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DISSERTATION

CIRCULAR ECONOMY AS A PATHWAY TO DECARBONIZATION: A CASE STUDY

BEATRIZ DA PAIXÃO LUÍS

SUPERVISOR: PROF. DRA. GRAÇA MARIA DE OLIVEIRA MIRANDA SILVA

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ABSTRACT

The urgency to decarbonize the global economy has led companies to adopt alternative business models that reduce environmental impact, while maintaining operational efficiency. Circular Economy (CE) strategies have emerged as a key pathway in this transition, enabling the reuse of resources, reduction of waste, and innovation in production systems.

This study aims to understand how CE practices are implemented in a company in the energy sector. Specifically, it examines PRIO, a leading Portuguese biofuel producer. The study adopts an exploratory qualitative case study approach. By analyzing PRIO's implementation of CE practices, this study examines how circular strategies can be embedded in industrial processes to contribute to the energy transition.

The findings reveal that PRIO applies CE principles throughout its value chain, particularly through the production of advanced biofuels derived from used cooking oil and industrial food waste. The company promotes circular initiatives supported by internal innovation programs, awareness campaigns, and investment in technologies for water reuse and waste recovery. As a result, PRIO has reduced its carbon footprint and reinforced its contribution to the energy sector decarbonization, in line with the Sustainable Development Goals (SDGs).

This research contributes to the understanding of how CE practices can accelerate the decarbonization of the energy sector and reinforces the importance of innovation, collaboration, and regulatory alignment in supporting the transition to a sustainable energy future.

Keywords: Circular Economy; Decarbonization; Energy Sector; Biofuels; Energy Transition; Barriers and Enablers of CE

RESUMO

A urgência de descarbonizar a economia global tem levado as empresas a adotar modelos de negócio alternativos que reduzam o impacto ambiental, mantendo a sua eficiência operacional. As estratégias de Economia Circular surgem como um caminho fundamental nesta transição, ao permitirem a reutilização de recursos, a redução de resíduos e a inovação nos sistemas de produção.

O objetivo do presente estudo é compreender de que forma são implementadas práticas de Economia Circular numa empresa do setor energético. Em particular, analisar o caso da PRIO, uma das principais produtoras de biocombustíveis em Portugal. O estudo adota uma abordagem qualitativa exploratória e recorre ao método de estudo de caso. Através da análise da implementação das práticas de Economia Circular na PRIO, pretende-se averiguar como é que estratégias circulares podem ser integradas nos processos industriais para contribuir para a transição energética.

Os resultados obtidos revelam que a PRIO aplica os princípios da Economia Circular ao longo de toda a sua cadeia de valor, particularmente através da produção de biocombustíveis avançados a partir de óleos alimentares usados e resíduos da indústria alimentar. A empresa promove ainda iniciativas circulares através de programas internos de inovação, campanhas de sensibilização e investimentos em tecnologias de reutilização de água e valorização de resíduos. Desta forma, a PRIO reduziu significativamente a sua pegada carbónica e reforçou o seu contributo para a descarbonização do setor energético, em alinhamento com os Objetivos de Desenvolvimento Sustentável.

Esta investigação contribui para uma melhor compreensão de como as práticas de Economia Circular podem acelerar a descarbonização do setor energético e destaca a importância da inovação, da colaboração e do alinhamento regulatório no apoio à transição para um futuro energético sustentável.

Palavras-chave: Economia Circular; Descarbonização; Setor Energético; Biocombustíveis; Transição Energética; Barreiras e Facilitadores da Economia Circular

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

CE – Circular Economy

CO_2 – Carbon Dioxide

CSRD – Corporate Sustainability Reporting Directive

EEA Grants – European Economic Area Grants

EMF – Ellen MacArthur Foundation

ESG – Environmental, Social, and Governance

EV – Electric Vehicle

GHG – Greenhouse Gas

HVO – Hydrotreated Vegetable Oil

I4.0 – Industry 4.0

IoT – Internet of Things

ISCC – International Sustainability & Carbon Certification

KPIs – Key Performance Indicators

LPG – Liquefied Petroleum Gas

SDGs – Sustainable Development Goals

UCO – Used Cooking Oil

1.Introduction

The rapid growth of the world population and economy raises concerns regarding the increase in energy demand, which continues to rely heavily on fossil fuels - the main drivers of global climate change - that will become scarce quickly if not replaced by sustainable alternatives (Cavelius et al., 2023; United Nations, 2021).

To achieve the target of keeping average global warming under 2ºC, as stipulated in the Paris Agreement, a third of oil and half of gas reserves should remain untouched until 2050. These figures rise to 60% for both reserves, when considering the more ambitious target of limiting the rise in global warming by 1.5ºC (Shapovalova, 2023; Heras & Gupta, 2023), therefore a transition to a greener form of energy is imperative.

The fossil fuel chain generates Greenhouse Gas (GHG) emissions throughout all stages - from extraction to the final use of resources - that can be categorized into upstream and downstream emissions (Shapovalova, 2023). Upstream emissions refer to the GHG emissions that primarily come from energy consumption that supports oil and gas production from activities such as flaring, used to burn off excess natural gas that cannot be used or sold (Iswara et al., 2022). The oil refining industry ranks as the third largest source of GHG emissions from stationary sources (Ma et al., 2023), accounting for approximately 6% of the GHG emissions of the refining industry (Gregory & Geels, 2024). On the other hand, downstream emissions are the most significant and relate to the combustion of fossil fuel, which is the primary source of GHG emissions globally (Shapovalova, 2023).

Thus, the role of this industry in the energy transition is crucial, specifically through the production of green hydrogen and biofuels (McKinsey & Company, 2022). Biofuels are a promising green alternative to conventional fuels that come from biomass, such as plants and organic waste, and are integrated into the CE framework by converting waste into energy (Ye et al., 2024). These fuels can be blended with fossil fuels or used as direct substitutes within existing infrastructure, enabling a transition without major system alterations (El-Araby, 2024). Biofuels not only address climate change but also foster agricultural diversity, energy security and rural development (Hasan et al., 2023), thus playing a significant role in the achievement of the Sustainable Development Goals (SDGs) of the Agenda 2030 proposed by the United Nations, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Raman et al., 2025).

There is a clear urgency to study the implementation of these CE strategies in the energy sector, particularly in the oil and gas industry, as it is a major contributor to climate change through environmental impacts such as air and water pollution, habitat destruction and GHG emissions

(Ozowe et al., 2024). As a result, the energy sector is under major pressure from stakeholders to mitigate its environmental footprint (Okeke, 2021), prompting companies to implement sustainable business practices, with a strong focus on the adoption of CE initiatives in their operations (Adebayo et al., 2024).

As part of the European Union's commitment to promoting renewable energy, Portugal stands out as one of the leading biodiesel producers in the European Union, particularly biodiesel derived from used cooking oil (UCO), a widely used form of biofuel (Ferrusca et al., 2023). The present study presents a case study of the company PRIO, the largest Portuguese producer of biofuels, and one of the biggest producers of biodiesel in Europe.

Hence, the primary purpose of the present study is to answer the following research question:
"How is PRIO implementing Circular Economy strategies in its operations?"

More specifically, the present study aims to identify the CE strategies implemented by PRIO, identify barriers and enablers found in the implementation of these CE practices, and explore what CE strategies will be implemented in the near future by this company.
To address the research question and achieve the proposed objectives, this study adopts a single case study research design, with semi-structured interviews being the primary source of data collection, complemented by document analysis.

The present dissertation is divided into six chapters, the first one being this introductory approach to the theme of the study, followed by the second chapter where scientific literature on the topic was reviewed to provide further context. The third chapter addresses the methodology chosen for this study, as well as a detailed description of how the data was collected and an overview of the company under analysis.
The fourth chapter consists of the presentation of pertinent findings and subsequent discussion of results in chapter five. Lastly, the sixth chapter presents the conclusions and limitations of the present study, along with recommendations for future research.

2. Literature Review

2.1. Circular Economy

The traditional linear model of "take-make-dispose", established in the early days of industrialization, leads to scarcity, volatility, and pricing levels that are unaffordable for our economy's manufacturing base (Ellen MacArthur Foundation, 2013), by relying on large quantities of cheap and easily accessible materials and energy (European Parliament, 2023). The linear model that has shaped commerce since the Industrial Revolution is inherently flawed, limiting the extent to which design can enhance processes and products to minimize environmental impacts (Orebäck, 2022). In response to these limitations, an increasing number of governments and companies are recognizing the growing importance of shifting towards a CE paradigm to address resource scarcity and environmental challenges (Maher et al., 2023). CE has gained significant recognition for its ability to address emerging global issues related to sustainability, resource efficiency, and economic growth. (Ahmadov et al., 2023). It embodies the idea of "closing the loop" in the production process, thus creating a restorative system where waste can be repurposed (D'Angelo et al., 2023), with a particular focus on urban and industrial waste, thereby promoting a better balance between economy, environment and society (Ghisellini et al., 2016).

This model involves designing products with a focus on their entire lifecycle - from initial use through to reuse and eventual value recovery - such that the outputs of one production cycle are repurposed as inputs for subsequent cycles (Orebäck, 2022). Hence, the core principles of CE include the **elimination of waste and pollution**, which emphasizes creating products and processes that minimize or entirely avoid waste generation; **keeping products and materials in use**, aimed at extending the life of resources through strategies like repair, reuse, and recycling; and **regenerating natural systems**, promoting practices that restore environmental health and utilize renewable resources. (Ellen MacArthur Foundation, 2013).

The concept of CE was first introduced in 1966 by Kenneth E. Boulding, who described our planet as a closed system where resources are finite and cannot be perpetually extracted and discarded. The author proposed a shift towards cyclical models, emphasizing the reuse and recycling of materials and energy to ensure sustainability and reduce waste.

The evolution of the CE concept can be divided into three main phases. In the first phase, between 1970 and 1990, Europe and the US implemented policies focused on pollution reduction and waste management and the 3R concept of 'reduce, reuse and recycle' gained more attention. The awareness for the relation between local and global issues became more evident and recycling rates grew considerably between the 1980s and 1990s.

In the second phase, between 1990 and 2010, environmental issues began to be seen as economic opportunities for organizations, based on improved efficiency and reputation gains. The focus shifts from absolute reduction to concepts like Industrial Ecology and life cycle thinking. System thinking grows, driven by scientific data on global issues and enhanced information sharing through digitalization.

The third phase, from 2010 onwards, is characterized by a growing concern for human survival, threatened by phenomena like unsustainable population growth and resource depletion. This phase emphasizes the need for decoupling economic growth from resource use, highlighting Circular Economy's potential as a solution to these pressing challenges (Reike et al., 2018).

There are multiple ways to define the concept of Circular Economy (Lieder & Rashid, 2016). However, the most renowned definition was proposed by the Ellen MacArthur Foundation (EMF) (Geissdoerfer et al., 2017), as "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" (EMF, 2013).

CE operates at three different levels: micro, meso and macro (Kristensen & Mosgaard, 2020). At the micro level, individual firms integrate CE principles into their operational and production procedures. The meso level emphasizes inter-firm cooperation, such as eco-clusters, to achieve sustainable development goals. At the macro level, policymakers implement national-level strategies to promote sustainability (Nikolaou et al., 2021).

2.2. Circular Economy Practices

Transitioning to a circular model requires a shift in the business paradigm (European Environment Agency, 2016) and its successful implementation largely depends on the effective adoption of CE practices (Khan & Haleem, 2021). These practices consist of a set of initiatives formulated to implement CE solutions in economic systems (Morseletto, 2020) and are implemented through a multi-level perspective that considers the micro, meso and macro levels (Heshmati, 2015).

At the micro-level, the implementation of CE practices relies on corporate-level strategies such as eco-design and cleaner production (Geng & Doberstein, 2008). The focus at the micro-level is about improving the sustainable performance of a particular organization through practices that involve recycling, end-of-life management, waste management and resource efficiency (Khalifa et al., 2022).

The meso-level is characterized by companies integrated into ecosystems of industrial symbiosis where separate organizations collaborate to obtain mutual benefits (Khalifa et al., 2022). These collaborations involve the recovery of material and the creation of markets for recycled materials (Abreu & Ceglia, 2018), which subsequently benefit the regional economy and natural environment (Prieto-Sandoval et al., 2018).

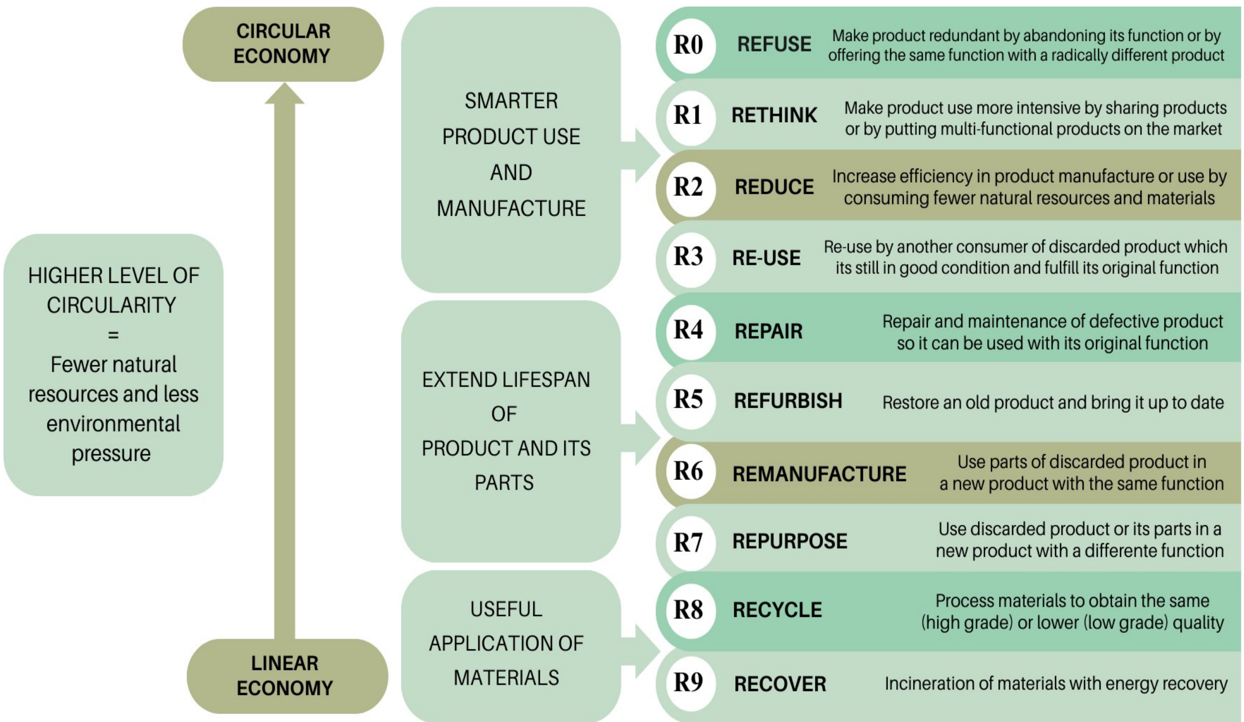
Macro-level integration of CE practices involves initiatives led by governments and policymakers (Khalifa et al., 2022). At this level, a micro-macro interaction occurs, characterized by an exchange of knowledge and policy shaping where firms give feedback that influences policymaking, which in turn affects micro-level compliance (Ahmadov et al., 2023). In this context, the implementation of CE practices is also increasingly regarded as an effective pathway to achieve the SDGs (Oliveira & Oliveira, 2022). The United Nations 2030 Agenda for Sustainable Development includes 17 SDGs and 169 targets that were presented in 2015 as a global framework to transition to a more sustainable planet. This Agenda recognizes the nature of challenges such as poverty, hunger, gender equality and environmental degradation, and states that these issues must be addressed collectively to achieve sustainable development (Weiland et al., 2021). CE initiatives contribute to all 17 SDGs, with relevant impacts on SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), and SDG 13 (climate action) (Garcia-Saravia Ortiz-de-Montellano & Rosano, 2023), but also address global issues from affordable clean energy (SDG 7) to sustainable consumption and production (SDG 12) (Ferraz & Pyka, 2023). The adoption of CE models enables businesses to contribute immensely to the achievement of SDGs, especially through the R-strategies **R3** reuse, that impacts 14 out of 17 SDGs, and **R2** reduce, **R4** repair, **R5** refurbish and **R6** remanufacture, which have a particular impact in SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Garcia-Saravia Ortiz-de-Montellano & Rosano, 2023).

Regarding the classification of CE strategies, there is a lack of consensus on a standardized approach. After reviewing 114 definitions of CE from existing literature, Kirchherr *et al*. (2017) identified a range of CE definitions that included strategies from 3R's (reduce, reuse, recycle) to 9R's (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover). In a more recent paper, the same authors state that the most mentioned framework in literature at the moment is the 4R framework (reuse, reduce, recycle and recover), largely driven by mentions of the 'recover' R-strategy (Kirchherr *et al*., 2023).

The R-strategies cover the entire lifetime of a product – from the extraction of resources to the end of its life (DIN, 2024) - and aim to create, preserve, and recover the value of inputs, thus promoting resource efficiency and mitigating environmental impacts across value chains. (European Circular Economy Stakeholder Platform, 2020).

Even though R's framework differs throughout literature, most authors establish an order of priority for the importance of strategies in achieving circularity (Henry et al., 2020) These strategies can be categorized into three distinct groups: start of design (resource extraction), product life (production and use) and end of life (end of use) (DIN, 2024).

Figure 1. *Circularity Strategies within the production chain in order of priority*



Source: Adapted from Potting et al. (2017)

Figure 1 summarizes the R's strategies and depicts the transition from a linear economy to a circular economy, going in an ascending order of priority, from R0 to R9, of strategies that reduce consumption of resources and generate waste (Potting et al., 2017).

R0-R2 strategies that fit into the "smarter product use and manufacture" category, are a top priority when implementing CE due to their efficiency in using fewer resources to deliver the same utility. These R-strategies hold an extreme importance because, if applied extensively, they allow the elimination of waste early in the value chain (Malooly & Daphne, 2023) since they precede other CE practices and support the implementation of subsequent strategies (Morseletto, 2020).

Intermediate priority is attributed to **R3-R7** strategies that fall under the "extend lifespan of products and its parts" category. These strategies aim to lengthen a product's lifespan by retaining finished goods and their components in the economy for a longer period, while maintaining or improving their value (Morseletto, 2020). For these practices to be effective, they depend on a receptive market, efficient reverse logistics systems, and ensuring profitability for the stakeholders involved (Malooly & Daphne, 2023).

Although recycling is the most mentioned R-strategy among CE definitions (Kirchherr *et al*., 2017), in a CE model the emphasis should be on avoiding the need to recycle by preventing the generation of waste from the start (World Economic Forum, 2019).

This approach aligns with the prioritization within CE strategies, where **R8 and R9** -recycling and energy recovery - rank lowest. When earlier efforts to reduce waste are insufficient, the last resort within the R-framework, R8 Recycle and R9 Recovery, come into play. These strategies manage materials that would otherwise end up in landfills and recover energy through incineration. Although they are at the bottom of priority in the R-framework hierarchy, they play a crucial role when industries are still producing waste (Malooly & Daphne, 2023).

It is important to notice this hierarchy is defined as a 'rule-of-thumb' because the order may vary when considering certain products and processes. This acknowledges the existence of exceptions; however, this hierarchy still provides valuable orientation when analyzing CE strategies in most cases (Morseletto, 2020).

To successfully implement these CE practices, companies rely on digital innovation. Industry 4.0 (I4.0) technologies, such as Internet of Things (IoT), Artificial Intelligence, Big Data and Blockchain, play an important role in the transition to a circular business model (Sun & Wang, 2022). These technologies provide organizations with a digital infrastructure that allows to track resource flows, lifecycle management of products, material and energy consumption and enable data-driven decision making that increases efficiency and performance (Ciano et al., 2025; Chauhan et al., 2022; Rajput & Singh, 2019). For example, IoT connects devices and systems in a way that allows companies to monitor material flows and production activities in real time, enabling them to use resources efficiently and cut down on waste (Rejeb et al., 2022). Additionally, I4.0 technologies contribute to the reduction of energy use, material consumption, and Carbon Dioxide (CO_2) emissions by enabling data-driven monitoring and traceable analysis throughout the supply chain (Bai et al., 2020).

Furthermore, to monitor the implementation of these CE practices, companies use specific indicators, such as Key Performance Indicators (KPIs), which provide quantitative measures to assess performance and guide their strategic decisions by tracking indicators related to resource efficiency, waste management, and material retention (Moraga et al., 2019). To complement the KPIs, frameworks have emerged to assess circularity such as the Material Circularity Indicator, that quantifies the restorative potential of material flows by accounting for factors like input origin and end-of-life treatment, and Circulytics, that evaluates not only material flows but also the organizational enablers of circularity, such as innovation, strategy, and operations (EMF, 2015; EMF, 2021). The I4.0 technologies also play an important role to collect, track, and analyze the data required to use these indicators (Bai et al., 2020).

2.3. Barriers and Enablers of Circular Economy

The shift from a linear to a circular business model brings several benefits for firms (Rizos et al., 2016). CE implementation allows firms to gain competitive advantage in the long run by lowering environmental costs, meeting market requirements (Preston, 2012), fostering company value creation, elevating processes and production and promoting resource efficiency (D'Angelo, 2022). However, companies implementing CE strategies face a multitude of barriers, (Rizos et al., 2021) that can be located either within the company itself or in the external environment (Govindan & Hasanagic, 2018), explained by the profound change in industrial practice and patterns of consumption required for this implementation (Preston, 2012).

Galvão et al. (2018) reviewed 195 articles on barriers and identified the most frequently mentioned as: **technological, policy and regulatory, financial and economic, managerial, performance indicators, customer-related, and social barriers**.

Technological barriers are rooted in the lack of expertise and technical know-how to transition from linear to circular product life cycles (Melati et al., 2021). The limited knowledge and technical know-how hinder the transition from a linear business model to a circular one. This transition requires new sustainable production and consumption technologies and trained professionals to manage them (Rizos et al., 2016). The combination of inadequate knowledge and insufficient investment in circular-oriented technologies, such as eco-design, often leads firms to persist with linear strategies instead of adopting circular ones (Tan et al., 2022). I4.0 technologies including IoT, cloud manufacturing and cyber-physical systems can facilitate the implementation of CE strategies by enabling more efficient resource management and supporting closed-loop production processes (Hina et al., 2022).

Policy and regulatory barriers often stem from the absence of a concrete, coherent, and strict legislative framework that poses significant barriers to shifting away from the traditional linear model (Melati et al., 2021). Key obstacles include inadequate systems for performance assessment, ineffective recycling policies, and new and existing laws that fail to support the implementation of CE strategies. (Govindan & Hasanagic, 2018).

Financial and economic barriers are often linked to the lack of capital, including insufficient initial funding, limited access to financial opportunities, or the absence of alternatives to private investments and traditional bank financing (Rizos et al., 2016). CE business models require significant investments in technological innovation, employee training and production and sales of circular goods (Hina et al., 2022). Therefore, it is crucial that the governments introduce better economic and financial instruments for industries, such as financial support, tax reductions and incentives (Govindan & Hasanagic, 2018).

Managerial barriers often stem from the lack of support from top management (Govindan & Hasanagic, 2018). The introduction of a new process typically occurs due to pressure from stakeholders or shareholders, alongside strong commitment from top management (Govindan et al., 2015). While some managers may have a positive attitude towards CE, others may not. From a management perspective, strong leadership that goes beyond routine operations is essential, as it acknowledges the long-term efficiency and effectiveness of a circular business model (Rizos et al., 2016).

Performance indicators barriers relate to the complexity of monitoring and reporting environmental performance data, since firms are frequently required to submit data to multiple authorities in various formats (Rizos et al., 2016).

Customer-related barriers are rooted in the vital role consumers play in the transition to a more sustainable society (Tan et al., 2022), as their preferences and purchasing behaviors significantly influence companies' willingness to adopt circular business models (Melati et al., 2021). One of the major obstacles in the adoption of CE is lack of consumer awareness (Szilagyi et al., 2022), so for this transition to occur, there needs to be a shift in consumer's lifestyle and preferences (Rizos et al., 2016). Thus, consumer engagement is essential, not only to understand their expectations but also to guide them towards the adoption of habits of responsible and informed consumption (Salvioni & Almici, 2020). Scholars highlight the need for public awareness campaigns on key environmental issues like waste pollution and the risks of the linear economy, as increased awareness of sustainability leads individuals are more likely to choose greener alternatives over mass-market options (Tan et al., 2022).

Social barriers are rooted in the pivotal role social awareness plays in the transition for a CE business model (Lieder & Rashid, 2016). Ferronato et al. (2019) identified the lack of public engagement in environmental matters as a significant obstacle to implementing CE business models. Furthermore, due to several socio-cultural challenges, companies tend to prioritize extending the lifespan of their current linear-focused systems until they are forced to change or until a more appealing alternative presents itself (Tan et al., 2022).

Alongside barriers, it is vital to focus on the enablers of CE implementation because despite the presence of obstacles, there are numerous viable strategies to overcome them (Rizos et al., 2016). These enablers can help companies integrate CE practices (Melati et al., 2021) and are the motivation behind the implementation of CE business models (Govindan & Hasanagic, 2018). Rizos et al (2016), identified the main enablers of CE being: **Company environmental culture, networking, support from the demand network, financial appeal, recognition, personal knowledge and government support.**

Company environmental culture relates to the mindset and commitment that firm managers and employees have towards sustainability (Rizos et al., 2016). The implementation of sustainable initiatives within firms is profoundly influenced by organizational culture, and active promotion from top management is essential for a successful implementation. (Fietz & Günther, 2021).

Networking is rooted in the key role business collaborations and partnerships have in the implementation of CE (Hina et al., 2022). This entails joining forces with like-minded enterprises that are committed to pursuing sustainability (Rizos et al., 2016), that allows firms to share knowledge and co-develop solutions, which is essential when implementing complex CE strategies (Brown et al., 2019).

Support from the demand network highlights how consumer behavior impacts demand and subsequently, production processes (Rosário et al., 2024). The demand for sustainable products compels firms to innovate and shift towards circular business models to meet consumer expectations and this pressure is vital for the implementation of sustainable practices within industries (Lopes et al., 2023).

Financial appeal refers to the fact that the implementation of CE practices has the potential to reduce costs, increase differentiation and make firms less resource-dependent (Melati et al., 2021), therefore increasing the long-term generation of revenue through recycling and manufacturing activities (Govindan & Hasanagic, 2018).

Recognition relates to external recognition of a sustainable business model, such as awards, prizes, certificates, or favorable treatment in government project tender procedures (Rizos et al., 2016). These incentives are crucial in mitigating risk aversion among firm managers, thus enabling the integration of CE practices into their business models (Tan et al., 2022).

2.4. Circular Economy in the Energy Sector

GHG emissions have been the primary driver of climate change since the 20th century (Ghazanfari, 2023), and the acceleration of global warming has become one of the major issues of the 21st century (Xu et al., 2022). Energy generated from fossil fuels accounts for more than 75% of global GHG emissions and 90% of CO_2 emissions (Osman et al., 2023), with approximately 34 billion tons of CO_2 being released each year (Ghazanfari, 2023). This led to an increasing urgency in world leaders to decarbonize the global economy that is reflected in the goals of 45% reduction of carbon emissions by 2030 and carbon neutrality by 2050, as stipulated by the Paris Agreement adopted by 196 nations in 2015 (Yang et al., 2022). By 2040, global energy demand is expected to increase by 56% (Rahman et al., 2022), therefore countries are working on strategies to replace fossil fuels with renewable sources of energy to mitigate these climatic impacts as much as possible (Lemm et al., 2020). However, renewable energy is not completely carbon-neutral, which highlights the need for circular approaches to achieve a more efficient energy transition (Ishaq et al., 2022).

In the oil and gas industry, the main CE practices include waste reduction, recovering resources, and closed-loop systems (Adebayo et al., 2024).

Biofuels are a sustainable alternative to fossil fuels that originate from organic matter such as plant residue, animal waste and algae (Singh et al., 2024). Biomass can be converted into fuel through biochemical and thermochemical processes (Ye et al., 2024) and is a viable substitute for fossil fuels owing to its abundance, availability and renewability (Arpia et al., 2021).

Biofuels are also non-toxic, biodegradable and sulfur-free, and produce less GHG emissions compared to fossil fuels (Cavelius et al., 2023), thus, contributing to the achievement of the United Nations SDGs, especially Goal 7 (affordable and clean energy), and Goal 13 (climate action) (Cavelius et al., 2023).

Biofuels include bioethanol, biogas, and biodiesel that are mainly used in the transport sector and heat production (Assaf et al., 2024). Biodiesel is a type of biofuel usually made from cooking oil, plant oil or animal fat (Malik et al., 2024), that is compatible with conventional diesel engines and allows a decrease in CO_2 emissions by up to 80% compared to fossil fuels (Ferrusca et al., 2023).

There are four generations of biofuels based on their feedstock and the method used to produce them (Neupane, 2023).

First-generation biofuels are mainly bioethanol and biodiesel and are produced from food crops (e.g., corn and sugarcane) that are grown exclusively for energy purposes (Singh et al., 2024). This practice is in direct competition with food production (Arpia et al., 2021), raising major food security and resource allocation concerns (Assaf et al., 2024).

Second-generation biofuels were developed with the aim to overcome the limitations faced by first-generation biofuels (Cavelius et al., 2023). They are obtained from non-food crops (e.g., crop residue, animal waste, wood, and UCO) and generate biofuels, such as biohydrogen, biodiesel, biobutanol, and bioethanol, whose by-products can be used as fertilizer (Ye et al., 2024). UCO, for instance, is a widely available feedstock that is obtained from households, restaurants, and food industries, whose improper disposal leads to soil and water pollution and presents a risk to human health. Its repurpose for biofuels offers not only a sustainable but also affordable option that allows a reduction of 70% to 80% in the production cost of biofuels (Raqeeb et al., 2015; Cerón-Ferrusca et al., 2023).

Third-generation biofuels are produced from algal biomass, which has high potential, given its high yield and low environmental impact (Singh et al., 2024). These biofuels include biohydrogen, biogas, biobutanol, bioethanol and biodiesel (Ye et al., 2024). Algal biomass grows at a rapid pace and does not require fertile land or fresh water, therefore not competing with the food industry, while also promoting the reallocation of unsustainable farming and fishing practices to unproductive regions (Assaf et al., 2024; Malik et al., 2024). This biomass requires a direct supply of CO_2, that can be collected from industrial emissions or atmospheric carbon capture, allowing for algae-derived biofuels to potentially have a negative carbon footprint due to directly sequestering GHG emissions within their biomass (Cavelius et al., 2023).

Finally, fourth-generation biofuels use genetically modified microorganisms to convert sunlight and CO_2 into biofuels (Padder et al., 2024). These biofuels, such as bioethanol, biodiesel, and biohydrogen, are considered carbon-negative due to the CO_2 capture and sequestration processes used during their production (Malik et al., 2024). This generation involves not only sequestration of CO_2 but also the development of wastewater treatment processes and reduction of GHG emissions, which results in a smaller environmental footprint than previous generations. However, research of the environmental implications of the genetic modification process is still in early stages (Assaf et al., 2024).

As of 2019, first and second-generation biofuels are still the only biofuels commercially produced (Abdullah et al., 2019), because biofuels derived from microalgae biomass remain not economically competitive compared to earlier generations (Aron et al., 2020) and require further technological development in upscaling and production cost reduction. These issues can be overcome by fourth generation biofuels, but political and public acceptance problems regarding genetically modified organisms remain, due to potential environmental or safety risks (Cavelius et al., 2023). These concerns must be addressed so they do not hinder acceptance, and widespread adoption must be encouraged through secure closed production systems, transparent risk assessments and transparent communication (Varela Villarreal et al., 2020).
Nevertheless, transitioning from first and second-generation biofuels to third and fourthgeneration biofuels is crucial, since first-generation biofuels clash with the sustainable development goal 2 (Zero Hunger) because they compete with the food production system and both first and second-generation biofuels are at conflict with the sustainable development goal 15 (Life on Land) because they require considerable land use. Hence, the latter generations of biofuels are considered the most promising pathways toward sustainable development (Aron et al., 2020).

Synthetic biofuels are emerging as a promising alternative to traditional biofuels, since they can be produced from sources such as captured CO_2 from industrial activities, surplus renewable energy and sustainable biomass, without depending on large crops, like some biofuels do (Janaki et al., 2024).
Green Hydrogen is one of the main synthetic fuels and its main advantage lies in its carbonneutral production, achieved by splitting water into hydrogen and oxygen through electrolysis powered by renewable energy sources, such as wind or solar (Maka & Mehmood, 2024). Unlike conventional fuels, green hydrogen does not release CO_2 during production, making it a promising ally to decarbonize sectors that are difficult to electrify, such as aviation, maritime transport, and heavy industry, and achieve carbon neutrality by 2050. (Doğan et al., 2025). Currently, synthetic fuels still face important production challenges related to costs, high energy demand, and the lack of clear legislation and regulatory frameworks, all of which must

be overcome through investment in infrastructure, technological development, and supportive policy measures (Scheelhaase et al., 2019; Doğan et al., 2025).

3. Methodology

The present chapter aims to describe and justify the methodological decisions of this study, including the research design, data collection methods, criteria for the selected case study and finally, a description of the targeted organization.

3.1. Research Design

High-quality research requires a well-defined research question, as it serves as a foundation that not only provides clarity and direction but also ensures methodological relevance. A strong research question helps to identify gaps in existing literature, refine research objectives and guide the selection of appropriate study designs (Ratan et al., 2019).
The present study aims to answer the following research question:

"How is PRIO implementing Circular Economy strategies in its operations?"

And includes the following objectives:

- Examine the CE strategies implemented by PRIO and its impacts.
- Identify barriers and enablers found in the implementation of these CE practices.
- Explore what CE strategies will be implemented in the future by PRIO.

For the present study, a qualitative research approach was chosen. Qualitative research seeks to understand complex phenomena through methods such as interviews, focus groups, document review, observation and ethnographic studies. This type of research aims to answer "how" and "why" questions, and unlike quantitative research, which focuses on numerical data, qualitative research focuses on context and interpretative analyses (Tenny et al., 2022; Watkins, 2012).
This study employs a single case study, that is a valuable approach in qualitative research, as it enables a deep understanding of complex organizational phenomena (Annamalah, 2024) and is especially useful when there is a need to obtain a comprehensive understanding of an event or phenomenon within its real-life context (Crowe et al., 2011).

3.2. Data Collection

In the present study, data was collected through semi-structured interviews and document analysis.

Interviews are the most used method in qualitative research (Thelwall & Nevill, 2021). In particular, semi-structured interviews allow researchers to gain in-depth insights from interviewees, while maintaining flexibility by incorporating new questions based on their responses (Ruslin et al., 2022).

During the current study, three interviews were conducted remotely, via *Microsoft Teams,* on 23rd of May 2025, 3rd of June 2025 and 5th of June 2025, and lasted an average of 50 minutes. The interviews featured employees with different roles at PRIO to ensure diversity of perspectives on the topics addressed. The first interview was held with Cristina Correia, PRIO's Innovation and Environmental, Social, and Governance (ESG) Director, the second with Inês Vieira, PRIO's Project Manager and the last one with Rosário Rocha, PRIO's Sustainability & International Sustainability & Carbon Certification (ISCC) Coordinator. To ensure clarity, throughout this dissertation the interviewees will be designated as Interviewees A, B, and C, respectively. The interview guide can be found in the Annex. It is important to note that each interview was conducted independently, meaning none of the interviewees knew each other's questions asked or answers beforehand. These interviews were conducted with the aim of obtaining in-depth information about PRIO's green practices, that only the company's employees with internal experience could provide.

Additionally, a complementary document analysis was performed to relevant company publications and PRIO's 2023 sustainability report, that at the time of this study, is the first and only one published by the company. According to Ibáñez-Forés et al. (2022), sustainability reports are an important research tool since they support companies in their transition to circular business models, by measuring, monitoring and communicating this transition and establishing future goals.

PRIO was the company chosen for the case study due to its pioneer sustainable path, particularly with the use of CE initiatives, in the Portuguese energy sector. Due to its relevance at the national level, by being the biggest biofuel producer in Portugal, and at the European level, it represents a huge player in the urgent roadmap toward decarbonization.

3.3. Company Overview

Founded in 2006, PRIO is a Portuguese energy company that has embedded sustainability into its principles since the very beginning. It began its journey by building a production plant in the Port of Aveiro and is currently the largest national biofuel producer and one of the top European biofuel producers. It entered the energy sector with the bold ambition of challenging the traditional fossil fuel industry by producing circular alternatives, thus playing a crucial role in Portugal's energy transition. Instead of treating sustainable practices as an afterthought, PRIO built its business model around them, with the aim of offering low-cost, cleaner fuels to Iberian drivers. PRIO produces biofuels for both B2B and B2C markets and operates a network of over 300 fuel stations across the Iberian Peninsula, while employing 1,047 workers.

The company's headquarters located in Aveiro, *New Energies Complex*, includes the *Biofuel Production Plant*, the *Green Energy Blending Center* and the *Liquefied Petroleum Gas (LPG) Storage and Filling Center*.

The **Biofuel Production Plant** has an annual production capacity of over 110,000 tons of biodiesel, a research and quality control laboratory which operates 24/7 that guarantees high product standards and compliance with international norms and has been operating under the ISCC since 2013, a globally recognized certification that covers all sustainable feedstocks, including agricultural and forestry biomass, circular materials, and renewables.

The **Green Energy Blending Center** has a storage capacity of over 96,000 m^3 for diesel, gasoline, biofuels, additives and 200m^3 for LPG, and allows a flexible mixing of fossil and renewable fuels, enabling PRIO to incorporate different percentages of green energy into their portfolio of fuels.

Both these centers are certified under ISO 9001 (Quality Management), ISO 14001 (Environmental Management), and ISO 45001 (Occupational Health and Safety Management).

Finally, the **LPG Storage and Filling Center** is dedicated to the handling, inspection, and refilling of PRIO's propane gas cylinders.

4. Main Results

4.1. PRIO's Circularity Strategy and Accomplishments

PRIO GREEN (2021- present)

PRIO Green is an energy transition strategy launched in 2021 that aims to support companies in their transition to decarbonize their fleets, without requiring vehicle modifications or new infrastructure. PRIO provides technical assistance and fleet analysis to identify optimal fuel solutions, ongoing support for implementation and collaboration in pilot programs and emissions monitoring. PRIO offers a portfolio of advanced biofuels, each developed to reduce GHG emissions of private fleet operators:

- **ZERO Diesel (B100):** 100% renewable biodiesel, fully fossil-free, biodegradable and compliant with diesel engines. Enables a reduction of up to 84% of CO_2 emissions in comparison to fossil fuels.
- **ZERO Diesel (HVO):** A hydrotreated vegetable oil (HVO) diesel produced from waste oils, 100% renewable, that is chemically similar to fossil diesel but does not contain aromatics or sulfur. This fuel enables a reduction of up to 90% of CO_2 emissions in comparison to traditional fuels.
- **ECO Diesel (B15):** A fuel that incorporates 15% of biodiesel blended with fossil diesel and enables a reduction of up to 18% of GHG emissions in comparison to traditional fuels and a reduction of up to 5% in fuel consumption.
- **B30 Diesel:** This fuel incorporates 30% of advanced biodiesel and allows for a reduction up to 25% in GHG emissions in comparison to fossil fuels.
- **FLEX Diesel**: A custom-blended fuel that allows tailored biofuel concentrations from 15% to 100% renewable content. It is ideal for progressive decarbonization strategies and is suited for professional clients under tailored agreements.
- **TOP Diesel**: A premium diesel with improved performance that incorporates 7% of biodiesel.
- **ECO Bunkers**: A fuel tailored for the maritime sector, that incorporates 15% of advanced biodiesel with marine diesel and allows for a reduction up to 18% of CO_2 emissions and a reduction of up to 10% in fuel consumption. PRIO is responsible for

the entire ECO Bunkers production process and ensures that it is in compliance with the parameters required by the ISO 8217 standard, specific to marine diesel.

Three examples of this project are the partnerships with the companies *Monteiro Carnes*, *Galliker* and *Francisco Sá Carneiro Airport.*

Partnership with Monteiro Carnes (2019- present)

Monteiro Carnes wanted to decarbonize its vehicle fleet but was faced with a challenge, as electrified solutions were not able to meet its needs. For this reason, ECO Diesel was presented as a great solution and that was when the partnership with PRIO started. Since 2019, as a result of this partnership, Monteiro Carnes was able to drive its fleet for 2.734 million kilometers with ECO Diesel and avoided the emission of 67 tons of CO_2.

Partnership with Galliker (2021- present)

The company Norauto wanted its service providers to become more sustainable and this led Galliker and PRIO to join forces and fuel Galliker's commercial vans with ECO Diesel. Galliker has used PRIO's ECO Diesel to fuel its vans since 2021 and has travelled 1.572 million kilometers using this biodiesel and avoided 42 tons of CO_2 emissions, besides reducing its fuel consumption by 5%.

Partnership with Francisco Sá Carneiro Airport (2024-present)

Francisco Sá Carneiro Airport in Porto has begun using PRIO's ZERO Diesel (B100) to fuel several airport vehicles, such as passenger shuttle buses and ground power units, which supply electricity to aircraft on the ground. This initiative is led by PRIO, Portway and Beyond Fuels and expected to last two years. During this period, the use of over 400,000 liters of ZERO Diesel in this airport's operations is expected to reduce CO_2 emissions by 1000 tons.

PRIO ECOWASTE (2017 - present)

Prio Ecowaste is a CE project implemented by PRIO in 2017, with the former name "TOP Level". Its focus is on the collection of UCO at the national level, that is later used by PRIO as a raw material to produce biofuels.
There are two types of UCO collection points, locally designated as *oleões:*

- **Simple UCO collection points**, found both at PRIO fuel stations and near recycling points. Anyone can deposit a plastic bottle up to six liters filled with UCO from domestic use.
- **Advanced UCO collection points,** found at PRIO fuel stations**,** where anyone can request a free mini *oleão* to take home. Once the mini *oleão* is full, it should be deposited at an advanced UCO collection point*,* that will automatically provide the customer a new free mini *oleão* to take home.

One of PRIO's main objectives with the implementation of the Ecowaste project was to collect around 30% of the 110 million liters of cooking oil sold in Portugal and develop the largest national network of UCO collection points, and that goal has been successfully achieved. Interviewee B, PRIO Ecowaste project manager, shared that, in 2024, around 90 tons of domestic UCO were collected. Currently, the network comprises over 1380 UCO collection points distributed across the country, as detailed below:

- 1242 simple UCO collection points across 60 municipal networks;
- 132 UCO collection points at 84 Prio fuel stations, including 73 advanced and 59 simple UCO collection points;
- At two private entities, that hosts 3 UCO collection points;
- At one private entity with public access, that also hosts 3 UCO collection points.

Once the UCO is collected from the collection points, it is transported, pre-treated and stored by specialized waste management operators, who subsequently forward it to PRIO for biofuel production.

One key aspect of the PRIO Ecowaste project is the close collaboration established with communities to make this initiative possible. From schools and universities to municipalities and private companies, PRIO has actively engaged in initiatives aimed at raising awareness for sustainable practices and promoting active collaboration with these entities. Interviewee A highlighted how these campaigns impact the population recycling habits: "*We've realized that once people are informed, they are indeed able to change their recycling habits. They come to understand that this type of waste (UCO), is very harmful to water if poured down the kitchen sink, or flushed down the toilet, as many people used to do*." (Interviewee A). Interviewee B explained how the collaboration with restaurants works: "*The contracts for the collection of UCO are made directly between restaurants and collectors, not with PRIO. Portuguese law requires any establishment with a kitchen to have an active waste management contract to operate. For restaurants, this partnership is beneficial: in addition to complying with the law and avoiding fines, they often receive something in return for the UCO they hand over such as cleaning services (e.g., exhaust or filter cleaning), cleaning products or a financial compensation.*" (Interviewee B). The company also ensures a strong presence at various events throughout the year, such as *Portugal Smart Cities Summit* and *GreenFest Estoril,* further reinforcing its role in the promotion of environmental responsibility.

In 2021, PRIO launched a collaborative sustainable initiative with Lisboa E-Nova and CARRIS, Lisbon's public transport operator, called **PRIO Beato Biobus (2021- present).** This initiative's main goal is to operate a dedicated bus line, CARRIS route 794, on 100% biodiesel, specifically PRIO's "Zero Diesel" fuel. This biodiesel is developed at PRIO's biofuel production plant in Aveiro, and it reduces GHG emissions by up to 84% in comparison to traditional fossil fuels. This project aims to promote the decarbonization of Lisbon's public transport fleet, by demonstrating that conventional diesel buses can run on renewable fuel without any engine modifications. A distinctive aspect of the *Beato Biobus* project is its strong community dimension: in 2022, PRIO collected 1264 liters of UCO by engaging 3500 students that study in ten schools in Lisbon, from pre-school to highschool, through the school contest *Beato Biobus*. PRIO installed advanced UCO collection points in each school and distributed a mini *oleão* per student and awarded the schools that gathered the most liters of UCO (volume collected per number of students) with educational materials and study visits. In 2024, the second edition of the Beato Biobus school contest involved 15 public schools in Lisbon and over 4500 students and avoided the release of 38.22 tons of GHG emissions. This project is integrated into the *Hub Criativo do Beato* program, and it follows a prior pilot project titled **Movido a Biodiesel** (2018–2020), in which six buses successfully ran on PRIO's biodiesel. During this pilot project, these buses carried around 2 million passengers over 340,000 kilometers, reusing 220,500 liters of UCO and avoiding approximately 500 tons of CO_2 emissions. In the future, PRIO aims to expand this CE model to additional bus routes in Lisbon, promoting carbon-neutral transportation.

In 2021, PRIO also partnered with the municipality of Cascais in a pilot project titled **Cascais Smart Pole by Nova SBE (February 2021- April 2024).** As part of this initiative, Cascais Ambiente installed 15 UCO collection points across the city and promoted an awareness campaign to encourage residents to properly dispose UCO in these collection points. The collected UCO in Cascais was forwarded to PRIO, that transformed it into biodiesel that was subsequently used to power the city's waste collection trucks.

Both projects, *PRIO Beato Biobus* and *Cascais Smart Pole by Nova SBE*, were co-funded by *European Economic Area Grants* (EEA Grants), managed by Norway, Iceland and Liechtenstein, that aim to support other countries in the promotion of sustainable development.

Interviewee A added that not only UCO is used in the production of biofuels: "*A variety of other waste types, particularly what we often refer to the term food waste, are used to produce biofuels. This includes, for example, expired margarine, industrial waste from margarine production, oils recovered from wastewater sludge, and oils extracted from coffee grounds. In other words, any oily substance rich in triglycerides that comes from other value chains. What we essentially do is use these raw materials instead of virgin feedstocks like soybean or rapeseed oil, which we used back when we started operations in 2007*." (Interviewee A).

PRIO JUMP START (2017-present)

PRIO Jump Start is an innovation program launched by PRIO to support innovative startup solutions and accelerate the energy transition. According to PRIO's 2023 sustainability report, Jump Start "was created to boost innovative ideas and foster collaboration with startups" and "particularly looks for projects in areas like circular economy, sustainable mobility, digitalization and customer experience", as interviewee C reiterated: "*The Jump Start program helps boost startups that offer sustainable solutions. It really focuses on co-creating innovative projects, especially in areas like the CE and clean energy. The goal is to strengthen PRIO's innovation ecosystem*." (Interviewee C). Each edition of the Jump Start Program involves a competitive selection process, where startups submit proposals aligned with PRIO's innovation challenges, and finalists are chosen via bootcamps and pitch rounds. There are three winners in every edition, each awarded at least 10,000€ to develop the proposed project, with on-going support from PRIO. Besides the cash prize, winners have the chance to learn from PRIO's mentorship, technical guidance and co-creation opportunities, and gain hands-on access to

PRIO's facilities and the valuable insights of applying their ideas into a real-world scenario. On the other hand, PRIO gains new solutions through these innovations for the proposed issues, that can be implemented in their operations, resulting in a symbiotic relationship, where every company gains something valuable to their activity.
Since 2017, there are three winning projects from the PRIO Jump Start program that are particularly aligned with CE:

- **PRIO x Enertecgreen (2019):** Enertecgreen is a start-up company from Latvia, who won PRIO's Jump Start Program 2019 edition and collaborated with PRIO by proposing a CE solution that transforms residual biomass, sourced from agricultural and urban waste, into advanced biofuels.

- **PRIO x Delta x Ecobean (2020)**: Ecobean is a start-up company that won PRIO's Jump Start Program 2020 edition and along with PRIO and Delta Cafés developed a CE project that transformed coffee grounds into briquettes and biodiesel. Daily, over 34 tons of coffee are consumed in Portugal and when the resulting coffee grounds end up in landfills, they release significant amounts of GHG emissions. The primary goal of this project was to close the loop in the coffee cycle by converting its waste into resources. During this initiative, coffee grounds that resulted from Delta coffee consumed in PRIO's fuel stations, was collected by Delta's vehicles, that optimized its existing logistics infrastructure to collect the coffee grounds, and sent to Ecobean that produced briquettes from this waste material. These briquettes developed for barbecues and heat were then sold at selected PRIO's fuel stations. During this process, the startup also extracted oil from coffee grounds that was sent to PRIO's biofuel plant where it was used to produce biofuel. During this initiative, 37,625 kilograms of coffee grounds were collected, and 45,150 kilograms of CO_2 emissions were avoided (Ecobean, n.d.).

- **PRIO x Evyon (2022):** Evyon is a startup company from Norway who won PRIO's Jump Start Program 2022 edition and collaborated with PRIO to integrate its electric vehicle (EV) battery system with PRIO's network of fast-charging stations. Evyon uses retired EV batteries that are still functional and repurposes them as stationary energy storage systems at fuel stations. This initiative extends the lifespan of batteries, while allowing PRIO to deploy fast EV charging infrastructure without the need for costly grid upgrades.

PRIO BIOFLEXPOR (2021-2023)

BIOFLEXPOR was a project led by PRIO in collaboration with *Laboratório Nacional de Energia e Geologia, Centro da Biomassa para a Energia* and *Florecha.* The primary goal of this initiative was to develop and validate a flexible and small-scale second-generation bioethanol production process, using agricultural and forestry waste as feedstocks. This project also emerged as a solution for the need to have a Portuguese industrial cluster able to produce this type of biofuel, to avoid future importations. In parallel, the consortium studied the availability of regional biomass, specifically forest and agricultural waste in central Portugal, to assess feedstock supply for a future biorefinery.

This initiative's goals were successfully met, including the operational validation of the secondgeneration bioethanol pilot, which met the EU RED II advanced biofuel criteria, that is European Union's requirements for the use of renewable energy, and broad dissemination of results that will serve as a pathway for future implementation of this biofuel production process in Portugal.

TOUR D'EUROPE (March 2025- June 2025)

Tour d'Europe is an initiative from the European automotive industry that aims to promote the decarbonization potential of renewable fuels. It raises awareness among citizens and policymakers about sustainable fuels, their availability across Europe and their crucial role in the achievement of EU's climate goals. Portugal was one of the countries that took part in the tour's route, and activities included fueling vehicles with 100% renewable fuels at PRIO's service stations, a visit to a biorefinery, an institutional event with vehicle exhibition and a roundtable discussion. In Portugal, five vehicles (three heavy-duty and two light-duty) covered 910 kilometers and from PRIO's biofuels consumed 150 liters of PRIO ZERO Diesel (B100) and 465 liters of PRIO ZERO Diesel (HVO).

PRIO's FACILITIES

PRIO's commitment to sustainability goes beyond its product offerings and extends into its own facilities and internal operations. The company puts great effort into balancing operational efficiency with its sustainability goals, and places particular emphasis on water management and CE practices to achieve this balance, as detailed below.

Liquefied Petroleum Gas (LPG) Storage and Filling Center

The *LPG Storage and Filling Center*, located within the facilities of the Port of Aveiro, is exclusively dedicated to processing and reusing PRIO's propane gas cylinders that have capacities of 9 and 45 kilograms. In this center, the cylinders are not discarded after the gas has been used. When customers return their empty gas bottles, they are collected and sent to this center, where they undergo a thorough inspection to make sure that each cylinder has the safety conditions that makes it suitable for reuse. PRIO uses an innovative radio-frequency identification system which allows the company to fully trace and assess the quality of each cylinder throughout its entire usage cycle, making it easier to identify damaged or defective cylinders. After being sorted and cleaned, these bottles go through several safety tests, and only after being approved by this verification stage, are refilled with PRIO's propane gas and returned to the points of sale. PRIO has also replaced the discs used in these gas bottles with a higher-quality material that reduces the amount of waste generated at the LPG Storage and Filling Center.

Energy consumption

In 2023, PRIO invested in photovoltaic panels for self-consumption at its *New Energies Complex*, with the aim of reducing electricity consumption from the grid. This initiative promotes the use of locally produced renewable energy. Interviewee B stated that around 50% of PRIO's fuel stations are equipped with photovoltaic panels, that produce energy equivalent to the consumption of around 600 households, avoiding the emission of around 100 tons of CO_2 annually. Additionally, Interviewee C mentioned the use of LED lighting instead of traditional lamps to improve energy efficiency at PRIO's facilities.

Logistics

During 2023, PRIO renewed 95% of the Executive Committee's fleet, replacing it with hybrid vehicles. The commercial vehicles were also replaced with five-seater models to optimize travel and reduce PRIO's carbon footprint. Interviewee C stated "*our transportation routes are optimized to reduce GHG emissions and fuel consumption. Our truck suppliers are asked to present emission reduction plans, for example through the use of low-carbon fuels, and a portion of our biofuels is transported by rail to reduce the need of trucks on the road.*" (Interviewee C).

Quay Bridge

PRIO in partnership with the Port of Aveiro, improved the quay bridge to enable the reception of ships with greater cargo capacity, that resulted in a reduction in the number of trips required and, consequently, the reduction of GHG emissions associated with maritime transport.

Biodiversity and Ecosystems

PRIO acknowledges that its construction and industrial activities may impact natural habitats, and because of this reason ensures all projects are licensed by local municipal authorities, to guarantee no irreversible damage occurs to biodiversity and ecosystems. While all construction activities involve some level of environmental impact, these are considered minor and reversible under existing evaluations, despite the limited information regarding affected species and impact area and duration. As a result, PRIO demonstrates a strong commitment in the conservation of ecosystems, specifically those related to *Ria de Aveiro*, due to its proximity and ecological importance. In 2023, PRIO's initiatives included the restoration of seagrass meadows and implementation of nature-based solutions in projects like **SEAREST-BC** and **AAAGORA Mission**. Launched in 2023, **SEAREST-BC** project is a collaboration between PRIO and *Centro de Estudos do Ambiente e do Mar*, from the University of Aveiro. This initiative aims to restore marine ecosystems in *Ria de Aveiro,* with a particular focus on the concept of blue carbon. This pilot project, that has a strong potential of replication, involved various stages of scientific work, such as mapping priority restoration areas and assessing levels of organic carbon in those areas. This project engaged 31 PRIO employees in fieldwork activities and led to the restoration of 100 square meters of seagrass meadows, that act as natural carbon sinks. In the future, PRIO shared it plans to expand the area of restored seagrass meadows in the *Ria de Aveiro* and promote the replication of this model across other parts of the ecosystem. The **A-AAGORA Mission** was launched in 2022 and is a cross-sectorial collaboration led by University of Aveiro, that aims to restore marine and coastal ecosystems by engaging local stakeholders in active and passive conservation and restoration efforts. The co-development of nature-based solutions led to a sale of 430 liters of more sustainable fuels in 2023 for use in tourist vessels, avoiding the emission of approximately 900 kilograms of CO_2.

Additionally, PRIO supports the development of a digital Atlantic-Arctic knowledge platform that promotes transformative ecological innovation and collaboration between eight European countries, with demonstrative measures in three of them: Portugal, Ireland and Norway.

Waste management

The water used in PRIO's facilities is one of the company's biggest concerns and there is an active effort to increase the efficiency of water use and reduce water pollution. At the *Green Energy Blending Center*, water management is integrated in a strategic map with performance indicators that enables monitoring and corrective measures to optimize water use in each business area. At the fuel station network, water use is monitored through an environmental assessment matrix that identifies high-impact activities related to water consumption or contamination and measures are activated to mitigate these impacts. Finally, at the biofuel production plant, water is sourced from private wells and the *Port of Aveiro* network. PRIO uses performance matrices ((Significance Assessment Matrix and Life Cycle Matrix) to introduce improvement actions to optimize its internal water consumption.
The discharge of liquid effluents that result from PRIO's activities is another huge concern for the company, that implemented measures to ensure a safe discharge back into the environment. At the *Green Energy Blending Center*, liquid effluents from the washing of facilities and from the washing of gas bottles at the *LPG Storage and Filling Center* are sent to hydrocarbon separators at each site. There is also a wastewater treatment plant for domestic effluents at this Center, and rainwater is used for washing whenever possible. At the fuel station network, water discharges undergo primary treatment, except at highway stations where secondary treatment is used. Most discharges go to surface water, except for four stations, at Mealhada and Benavente, which discharge underground. Lastly, at the *Biofuel Production Plant*, water drawn from wells for the production process is desalinated and deionized in water treatment stations. Effluents are stored and treated in the Industrial Wastewater Treatment Plant, before being discharged into the municipal collector, which directs them to the local Wastewater Treatment Plant. A PRIO initiative called ***Poupar para Ganhar*** was implemented in 2022 and uses a system to reuse water used in oil washing, allowing it to be reintegrated in the centrifugation process. With this project, PRIO expects to reduce groundwater extraction by 50% while also reducing costs related to citric acid, energy and osmosis-treated water.

Regarding the by-products and waste that result from PRIO's production processes that cannot be reused internally, most are sent for recovery and recycling operations, including the commercialization of these residual materials as raw materials for other industries. Depending on the type of waste generated, the *Biofuel Production Plant* may or may not have the capacity to carry out recovery operations. When these operations are not possible internally, the waste is sent to licensed waste management operators that are responsible for collecting and treating industrial waste generated in PRIO's production processes, as Interviewee A explained: "*Among the waste we generate, there are by-products such as soaps and fatty acids, that result both from the pre-treatment of the raw materials we receive and from the biodiesel production process itself. Initially, our priority is always to recover all the fat content within our own production process, maximizing its use internally. When that is not possible, as is the case with certain residues that can no longer be used, we always seek to valorize them through partners, either by delivering or selling them. Some of these by-products even have commercial value and are used by other partners in different value chains*." (Interviewee A).

In 2023, the amount of hazardous waste (1079,80 tones) increased in comparison to 2021 (676,4 tones), while non-hazardous waste decreased in comparison to the same year (1131,89 tones and 1989,57 tones, respectively), but rose in comparison to 2022 (963,79 tones) due to a fire in the *Green Energy Blending Center*, that required cleaning of hydrocarbon separators and tanks. In 2023, the recovery of hazardous waste (525,97 tones) rose significantly in comparison to the results achieved in 2021 (85,45 tones) and 2022 (66,23 tones).
In PRIO's fuel stations, besides the efforts mentioned before concerning water management, there are measures that aim to combat waste generated in activities such as car washes, surface cleaning and retail activities. PRIO collaborates with specialized entities to ensure environmentally responsible treatments. These entities include hydrocarbon separator companies, Wastewater Treatment Plants, conventional waste management companies, and paper and cardboard recycling services. The consumables are also a concern related to the fuel stations, and as a result PRIO implemented in 2024 the elimination of single-use plastic gloves, and the replacement of virgin paper towels with recycled and recyclable paper towels.

PRIO CarWash (2023-present)

In 2023, PRIO began the development of a plan to implement a car wash center that reuses 100% of the water used. It officially inaugurated in 2024 in Lagoa, Algarve, a Portuguese region that often faces challenges related to water scarcity. The water used by customers in car washing goes through a treatment system that includes several stages, such as decantation, hydrocarbon separation, a biological reactor and filtration, that allows the water to meet the quality standards to be safely reused within the car washing cycle, thereby closing the water loop. In the future, PRIO plans to expand the implementation of this initiative to other locations.

PRIO'S Electric Mobility

PRIO has developed a nationwide EV charging network integrated into its fuel stations. In 2023, the company was ranked among the top three energy suppliers for electric mobility in Portugal and as of 2025, it operates 128 charging points nationwide (67 fast chargers and 15 ultra-fast chargers). The electricity used for EV charging is 100% renewable since 2020 and therefore aligned with PRIO's decarbonization journey. To enhance the EV user experience, PRIO offers two digital tools for EV drivers. The company launched its own **PRIO Electric mobile app**, which allows customers to locate available charging points, start a charging session and pay securely via smartphone. PRIO is also developing an online portal, **PRIO.E Informa** platform**,** which will be available through the **"**MyPRIO" portal and will include a personalized dashboard for EV customers. This dashboard will show each customer's charging history and usage statistics, allowing drivers to monitor consumption and allow them to make informed decisions to reduce costs. In 2024, PRIO recorded a total of 143,559 charging sessions across its EV charging network, representing an increase of approximately 65% compared to 2023.

A summary of PRIO's key accomplishments from CE implementation is shown in Table I.

Table 1 - PRIO's Key Accomplishments from CE Implementation

CE INITIATIVE	CIRCULAR ACTION	KEY ACCOMPLISHMENTS
Monteiro Carnes & Galliker	Fleet decarbonization using ECO Diesel B15	Over 109 tons of CO_2 avoided through lowemission fuels used in the companies' fleets since 2019
Francisco Sá Carneiro Airport	Airport vehicles powered by ZERO Diesel (B100)	400,000 L biodiesel forecast to avoid 1,000 tons of CO_2 in 2 years (until 2026)
PRIO Ecowaste	Nationwide UCO collection for biodiesel production	90 tons of UCO collected in 2024, and currently over 1,380 collection points across Portugal
Beato Biobus	Public transport line running on 100% biodiesel	4,500 students involved, 38.22 tons of CO_2 avoided in 2024 and 1,264 Liters of UCO collected
Delta x Ecobean x PRIO	Coffee waste valorization into briquettes and biodiesel	37.6 tons of coffee grounds reused and 45.15 tons of CO_2 avoided (2020)

PRIO x Evyon	Second life of EV batteries for energy storage	Reused EV batteries in charging stations, reduced grid stress
PRIO BIOFLEXPOR	2nd generation bioethanol from forestry residues	Validated as advanced biofuel under EU RED II, national production pilot
Photovoltaic Panels	Renewable energy in PRIO's fuel stations	50% of PRIO's fuel stations equipped, around 100 tons of CO_2 emissions avoided annually
SEAREST-BC	Marine ecosystem restoration (seagrass)	100 m² restored in Ria de Aveiro, results in biodiversity and CO_2 capture benefits
A-AAGORA Mission	Ocean biodiversity regeneration and science outreach	430 liters of sustainable fuels for tourist vessels, that allowed a reduction of 900 kilograms of CO_2 emissions in 2023
Car Wash (Algarve)	Closed water reuse system at fuel station	100% water reuse implemented in drought-prone region
Electric Mobility	Infrastructure and behavior change toward EVs	Increase by 65% in EV charging in 2024 in comparison to 2023

Source: Own

4.2. Barriers of PRIO's CE Initiatives

The data collected in the interviews conducted with PRIO's employees demonstrated that the main barriers faced by the company in the implementation of CE initiatives were mainly related to technical knowledge, high initial costs, economic viability, legislation and lack of residual raw materials.

Technical knowledge is mentioned by interviewee A as one of the main challenges faced by the company in the implementation of CE initiatives. They mentioned a project involving the recovery of greywater from restrooms and rainwater at fuel stations, which has not yet been implemented due to technical constraints: "*Technically, none of the solutions we studied proved feasible due to several constraints, at least not in the way we had envisioned them*." (Interviewee A). They also added that technical barriers often arise during the development phase, requiring several alterations before becoming viable solutions:" *When we implemented the water recovery project in the biodiesel washing process, we had to go through multiple adjustments until we* *reached a point where we could clearly assess the actual impact of the project*" (Interviewee A), concluding that kind of technological adjustment is always part of the process.

Financially, the interviewees identified high initial costs and economic viability as relevant barriers. Some CE initiatives are not implemented for economic reasons, even if the environmental impact would be positive. Interviewee A stated that this economic factor is very limiting and heavily influences the decision of moving forward with a project: "*We may ask ourselves: "Should we go ahead with this?" But if the impact is small and the initial cost is high, it doesn't really make sense*." (Interviewee A). Economic viability is also a major concern, as mentioned by interviewee C, that explained that economic viability is always evaluated for each project and some are not implemented for this reason: "*There have been cases where the project did not move forward because, in the end, it was simply too expensive for the economic benefit it would bring.*" (Interviewee C). The Partnership established between PRIO, Delta and Ecobean that was launched to produce briquettes from coffee grounds illustrates this type of barrier. According to interviewee C, even though the project had great potential, particularly due to the high availability of coffee grounds in Portugal, the final product was not competitive:" *Briquettes are an expensive product to make, which makes it very hard to compete with conventional alternatives in the market. That is unfortunate, given how much coffee is consumed in Portugal*." (Interviewee C), once again, illustrating how economic viability influences the decision-making process of the implementation of CE initiatives at PRIO.

Lack of residual raw materials was also identified as a significant challenge in PRIO's CE initiatives by interviewee A, that shared that there are not enough residual raw materials available in Portugal to supply PRIO's factories. For this reason, the company relies on the importation of residual feedstocks: "*UCO is often sourced from other European countries and the Middle East due to scarcity in Portugal*." (Interviewee A). However, this situation is not desirable since the company wants to purchase local residual feedstocks to reduce their carbon footprint. Therefore, great effort is put into reverting this barrier through awareness campaigns: "*To address this issue, we keep promoting the collection of UCO with schools and citizens to encourage a bigger participation in the recycling of domestic UCO"* (Interviewee A). This challenge is not only felt in the collection of UCO, but also other residual raw materials that are useful for biofuel production.

Finally, **legislation** was the last barrier identified by the interviewees. Interviewee C pointed out the challenges faced in terms of regulations and legislation and how the national legal panorama affects PRIO's activity: "*In many cases, legal framework has not kept pace with developments, and Portugal tends to fall behind in these areas*." (Interviewee C). This misalignment affects competitiveness in the global market, as some countries have advantages over others, posing as a serious drawback for companies that are located in countries with slower regulatory adaptation.

At the local level, PRIO also faces some challenges, especially in the expansion of the UCO collection points network. According to interviewee B, the installation of these collection points is subject to municipal regulation, meaning PRIO cannot install collection points without prior approval. In coordination with licensed collectors, PRIO establishes protocols with these municipalities. However, this is a lengthy process:" *When we want to increase the number of collection points, it is a complex process. It involves public tenders, that typically last three to four years. During this period, nothing can be done in those municipalities*." (Interviewee B).

4.3. Enablers of PRIO's CE Initiatives

When questioned about the enablers that drove PRIO to implement CE initiatives, interviewees mentioned similar drivers, that align with those proposed by Rizos et al. (2016). The most mentioned enabler was the company's culture that is aligned with sustainability and Agenda 2030. Interviewee A mentioned that the contribution for the achievement of the SDGs is a central focus at PRIO and explained the impact that the first analysis to evaluate how each activity contributed to the SDGs, conducted by PRIO seven years ago, impacted their activity: "*This mapping highlighted our contributions and areas for improvement and was seen as a starting point for our teams to work on improving our role for the SDGs*." (Interviewee A).
PRIO's 2023 Sustainability Report highlights how each activity and project contributes to Agenda 2030, and each initiative is assigned to a specific SDG, as shown in the figure below.

Figure 2. *PRIO's commitment to the SDGs*

Source: PRIO's 2023 Sustainability Report

The SDGs mentioned by interviewees as the most relevant in PRIO's CE initiatives are **SDG 7** (Affordable and Clean Energy); **SDG 11** (Sustainable Cities and Communities), as PRIO works closely with municipalities, particularly in awareness campaigns to the population and installation of UCO collection points; **SDG 12** (Responsible Consumption and Production) since, as interviewee B mentioned, PRIO is always trying to reduce its environmental footprint

at the production level, by incorporating national raw materials to reduce the transportation distances, and consequent emissions: "*Even though Portugal is a small country, we continuously strive to optimize our logistics to minimize the transportation of our products as much as possible."*(Interviewee B); **SDG 13** (Climate Action) through the company's decarbonization commitment and **SDG 17** (Partnerships for the Goals) as interviewee A pointed out that PRIO works under an open innovation model : "*Where the vast majority of innovation projects, whether related to CE or not, are developed in partnership with external entities, such as universities, research institutes and private companies.*" (Interviewee A).
The **SDG 14** (Life Below Water) holds a special relevance in PRIO's activity, since the UCO that is used in the Ecowaste initiative is a serious threat for water resources if disposed incorrectly. Interviewee B highlighted the environmental impact of UCO, especially on water resources, which is emphasized during school awareness campaigns: "*We often show a powerful video that illustrates this impact. It features a small inflatable boat on a lake, where a boy pours one tablespoon of oil into the water. Filmed by a drone, the footage shows how, within two to three minutes, the oil spreads across a radius of two to three meters. This demonstrates to students how harmful UCO can be to water and marine life*." (Interviewee B). Interviewee A mentioned that PRIO is involved in several sustainable projects related to marine life due to their headquarters location near Ria de Aveiro, that flows directly to the ocean:" *Because of this proximity, we are particularly mindful of the surrounding environment and have developed specific projects focused on this area."* (Interviewee A).

One of the main enablers mentioned by interviewees in the implementation of CE initiatives was **networking**. As stated before, partnerships with other entities are a crucial part of the development and implementation of CE initiatives at PRIO. Interviewee A identified the main partners for these initiatives as: universities, such as *University of Aveiro* and *Instituto Politécnico de Leiria*; research institutes; startups through the PRIO JUMP START Program and local entities, like private companies and municipalities. For instance, for the PRIO Ecowaste project, besides the collaboration with schools, citizens and municipalities, PRIO works closely with licensed waste collectors. Interviewee B explained how it is more efficient for PRIO to establish these collaborations, instead of holding a required environmental license, since in Portugal there are many specialized companies operating in this sector. These collectors are responsible for managing the more localized collection points where the oil is picked up, such as restaurants. The contracts with restaurants are not made with PRIO, but with the waste collectors, who then deliver the collected UCO to PRIO. At the technological level, partnerships are also a great ally, specifically for water reuse initiatives, as mentioned by interviewee A:" *Whether it is water that results from the production process, rainwater, or more recently, greywater from the company's offices, we have consistently worked in partnership with companies that supported us in developing the most suitable technological solutions for each specific challenge*" (Interviewee A), illustrating the value of these partnerships, not only in logistic support but, most importantly, in addressing complex operational challenges.

I4.0 technologies were also mentioned as an essential driver for CE initiatives. Interviewee C mentioned that PRIO uses several technologies to support its operations, such as Big Data to make PRIO's waste collection routes more efficient, sensors and IoT to keep track of environmental conditions and digital systems to monitor and control the entire biofuel value chain. Interviewee A highlighted the importance of technology in the monitoring of CE initiatives and how I4.0 can help companies implement them: "*For the Ecowaste project, we have implemented a sensor-based solution that allows us to monitor the fill levels of the containers. This helps us determine whether the operator needs to collect the oil or not. It also supports maintenance through alarm systems that alert us if the equipment requires attention.*" (Interviewee A). Interviewee B supported this statement by explaining how PRIO optimizes their transportation routes with the help of sensors: "*Our sensors help us avoid inefficient trips to collect small amounts of oil, especially from containers that are further away from our usual routes. We only send a collection vehicle when the container has reached a minimum fill level*." (Interviewee B), but also emphasized certain limitations, specifically related to the fact that sensors still cannot distinguish if the matter inside the collectors is only UCO: "*If someone throws trash into the container, the sensor still reads it as full, whether it's oil or not. This is still under study. Also, we often face acts of vandalism, which makes it harder to justify certain technological investments unless they are highly advanced and resilient*." (Interviewee B). Regarding the UCO collection process by licensed collectors, interviewee B stated that the restaurants that are part of the UCO collection network request pickups through a mobile app, where they request collection once the barrels are nearly full and receive a scheduled response promptly, and emphasized how this app helps PRIO in the reporting process: "*This digital platform records all collections and as the container operator, we can track all collections by date and location, which is crucial for our annual municipal reporting. The platform simplifies this process by providing data by container, district, and municipality, significantly easing our operational and reporting tasks*." (Interviewee B). At the internal production processes, technology is also highly valued, especially in monitoring aspects: "*In our other projects, more related to industrial processes, we use digitalization primarily for monitoring purposes. By installing sensors, we're able to track operations in real time, which allows us to monitor and measure our impact more effectively and ensure proper functioning*" (Interviewee A).

During interviews, it was also noticeable the relevance of **training for PRIO's employees**, and the encouragement to be creative and think outside the box to develop new sustainable solutions. Interviewee A explained that PRIO has an internal training structure called PRIO School, that is delivered through a digital platform: *"One of the first trainings modules, mandatory for everyone, whether you're a manager or a station operator, is about the Ecowaste project. The goal is to raise internal awareness about CE practices*." (Interviewee A), highlighting PRIO's commitment in fostering organizational engagement with CE principles in their operations. As part of PRIO's internal ideation project *TOP Ideas*, teams were asked to present ideas and identify which SDG their idea contributes to: "*15 teams joined a bootcamp, where they pitched their ideas to advance to the final stage. One mandatory requirement was identifying which SDG their idea relates to. Through awareness activities during the bootcamp, we encouraged teams to reflect critically, for example, connecting a water-saving idea to sustainable consumption goals*." (Interviewee B), reinforcing the company's commitment to Agenda 2030. Nowadays, **customers** are becoming more aware and exigent to environmentally responsible solutions when it comes to their purchasing choices. For this reason, PRIO forecasts that the demand for biofuels will continue to raise in the next years, which promotes the continuous development of sustainable options. Interviewee C stressed: "*We know our customers are increasingly aware of sustainability issues and that quality is not the only aspect they consider when buying a product. That is why we are focused on offering products that are not only environmentally friendly, but also low-cost and good for vehicles' engines*." (Interviewee C). Lastly, **legislation** is also regarded as a driver of PRIO's CE practices. According to PRIO's 2023 Sustainability Report, in response to recent changes in European legislation, the company has been putting effort into the integration of advanced feedstocks, those listed in Annex IX (Part A) of the European Renewable Energy Directive (RED II), into its operations. This strategy has been employed by PRIO as a protective measure to not only comply with current legal requirements, but also prepare the company for future regulatory changes.

4.4. PRIO's Future Strategic Directions

In terms of prospects, PRIO's future journey is anchored on the path to decarbonization by 2050, as stipulated in the Paris Agreement. When questioned about future CE strategies, all interviewees referred how PRIO's mission to deliver affordable sustainable energy is their main goal. Interviewee C shared that PRIO believes the solution for a carbon-neutral future lies on an energetic mix, that includes electric mobility, biofuels and synthetic fuels, and other sustainable energy solutions that will emerge, rather than a single solution.

Expansion is one of the driving forces behind PRIO's future projects. Interviewee B, manager of the PRIO Ecowaste project, expressed the desire to expand the UCO collection points network, and to keep doing awareness campaigns at schools and to the general population to promote the recycling of UCO. Also, PRIO's ZERO Diesel is expected to be available at more fuel stations in the future, to allow more customers to access this sustainable fuel. At the electric mobility level, PRIO's goal is to expand the EV charging stations network even more. Interviewees agreed that electric mobility will be one of the main pillars of the decarbonization pathway. The expected increase in EV adoption in the next years, motivated PRIO to invest in this type of product, as mentioned by interviewee C: "*PRIO made an investment of 11.5 million euros to, by 2025, expand the EV charging network to 300 stations*." (Interviewee C), while also renewing equipment and updating technology across the charging network.

The future, according to interviewee C, also lies in diversification of residual raw materials used in their biofuel production and in the expansion of their portfolio of sustainable fuels, with biomethane, bioethanol, green hydrogen, and others that may emerge. Since 2023, PRIO has made efforts to diversify the advanced raw residual materials used in the production of their biofuels to meet recent legislative changes at the European level. In comparison to 2022, this incorporation rose around 20%, and sulfur-contaminated soap stock acid oil and wastewater from ship transport were integrated into PRIO's production process. Desires for the European directive RED to allow richer blends through a broader range of feedstocks, to give more flexibility to producers, were expressed by interviewee B.

As part of the expansion of sustainable fuel options, PRIO has placed efforts into developing the production of green hydrogen. When questioned about its development and commercialization, Interviewee A stated that PRIO has a project and that the company will eventually include green hydrogen to its portfolio of products but that, for now, it will remain a project due to Portuguese legislation:" *In Portugal, this [green hydrogen commercialization] is not yet a reality. There are no green hydrogen fueling stations, because the regulatory framework is still incomplete. Some legislative pieces have been released, but the final regulation, the one that sets out the technical conditions a public hydrogen fueling station must meet (such as safety distances and infrastructure requirements), has not yet been published*."(Interviewee A), and mentioned that this initiative will not move forward until two requirements are met: "*first, the current legal gap must be resolved, and second, we want to better understand how the market will evolve*." (Interviewee A), reiterating the legislation barrier to CE initiatives mentioned in section 4.2.

In 2022, the company launched the **M-ECO$_2$ project**, currently still being developed, where PRIO is the leader and involves 15 national entities, 10 business organizations and five nonbusiness organizations that are part of the *Research and Innovation System*. The aim of this project is to develop an innovative industrial cluster to produce advanced sustainable biofuels, based on green hydrogen and residual raw materials. Interviewee A shared that this project is contributing to the expansion of PRIO's renewable fuels portfolio and that the company intends to implement CE principles in its production process: "*The concept we've identified, and have already discussed with several partners, involves the reuse of treated wastewater. It is technically feasible to further treat this water to reach the quality required for green hydrogen production."* (Interviewee A) and reinforced their commitment to CE practices in the production of these sustainable fuels: "*We have the technology identified, we have partners on board, and if we move ahead, we intend to apply these CE principles throughout the production process*." (Interviewee A).

Water management is in the current and future CE plans of the company. Interviewee A shared that for the car washing stations, the reuse system can only be installed in new stations. PRIO is still researching a viable way to transform existing car washes to be able to reuse the water: "*We have not yet found a solution that is both technically and economically viable for the existing car wash systems. That's a challenge we want to overcome.*", (Interviewee A), addressing, once again, some of the barriers in the implementation of CE initiatives identified in section 4. 2..
According to PRIO's sustainability report, in 2024 one of key CE initiatives was the rainwater reuse project at the *New Energies Complex*. For the future, Interviewee B expressed the goal to implement the reuse of rainwater systems in PRIO's fuel stations. However, mentioned that at PRIO's headquarters this type of project is implemented in a large scale, that cannot be replicated at the fuel stations: "*Implementing rainwater recovery systems at station level is often challenging, both technically and economically. The limited space and the dispersed nature of the stations makes it difficult for such projects to reach a scale that justifies the investment.*" (Interviewee B).

According to the *Greenhouse Gas Protocol*, GHG emissions are categorized into three scopes: *Scope 1*, that encompasses direct emissions from sources owned or controlled by the organization; *Scope 2*, that covers indirect emissions associated with the generation of purchased electricity, steam, or heat; and *Scope 3* that includes all other indirect emissions arising from the organization's value chain, both upstream and downstream (WRI & WBCSD, 2004).

The following goals have also been outlined by PRIO to be achieved by the years 2030 and 2040:

- Reduce GHG emissions from Scope **1** and **2** operations by 92% by 2030 and achieve a 100% reduction by 2040.
- Reduce Scope **3** GHG emissions by 10% by 2030 and by 26% by 2040.
- Increase renewable energy generation capacity for self-consumption to 85% by 2030.
- Reduce operational energy intensity to 0.023 kgep/€ (kilograms of oil equivalent per Euro) by 2030.

5. Discussion of Results

The main objective of the present study was to analyze how CE practices are implemented in the energy sector, with a particular focus on the Portuguese fuel distributor company PRIO, a national pioneer in CE adoption in this sector. To fulfill the main objective of this study, some specific aspects were explored, namely a detailed description of the CE initiatives implemented by the company and its environmental impacts, the barriers and enablers faced in this implementation and finally, PRIO's future directions concerning CE initiatives.

The collected data showed that PRIO has embedded CE principles at the core of its business model. There is an evident commitment to sustainability, reinforced by continuous investment in innovation and development of various CE initiatives and practices throughout PRIO's value chain. The company's approach to circularity reveals a strong relation to CE principles, as proposed by the Ellen MacArthur Foundation (2013), namely, to **eliminating waste and pollution**, through the production of biofuels with residual raw materials**; keeping products and materials in use**, through the reuse of LPG cylinders and EV batteries and to **regenerating natural systems**, through marine restoration projects such as SEAREST-BC, that focuses on restoring seagrass meadows in Ria de Aveiro. Moreover, PRIO's use of various waste streams in their production processes, that range from UCO and expired margarine to coffee grounds, illustrates its commitment to the "closing the loop" concept, as proposed by D'Angelo et al. (2023).

The CE R-practices framework can also be clearly identified in PRIO's activity. The company implements strategies such as **Refuse (R0)** and **Rethink (R1)** by replacing virgin materials with waste-based raw materials and redesigning its supply chain through innovations like ECO Diesel and the PRIO Ecowaste initiative. This approach reflects the emphasis placed by Potting et al. (2017) and Morseletto (2020) on the importance of upstream actions, which are considered the most effective and desirable within the circularity hierarchy. It also applies **Reduce (R2)** through logistics optimization and the integration of renewable energy and water reuse systems at its facilities. In terms of extending product life, PRIO integrates **Reuse (R3)** in its LPG cylinder return system and **Repurpose (R7)**, through its partnership with Evyon to repurpose EV batteries for stationary storage that, as emphasized by Malooly and Daphne (2023), contributes to reverse logistics and product durability. CE Strategy **Recycle (R8)** is also a part of PRIO's strategy, through the transformation of collected UCO and other residual raw materials into advanced biofuels. This practice reduces dependency on virgin raw materials and reintegrates waste into the value chain as renewable energy. Finally, the **Recover (R9)** strategy, a last-resort measure in the R-strategy framework (DIN, 2024), is present in PRIO's activity, since non-reusable industrial by-products are either internally valorized or sent to licensed waste management operators. Although it is not explicitly stated whether these operators use incineration with energy recovery, this is the most likely scenario, considering the limited reuse potential of these residues and the commercial value attributed to them, as stated by Interviewee A.

PRIO's approach to circularity also illustrates how CE practices function across the micro, meso, and macro levels, as proposed by Heshmati (2015). At the micro level, the company applies CE principles internally through waste valorization, eco-design, logistics optimization, and renewable energy use, practices that are aligned with Geng and Doberstein's (2008) view of firm-level circular strategies. At the meso level, as mentioned before, PRIO actively collaborates with municipalities, startups, and academic institutions, which reinforces the importance of industrial symbiosis to develop solutions for CE implementation (Khalifa et al., 2022). At the macro level, PRIO plays an active role in shaping European CE policies in the context of low-carbon fuels. Interviewee A shared that after the European Union proposed banning fossil-fuel vehicles by 2035, Germany secured an exception for carbon-neutral synthetic fuels. This led to broader recognition that other renewable fuels derived from waste, such as biofuels, biomethane, and HVO, should also be considered. In response, the European Commission requested methodologies to certify that new combustion vehicles sold after 2035 would run solely on carbon-neutral fuels. PRIO joined a European working group in September 2023, composed of automakers, fuel producers, and technology experts, tasked with developing these solutions. In December 2024, the group submitted its first report, outlining technical methods for monitoring and verifying the use of sustainable fuels. This initiative exemplifies the macro-level integration of CE, where firms contribute to institutional design and policy development (Khalifa et al., 2022). It also reflects a micro–macro symbiosis, in which companies like PRIO shape and respond to regulation, helping align policy ambition with practical implementation (Ahmadov et al., 2023).

Concerning the barriers and enablers identified in the data collection process, those are consistent with the factors proposed in literature. The interviews conducted reveal that, despite PRIO's strong engagement with the CE principles, the company still encounters several barriers. On the **technical side**, challenges like the lack of viable water reuse systems reflect what Tan et al. (2022) described as practical constraints that often delay implementation. **Financially**, projects such as converting coffee grounds into briquettes, despite their environmental value, proved economically unviable, highlighting tension between environmental protection and cost-effectiveness. **Legislation** also emerged as a clear limiting factor. Regulatory hurdles, such as delays in approving UCO collection points or the lack of regulation for green hydrogen production, reflect the systemic delays in policymaking identified by Govindan and Hasanagic (2018), that hinder significantly the adoption of circular business models. In addition, PRIO's case brings attention to a less discussed in literature, but critical limitation: **the insufficient availability of domestic residual feedstocks**. As Interviewee A explained, the company frequently relies on imported UCO to the low volume collected at the national level, that introduces logistical complexity to the implementation of strategies based on CE principles. These issues show how even forward-thinking companies like PRIO can be held back by wider structural and institutional limitations.

Yet, it is equally important to recognize the enablers. A **strong internal culture**, deeply aligned with the SDGs, clearly shapes the company's approach to sustainability and conducts the process of overcoming these barriers. **Technologies** linked to I4.0, like sensor-based monitoring and digital traceability, have been fundamental in making PRIO's operations more circular, supporting the role of digitalization emphasized by Hina et al. (2022). **Strategic partnerships** with municipalities, universities, and startups have also proved vital, not only helping PRIO overcome technical challenges but also nurturing an innovation ecosystem, an insight supported by Brown et al. (2019).
In the end, PRIO's journey shows that while the transition to CE sustainable initiatives is complex and uneven, it is not impossible with the right mix of cultural commitment, technological investment, and collaborative partnerships.

By analyzing the data collected, it is also noticeable that PRIO goes beyond conventional energy sector practices, particularly by investing in second-generation biofuels derived from UCO and industrial food waste. This strategy is aligned with authors such as Cavelius et al. (2023), that advocate for a shift toward biofuel options that do not compete with the food supply chain or require extensive land use. However, the development and commercialization of synthetic fuels, such as green hydrogen, remain on hold due to the lack of a clear and complete regulatory framework in Portugal. This situation reflects the institutional constraints described by Scheelhaase et al. (2019), who emphasize the challenges of the development of synthetic fuels without proper legal support.

Despite all the sustainability accomplishments, that PRIO has achieved through the years and strives to achieve in the future, there is still a clear long road ahead, not only for this company but for the energy sector in general. During the interviews, interviewee B mentioned how the idea that we will discard fossil fuels in the near future is completely utopian and unfeasible, not in a technical sense, but in availability of residual raw materials and regulations. Life as we know would simply not be able to exist, from the interviewee's perspective, and PRIO's mission is based on the reduction of society's dependence on fossil fuels, not its complete elimination in the near future.

This demonstrates the amount of work that still must be done regarding the development of sustainable alternatives, at the technological, corporate and legislative levels, specifically in this sector, whose impact in pollution is so significant. PRIO's case also brings to light the temporal gap between ambition and structural readiness. It was revealed during interviews that the internal Innovation and Sustainability Department was only formally established in 2024, even though active sustainable and CE practices have been implemented internally several years prior. Throughout the collection of data through document analysis and semi-structured interviews, and even though interviewees shared PRIO uses several KPIs to track their progress, it was revealed a certain level of immaturity, particularly in monitoring and reporting. This is especially evident in the limited numerical data available regarding the impacts and ambitions of PRIO's sustainability strategy. According to interviewee C, the company's certifications such as ISCC, ISO 9001, ISO 14001 and ISO 45001, help ensure the traceability of the biofuels value chain and explores PRIO's intentions to expand its product portfolio and reporting and monitoring practices, and consequently, obtain new certifications. PRIO's commitment to strengthening its monitoring and reporting practices is also reflected in its 2023 Sustainability Report, which states the company's goal of conducting a Double Materiality Assessment by

2025, in line with Corporate Sustainability Reporting Directive (CSRD) requirements. The double materiality assessment is a fundamental approach, by firstly evaluating financial materiality, which examines how ESG factors influence the company's financial performance, and secondly, evaluating impact materiality, which assesses how PRIO's operations affect the environment and society.

While PRIO's strategy stands out as a strong example of CE implementation within the energy sector, it is important to acknowledge that the replicability of such practices in other organizational or national contexts may not be so straightforward. PRIO benefits from specific enabling conditions, including its infrastructure, sustainability-oriented culture, and collaborations with other entities. In contexts with less regulatory clarity, lower waste availability, the absence of a sustainability-oriented culture or limited technological skills, the implementation of similar CE models may face greater resistance. This underscores that CE implementation is not a one-size-fits-all model, but one shaped by each region's unique institutional, cultural, and infrastructural realities.

6. Conclusion

The present dissertation aims to answer the research question: **"How is PRIO implementing Circular Economy strategies in its operations?".** Thus, the main objectives of the study include the analysis of the CE strategies implemented by PRIO and its impacts, the identification of barriers and enablers found in the implementation of these CE practices and the exploration of what CE strategies will be implemented in the future by PRIO.

Regarding the first objective, the findings show that PRIO has implemented a wide range of CE practices and initiatives across its operations. The company produces advanced biofuels through the incorporation of a variety of waste-based feedstocks, including UCO, expired margarine and industrial residues, aligning with the "close the loop" concept. In 2024, 90 tons of UCO were collected, contributing not only to renewable fuel production but also the prevention of improper disposal that would contaminate water resources.

Additionally, partnerships with companies, such as Monteiro Carnes, Galliker, and Francisco Sá Carneiro Airport, have resulted in the avoidance of over 1,100 tons of CO_2 emissions through the use of PRIO's biodiesel solutions. PRIO's strategy embraces most Rstrategies identified by Potting et al. (2017), through the design of its products and services, integration of reverse logistics, promotion of consumer and community awareness and practices extended producer responsibility, especially in the management of residual waste and byproducts.

Concerning the second objective, the study identified a range of barriers and enablers in the implementation of CE initiatives by PRIO. The barriers encountered in this implementation include technical constraints, high initial costs, regulatory delays, and limited availability of local residual feedstocks. At the same time, its sustainable progress has been driven by a strong sustainability culture aligned with Agenda 2030, the use of advanced technologies, and close partnerships with various entities, all of which have helped foster circularity and overcome the barriers faced by the company.

Finally, in relation to the third and final objective of this dissertation, the findings demonstrate that PRIO has clear objectives regarding the company's future CE strategies, by planning to expand its circular practices through the diversification of its portfolio of sustainable fuels, expanding its EV charging network, continuing to work on water reuse and waste recovery technologies and investing in synthetic fuels, such as green hydrogen, positioning itself as a key contributor to the long-term decarbonization pathway.

This study enriches the academic understanding on CE integration in the energy sector, which has traditionally relied on linear business models, by illustrating a concrete pathway toward decarbonization. The identification of this sector's enablers and barriers highlights how factors such as organizational culture, innovation, and stakeholder collaboration facilitate CE adoption, while high initial costs, technical constraints, and regulatory and institutional barriers help explain the sector's slow transition toward more sustainable models. These insights contribute to CE theory, by clarifying how the energy sector is incorporating CE principles, that majorly contribute to the energy transition and the achievement of the SDGs. Moreover, by showing how existing infrastructure, regulations, and resource-dependency make the adoption of CE models more difficult, the study reinforces the relevance of path dependency theory in explaining why even innovative, sustainability-driven companies face limitations in circular transformation.

The present study offers practical guidance for multiple stakeholders involved in implementing CE models in the energy sector. Energy companies can take inspiration from PRIO's strategies, such as waste-to-biofuel production and closed-loop water systems, as practical benchmarks for adopting circular business models. Policymakers can use the findings to identify necessary regulatory adjustments that remove legal and institutional barriers to CE implementation. The results also highlight the importance of workforce training and cross-sector collaboration, which can guide programs focused on the development of CE-related skills to better prepare employees for the transition to circular practices in the energy sector. Finally, for investors, the study clarifies which CE initiatives are most viable and where economic and regulatory risks remain, supporting more informed investment decisions in sustainable innovation.

The present dissertation faced some limitations. Firstly, the limited availability of numerical data, as PRIO only recently began reporting on sustainability. Since their disclosure practices are still in early stages, there is a lack of detailed numerical information, which restricted the depth of the analysis. Alongside this, the existence of only a single sustainability report prevented any comparative assessment with previous years. Secondly, although three interviews were conducted and provided valuable insights into internal processes, a larger number of interviews would have enriched the study. Finally, this research focuses on a single case study which, although explored in depth, does not capture diverse realities or allow for comparisons with other energy companies.

For future research, it would be interesting to conduct a comparative study analyzing PRIO's CE practices in relation to those implemented by other companies within the energy sector. Expanding the research to include multiple Portuguese companies could also contribute to a better comprehension of the national context and how cultural, regulatory, and market-specific factors influence CE implementation. Additionally, future studies could benefit from a longitudinal approach, examining PRIO's progress over time as its sustainability reporting and initiatives evolve.

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Annex

Annex A- Interview Guide

Bom dia / boa tarde,

O meu nome é Beatriz Luís e encontro-me a desenvolver um projeto de investigação no âmbito da minha dissertação de mestrado em Gestão Industrial e Estratégia no ISEG – Universidade de Lisboa. O principal objetivo deste estudo é compreender quais as práticas de economia circular adotadas pela empresa PRIO, os desafios enfrentados na sua implementação e os resultados alcançados até ao momento.

Em primeiro lugar, gostaria de agradecer a sua disponibilidade para participar nesta entrevista, a qual é crucial para o sucesso deste estudo. A entrevista consistirá em várias questões abertas, e peço-lhe que responda de acordo com a sua opinião. Por favor, tenha em consideração que não existem respostas certas ou erradas; o que importa é a sua opinião baseada na sua experiência na empresa. Com o seu consentimento, a entrevista será gravada para garantir que os dados recolhidos sejam completos e coerentes. A entrevista terá uma duração aproximada de 60 minutos.

Questões da entrevista:

1. Em primeiro lugar, gostaria de saber como define a economia circular no contexto do setor energético.
2. Quais práticas e iniciativas de economia circular foram já implementadas ou estão atualmente a ser implementadas pela PRIO?
3. Na sua opinião, quais foram as principais motivações para a implementação das práticas de economia circular adotadas pela PRIO?
4. Na sua opinião, quais foram os principais obstáculos encontrados durante a implementação das práticas de economia circular mencionadas? Como foram ultrapassados esses obstáculos?
5. Que tecnologias digitais são utilizadas pela PRIO e qual o seu papel na adoção de projetos de economia circular?
6. A PRIO desenvolveu algum programa de formação específico para apoiar o desenvolvimento de iniciativas de economia circular na empresa? Em caso afirmativo, quais os colaboradores que participaram nesta formação?
7. De que forma são avaliados os resultados (ambientais, económicos e sociais) decorrentes da adoção de práticas de economia circular? Que ferramentas e indicadores de desempenho são utilizados? Quais os objetivos definidos para estes indicadores?
8. Quais os Objetivos de Desenvolvimento Sustentável (ODS) que a PRIO considera prioritários? De que forma a adoção de práticas de economia circular se alinha ou contribui para estes ODS?
9. Na sua opinião, quais práticas/projetos de economia circular adotados pela PRIO mais contribuíram para a redução do impacto ambiental?
10. Que outras práticas/ iniciativas de economia circular a PRIO pretende implementar futuramente?

Esta foi a última questão. Gostaria de saber se tem alguma questão. Agradeço imenso o seu tempo e colaboração, que contribuem de forma significativa para o sucesso do meu projeto de investigação.