every stage of production maximizes resource efficiency and minimizes waste. This approach is not only environmentally friendly, but also economically, as cork by-products are continuously reintroduced into new product lines across the group's various business units.

Given the agroforestry activity of the company, carbon sequestration is an important topic for GA. Different types of land use have distinct sequestration potentials, with cork oak forests standing out for their ability to store CO_2 over long periods, especially since cork harvesting does not involve deforestation and trees can live for over 200 years. In 2024, the company performed its first estimate of carbon sequestration potential, based on the GHG Protocols "Land Sector and Removals Guidance". Although not yet fully detailed, this initial approach estimates a total of 42 368 tCO_2 sequestered [5].

Grupo Amorim has also been positioned at the forefront of industrial innovation, investing in advanced technologies that reduce energy consumption, lower emissions, and optimize production processes. This includes initiatives to modernize equipment, implement renewable energy solutions, and explore low-carbon alternatives for thermal energy needs. Between 2021 and 2024, GA invested more than 11 million euros in a photovoltaic project that resulted in 24MWp of installed capacity across 18 of its industrial units [5].

Following Sustainable Development Goals (SDG), the project "Sustainable by Nature" came to life, quantifying targets to achieve every 3 years. By 2030, the ambition is that all the energy used is renewable and that the carbon footprint for scopes 1 and 2 will be zero [5].

The companys alignment with international sustainability goals (such as those set by the European Union and embedded in regulatory frameworks such as the CSRD and SDG) demonstrates its proactive attitude to adapt to global climate targets. By integrating sustainability and innovation, Grupo Amorim not only enhances its competitive advantage, but also strengthens its contribution to a more resilient and environmentally responsible industrial sector.

5.4 Energy Usage and Thermal Process Overview

In 2024, Corticeira Amorim recorded a total energy consumption of approximately 539 000 MWh, of which 79,1% originated from renewable sources. A significant share (63,4% of the total) came from renewables directly controlled by the company, including cork dust biomass and photovoltaic electricity. Cork dust, a by-product of the industrial process, was the main energy source, accounting for 46,2% of total consumption. Non-renewable energy sources, such as natural gas, propane, gasoline, and diesel, were mainly used to support thermal processes and power the internal fleet. The company reported an energy intensity of 2065 MWh per million euros of net revenue.

Thermal Processes Fundamental to the production chain in the cork industry, they contribute significantly to the preparation and transformation of this material for numerous applications. From wine stoppers to insulation and flooring, cork products are subjected to heat-intensive stages that are essential to achieve certain quality standards. Some of these processes are the boiling of cork planks to improve flexibility and remove impurities, the drying of cork materials during production, and the agglutination of granules to create agglomerated cork products [13].

Thermal processes typically rely on fossil fuels or biomass combustion. However, the cork industry has long been a hallmark of industrial sustainability by using cork powder, a byproduct of production, as an energy source. This approach not only minimizes waste, but also reduces the dependency on non-renewables. The increasing concerns on climate change matters and environmental regulations, such as the Corporate Sustainability Reporting Directive (CSRD), demand even lower emissions levels, pressuring the industries to adopt electrified systems. By electrifying the current processes, it is possible to reduce emissions, while also improving efficiency and optimizing the use of by-products, such as cork powder, ensuring compliance with evolving standards.

Despite the industry's already commendable efforts in sustainability, such as Corticeira Amorim's commitment to renewable energy [5], thermal processes remain an area susceptible to innovation. Through advanced technologies such as heat pumps and induction systems, electrification could address current challenges while also enabling better efficiencies. The transition of these processes to electric systems not only aligns with the EU's decarbonization goals but also improves the role of the cork industry as a leader in sustainable practices.

5.4.1 Steam boilers

Industrial steam boilers operate on the basis of a sequential and interdependent set of thermal and mechanical processes that allow for the generation and distribution of high-pressure steam. The operation begins with the combustion of a fuel source (typically biomass) within a combustion chamber or furnace. This chemical reaction releases large amounts of thermal energy in the form of high-temperature flue gases. These gases serve as the heat source that initiates the subsequent thermodynamic processes within the boiler.

The heat produced by combustion is transferred to the working fluid of the boiler (water) through three principal mechanisms: radiation, convection, and conduction. Radiation involves the direct transmission of heat from the flame and hot surfaces to the water or the containment surfaces in contact with the water. Convection occurs when hot flue gases flow across surfaces, transferring energy to the water through fluid motion. Conduction refers to the transfer of thermal energy through solid metal walls that separate the hot gases from the water, allowing energy to flow into the fluid.

As this thermal energy is transferred into the water, its temperature increases until it reaches its saturation point at the prevailing pressure. At this stage, the water begins to change phase into saturated steam. In some configurations, this steam is directed through additional heating surfaces to increase its enthalpy, producing superheated steam, which is required in applications such as turbine drives or high-temperature processing.

Once generated, the steam is distributed through a network of pipes to various end-use systems across the industrial facility. These can include turbines, autoclaves, process heat exchangers, boiling of cork planks or drying systems. After delivering its thermal energy, the steam condenses back into water. This condensate is commonly returned to the boiler feed system to be reheated, completing a closed-loop cycle that enhances thermal efficiency and conserves water.

The functionality of the steam boiler depends on a series of integrated components. The furnace is the combustion zone where the heat is initially generated. The burner manages fuel and air injection to ensure complete and efficient combustion. The heat exchanger, usually composed of tubes, facilitates thermal transfer from the flue gases to the water. A steam drum separates steam from water, ensuring that only dry saturated or superheated steam enters the distribution lines. The exhaust pipe safely directs exhaust gases out of the system, and the boiler control system monitors the pressure, temperature, water levels, and fuel input to maintain operational safety and efficiency.

These systems, operating under precise thermodynamic control, form the backbone of steam-based industrial processes, delivering reliable and controllable heat energy at scales suitable for everything from textile manufacturing to chemical processing.

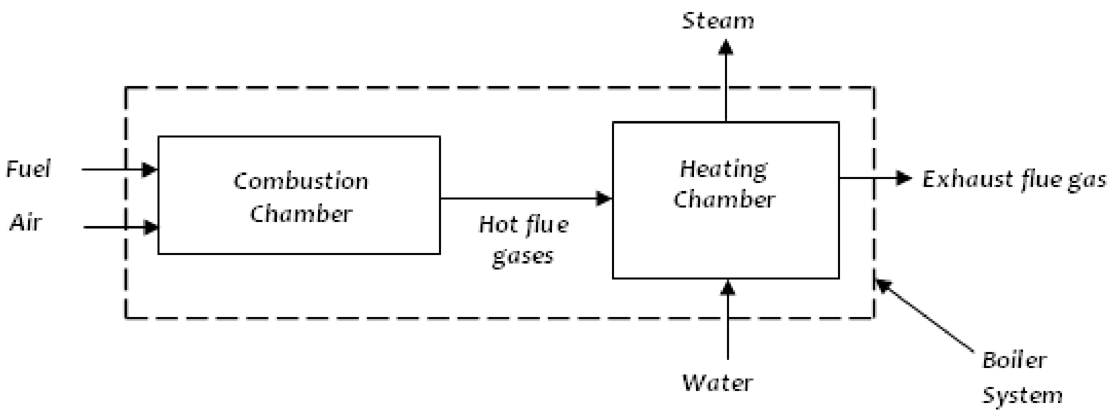

Figure 5.2: Steam boiler fluxogram. Source: [20]

Unlike conventional boilers that rely on combustion to generate heat, electric steam boilers produce steam through the direct conversion of electrical energy into thermal energy. In these systems, electric resistive elements or electrodes heat the water inside a pressurized vessel, eliminating the need for fuel combustion and thereby reducing local emissions to zero. Electric steam boilers offer exceptionally high thermal efficiency (typically above 98%) due to minimal heat losses and the absence of exhaust gases from combustion. Their compact design, precise control capabilities, and compatibility with renewable energy sources make them particularly attractive for industries seeking to decarbonize their thermal energy use. In the context of this work, electric steam boilers are selected as the core electrification technology, replacing existing gas-fired systems to enable cleaner, more efficient, and CSRD-compliant industrial steam generation.

5.4.2 Cork washing machines

Washing is one of the stages in the production of natural cork stoppers. In addition to sanitary concerns such as ensuring cleaning, disinfection (necessary due to contact with food) and dedusting of the cork stoppers, there are also aesthetic and functional objectives like whitening (to standardise and improve the cork appearance).

The washing process consists of four stages. First, the cork stoppers are subjected to a bleaching treatment, a solution of hydrogen peroxide, H_2O_2, and then an aqueous solution of sodium hydroxide, NaOH, in order to guarantee a basic pH value to promote the performance of the bleaching agent.

This is followed by a water rinse to wash and remove excess chemicals used previously. During this process, the mixture of cork stoppers and chemical agents is heated and hot air is injected throughout the various stages.

Afterwards, an aqueous solution of sodium bisulfate, $NaHSO_4$, an acidic solution used to neutralise the remaining sodium hydroxide, is applied. Then, to end the washing process, the cork stoppers undergo hot air injection to dry, with temperatures going up to 120 C, ensuring that their relative humidity is within the permitted specifications.

It is possible to apply a second wash, depending on the needs of the end consumer, which should be applied after a basic wash, which can be called a coating.

5.5 Conclusions

This chapter positions the case studies within the reality of Grupo Amorim: a diversified, innovation-driven cork group with a broad industrial footprint concentrated around Santa Maria da Feira and complemented by units across Portugal. The sustainability strategy, which includes the circular use of cork, large-scale PV expansion and Scope 1–2 decarbonisation goals, sets clear direction and enables electrification to create value beyond compliance. Energy data show a high share of renewables (notably cork dust and PV) yet leave meaningful thermal loads still met by fossil fuels, particularly steam and medium-temperature air heating.

Against this backdrop, the selected sites (Socori 2, Discork, V&L) provide complementary contexts to test electrification: small LPG steam at Socori 2, NG-based steam in a more centralised setup at Discork, and a PV-rich system at V&L. Technologically, electric steam boilers and heat-pump-assisted hot-air/wash processes emerge as practical levers, provided grid capacity, scheduling with PV, and operational integration are managed. These insights frame the targeted interventions quantified in the next chapters.

Chapter 6

Case Studies

6.1 Electrification of Steam Boilers

Among the most energy-intensive and emissions-relevant systems are the steam boilers that are currently under operation in Socori 2 and Discork. These boilers are fundamental for the delivery of thermal energy that's needed in the various manufacturing processes and are still powered by fossil fuels (LPG and natural gas), resulting in considerable greenhouse gas emissions.

The analysis focuses on evaluating the technical feasibility and economic implications of replacing these fossil-fuel boilers with electric models of equivalent capacity, including the integration of renewables. This process was informed by the methodology outlined in Chapter 3, combining real consumption data, emission factors, and equipment benchmarks.

The goal is to assess whether electrification can maintain or improve thermal performance while delivering measurable reductions in emissions and operational costs. Special attention is given to how much of the required electricity could be covered by renewable sources, particularly from on-site photovoltaic systems or local energy communities derived, to ensure that electrification effectively translates into decarbonisation.

6.1.1 Case Study 1: Socori 2

The Socori 2 unit currently relies on two steam boilers powered by liquefied petroleum gas (LPG) to supply thermal energy for its industrial operations. These boilers play a key role in supporting processes that require stable and continuous steam delivery, such as cork treatment and drying. They are responsible for producing steam, which then heats water to increase the temperature in the reactors. However, the current system no longer meets production demands in full, particularly during peak operational periods.

The proposal studied for Socori 2 involves replacing the existing LPG boilers with electric steam boilers. This upgrade is expected not only to meet the current thermal demands more effectively but also to contribute to emission reductions and alignment with the companys decarbonisation strategy.

6.1.1.1 Current System

The current system at Socori 2 is composed of two Flucal boilers (model FVR 220), shown in Images 6.1 and 6.2, each with a nominal power of 163 kW and a maximum steam production capacity of 200 kg/h. Installed in 2010, these units have undergone several adjustments over the years and are no longer operating at full capacity. Operational degradation, combined with growing production needs, has led to performance limitations that affect the consistency and reliability of steam supply. Also, these boilers do not have storage capacity, which is critical at times when there are peaks in steam consumption (the pressure drops very quickly and the burners cannot recover in time). This limitation is not so much imposed by the process, but rather by the design of the boilers.

As part of the electrification assessment, the replacement boilers were requested to exceed the original capacity by approximately 50% in steam production capacity, providing not just a technological upgrade, but also an opportunity to adapt the system to current and future production requirements.

Figure 6.1: Current boilers in Socori 2

Figure 6.2: Detailed imagem of the boiler

6.1.1.2 Energy Analysis

LPG consumption data, for the years 2023 and 2024, was obtained through e+Monitor. A significant increase can be observed in the latest year, and this is due to the adoption of a new process in this industrial unit, which can be seen in the following graph:

Table 6.1: Technical Specifications of Existing Boilers at Socori 2

Parameter	**Value**
Model	Flucal FVR 220
Fuel Type	Liquefied Petroleum Gas (GPL)
Nominal Power (each)	163 kW
Steam Production Capacity (each)	200 kg/h
Installation Year	2010
Operating Pressure	5 to 8 bar
Water Tank Capacity	39.5 litres
Total Installed Units	2

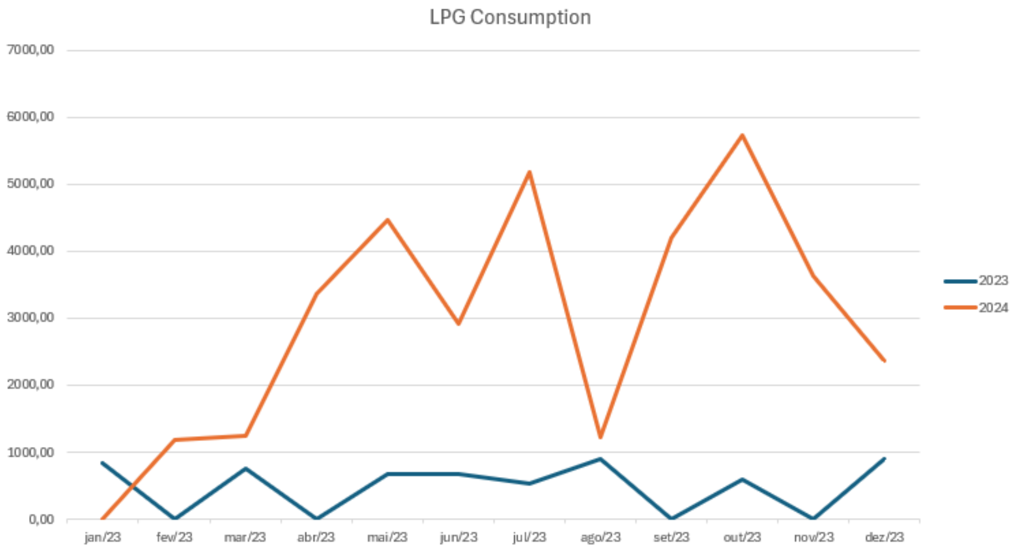

Figure 6.3: LPG Consumption in Socori 2 - 2023 vs 2024 (kg)

Table 6.2: LPG Consumption in Socori 2 - 2023 vs 2024 (kg)

Month	**2023**	**2024**
Jan	840	0
Feb	0	1180
Mar	760	1240
Apr	0	3360
May	680	4460
Jun	680	2920
Jul	540	5180
Aug	900	1220
Sep	0	4200
Oct	600	5727
Nov	0	3640
Dec	900	2360
Total	**5900**	**35487**

In the first quarter of 2024 an innovative system went into operation, and these two boilers were made responsible for producing steam to aid this process. Knowing this, and comparing the values before the boilers went into operation and afterwards, we can attribute a big part of Socori 2's consumption to the boilers in use.

In numbers, there was an increase from 5900 kg of LPG consumed in 2023 to 35487 kg in 2024, which means that the boilers themselves are responsible for more than 80% of the total consumption of the industrial unit.

Focusing on 2024, and using the appropriate conversion factors, also used in Corticeira Amorim's Suntainability Report [5], these numbers convert to equivalent energy (in GJ) as follows:

$$1\,\text{ton}\,LPG = 46{,}65\,\text{GJ} \tag{6.1}$$

$$E_{\text{consumed}} = \frac{35487}{1000} \times 46{,}65 \approx 1656\,\text{GJ} \tag{6.2}$$

And with this, we can then convert the values into kWh:

$$1\,\text{GJ} \approx 278\,\text{kWh} \tag{6.3}$$

$$E_{\text{consumed}} = 1656 \times 278 \approx 460\ \text{MWh} \tag{6.4}$$

Assuming a current efficiency of the process around 85%, which is in normal operating conditions for combustion steam boilers, we can calculate the useful energy:

$$E_{\text{useful}} = 460 \times 0{,}85 = 391\ \text{MWh} \tag{6.5}$$

Replacing the current equipment with electrical steam boilers, which tend to have an efficiency of around 98%, the estimated total energy needed to produce the same results is:

$$E_{\text{estimated}} = \frac{391}{0{,}98} = 399\ \text{MWh} \tag{6.6}$$

To convert back into GJ the result from equation 6.6 the result must be multiplied by 1000 to be in kWh:

$$E_{\text{estimated}} = \frac{399 \times 1000}{278} = 1436\ \text{GJ} \tag{6.7}$$

The implementation of this measure results in a significant decrease in the total energy consumed yearly:

$$E_{\text{saved}} = 460 - 399 = 61\ \text{MWh} \tag{6.8}$$

$$E_{\text{saved}} = \frac{61 \times 1000}{278} = 220\ \text{GJ} \tag{6.9}$$

Emissions Most importantly, and in terms of compliance with the European Regulations, this upgrade translates into a large scale reduction of CO_2 emissions. To calculate this, we must take into consideration not only the emissions associated with the burn of LPG, but also the ones associated to electricity generation. Based on the known emissions factors, also used in Corticeira Amorim's Sustainability Report, the amount of emissions associated with both these activities are:

$$1\,\text{GJ (burning LPG)} = 63\,\text{kg equivalent } CO_2 \text{ emitted} \tag{6.10}$$

$$1\,\text{GJ (market energy)} = 33{,}83\,\text{kg equivalent } CO_2 \text{ emitted} \tag{6.11}$$

It is now possible to quantify the emissions in each of the situations. The emissions in 2024 using the current boilers, based on their consumption from equation 6.2 and the conversion formula 6.10:

$$1656 \times 63 \approx 104\ tCO_2 \text{ emitted} \tag{6.12}$$

From the estimates in equation 6.7 and the conversion formula 6.11, considering that all the energy supplying the electrical boilers comes from the public grid, the emissions associated with their activity would be:

$$1436 \times 33{,}83 \approx 49\,tCO_2 \text{ emitted} \tag{6.13}$$

Finally, we can obtain the estimated amount of emissions avoided with the adoption of this solution:

$$104 - 49 \approx 55\,tCO_2 \text{ avoided} \tag{6.14}$$

In summary, the current steam generation system at Socori 2 represents a significant source of energy consumption and CO_2 emissions. The energy analysis confirms that replacing it with an electric alternative would not only increase energy efficiency but also result in substantial emission reductions. These findings support the viability of exploring a full electrification strategy, which will be detailed in the next section.

6.1.1.3 Electrification Proposal

To address the limitations of the current steam generation system and meet future thermal energy needs, the proposed solution for Socori 2 consists of replacing the two existing boilers with two electric equivalents. These new units are engineered to operate at a pressure of 8 bar and offer a significant increase in steam production capacity.

Each electric boiler is rated at 225 kW of nominal power and capable of producing 330 kg/h of steam, representing a 65% increase in output compared to the existing units. The boilers also feature a flow rate of 429 litres per hour and a maximum service temperature of 105C, making them suitable for the continuous and high-demand steam applications typical of cork industry operations.

In addition to better thermal performance, the proposed system includes a fully integrated electrical control panel with a programmable logic controller (PLC). This improves system automation, reliability, and operational safety, as well as increased control, supporting process stability, particularly in applications where temperature and pressure consistency are critical.

Table 6.3: Technical Specifications of Proposed Electric Boilers

Parameter	Value
Number of Units	2
Nominal Power (each)	225 kW
Steam Production Capacity (each)	330 kg/h
Operating Pressure	8 bar
Flow Rate	429 litres/hour
Maximum Service Temperature	105C
Control System	Electric control panel with PLC

The selection of this equipment was based not only on technical compatibility and capacity requirements but also on its potential for integration with renewable energy sources. Given Socori 2s ongoing participation in energy community initiatives and its access to its own photovoltaic generation, the proposed electric boilers can be partially or fully powered by clean electricity, strengthening the decarbonisation strategy of this industrial unit.

6.1.1.4 Economical Evaluation

In order to assess economic viability, a comparison was made between current and post-replacement annual costs.

Current Boilers Obtainable through e+Monitor, the total expenditures for 2024 in LPG were 55157 . Being $p_{\text{current boilers}}$ the percentage that these boilers make up of the industrial unit's total consumption and accounting for the LPG consumed in both 2023 and 2024 as shown in table 6.2, the share associated with their use can be calculated:

$$p_{\text{current boilers}} = \frac{35487 - 5900}{35487} \times 100 = 83{,}4\% \tag{6.15}$$

It is now possible to determine $c_{\text{current boilers}}$, which is how much of the total costs with LPG in 2024 were in fact related to the boilers operation:

$$c_{\text{current boilers}} = 55157 \times \frac{83{,}4}{100} = \mathbf{45\,987} \tag{6.16}$$

Electric Boilers (CAPEX) The cost of equipment for the new electric boilers, $c_{\text{equipment}}$, is 44 800 per unit, plus 2 100 for the installation and start-up of each. This represents a total of:

$$c_{\text{equipment}} = 2 \times (44800 + 2100) = \mathbf{93800} \tag{6.17}$$

In addition to the cost of equipment, the electrical infrastructure required to power the new boilers was estimated. The following formula is used to calculate the current, I, in three-phase systems:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot \cos\phi} \tag{6.18}$$

where I is the current per phase (A), P is the active power (W), V is the voltage per phase (V) and $\cos\phi$ is the power factor (assumed to be 1 for resistive loads).

Applying 6.18, for a 225 kW electric boiler, and using the typical voltage in three-phase systems of 400 V, the current to be transported is:

$$I = \frac{225\,000}{\sqrt{3} \cdot 400 \cdot 1} \approx 325 \text{ A (for one boiler)} \tag{6.19}$$

$$I \approx 2 \times 325 = 650 \text{ A (for both boilers)} \tag{6.20}$$

The selection of cables to supply the proposed electric boilers was based on the total current required by the installation, approximately 650 A. Given the high current and an estimated distance between the main electrical panel and the location of the boilers of 150 meters, the selected solution involves the use of copper cables with large cross sections, preferably requiring parallel cables per phase (two cables of 240 mm^2). Recently, there was an installation in this same industrial unit that required cabling with similar specifications, and the total cost of implementation was around 27 000 . Assuming the same costs for the situation in analysis:

$$c_{\text{cabling}} = \mathbf{27\,000} \tag{6.21}$$

Taking the results from 6.17 and 6.21, the total CAPEX is:

$$\mathbf{CAPEX} = 93\,800 \; + 27\,000 \; = \mathbf{120\,800} \tag{6.22}$$

In summary, the total CAPEX for this electrification project is estimated at around 120 800 , combining the cost of equipment and the necessary electrical infrastructure. Although this represents a significant upfront investment, it is a crucial step towards reducing emissions and aligning the facility with modern sustainability standards.

Electric Boilers (OPEX) Post-electrification costs, $c_{\text{electric boilers}}$, were calculated considering the total estimated energy consumption after the replacement, obtained in 6.6, and a price of **115 /MWh**, a value that is in line with the average cost of electric energy for Grupo Amorim:

$$c_{\text{electric boilers}} = 399 \times 115 \approx \mathbf{45\,868} \tag{6.23}$$

The costs associated with the maintenance of electrical systems generally range between 1% and 3% of the initial investment (CAPEX) [26], corresponding to:

$$1\% \text{ of CAPEX} = 0{,}01 \times 120\,800 \approx 1\,200 \tag{6.24}$$

$$3\% \text{ of CAPEX} = 0{,}03 \times 120\,800 \approx 3\,600 \tag{6.25}$$

This means that an average value of **2 400** should be taken into account in terms of annual maintenance expenditures. Adding these two costs together, the OPEX is totalled at:

$$\textbf{OPEX} = 45\,868 + 2400 = \textbf{48 268} \tag{6.26}$$

Considering that there is no self-consumption of photovoltaic production and that all the energy used comes from the public grid, this results in a negative economic benefit:

$$\text{Economic Benefit} = \text{Cost before} - \text{Cost after} \tag{6.27}$$

$$\text{Economic Benefit} = 45\,987 - 48\,268 = -2\,281 \tag{6.28}$$

Since in this situation the economic benefit is negative there is no payback time, which can difficult the decision for the company to go through with the implementation of this measure. However, if part or all of this electricity comes from local PV generation or energy communities, the operational costs would decrease, potentially turning this benefit into a positive value. Additionally, the environmental benefit would be even greater, with potential for full decarbonisation of the thermal process.

6.1.1.5 Environmental Impact

As shown in Section 6.1.1.2, replacing existing LPG steam boilers with electric equivalents is an environmentally relevant measure that greatly contributes to reducing the carbon footprint. This transition results in a reduction of approximately 55 tonnes of equivalent CO_2 emissions per year (6.14) taking into consideration both the emissions associated with the burn of liquefied petroleum gas (6.10) as well as electricity generation (6.11).

This translates to a significant drop in Scope 1 emissions, related to the direct combustion of LPG, therefore eliminating 83,4% of the total consumption (6.15). Although part of the environmental benefit is offset by the carbon intensity of grid electricity (Scope 2), the net reduction remains considerable. Furthermore, if the electricity supply is partially or fully sourced from renewables, this environmental benefit could increase even further.

In the context of the CSRD, this kind of intervention directly supports the companys decarbonization roadmap and improves the transparency and relevance of its sustainability reporting.

6.1.2 Case Study 2: Discork

The Discork unit (ATS 2) has a steam boiler powered by natural gas. It is assumed that all consumption of this non-renewable source comes from its operation, making its electrification an important step in the decarbonisation process.

In order to mitigate gas consumption, it was studied whether to replace it with an electric steam boiler with the same characteristics as the one currently in use.

6.1.2.1 Current System

The system currently in use at Discork consists of a boiler with a production capacity of 200 kg/h.

It has been said that the steam production needs at this industrial unit are not as high as those currently installed, so a reduction in the boiler's power can be evaluated when it is installed.

Table 6.4: Technical Specifications of Existing Boiler at Discork (ATS 2)

Parameter	**Value**
Fuel Type	Natural Gas (NG)
Nominal Power	130 kW
Steam Production Capacity	200 kg/h
Operating Pressure	5 to 8 bar
Total Installed Units	1

6.1.2.2 Energy Analysis

The consumption of this unit is not described in eMonitor+. In order to obtain these values, a direct consultation of the 2024 gas invoices was performed.

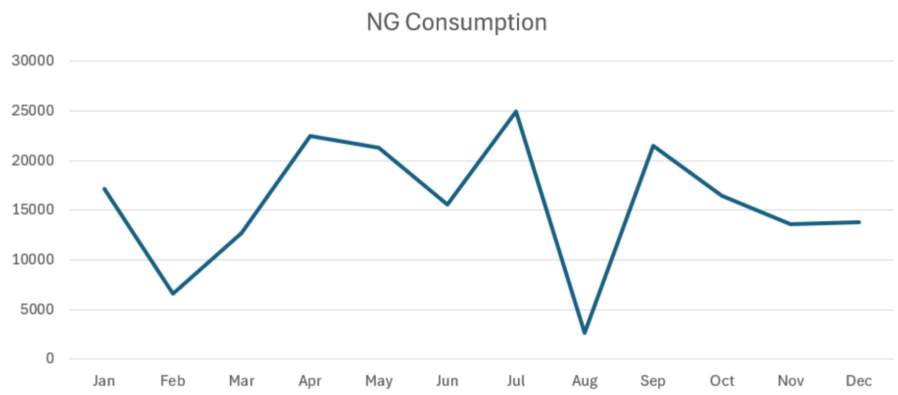

Figure 6.4: NG Consumption in Discork - 2024 (kWh)

There was a negative peak in August, related to the summer break that takes place every year in GA factories.

The total NG consumption for 2024 was 188 690 kWh, as read on the invoices. This translates to an equivalent energy consumption of:

$$E_{\text{consumed}} = 188\,690\,\text{kWh} \tag{6.29}$$

$$1\,\text{GJ} \approx 278\,\text{kWh} \tag{6.30}$$

$$E_{\text{consumed}} = \frac{188\,690}{278} \approx 679\ \text{GJ} \tag{6.31}$$

Table 6.5: NG Consumption in Discork - 2024

Month	kWh
January	17 148
February	6 588
March	12 704
April	22 485
May	21 331
June	15 599
July	24 913
August	2 632
September	21 513
October	16 430
November	13 571
December	13 776

Using the known conversion factors, also adopted by Corticeira Amorim's Suntainability Report [5], these numbers convert to equivalent consumption (in m^3):

$$1000\,m^3\,NG = 37{,}9\text{ GJ} \tag{6.32}$$

$$NG_{\text{consumed}} = \frac{679 \times 1000}{37{,}9} \approx 17\,923\,m^3 \tag{6.33}$$

Taking into account the current efficiency of the process around 85%, which is in normal operating conditions for steam boilers, the useful energy can be calculated:

$$E_{\text{useful}} = 679 \times 0{,}85 = 577\text{ GJ} \tag{6.34}$$

$$E_{\text{useful}} = 188\,690 \times 0{,}85 = 160\,387\text{ kWh} \tag{6.35}$$

By replacing this boiler with an electric equivalent, which has an efficiency of 98%, the expected consumption will be:

$$E_{\text{estimated}} = \frac{160\,387}{0{,}98} \approx 163\,660\text{ kWh} \tag{6.36}$$

$$E_{\text{estimated}} = \frac{163\,660}{278} \approx 589\text{ GJ} \tag{6.37}$$

By implementing this measure, the results regarding the saved energy were calculated as follows:

$$E_{\text{saved}} = 188\,690 - 163\,660 = 25\,030\,\text{kWh} \tag{6.38}$$

$$E_{\text{saved}} = \frac{25\,030}{278} \approx 90\ \text{GJ} \tag{6.39}$$

Emissions In order to calculate the reduction in the amount of equivalent CO_2 emissions, both values related to natural gas consumption and those of electricity production (equation 6.11) were taken into account. Based on the emission factors used in Corticeira Amorim's Sustainability Report, these values are:

$$1\,\text{GJ (burning NG)} = 64{,}1\,\text{kg equivalent CO}_2\text{ emitted} \tag{6.40}$$

Taking into account the result of equation 6.31, it is possible to obtain the resulting emissions for the year of 2024 regarding natural gas consumption:

$$679 \times 64{,}1 \approx 44\ \text{tCO}_2\text{ emitted} \tag{6.41}$$

Based on the estimated consumption obtained in equation 6.37 and the emissions factor of electric generation from the grid in equation 6.11, considering that the electric supply derives entirely from the public grid:

$$589 \times 33{,}83 \approx 20\ \text{tCO}_2\text{ emitted} \tag{6.42}$$

Finally, we can calculate the amount of emissions avoided after proceeding to the implementation of this measure:

$$44 - 20 \approx 24\ \text{tCO}_2\text{ avoided} \tag{6.43}$$

Through this energy analysis, it can be concluded that the transition to an electrical system would be a great asset for the industrial unit. Not only because of the increased energy efficiency of the process, but also because of the goal of achieving carbon neutrality by 2030. The next section presents the electrification proposal that continues this study.

6.1.2.3 Electrification Proposal

Following budget requests for electric equivalents to replace the current boiler, a certain equipment was selected. This unit is built to operate at a pressure of 8 bar and ensure the steam production needs in this industrial facility.

The equipment includes an electric water supply pump, electric support resistors with a total power of 115 kW, an electrical control panel with programmable logic controller (PLC) and a manual bottom drain valve. With a capacity of up to 175 kg/h of steam production, it was determined that it is enough to suppress the delivery required for the thermal processes that occur in Discork.

The selection of this boiler takes into consideration the technical compatibility, capacity requirements and also the potential of integrating renewable energy sources to power the system.

Table 6.6: Technical Specifications of Proposed Electric Boiler

Parameter	**Value**
Number of Units	1
Nominal Power (each)	115 kW
Steam Production Capacity	175 kg/h
Operating Pressure	8 bar
Flow Rate	228 litres/hour
Maximum Service Temperature	105C
Control System	Electric control panel with PLC

To supply the proposed electric steam boiler at the Discork facility, the power cables were dimensioned according to the requirements of IEC 60364-5-52 and standard reference tables (Table C4 of the Portuguese RGIEBT) [19]. The boiler operates at a nominal power of 115 kW, with a three-phase 400 V connection.

The design current (I_B) is calculated as:

$$I_B = \frac{S}{\sqrt{3} \cdot U} = \frac{115\,000}{\sqrt{3} \cdot 400} \approx 166\,\text{A} \tag{6.44}$$

A copper cable of type XV (0.6/1 kV) with a cross-section area of 70 mm^2 was considered, installed in an embedded conduit, with a total length of 150 meters from the transformer station to where the boiler is going to be placed. According to Table C4, the admissible current (I_z) for this configuration is approximately 222 A.

Circuit protection is ensured by a molded-case circuit breaker rated at $I_n = 200$ A. The thermal verification condition is, thus:

$$I_B \leq I_n \leq I_z \quad \Rightarrow \quad 166 \leq 200 \leq 222 \quad \text{(Condition satisfied)} \tag{6.45}$$

To evaluate the voltage drop, the linear resistance of the cable must first be calculated using the resistivity of copper at operating temperature. According to technical references, the copper resistivity is:

$$\rho = 0.0225\ \Omega \cdot \text{mm}^2/\text{m} \tag{6.46}$$

The resistance per unit length is then:

$$R = \frac{\rho}{S} = \frac{0.0225}{70} \approx 0.000321\ \Omega/\text{m} \tag{6.47}$$

Using the standard formula for three-phase voltage drop:

$$\Delta V = \sqrt{3} \cdot I \cdot L \cdot R = 1{,}732 \cdot 166 \cdot 150 \cdot 0.000321 \approx 13{,}9 \text{ V} \tag{6.48}$$

Which corresponds to a relative voltage drop of:

$$\frac{13.9}{400} \cdot 100 \approx 3{,}48\% \tag{6.49}$$

This result is within the admissible limits for industrial distribution circuits, however, it is close to the upper limit typically recommended of 5%. If further margin is desired, an increase in cable cross-section (for example, to 95 mm^2) may be considered to reduce the voltage drop.

6.1.2.4 Economical Evaluation

In order to determine the economic viability of this investment, a comparison was made between current costs and those incurred when the process is electrified.

Current Boiler As mentioned above, after consulting the gas invoices for 2024, the total costs for natural gas consumption were 17 302 . Taking into consideration that this comes only from the boiler in operation, we can attribute full responsibility for these costs, $c_{\text{current boiler}}$, to it.

$$c_{\text{current boiler}} = \mathbf{17\,302} \tag{6.50}$$

Electric Boiler (CAPEX) The cost of the new unit is 37 100 , plus 2 100 for installation and start-up. This, $c_{\text{equipment}}$, represents a total of:

$$c_{\text{equipment}} = 37\,100 + 2\,100 = \mathbf{39\,200} \tag{6.51}$$

Installation (CAPEX) The cost associated with changes to the infrastructure was calculated more thoroughly than in the previous case, because there was no similar installation to make a direct budget comparison.

The total cost is estimated by accounting for the cost of materials, protection devices, labour, and accessories, using market values available in Portugal.

The main power supply is implemented using copper conductor cable, type XV (0.6/1 kV), with a cross-sectional area of 70 mm^2, installed over a total length of 150 m. As of 2024, the average market price of this type of cable in Portugal ranges between 30 and 40 per metre, according to publicly available data from national suppliers [12]. Using an intermediate value of 35/m, the cost of the three-phase power cable, c_{cable}, is:

$$c_{\text{cable}} = 150 \times 35 = 5\,250 \tag{6.52}$$

A separate protective earth (PE) conductor of 35 mm^2 is considered, with a unit price of approximately 6/m:

$$c_{PE} = 150 \times 6 = 900 \tag{6.53}$$

The cost of accessories, $c_{accessories}$, including terminations, cable trays, supports, and other materials, was estimated based on experts' opinions and considered to be:

$$c_{accessories} \approx 2\,000 \tag{6.54}$$

The protective device selected is a 200 A circuit breaker, and based on different national suppliers online, the price ranges from 1000 to 1400. Using an intermediate value:

$$c_{protection} = 1\,200 \tag{6.55}$$

The total cost of the installation, $c_{installation}$, is then given by:

$$c_{installation} = 5\,250 + 900 + 2\,000 + 1\,200 = \mathbf{9\,350} \tag{6.56}$$

This gives a total cost for CAPEX of:

$$\mathbf{CAPEX} = 39\,200 + 9\,350 = \mathbf{48\,550} \tag{6.57}$$

Electric Boilers (OPEX) Having estimated the energy consumption after electrification of the process, as demonstrated in equation 6.36, and a price of **100 /MWh**, a value that is in line with the average cost of electric energy for this industrial unit:

$$c_{electric\ boiler} = \frac{163\,660}{1000} \times 100 = \mathbf{16\,366} \tag{6.58}$$

As established above, considering that maintenance costs for electric boilers typically range between 1%-3% of the CAPEX, the annual expenditures for this purpose are:

$$1\% \text{ of CAPEX} = 0{,}01 \times 48\,550 \approx 500 \tag{6.59}$$

$$3\% \text{ of CAPEX} = 0{,}03 \times 48\,550 \approx 1\,500 \tag{6.60}$$

This means that an average value of **1 000** should be considered in terms of annual maintenance expenditures. Adding these two costs together, the total OPEX is:

$$\mathbf{OPEX} = 16\,366 + 1\,000 = \mathbf{17\,366} \tag{6.61}$$

Considering that there is no self-consumption of photovoltaic production and that all the energy used comes from the public grid, this results in a negative economic benefit:

$$\text{Economic Benefit} = \text{Cost before} - \text{Cost after} \tag{6.62}$$

$$\text{Economic Benefit} = 17\,302 \; - 17\,366 \; = -64 \tag{6.63}$$

Once again, the economic benefit is negative, which means that it is more expensive to operate the new electric equipment than the one in operation at the moment. However, maintenance costs are not being taken into account in the current system, as well as no use of energy from on-site generation or energy communities is being considered. These considerations would definitely increase the economic benefit, enabling the calculation of an acceptable payback. Additionally, if part or all of this electricity comes from local PV generation or energy communities, the environmental benefit would be even greater, with potential for full decarbonisation of the thermal process.

6.1.2.5 Environmental Impact

As shown in Section 6.1.2.2, replacing the existing natural gas steam boilers at Discork with electric models presents a significant opportunity to reduce direct emissions and improve the environmental performance of the facility. The transition leads to a reduction of approximately 24 tonnes of equivalent CO_2 emissions per year (6.43), considering both the emissions avoided from natural gas combustion (6.41) and the emissions associated with electricity consumption (6.42).

This translates into a significant reduction in Scope 1 emissions, directly related to the elimination of local fossil fuel combustion. Although the environmental benefit is partially offset by the carbon intensity of the electricity consumed (Scope 2), the net reduction remains relevant. If electricity is supplied by renewable sources, the overall impact can be further enhanced.

In line with the principles of the CSRD and the ESRS E1 standard, this type of intervention contributes to reducing the companys carbon footprint and reinforces the transparency and accountability of its sustainability disclosures.

6.2 Electrification of Washing Processes

Among the thermal processes present in cork manufacturing, the drying phase following the washing of cork stoppers represents a significant source of energy consumption and CO_2 emissions. In several facilities, including those analyzed in this study, washing machines rely on gas-powered hot air generators to ensure proper drying conditions. These systems are typically fed by natural gas and, while effective, they contribute directly to the site's carbon footprint.

This analysis explores the technical and economic feasibility of replacing fossil-fuel-based hot air generators with electric systems, namely high-efficiency air-to-water heat pumps coupled with resistors. The evaluation follows the methodology presented in Chapter 3, integrating historical consumption data, equipment specifications and thermodynamic performance (including Carnot-based efficiency comparisons).

The objective is to determine whether the electrification of the washing process can ensure adequate drying performance while reducing greenhouse gas emissions and operating costs.

Particular emphasis is placed on the extent to which local renewable electricity sources can supply the thermal demand, supporting a deeper decarbonisation of this key production step.

6.2.1 Case Study 3: Vasconcelos and Lyncke

The Vasconcelos and Lyncke industrial facility is equipped with four washing machines, one of which is disconnected and getting ready to be sent to another factory. This unit is the one under analysis for electrification.

This proposal studies the possibility of reducing, or even mitigating, the dependence on non-renewable energy sources.

6.2.1.1 Current System

The current system at Vasconcelos and Lyncke is described in the following flowchart, Figure 6.5.

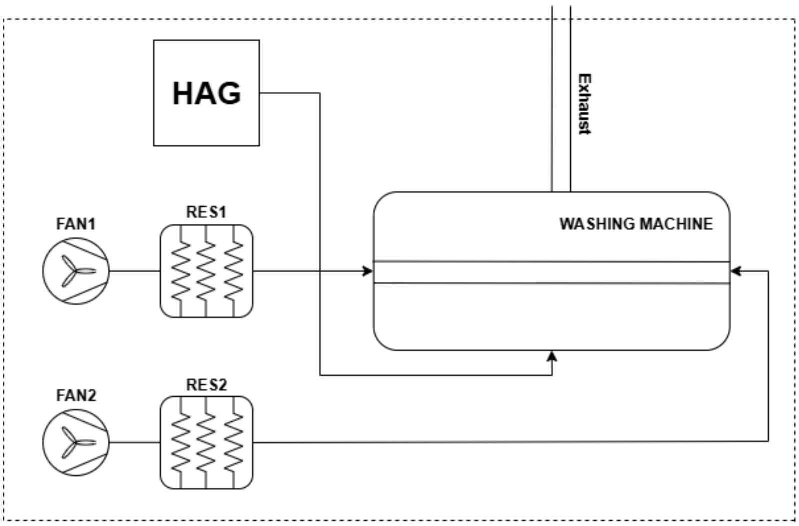

Figure 6.5: Flowchart Washing Machine

The electric consumption of the studied equipment derives from the three components shown in the Image 6.6: an air supply fan, an extraction fan and the tilting system, as described in the table.

Table 6.7: Technical Characteristics of the Washing Equipment

Equipment	Brand	Control	Nominal Power (kW)
Air Supply Fan	Sodeca	ON-OFF	5.5
Extraction Fan	Sodeca	ON-OFF	4.0
Tilting System	-	ON-OFF	7.5

Figure 6.6: Motors Present in the Washing Process

The air supply and extraction fans are subject to speed variation, adjusting the frequency according to the desired humidity and product quality objectives.

Heating is provided by a hot air generator in conjunction with two boxes of resistors.

Table 6.8: Technical Characteristics of the Heating Method WM4

Equipment	**Heating Method**	**Model**	**Thermal Power (kW)**	**Nominal Efficiency (%)**
WM4	Hot Air Generator using Natural Gas and Electrical Resistances	Blowtherm IH/AR 100	105.1	78.7

The following table presents performance data for the hot air generator. This was obtained from a study previously conducted by EWEN, and allows the value used for the generator efficiency to be realistic.

Table 6.9: Thermal performance of current gas-fired hot air generator

Parameter	**Machine 1**
Exhaust gas temperature (řC)	185
Combustion air temperature (řC)	20
O_2 concentration in exhaust gases (%)	6.5
CO concentration in exhaust gases (%)	0.0
CO_2 concentration in exhaust gases (%)	8.4
Sensible heat losses in dry gases (%)	11.1
Radiation and convection losses (%)	5.3
Losses due to unburnt gases and purges (%)	0.0
Total thermal losses (%)	16.4
Thermal efficiency (%)	**83.6**

Due to the lack of a rating plate, it was not possible to characterise the nominal power of the electrical resistors, but electrical measurements indicate a value around 70 kW.

The WM4 burner operates with hysteresis based on the temperature inside the drum, i.e. depending on the operating mode and the required temperature, a thermal sensor indicates whether or not it is necessary to activate its operation.

Figure 6.7: Washing Process

6.2.1.2 Energy Analysis

The total natural gas consumption for this industrial unit in 2024 was obtained through e+Monitor, and were as shown in this table:

Table 6.10: Total NG Consumption in VL - 2024

Month	**Consumption (m^3)**
January	918.9
February	1160.2
March	1666.0
April	1045.4
May	615.4
June	663.2
July	878.1
August	96.9
September	427.7
October	841.7
November	920.5
December	553.1
Total	**9787.1**

The visible decrease in August is related to the interruption of factories during that month.

Using e+Monitor, it was also possible to determine the specific consumption of the washing machines, described in the following graph:

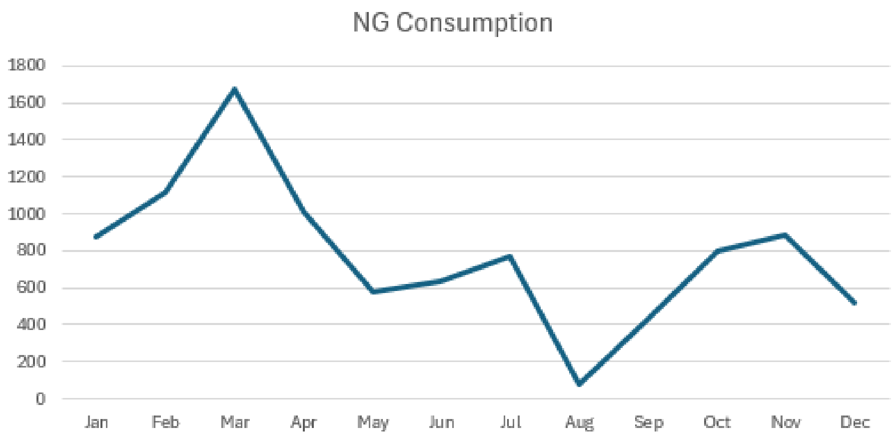

Figure 6.8: NG Consumption in VL - 2024 (m^3)

Table 6.11: NG consumption by washing machines in 2024

Month	**Consumption (m^3)**
January	874.0
February	1116.8
March	1672.6
April	1010.2
May	578.6
June	633.3
July	769.1
August	81.1
September	430.5
October	802.8
November	848.9
December	516.6
Total	**9374.5**

This shows that these washing machines are responsible for almost all the NG consumed in this industrial unit.

Based on 2024 data, the total natural gas consumption regarding the drying stage within the washing machines was:

$$E_{\text{consumed}} = 9374{,}5 \text{ m}^3 \tag{6.64}$$

Using the conversion factor from natural gas volume to energy content:

$$1\,000 \text{ m}^3\, NG = 37{,}9 \text{ GJ}$$

we obtain:

$$E_{\text{consumed}} = 9374{,}5 \times \frac{37{,}9}{1000} \approx 355 \text{ GJ} \tag{6.65}$$

Converting to kWh:

$$1 \text{ GJ} = 278 \text{ kWh}$$

$$E_{\text{consumed}} = 355 \times 278 \approx 99 \text{ MWh} \tag{6.66}$$

Assuming a thermal efficiency of 83.6% for the gas system, as shown in Table 6.9, the useful energy delivered to the drying process is:

$$E_{\text{useful}} = 99 \times 0{,}836 \approx 83 \text{ MWh} \tag{6.67}$$

Emissions To ease the calculations, the current washing system is assumed to consume approximately 100 000 kWh_{PCI}/year from the gas-fired hot air generator and 70 000 kWh/year of electrical energy from resistive heaters. To quantify the associated emissions, we apply the official emission factors: 64.1 kgCO_2/GJ for natural gas and 0.2243 kgCO_2/kWh for electricity.

First, we convert the gas energy from kWh_{PCI} to GJ:

$$E_{\text{NG}} = \frac{100\,000}{278} \approx 360 \text{ GJ} \tag{6.68}$$

Then, the emissions from gas combustion are:

$$360 \times 64.1 \approx 23.1 \text{ tCO}_2 \tag{6.69}$$

The emissions from electricity use are:

$$70\,000 \times 0.2243 \approx 15.7 \text{ tCO}_2 \tag{6.70}$$

Taking both contributions together, the total annual CO_2 emissions from this thermal process are:

$$\text{Emissions}_{\text{total}} = 23.1 + 15.7 = 38.8 \text{ tCO}_2/\text{year} \tag{6.71}$$

6.2.1.3 Electrification Proposal

As part of the proposed electrification strategy for the cork washing process, a technically viable and energy-efficient measure consists in introducing a medium-temperature heat pump to preheat the intake air before it is used in the drying cycle. The current configuration relies mainly on electric resistances for heating, while a gas-fired hot air generator is only used during specific modes of operation that require higher thermal loads.

The thermal process heats the air from ambient temperature ($T_{\text{initial}} = 20\,^{\circ}\text{C}$) up to the target drying temperature ($T_{\text{final}} = 110\,^{\circ}\text{C}$). The proposed electrification strategy introduces a heat pump that preheats the intake air to $T_{\text{preheated}} = 40\,^{\circ}\text{C}$, thus reducing the required thermal lift and substituting part of the thermal demand previously met by the HAG.

Hot Air Generator Circuit The proportion of energy displaced from the HAG due to this preheating step is given by:

$$\text{Savings}_{\%} = \frac{T_{\text{preheated}} - T_{\text{initial}}}{T_{\text{final}} - T_{\text{initial}}} = \frac{40 - 20}{110 - 20} \approx 22.2\,\% \tag{6.72}$$

The total useful thermal energy currently supplied by the HAG (that has a thermal efficiency of approximately 84%) to the process is estimated at:

$$E_{\text{useful,HAG}} = 100\,000 \times 0,84 = 84\,000\,\text{kWh/year} \tag{6.73}$$

$$E_{\text{saved,HAG}} = \frac{84\,000 \times 0,222}{0,84} = 22\,222\,\text{kWh/year} \tag{6.74}$$

The amount of useful energy replaced by the heat pump is estimated at:

$$E_{\text{replaced,HAG}} = E_{\text{useful,HAG}} \times \text{Savings}_{\%} = 84\,000 \times 0.222 \approx 18\,667\,\text{kWh/year} \tag{6.75}$$

To supply this energy, a heat pump with a coefficient of performance (COP) of 3.0 is proposed, requiring:

$$E_{\text{elec,HAG}} = \frac{E_{\text{replaced,HAG}}}{COP} = \frac{18\,667}{3} \approx 6\,222\,\text{kWh}_e/\text{year} \tag{6.76}$$

Resistors Circuit In parallel to the hot air generator, the current drying process also relies on electrical resistive heaters, which supply thermal energy with nearly perfect efficiency. The system consumes approximately:

$$E_{\text{RES}} = 70\,000\,\text{kWh/year} \tag{6.77}$$

Given the efficiency of resistive heating is essentially 100%, this energy is fully converted into useful heat:

$$E_{\text{useful,RES}} = E_{\text{RES}} = 70\,000\,\text{kWh/year} \tag{6.78}$$

The proposed heat pump system is expected to replace part of this load, providing:

$$E_{\text{replaced,RES}} = E_{\text{useful,RES}} \times \text{Savings}_{\%} = 70\,000 \times 0,222 \approx 15\,540\,\text{kWh/year} \tag{6.79}$$

Assuming the same coefficient of performance (COP) of 3.0 as in the gas system, the electrical energy required by the heat pump to deliver this useful energy is:

$$E_{\text{elec,RES}} = \frac{E_{\text{replaced,RES}}}{COP} = \frac{15\,540}{3} \approx 5\,180\,\text{kWh}_e/\text{year} \tag{6.80}$$

Based on these simulation data, this preheating strategy is expected to substitute 18 667 kWh of useful thermal energy currently provided by the gas circuit and 15 540 kWh from the resistive heating system, totalling:

$$E_{\text{useful}} = 18\,667 + 15\,540 = 34\,207\,\text{kWh} \tag{6.81}$$

Assuming the conservative coefficient of performance (COP) of 3.0, the total electrical energy required to supply the same amount of useful heat would be:

$$E_{\text{elec}} = \frac{E_{\text{useful}}}{\text{COP}} = \frac{34\,207}{3} \approx 11\,402\,\text{kWh} \tag{6.82}$$

This implies a substantial reduction in primary energy use, especially in the natural gas subsystem.

In summary, the combined analysis of both the gas-fired hot air generator (HAG) and the electrical resistance (RES) circuits reveals that a total of 34 207 kWh of useful thermal energy can be supplied by a heat pump system, partially replacing the existing sources. This electrification measure not only significantly reduces primary energy consumption, but also enables an overall optimisation of operating costs. The next section outlines the economic impacts based on these baseline values.

6.2.1.4 Economical Evaluation

Hot Air Generator Circuit Assuming an energy price of 40 /MWh for natural gas and 100 /MWh for electricity, the avoided cost of gas is:

$$c_{\text{NG,avoided}} = 22\,222 \times \frac{40}{1000} = 889/\text{year} \tag{6.83}$$

where 22 222 kWh is the primary energy avoided. The new electricity cost is:

$$c_{\text{elec}} = 6\,222 \times \frac{100}{1000} = 622/\text{year} \tag{6.84}$$

The net annual savings from electrifying this share of the GAQ system are, therefore:

$$\text{Savings}_{\text{GAQ}} = 889 - 622 = 267/\text{year} \tag{6.85}$$

The cost per unit of useful energy produced by the GAQ can also be calculated as:

$$\text{Cost}_{\text{kWh,GAQ}} = \frac{40}{0,84} = 47,6\,/\text{MWh}_{\text{useful}} \tag{6.86}$$

Resistors Circuit Assuming a unit cost of electricity of 100 /MWh, we can estimate the energy costs before and after the intervention:

$$c_{\text{RES,original}} = 15\,540 \times \frac{100}{1000} = 1\,554\,/\text{year} \tag{6.87}$$

$$C_{\text{RES,new}} = 5\,180 \times \frac{100}{1000} = 518\,/\text{year} \tag{6.88}$$

Thus, the expected economic savings in the resistive heating circuit are:

$$\text{Savings}_{\text{RES}} = 1\,554 - 518 = 1\,036/\text{year} \tag{6.89}$$

This means that, with the installation of a heat pump to pre-heat the intake air would result in a a total of:

$$\text{Savings}_{\text{total}} = 267 + 1\,036 = 1\,303\,/\text{year} \tag{6.90}$$

6.2.1.5 Environmental Impact

To quantify the environmental benefits of the proposed electrification strategy, we calculate the difference between current gas and resistive heating emissions and the emissions associated with the new heat pump electricity consumption. The emission factors used are those that were used before, both for natural gas and electricity generation.

The amount of natural gas replaced corresponds to 22 222 kWh_{PCI}/year (6.74), equivalent to:

$$E_{\text{GN,replaced}} = \frac{22\,222}{278} \approx 80\,\text{GJ} \tag{6.91}$$

The associated avoided emissions from natural gas are:

$$\text{Emissions}_{\text{NG,avoided}} = 80 \times 64,1 \approx 5,1\,\text{tCO}_2 \tag{6.92}$$

The avoided electricity consumption from resistive heating, from the results of equation 6.79 is:

$$\text{Emissions}_{\text{RES,avoided}} = 15\,540 \times 0,2243 \approx 3,5\,\text{tCO}_2 \tag{6.93}$$

The new electricity consumption by the heat pump totals 11 402 kWh, as shown in equation 6.82. This results in new emissions of:

$$\text{Emissions}_{\text{BC}} = 11\,402 \times 0,2243 \approx 2,6\,\text{tCO}_2 \tag{6.94}$$

The net emissions avoided annually are, therefore:

$$\text{Emissions}_{\text{avoided}} = (5,1+3,5) - 2,6 = 6\,\text{tCO}_2/\text{year} \tag{6.95}$$

As demonstrated, replacing the existing cork drying system with a fully electric heat pump configuration allows a significant reduction in carbon emissions. The analysis revealed that this transition would reduce emissions by approximately 6 tCO_2 per year, taking into account both the emissions avoided from natural gas combustion and the new emissions associated with electricity consumption.

This reduction corresponds primarily to a decrease in Scope 1 emissions, as it directly eliminates the combustion of fossil fuels. Although some Scope 2 emissions remain due to the carbon intensity of grid-supplied electricity, the net environmental gain is still substantial. This benefit could be further enhanced if part of the electricity used by the heat pump is sourced from on-site PV generation or other renewable sources.

Aligned with the objectives of the CSRD and the ESRS E1 standard, this measure directly contributes to the company's decarbonisation efforts. By reducing Scope 1 emissions and increasing the transparency and traceability of energy-related disclosures, the electrification of this process supports the overall sustainability strategy and reinforces the credibility of the organisations environmental reporting.

Chapter 7

Conclusions

This dissertation aimed to evaluate the potential for electrifying thermal processes within the cork industry, with a clear focus on reducing Scope 1 emissions and, therefore, supporting compliance with the Corporate Sustainability Reporting Directive (CSRD). Through the detailed analysis of three different industrial units belonging to Corticeira Amorim, the work aimed to assess not only the technical feasibility of electrification, but also its economic and environmental impact.

The case studies developed for Socori 2 and Discork demonstrated that replacing fossil-fuelled steam boilers with electric alternatives is both technically viable and environmentally beneficial. In both cases, significant reductions in direct equivalent CO_2 emissions were observed and operational cost savings were also identified, particularly when factoring in the increasing cost of carbon and the integration of on-site photovoltaic generation. Although technical restrictions and energy profiles varied between sites, the general conclusion remains that electrification can be implemented without compromising process performance, while at the same time reducing the companys reliance on fossil fuels.

Although the analysis of the V&L unit remains subject to further development, substantial progress has been made in characterising the energy and emissions profile of the proposed electrification scenario. The replacement of gas-dependent systems with electric heating technologies has shown measurable gains in efficiency and emissions reduction.

It is worth noting that the results are specific to each site and depend on a number of factors, including the existing infrastructure, energy contracts, equipment lifetimes and operational schedules. Still, the methodology applied in this study offers a replicable framework that can be used in other contexts within the group or even in other industrial sectors facing similar challenges.

Ultimately, this work shows that electrification is more than just a technical upgrade, it is a strategic tool for industrial decarbonisation, cost control, and alignment with emerging sustainability regulations such as the CSRD. The case for electrifying thermal processes in the industry will only become stronger with time, as we walk a path towards carbon neutrality.

7.1 Future Work

Although this dissertation provides a practical and data-driven assessment of electrification options within the cork industry, there are still areas that could benefit from further exploration.

One obvious extension would be the completion and refinement of the analysis for the V&L unit, particularly with regard to the interaction between electrified systems and local renewable generation. This can also be extended to the other case studies, where future work could explore how increased self-consumption of on-site solar or integration with local energy communities might further reduce emissions and improve economic performance.

Although CAPEX, OPEX and payback periods were calculated for each scenario, the economic evaluation could be significantly strengthened through sensitivity studies. Exploring variations in electricity prices, unexpected maintenance costs, or changes in system efficiency would offer a more robust view of financial risk. It would also be valuable to factor in fiscal incentives, public subsidies, and long-term trends in fuel and electricity markets, which can greatly influence investment decisions.

From an environmental perspective, while the study focused on avoided CO_2 emissions, a more complete picture could be drawn by assessing the full life cycle of the equipments involved, from production to end-of-life. This would help quantify the total emissions of electric systems and clarify any trade-offs, such as shifting away from internally sourced biomass. In addition, broader environmental benefits like reductions in local pollutants (NO_x, SO_x), improved air quality, and even reputational gains could be included in future work.

Finally, it would be useful to further explore the scalability of the approaches proposed here. This means not only applying the methodology to other thermal processes or production lines within Corticeira Amorim, but also adapting it to other industrial sectors facing similar decarbonisation challenges. The framework developed throughout this dissertation has the potential to support decision-making beyond the specific sites analysed.

In short, while the results presented here are encouraging, there is still room to push the analysis further technically, operationally, and strategically, so that electrification becomes a real focus when it comes to industrial decarbonisation planning.

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