DEPARTAMENT OF
CHEMISTRY

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BSc in Chemical and Biochemical Engineering

Comparative cost analysis of different CO_2 Capturing, Storage and Transport modes in Portugal

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A Very Long and Impressive Thesis Title with a Forced Line Break

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"The capacity to learn is a gift; the ability to learn is a skill and the willingness to learn is a choice." (Brian Herbert).

ABSTRACT

Global concerns over rising CO_2 levels driving climate change have led to initiatives like the Paris Agreement and European Green Deal, supported by the EU and Portugal, urging advanced emission-reduction technologies. Various strategies are available for CO_2 reduction, such as adopting cleaner fuels and enhancing energy efficiency. However, some emissions, particularly from primary processes, are challenging to eliminate entirely. This is where Carbon Capture and Storage (CCS) technology becomes crucial. Much of Portugal's storage capacity Is In offshore, increasing costs, prompting exploration of alternative CO_2 utilization methods like e-methanol production for marine, aviation, and road fuels.

This study focuses on assessing the costs and logistical aspects of transporting CO_2 within the glass, cement, and ceramic industries in the central and northern regions of Portugal. In summary, the research identifies the most cost-effective transportation mode for various scenarios: for shorter distances, pipelines prove to be the most economical option (€1,82/tonCO_2 at flowrates around 900 tons of CO_2 per day); for moderate distances, either diesel (€5,6/tonCO_2 for flowrates between 240 and 3 000 tons of CO_2 per day) or electric trucks (€4,9/tonCO_2 for flowrates between 240 and 3 000 tons of CO_2 per day) are advantageous; and for longer distances (up to 200 km), railways emerge as the optimal choice (€3,63/tonCO_2 for a flowrate of approximately 550 tons of CO_2 per day). However, it's worth noting that the cost of transporting CO_2 from railway lines to the destination is not considered, which can sometimes be substantial due to the distance involved.

Understanding CO_2 transport costs is crucial for e-methanol's economic sustainability. Efficient transport lowers production costs, enhancing e-methanol's competitiveness, and accelerating the transition to cleaner energy, reducing emissions.

Keywords: Carbon Capture and Utilization; Capital Expenditures, Operational Expenditures

Resumo

As crescentes preocupações globais com o aumento dos níveis de CO_2 que impulsionam as mudanças climáticas levaram a iniciativas como o Acordo de Paris e o Pacto Ecológico Europeu, apoiados pela União Europeia e Portugal, que incentivam o uso de tecnologias avançadas para a redução de emissões. Inúmeras soluções podem ser empregues para a redução de CO_2, como a transição para combustíveis mais limpos e o aprimoramento da eficiência energética. No entanto, algumas emissões, especialmente as provenientes de reações primárias, são inevitáveis. É aqui que a tecnologia de Captura e Armazenamento de Carbono (CCS) se torna crucial. Em Portugal, grande parte da capacidade de armazenamento é offshore, o que aumenta os custos, incentivando a exploração de métodos alternativos para a utilização de CO_2, como a produção de e-metanol para combustíveis marítimos, de aviação e rodoviários.

Este trabalho visa estudar os custos e as condições de transporte de CO_2 por pipeline, camião (diesel ou elétrico) e comboio nas indústrias de vidro, cimento e cerâmica nas regiões central e norte de Portugal. Em suma, foi possível determinar o modo de transporte mais adequado para cada cenário: para distâncias curtas, os pipelines apresentam a opção mais económica (1,82€/tonCO_2 para fluxos em torno de 900 tonCO_2/dia); para distâncias moderadas, tanto camiões a diesel (5,6€/tonCO_2 para fluxos entre 240 e 3 000 tonCO_2/dia) como elétricos (4,9€/tonCO_2 para fluxos entre 240 e 3 000 tonCO_2/dia) são preferíveis; e para distâncias mais longas (até 200 km), as ferrovias surgem como a seleção ideal (3,63€/tonCO_2 para um fluxo de aproximadamente 550 tonCO_2/dia), embora o custo de transporte entre as linhas ferroviárias até ao destino não seja considerado.

Compreender os custos de transporte de CO_2 é crucial para a sustentabilidade económica do e-metanol. Uma vez que, um transporte eficiente reduz os custos de produção, melhorando a competitividade do e-metanol e acelerando a transição energética, reduzindo as emissões.

Palavas chave: Captura e Utilização de Carbono; Despesas de Capital, Despesas Operacionais

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ACRONYMS

ADR	Agreement on the Carriage of Dangerous Goods
APA	Portuguese Environment Agency
ASU	Air separation unit
ATIC	Technical Association of the Cement Industry
CAPEX	Capital Expenditures
CCL	Clean Cement Line
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CEMBUREAU	European Cement Association
CER	Certified Emission Reductions
CKD	Cement Kiln Dust
CO	Carbon monoxide
COMET	Integrated infrastructure for CO_2 transport and storage in the west Mediterranean
COP	Conference of the Parties
CPU	Compression and Purification Unit
CSI	Cement Sustainability Initiative
DAC	Direct Air Capture

DOE	Department of Energy
ECBM	Enhanced Coal Bed Methane recovery
ECIF	European Commission Innovation Fund
EDI	Electronic data interchange
EEA	European Economic Area
EED	Energy Efficiency Directive
EIB	European Investment Bank
EOR	Enhanced Oil Recovery
ERPA	Emissions Reduction Purchase Agreement
EU	European Union
EU-ETS	European Union Emissions Trading System
EVs	Electrical vehicles
FCC	Future Carbon Credits
GCCA	Global Cement and Concrete Association
GHG	Greenhouse gas
HAZOP	Hazard and operability study
IEA	International Energy Agency
IETA	International Emissions Trading Association
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KP	Kyoto Protocol
LCOE	Levelized cost of energy
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas

LULUCF	Land-Use and Land-Use Change
MCFC	Molten carbonate fuel cells
MEA	Monoethanolamine
NER	New Entrants' Reserve
NETL	National Energy Technology Laboratory
O&M	Operation and Maintenance
OPEX	Operational Expenditures
PIMS	Pipeline Integrity Management Program
ppm	parts per million
RCC	Regenerative carbon cycle
RED	Renewable Energy Directive
RRP	Recovery and Resilience Plan
SACROC	Scurry Area Canyon Reef Operator's Committee
SDGs	Sustainable Development Goals
SET	European Strategic Technology
SOFC	Solid oxide fuel cells
TEI	Information handling techniques
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United Nations Dollar
VCC	Verified Carbon Credits
WBCSD	World Business Council for Sustainable Development
ZEP	Zero Emissions Platform

1

INTRODUCTION

In the following section, we will delve into a comprehensive framework that encompasses various environmental strategies implemented within the European Union (EU) and Portugal to address the pressing issue of rising CO_2 levels and their implications for climate change. This framework sets the stage for our exploration of Madoqua, a forward-looking study that seeks to understand and optimize the costs and logistics associated with the transportation of CO_2 within the glass, cement, and ceramic industries in central and northern Portugal.

1.1 Framework

It was not an understatement when in December 2018 the Secretary General Antonio Guterres of the United Nations (UN) observed, "*We are in trouble. We are in deep trouble with climate change...*" during the opening of the 24th annual UN Climate Change Conference held in Poland.

Before that, in September 2015 all United Nations Member States agreed to adopt the 2030 Agenda for Sustainable Development, which include 17 Sustainable Development Goals (SDGs). Building on the principle of "leaving no one behind", the new Agenda emphasizes a holistic approach to achieving sustainable development for all.[1]

Figure 1.1 - The Sustainable Development Goals [1]

Engagement and participation of provincial, territorial, municipal, and Indigenous stakeholders are integral for both the implementation of the SDGs and the transition to a clean economy.

There are four SDGs that relate directly to the energy system:

- SDG 7: Affordable and clean Energy

Access to energy plays a fundamental role in promoting human welfare, fostering economic growth, and alleviating poverty. Globally, there is a growing trend towards increased access to electricity, ongoing enhancements in energy efficiency, and a rising presence of renewable energy sources in the energy landscape. However, it is essential to recognize that the current energy system is a major contributor, accounting for 73% of greenhouse gas emissions responsible for the climate crisis.[2][130]

- SDG 8: Decent work and economic growth

Roughly 50% of the global population subsists on an income equivalent to approximately $2 per day. Achieving inclusive and sustainable economic growth has the potential to propel advancement and generate more job opportunities.[131]

- SDG 9: Industry, innovation and infrastructure

A functioning and resilient infrastructure is the foundation of every successful community. To meet future challenges, our industries and infrastructure must be upgraded. For this, we need to promote innovative sustainable technologies and ensure equal and universal access to information and financial markets. This will bring prosperity, create jobs and make sure that we build stable and prosperous societies across the globe.

SDG 11: Sustainable cities and communities

Efficient urban planning and management practices must be established to address the challenges arising from urbanization and the increasing energy requirements.[132]

- SDG 13: Climate Action

With rising greenhouse gas emissions, anthropogenic climate change is occurring at rates much faster than expected, and their impacts are being felt around the world today with rising sea levels.[133]

Although key greenhouse gases - CO_2, CH_4, N_2O, Ozone – occur naturally in the atmosphere, human activities have increased the atmospheric concentrations of greenhouse gases since the pre-industrial era.

Land-Use and Land-Use Change (LULUCF), particularly deforestation, is another factor that contributes to the phenomenon of global warming and climate change as it changes carbon stocks and carbon sequestration and consequently the CO_2 fluxes from and to the atmosphere. According to the IPCC (Intergovernmental Panel on Climate Change), the average surface temperature of the earth has risen by about 0,6-0,7°C in the past 100 years and will rise by another 1,4 -5,8°C in the next 100 years, depending on the GHG's emissions scenario.[134,135]

The CO_2 concentration has increased significantly over the years, in 2015 the concentration was around 400ppm and in December of 2022 was 420ppm. Comparing with the period between 1960-1965 the concentration of CO_2 has increased 32%.[136]

These figure shows atmospheric CO_2 levels measured at Mauna Loa Observatory, Hawaii, in recent years, with natural, seasonal changes removed. [3]

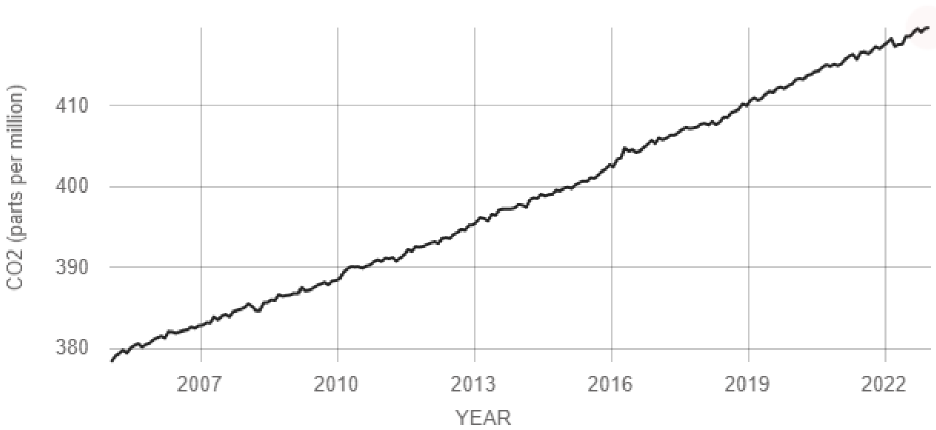


Figure 1.2 - Atmospheric CO_2 levels measured at Mauna Loa Observatory, Hawaii, in recent years [3]

According to the IEA, without the widespread adoption of renewable energy technology and electric vehicles (EVs), the surge in worldwide CO_2 emissions in 2022 would have more than tripled to reach close to 1 billion tonnes. Even though the energy crisis brought on by Russia's invasion of Ukraine encouraged an increase in global coal demand in 2022 by making natural gas much more costly, the growth of renewables considerably outweighed the relatively small increase (1,2%) in coal emissions.[4]

1.1.1 Portugal

After experiencing a rapid surge in greenhouse gas (GHG) emissions during the 1990s, Portugal reached its peak emissions in 2005. Subsequently, the nation witnessed a significant and sustained decline in emissions, establishing a consistent trend towards decarbonizing the economy.[137] This reduction can be attributed to various measures, including the substitution of more environmentally harmful energy sources, such as fuel oil, with natural gas (initiated in 1997), the adoption of combined cycle power plants using natural gas (implemented in 1999), the gradual deployment of cogeneration units, enhancements in energy and technological efficiency within industrial processes, improvements in vehicle efficiency through fleet renewal, and enhancements in fuel quality, among other factors. [5]

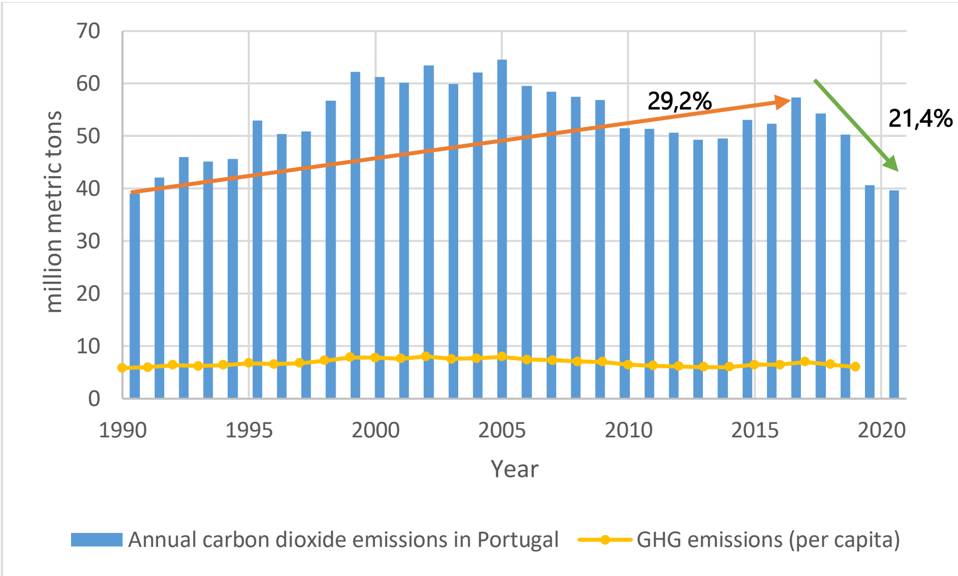


Figure 1.3 - Annual carbon CO_2 emissions in Portugal and the GHG emissions per capita. Source: [5,6]

As of 2017, as indicated by the latest revision of the "2019 National Emissions Inventory," greenhouse gas (GHG) emissions, excluding emissions related to changes in land use and forests (LULUCF), are estimated at approximately 70,7 million metric tons of CO_2 equivalent. This marks an increase of roughly 19,5% when compared to the levels observed in 1990. When accounting for emissions from the LULUCF sector, the total emissions for 2017 are estimated to be around 78 million metric tons of CO_2 equivalent, representing a 29,2% increase compared to the levels in 1990. [138]

This marked growth is related to the rural fires that occurred in the tragic year of 2017, a situation associated with a particularly dry year, the high recorded temperatures that occurred outside the normal summer period (the largest rural fires occurred in June and October), and unusually strong winds, such as Hurricane Ophelia that struck the coast of the Iberian Peninsula in October 2017.

In 2019, the carbon intensity of Portugal's economy was 22% above the EU average and fell at a slightly slower pace than the EU average over the 2005-2019 period. The transport sector reduced its emissions by 10,3 % between 2005 and 2019 and is the sector with the highest emissions, accounting for 26 % of Portuguese emissions in 2019. [7]

The energy sector in Portugal saw a substantial 36,7% decline from 2019 to 2020, primarily due to factors such as an increased share of renewable energy (about 53% in 2020), higher reliance on imports, reduced thermal energy production, and a shift from coal to natural gas.

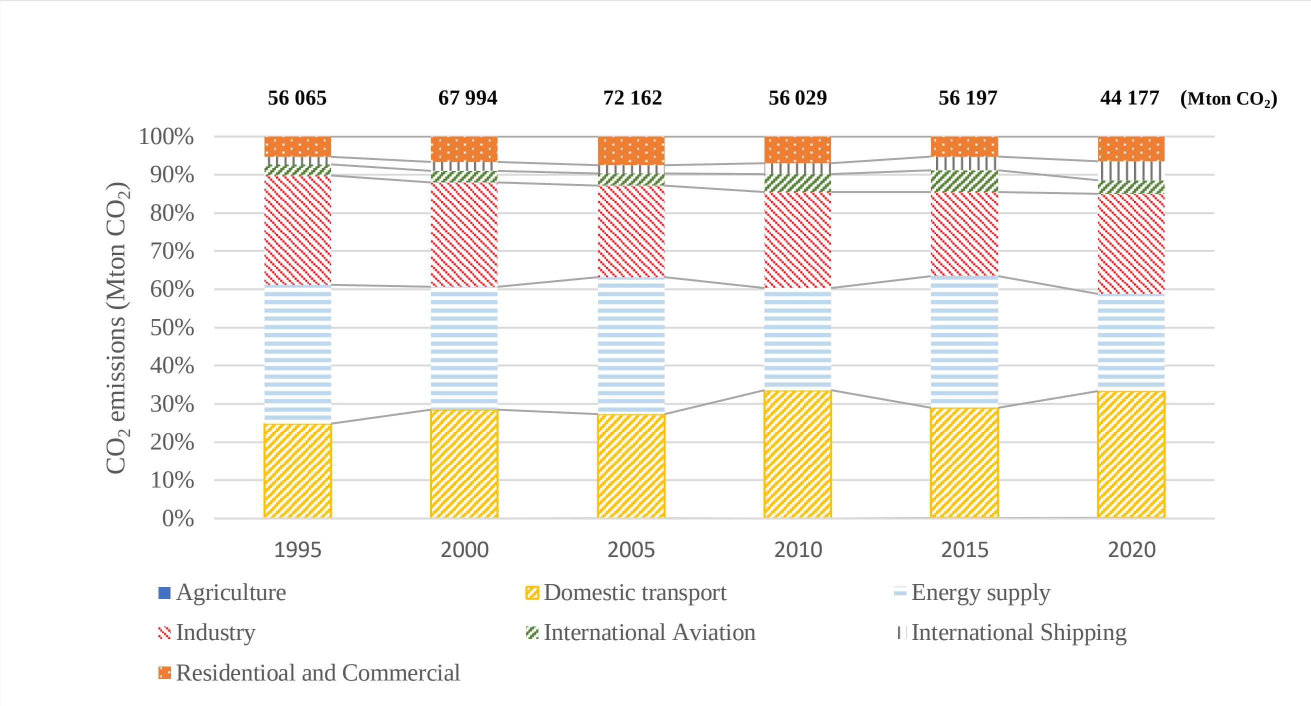


Figure 1.4 - CO_2 emissions per sector in Portugal. Source: [7]

Tabela 1.1 - Growth rate per year

Sector	Growth rate (1995-2005) %	Growth rate (2005-2020) %
Agriculture	13,8	10,9
Energy supply	26,9	- 56,5
International Aviation	39,8	-31,2
Residential and Commercial	82,3	-47
Domestic transport	41,9	- 25,5
Industry	7,8	-32,9
International Shipping	38,8	41,2

Furthermore, the average temperature has increased across all regions of Portugal since the 1970s, with a rate of approximately 0,3 ºC per decade. Analysing the long-term temperature data from 1931, it becomes evident that 1997 stood as the warmest year, and the five highest annual temperatures were recorded in the years following the 1990s. [139]

Temperature indices reveal that the rise in average temperatures coincided with a shift in the occurrence of extremely hot days increasing while the frequency of very cold days decreased.[8] In order to avoid an environmental catastrophe, some strategies were implemented:

1.1.2 Environmental Strategies

The United Nations Framework Convention on Climate Change (UNFCCC)[9] emerged in response to the mounting evidence of climate change and was adopted and made available for signing in Rio de Janeiro in 1992 by the international community. [10]

The Convention's primary goal is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent harmful human-induced disruption of the climate system." Portugal became a party to the UNFCCC by ratifying it on May 31st, 1994.[11] The Kyoto Protocol (KP), established a few years later in 1997, marked a strengthening of the obligations outlined in the Convention. The Protocol introduced legally enforceable commitments for developed nations, mandating a reduction of their combined greenhouse gas emissions by a minimum of 5% compared to their 1990 levels within the 2008-2012 timeframe (the initial commitment period of the Protocol). [12] Portugal signed and ratified the KP on the April 29th, 1998, and May 31st, 2002, respectively.[13] The EU agreed to a -8% reduction.

The Kyoto Protocol (KP) came into effect on February 16, 2005, following Russia's ratification in November 2004. This ratification met the stipulated condition that at least 55 Parties to the Convention, including developed countries responsible for at least 55% of that group's CO_2 emissions in 1990, had to be on board for the protocol to become operational. For the second commitment period, Parties committed to reduce GHG emissions by at least 18 % below 1990 levels in the eight-year period from 2013 to 2020.[14] The EU and its Member States have pledged to participate in the subsequent stage of the Kyoto Protocol, committing to lower their combined emissions to a level 20% below what they were in 1990 or other selected reference years.

The Paris Agreement, adopted on December 12, 2015, in Paris, represents the most recent advancement in the development of the UN climate change framework, building upon the initiatives undertaken within the Convention. This accord establishes a fresh direction for global climate change mitigation efforts beyond the year 2020. [15]

The primary goal of the Paris Agreement is to enhance the global response to the climate change threat by ensuring that the rise in global temperature this century remains significantly below 2 ºC above pre-industrial levels and striving to limit it further to 1,5 ºC. Additionally, the agreement aims to bolster countries' capacity to address the consequences of climate change. The Paris Agreement became effective on November 4, 2016, after at least 55 Convention parties, representing a minimum of approximately 55% of the total global greenhouse gas emissions, ratified it. In 2016, following the ratification of the Paris Agreement, Portugal established a national goal of achieving carbon neutrality by 2050. The 2050 Carbon Neutrality Roadmap outlines a path for reducing GHG emissions by -45% to -55% by 2030, -55% to -65% by 2040, and -85% to -90% by 2050.

1.2 Background of the company

Madoqua Renewables specializes in Carbon Capture and Utilization (CCU) specifically with non-biogenic CO_2 sources, primarily from cement industries. Nevertheless, certain companies can directly repurpose the captured CO_2. For instance, the food industry utilizes CO_2 for beverage production or as dry ice for the transportation of perishable goods. Madoqua Renewables intends to transform the captured CO_2 into Synfuel. The challenge lies in transporting this captured CO_2 to the synfuel facility, and my primary objective is to ascertain the associated cost in my work.

1.3 Goals

The main goal of this research is the following:

Access the comparative cost analysis of different CO_2 Capturing, Storage and Transport modes in Portugal.

In order to fulfil it, the following subgoals needs to be addressed:

- Access the cost of capture and the technology used depending on the amount of CO_2 emissions.
- Create scenarios of locations of CO_2 emission plants and the possible transportations means, thermodynamic conditions and associated costs.
- Study the right-of-way of transportation systems.
- Analyse the CO_2 conditions to storage.
- Analyse the Impact of CO_2 transportation in e-methanol production costs.

1.4 Structure of the Dissertation

The dissertation is divided into 5 chapters, with the following descriptions:

Chapter 1: with the framework of the dissertation, goals, structure of the dissertation and the background of the company.
Chapter 2: a review of the bibliography is carried out, in which all existing concepts and information regarding the subject addressed in this work are presented, such as understanding why CO_2 is a challenge, environmental strategies, cement manufacturing process and the capture, transport, storage and use of carbon dioxide.
Chapter 3: comprises the methodology, where all the procedures carried out in the work are explained in relation to the different scenarios and the evaluations of economic viability.
Chapter 4: all results obtained, and their analysis are presented.
Chapter 5: final conclusions and suggestions for future work.

2

State of the Art

This chapter highlights the challenges related to carbon dioxide emissions and ways to prevent some of the emissions released in the cement industry. Moreover, it mentions the CO_2 transportation modes: truck, pipeline and railway which focuses on their right-of-way and conditions. Lastly, it is referenced some EU funds and Carbon Credit markets, in the EU and more specifically in Portugal.

2.1 Carbon dioxide (CO_2) properties

Carbon dioxide is a colourless and non-flammable gas at normal temperature and pressure. Although much less abundant than nitrogen and oxygen in Earth's atmosphere, carbon dioxide is an important constituent of our planet's air. A molecule of carbon dioxide (CO_2) is made up of one carbon atom and two oxygen atoms.[16]

Carbon dioxide (CO_2) is an important heat-trapping gas, or greenhouse gas, that comes from the extraction and burning of fossil fuels (such as coal, oil, and natural gas), from wildfires, and from natural processes like volcanic eruptions.

Table 2.1 - Properties of CO_2 [17][18]

Property	Value	Unit
Boiling Point	194,68	K
Density	40,8	mol/dm^3
Molecular Weight	44,009	g/mol
Thermal Conductivity	0,01663	W/m°C
Heat (enthalpy) of formation	-393,5	kJ/mol

Table 2.1 - Properties of CO_2 [17][18]

Property	Value	Unit
Critical Point	31,1	ºC
	73,8	bar

It's crucial to recognize that supercritical CO_2 possesses characteristics that make it an exceptional working fluid and solvent for a wide range of applications. This is due to CO_2's relatively accessible critical point, which facilitates the implementation of trans-critical processes with relative ease. Supercritical CO_2 finds utility in diverse applications, including power generation as a working fluid, in the textile industry as an environmentally friendly solvent, and in food-safe chemical extractions as a safe and suitable solvent for food-related processes.[19]

The phase diagram depicting pure CO_2 exhibits two notable characteristics: the triple point (at 5,2 bar and -56,5°C) and the critical point (at 73,8 bar and 31,1°C), as illustrated in Figure 2.1. The triple point is identified by a specific temperature and pressure at which all three phases - gas, liquid, and solid - of a substance coexist in thermodynamic equilibrium. In contrast, the critical point is defined by the critical pressure and temperature of the fluid composition beyond which the substance exists as a supercritical fluid, devoid of distinct liquid and gas phases.

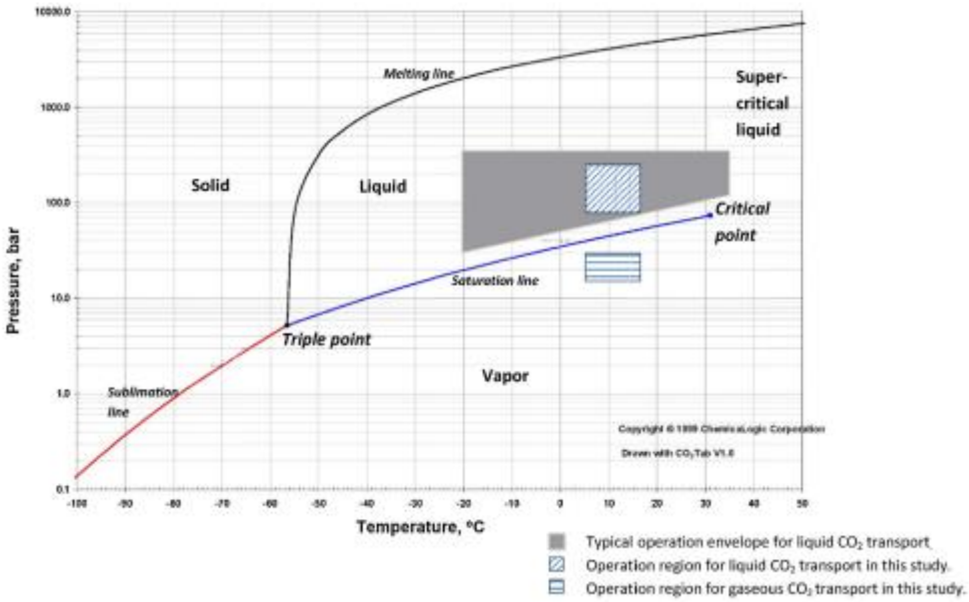


Figure 2.1 - Carbon dioxide: temperature-pressure Diagram. Adaptado: [19]

The major challenge associated with utilizing CO_2 from waste streams is the cost of capturing it from those streams as opposed to acquiring CO_2 from natural sources. Large amounts of CO_2 can be obtained directly from natural gas reservoirs and industrial emissions, but in many cases the former has an economic advantage over the latter.[20]

It absorbs infrared light near 15 µm which results in its greenhouse gas potential, as these wave lengths have significant overlap with the radiative emissions from the Earth's surface.

Thermodynamically, the oxygen bonds with carbon are very strong making CO_2 molecule highly stable. Moreover, CO_2 Gibbs free energy (ΔG^o = -394KJ /mol) is much lower than that of the products from CO_2 conversion.[21] Therefore, CO_2 stability must be overcome for the synthesis of value-added products. This leads to three main scientific challenges namely:[140,141]

1) The need for substantial energy input which must come from carbon-neutral sources to avoid further CO_2 emissions.
2) The need for active catalysts to lower the activation energy of CO_2 conversion processes.
3) High temperatures and/ or pressures to weaken the CO_2 stability.

Attaining significant CO_2 conversion remains a prevalent hurdle in numerous CO_2 conversion techniques, primarily attributed to the thermodynamic resilience of C=O bonds and the swift deactivation of catalysts. While certain technologies, such as reforming, hydrogenation, carboxylation, and electrochemical methods, have demonstrated commendable conversion efficiencies (equal to or greater than 60%), these processes have typically operated under conditions involving elevated temperatures/pressures, excessive overpotentials, or the utilization of catalysts that are both scarce and costly, such as noble metals and ionic liquids.[22]

2.2 Classification of CO_2 emissions

Certainly, carbon emissions undeniably contribute to the climate challenges affecting Earth and its inhabitants. However, it's important to recognize that not all carbon carries the same level of harm. Scientists, in fact, make a distinction between biogenic carbon, which is absorbed, stored, and released by organic matter such as soil, trees, plants, and grasses, and non-biogenic carbon, found in all other sources, notably in fossil fuels like oil, coal, and gas.[23]

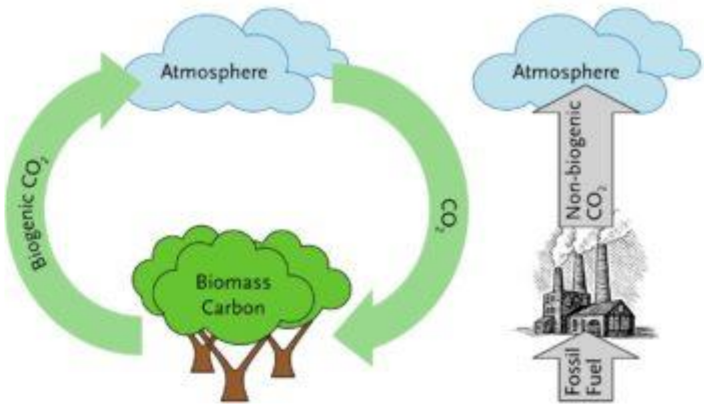


Figure 2.2 - Biogenic and non-biogenic emissions [24]

2.2.1 Average biogenic emissions by sector (% of total emissions)

Average biogenic emissions are calculated for countries which do report their biogenic emissions separately by sector and are presented in the table below.

Table 2.2 - Average biogenic emissions by sector. Source: [25] [26]

Paper, pulp and primary wood products	54,2%
Power generation	3,1%
Waste management	15,6%
Cement and lime	1,6%
Chemicals	0,3%
Food and drinks	0,2%

2.3 Cement Industry

The cement subsector consumes approximately 12–15% of the total industrial energy use. Therefore, this subsector releases CO_2 emissions to the atmosphere as a result of burning fossil fuels to produce energy needed for the cement manufacturing process. The cement industry contributes about 7% of the total worldwide CO_2 emissions.

The first step to develop strategies for CO_2 emission reduction is to acquire a deep understanding on the process and product specifications, so as to know what changes can be made to the process or product, and whether they would result in CO_2 mitigation.

2.3.1 Cement manufacturing process

The basic chemistry of the cement manufacturing process begins with calcination, the decomposition of calcium carbonate ($CaCO_3$) at about 900 °C to leave calcium oxide (CaO, lime) and liberate gaseous carbon dioxide (CO_2). This is followed by the clinkering process in which the calcium oxide reacts at high temperature (typically 1400–1500 °C) with silica, alumina, and ferrous oxide to form the silicates, aluminates and ferrites of calcium which comprise the clinker. [27] [28]

The main constituent of cement is clinker (Ck), a mineral rock produced from the sintering process of the raw material mixture, composed of different crystalline phases, the main being: C_3S, C_2S, C_3A e C_4AF. The clinker is subsequently ground together with gypsum and other additives to produce cement. [29]

$$\begin{gathered} CaCO_3 \rightleftarrows CaO + CO_2 \\ 3CaO + SiO_2 \rightleftarrows C_3S \\ 3CaO + Al_2O_3 \rightleftarrows C_3A \\ 4CaO + Al_2O_3 + Fe_2O_3 \rightleftarrows C_4AF \end{gathered} \tag{2.1}$$

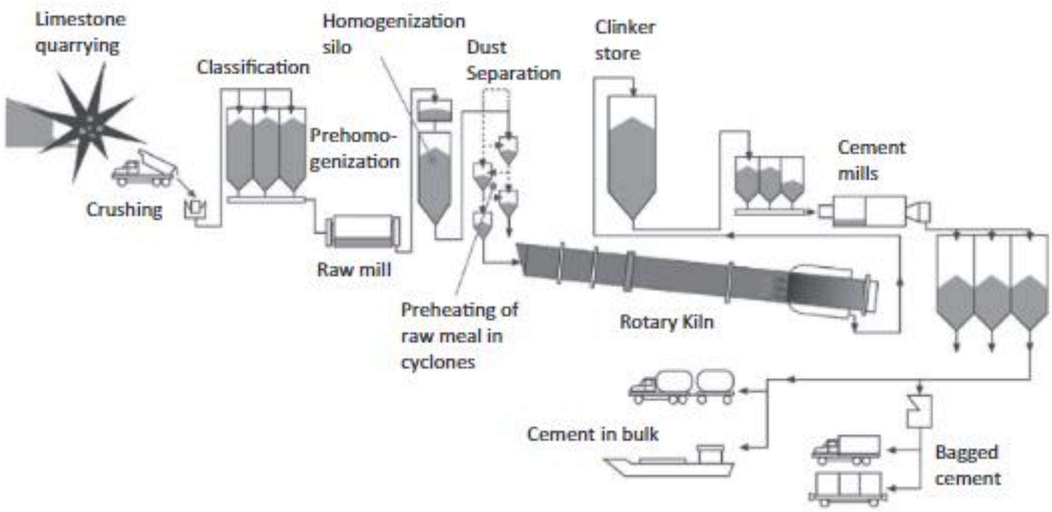


Figure 2.3 - Cement manufacturing process [29]

Emissions are produced mainly by de-carbonation of limestone and the use of carbon-based fuels for heating. Thereabout of 60% of the CO_2 is produced from the calcination process where conversion of raw materials takes place.

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2.2}$$

The typical electrical energy consumption of a modern cement plant is about 110–120 kW h per tonne of cement. In the process thermal energy is used mainly during the burning, while maximum share of electrical energy is used for cement grinding.

2.3.1.1 Case Study: Cement's production Center in Alhandra

This study is associated to a research project with the purpose of exploring strategies to reduce CO_2 emissions in the cement industry, with focus on CO_2 capture through calcium looping cycle. [30]

In the end it was obtained a total CO_2 emissions of **840 kgCO_2/t$_{Clinker}$**, which for cements represents approximately 59% from calcination of the raw materials, 33% from fuel combustion and 8% from electricity consumption.[30]

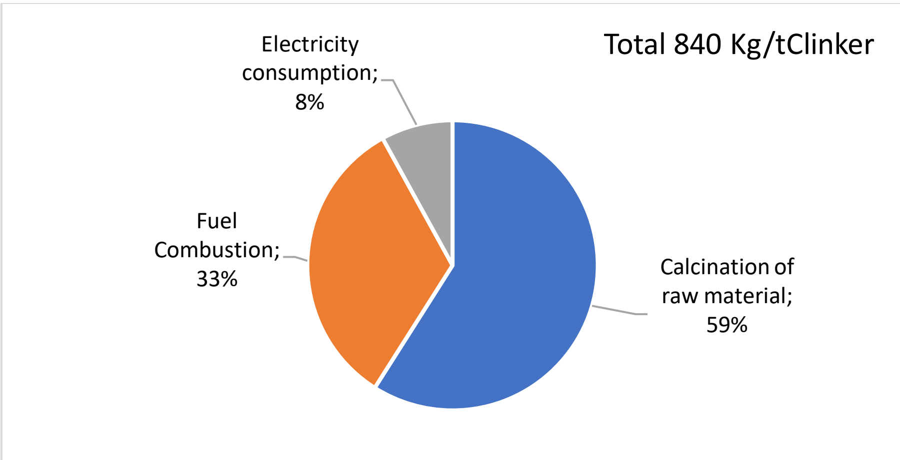


Figure 2.4 - CO_2 emissions per tClinker. Source: [30}

Two primary sources of wasted heat were identified: the gas conditioning tower, accounting for 10MW, and the excess air stream from the clinker cooler, amounting to 12MW. Additionally, two potential feed streams for the carbon capture process were determined: the effluent stream from the pre-heating tower, which has a temperature of 340ºC, and the effluent stream from the entire process before the dedusting unit, which can be either 130ºC or 340ºC.

The Alhandra plant comprises two distinct production lines, both utilizing dry processes with a cyclone tower. One line is equipped with a satellite cooler and boasts a production capacity of 3 969 tons per day, while the other features a grate clinker cooler and a pre-calciner, producing 2 653 tons per day. Both production lines incorporate alternative fuels into their operations. The annual clinker production is evenly split between the two production lines, with a typical clinker composition presented in Table 2.3.

Table 2.3 - Typical clinker composition [30}

Clinker Phase	C_3S	C_2S	C_3A	C_4AF	CaO_{livre}
%	74,6	5,8	5,6	11,3	1,7

Cement is produced by milling of clinker with gypsum and other additives, depending on the type of cement. Cement quality is regulated by the European Standard EN197-1.

Alhandra's plant produces the following types of cement: CEM I 52,5R, CEM I 42,5R, CEM II/A-L 42,5R, CEM II/B-L 32,5N and CEM IV/B(V) 32,5R. Their material composition is presented in the next table.

Table 2.4 - Material composition of different types of cement in w% [30}

Type of Cement	Clinker	Limestone	Gypsum	Fly Ash
CEM I 52,5R	94	1	5	0
CEM I 42,5R	92	3	5	0
CEM II/A-L 42,5R	79	16	5	0,1
CEM II/B-L 32,5N	63	32	5	0,1
CEM IV/B(V) 32,5N	54	0	3	43

It is possible to determine the total specific CO_2 emissions, for clinker and each type of cement. For this total, the average value of emissions from combustion was used.

Table 2.5 - CO_2 emissions due to fuel combustion in CPA cement plant [30}

	CO_2 emissions (Kg/ton $_{Ck}$)
Maximum	344
Average	262
Minimum	224

Table 2.6 - Percentage of direct and indirect CO_2 emissions in each type of cement [30}

Product/ Emission type		Clinker	CEM I 52,5R	CEM I 42,5R	CEM II/A-L 42,5R	CEM II/B-L 32,5N	CEM IV/B(V) 32,5N
CO_2 emissions (Kg/t)		840	813	792	684	479	542
Direct (%)	Calcination	61	59	59	59	59	58
	Combustion	35	33	34	34	34	33
Indirect (%)	Electricity	5	8	7	7	8	9

Cement's CO_2 emissions due to electricity consumption are small compared to direct emissions an average of 8%. [30]

2.3.1.2 CO_2 challenges: CO_2 emissions that can be eliminated and the emissions that can be reduced in the cement industry

There are associations that provide information on ways to reduce CO_2 emissions in the cement industry, such as: [31]

- The Cement Sustainability Initiative (CSI), a WBCSD (World Business Council for Sustainable Development) program that brings together cement producers from all over the world, including CIMPOR;
- The European Cement Association (CEMBUREAU), an organization representing cement producers in Europe. Both organizations have published Roadmaps that outline areas of focus for developing CO_2 emission reduction strategies.

Decarbonization of the sector **occurs mainly due to reduced incorporation of clinker in cement** production and **the incorporation of alternative fuels such as those derived from waste, vegetable waste** and others. In addition, recovery of part of the residual process heat will enable the industry to increase its energy efficiency.

The manufacturing of clinker, the main constituent of cement, takes place in a rotary kiln where raw materials are heated up and CO_2 is separated from limestone through a chemical process referred to as calcination. Calcination causes 60%-65% of cement manufacturing's

CO_2 emissions (process emissions) with the remainder of the emissions coming from the fuels heating the kiln (combustion emissions).

The recourse to alternative fuels frames in an increasing self-sufficiency of the cement sector in terms of thermal energy supply and responds into the key objective set forth by the European Commission which seeks to reduce energy dependency from third countries. In figure 2.5, there is the percentage of alternative fuel mix in German for the cement production, where 60% accounts for Industry waste.

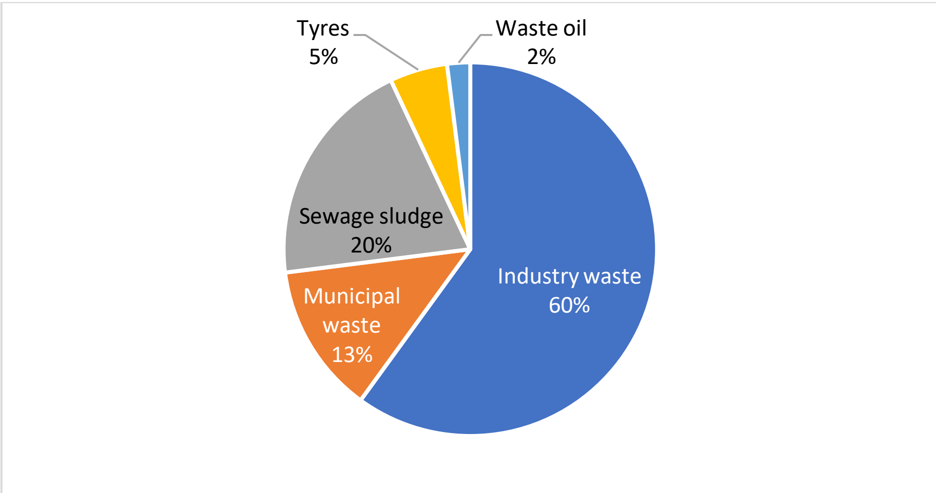


Figure 2.5 - Alternative fuel mix of German cement production. Source: [142]

Process emissions are unavoidable emissions and that is the reason why around 40% of the CO_2 emission reduction efforts towards carbon neutrality in the cement industry in 2050 need to be achieved through carbon capture and storage/use.[32]

New technologies such as the emergence of Oxyfuel furnaces with CO_2 capture may be an alternative in the future, although their viability has not yet been seen to be cost-effective today.

The sector may be the subject of some competition due to the substitution of cement with alternative construction materials, associated with changes in the construction sector, which also involves a significant increase of productivity in the use of materials.[33]

2.3.1.3 Portugal

In 2020, the Manufacturing Industries and Construction sector contributed to 7,5 million metric tons (Mt) of Portugal's total greenhouse gas (GHG) emissions, making up 13,2% of the total emissions. This sector has achieved a notable reduction of 1,38 Mt (equivalent to 15,4%) in emissions since 1990. Within the Manufacturing Industries and Construction category, a significant portion, 2,6 Mt (or 33,7%), of the GHG emissions are attributed to the Non-metallic Minerals sector, which includes activities related to Cement, Glass, and Ceramic Industries. [33]

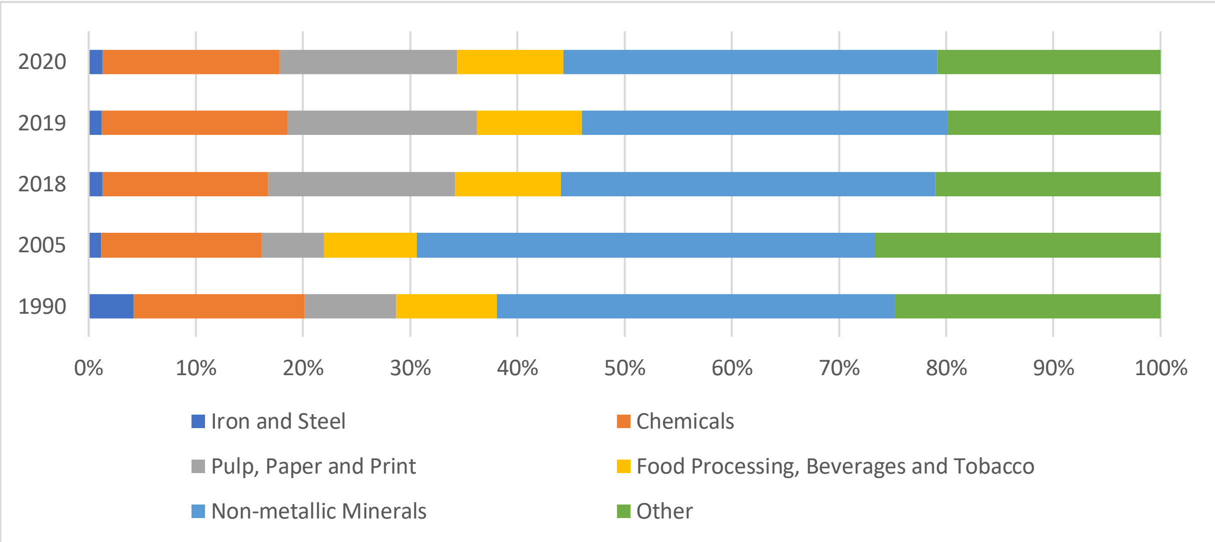


Figure 2.6 - Portugal's total GHG emissions within the Manufacturing Industries and Construction category. Source [33]

The emissions from the Non-metallic Minerals sector, specifically driven by the cement and ceramic industries, exhibit a trend that aligns with reduced production levels during the period from 2009 to 2012. This reduction can be attributed to the economic recession and the crisis in the building construction sector during that time.

Cement producers Cimpor and Secil, plus glassmakers BA Glass, Crisal and Vidrala produce more than 1 million tonnes of CO_2 emissions a year, equivalent to 2,5% of Portugal's total CO_2 emissions. Portugal has six cement production plants, primarily dedicated to Portland cement production, and most of them are situated in the southern part of the country. Five of these units use the dry process for clinker production, while one employs both the dry and semi-wet processes, although the dry process is predominantly used in that unit as well.

Additionally, there are various other carbonate materials used in Portugal's cement industry, including sand, malm, mixed carbonate and dolomite, kaolin, limestone cream, and sludge with limestone. However, these sources contribute negligibly to emissions.

Until 2019, Portuguese cement facilities recycled all the Cement Kiln Dust (CKD) captured back into the kilns or raw meal storage silos. This recycling was factored into emissions estimates through an adjustment in raw meal consumption (Mi). Each facility determined this correction based on the raw meal's weight before entering the kilns and a recirculation factor.

Starting in 2020, the EU-ETS (European Union Emissions Trading System) approved a methodology for accounting bypass dust emissions in clinker production facilities. These emissions are now reported as a separate raw material input. Bypass dust consists of the portion of raw meal that isn't fully calcined and is carried along with exhaust gases into the pre-heater equipment. It is captured using specific dust control technology. Consequently, this quantity must be subtracted from raw meal consumption and has a considerably lower emission factor. This particular CKD portion is not returned to the storage silos or kilns (due to excessive alkali content) but is captured and stored separately for potential future use or marketing.

Table 2.7 - Cement Plants located in Portugal and their capacity. Source: [34]

Group name	Company name	Facility name	Cement plant capacity (2020)	CO_2 emissions
Dutch OYAK TCC Holdings BV	Cimpor Portugal SGPS S.A.	Alhandra	3,1 Mt/year	2,1Mt/year
Dutch OYAK TCC Holdings BV	Cimpor Portugal SGPS S.A.	Loulé	0.9 Mt/year	0,6 Mt/year
Dutch OYAK TCC Holdings BV	Cimpor Portugal SGPS S.A.	Souselas	3,2 Mt/year	2,2 Mt/year
Secil S.A.	CMP – Cimentos Maceira e Pataias S.A.	Maceira – Liz	1,4 MT/year	0,95 Mt/year
Secil S.A.	CMP – Cimentos Maceira e Pataias S.A.	Cibra-Pataias	0,4 Mt/year	0,27 Mt/year
Secil S.A.	CMP – Cimentos Maceira e Pataias S.A.	Outão	2 Mt/year	1,4 Mt/year

2.3.1.4 CIMPOR Portugal SGPS S.A.

The CIMPOR' strategies to reduce CO_2 emissions[35] passes by transforming waste, an environmental liability, into alternative fuels and alternative raw materials. Co-processing is, therefore, an important pillar in CIMPOR's CO_2 emission reduction strategy. Their commitment is to: [36]

- Modernize their kilns to improve even further their energy efficiency according to BAT;
- Modernize the substitution of fossil fuels for alternative energy sources, from 30% today to 70% to avoid landfilling and conventional fossil fuels use;
- Replace natural raw materials for alternative ones by circa 3% until 2030;
- Until 2030, CIMPOR intends to decrease clinker incorporation in cement from 78% to 62,5%, underpinned by expected hard-won achievements that will both substitute the consumption of natural resources and reduce CO_2 emissions;
- Limestone activated clay cements are part of next set of products that CIMPOR is already developing and will be presenting in the near future as a commercial offer to reduce the carbon footprint of its cement portfolio;
- CIMPOR will invest in renewables and equipment to recover process waste heat for electric power self-generation, which will allow producing 30% of our electric needs.

2.3.1.5 Secil S.A.

Secil has followed the Cembureau's Roadmap to Carbon Neutrality in 2050 and subsequently participated in the preparation of the roadmap for the national sector, which was publicly presented to the national authorities in March 2021, in a commitment to the objectives for 2030 and 2050, promoted by the Technical Association of the Cement Industry (ATIC).

Secil has also been a member of the GCCA (Global Cement and Concrete Association) since its inception, having signed the pledge that includes the Climate Change and Energy commitment. In October 2021, the GCCA presented its Roadmap to Carbon Neutrality by 2050, in which leading cement and concrete producers from around the world.

CCL(Clean Cement Line) is Secil's flagship project in the process of decarbonisation, and is the result of an 86 million euros investment by the Company in its plant in Outão, Setúbal. With this project, Secil intends to position itself as the main supplier of low carbon cement for the public works and civil construction cycle, which is announced with the Recovery and

Resilience Plan and PT2030, whose green procurement criteria and objective are to eliminate the use of primary fossil fuels and thus achieve a 20% reduction in CO_2 emissions, increasing energy efficiency by 20%, and generating 30% of electricity through heat recovery.

2.4 CCUS (Carbon Capture Utilization and Storage)

As it was mentioned earlier, not all CO_2 emissions can be eliminated. Calcination causes 60%-65% of cement manufacturing's CO_2 emissions, which are process emissions. So, to prevent these emissions to be released to the atmosphere it is used technology to capture them: **CCUS**, this technology is expected to play an important role in meeting the global warming targets set by the IPCC6 and at COP21.

The goal of CCS (Carbon Capture and Storage) is to permanently sequester the CO_2 in certain geological formations.

Carbon capture and storage (CCS), in its various forms, is a resource-intensive and expensive procedure. As anticipated, a 2010 report from the National Energy Technology Laboratory (NETL), a branch of the U.S. Department of Energy (DOE), has determined that CCS has a detrimental impact on the overall efficiency of the system, the initial investment required for power plants, and the long-term cost of electricity generation for a significant portion of advanced thermoelectric power production based on fossil fuels. Additionally, according to the BLUE Map scenario outlined by the International Energy Agency, CCS could contribute to as much as 19% of the worldwide reduction in greenhouse gas emissions by the year 2050.

The process of carbon capture, utilization, and storage comprises four key stages: capture, transportation, utilization, and storage. Among these four stages, the capture of carbon dioxide (CO_2) stands out as the most expensive and resource-intensive step within the entire value chain.

Additionally, the capital costs and energy penalties associated with CO_2 capture exhibit significant variations based on various factors such as the type of power plant, the choice of fuel, geographical location, volume of CO_2 emissions, intended end use of captured CO_2, the CO_2 content in the flue gas stream, and the specific capture technology implemented. For instance, the total cost of implementing carbon capture and storage (CCS) in power plants can range from as low as $4,5 per metric ton of CO2 (tCO_2) for a coal-based integrated gasification combined cycle (IGCC) plant when the captured CO_2 is intended for enhanced oil recovery, to as high as $72,4 per tCO_2 for a natural gas combined cycle plant with the objective of long-term CO_2 storage in saline formations.[37]

2.4.1 Capture:

A crucial factor to take into account when it comes to CO_2 capture is the level of CO_2 concentration (or partial pressure) in the exhaust stream. As anticipated, the expense and energy penalty associated with capture tend to rise as the CO_2 concentration decreases in the output stream. Furthermore, the temperature and chemical composition of other components present in the exhaust stream also influence the suitability and effectiveness of the capture technology. These considerations become especially significant when capturing CO_2 from large point source exhaust streams, such as those generated by fossil fuel-based power plants, cement production facilities, and iron and steel plants. In these cases, the gases produced typically exit the process stream at considerably high temperatures, necessitating a cooling process.[39]

Carbon capture methods are divided into two types: CO_2 capture techniques and CO_2 separation techniques.

There are different types of CO_2 capture systems:

- Post-combustion,
- Pre-combustion,
- Oxyfuel combustion.

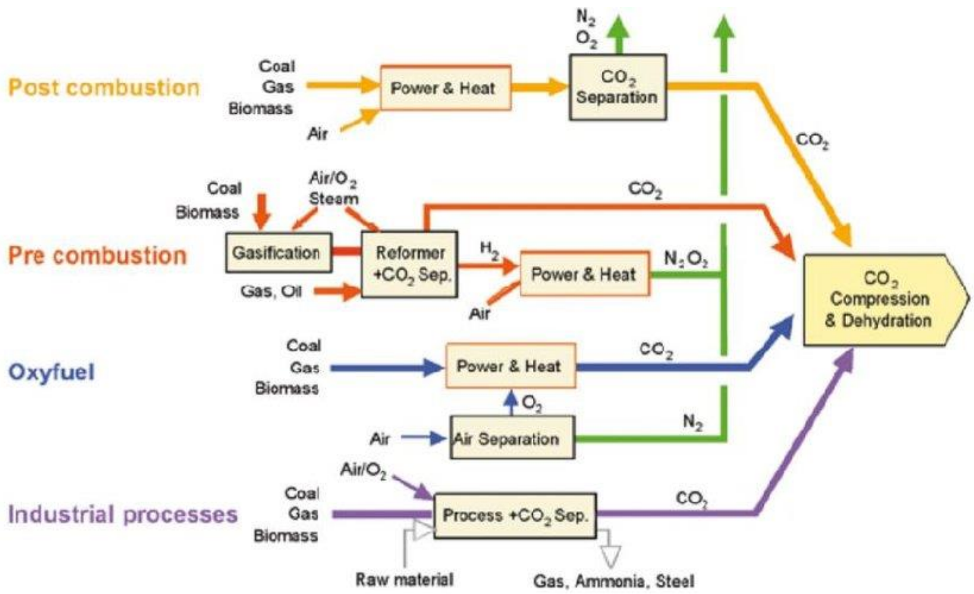


Figure 2.7 - Types of CO_2 capture systems [143]

The concentration of CO_2 in the gas stream, the pressure of the gas stream and the fuel type (solid or gas) are important factors in selecting the capture system.

2.4.1.1 Pre-Combustion

The aim of this separation process is to generate syngas, which consists of hydrogen (H_2) and carbon monoxide (CO), by means of chemical reactions. These reactions involve the conversion of CO and H2O into CO_2 and H_2, followed by the separation of CO_2. Typically, in pre-combustion capture, there is an initial step to extract oxygen from the air, and then this pure or highly concentrated (>90%) oxygen is used in the combustion or gasification of the fuel. The theoretical minimum energy required to separate oxygen from air is 176 MJ per ton of oxygen (or 49 watt-hours per kilogram of oxygen). However, in practical applications, the actual energy penalty can often exceed this theoretical minimum by a significant margin.[39] Nonetheless, employing pure or highly concentrated oxygen presents a distinct advantage when it comes to capturing CO_2 in fossil fuel-based thermoelectric power generation, as the exhaust stream from the stack contains a high concentration of CO_2. There are various technological approaches to generate oxygen from air, including cryogenic distillation, adsorption, and membrane separation. Each of these methods necessitates energy input for the separation process.[40]

By contrast, high temperature (>650 ˚C) fuel cells such as solid oxide (SOFC) and molten carbonate fuel cells (MCFC) electrochemically provide oxygen in a downhill process while generating electricity not by combustion of fuels but by electro-oxidation. The syngas stream consists of 16% - 40% CO_2 at 13 - 40 atm pressure. Pre-combustion capture is generally applied to Integrated gasification combined cycle (IGCC) power plants.[41]

In table 2.8. and 2.9. is all the pre-combustion technology available and its maturity status.

Table 2.8 - Pre-combustion technology [144]

Technology	Separation Method	Driving Force	Oxygen Purity	Maturity status
Cryogenic Air Separation	Multi-stage distillation	Difference in boiling points	95% to 97%	Commercial
Adsorption on solid sorbents	Cycling pressure or temperature	Surface binding energy difference	Enriched O_2	Commercial
Polymeric Membranes	Bulk sorption and diffusion	Pressure differential	Enriched O_2	Commercial
Porous Inorganic membranes	Size sieving, pore adsorption-diffusion	Pressure differential	Enriched O_2	Limited availability

Table 2.8 - Pre-combustion technology [144]

Technology	Separation Method	Driving Force	Oxygen Purity	Maturity status
Dense (nonporous ceramic membranes)	Mixed ionic and electronic transport	Pressure differential	100% O_2	Limited availability
Carbon Fuel Cells	Selective Ionic Transport	Electrochemical pumping	100% O_2	Not commercial
		O_2 chemical potential gradient	100% O_2	Not commercial

2.4.1.1.1 Cryogenic air separation

Cryogenic air separation is a well-established and reliable technology used for high-volume oxygen production. It has been commercially available for many decades and is considered the most mature method for producing large volumes of oxygen. The process is based on the principles of Joule-Thomson refrigeration and multi-stage distillation.

In this process, ambient air is compressed to approximately 1,3 MPa pressure and then expanded in multiple steps to cool it down to the melting point of air (-194,35°C). Through subsequent cycles, the liquid phase becomes increasingly enriched in oxygen while the gas phase becomes enriched in nitrogen. The oxygen is extracted in liquid form from the distillation column and then vaporized to its gaseous state before being used in the desired process stream.

Cryogenic air separation plants typically achieve oxygen purity levels of over 95%. However, this technology comes with an energy penalty, requiring around 240 Wh/kgO_2 of energy to produce 95% pure oxygen. This energy penalty reduces the overall power output of the plant by approximately 15%. Nonetheless, the efficiency of the process can be improved by up to 20% by utilizing waste heat from the air separation unit (ASU).

Typical cryogenic plant sizes can vary between 30,000 and 50,000 Nm^3 of oxygen produced per hour, which is equivalent to 9,000 to 15,000 tons of oxygen per day.

2.4.1.1.2 Adsorption-based air separation

Usually, this method operates at room temperature, but it has relatively limited production capabilities, typically producing less than 1500 normal cubic meters (Nm^3) of oxygen per hour. Additionally, achieving the desired oxygen purity of around 90% to 94% may require multiple adsorption-desorption cycles. Typically, the plant uses a setup with two reactors operating together. The exhaust gases from the pressurized stage 1 reactor are passed to the unpressurized stage 2 reactor until the pressure in the latter reaches the desired level. This sequence is then reversed in the subsequent cycle. [43]

2.4.1.1.3 Membrane-based air separation

Basically, there are three major types of membrane technologies with vastly different operating principles. In **polymeric membranes**, air separation is achieved by relative dissolution and diffusion of O_2 and N_2 through the structural voids in between the polymer chains, while in **microporous inorganic membranes**, which are usually made of ceramics, separation is achieved by selective, or differential adsorption, desorption, and pore diffusion of O_2 and N_2. **Composite membranes** combine the advantages of polymers.[44]

2.4.1.2 Post-combustion

It is used to capture CO_2 from part of the flue gases from several existing power plants. Separation of CO_2 in the natural gas processing industry, which uses similar technology, operates in a mature market. post-combustion techniques, such as absorption, adsorption, chemical looping, or membranes, isolate CO_2 in the flue gas.

In post combustion capture, a low-pressure CO_2 (around 1 atm and 3% - 20% purity) is absorbed into liquid absorbent solutions/solid adsorbents. The commonly used absorbent solutions are monoethanol amine (MEA), aqueous ammonia and alkali absorbents like sodium carbonate and sodium hydroxide. Post-combustion capture can achieve CO_2 capture efficiencies around 90% -100%.[45]

2.4.1.2.1 Amine scrubbing using Monoethanolamine (MEA)

The MEA process has been considered as the most suitable technique for post-combustion CO_2 capture due to its high reactivity for even low CO_2 concentration flue gas. However, this MEA process consumes a lot of heat energy for solvent regeneration because the MEA solvent is aqueous based. The reboiler heat energy occupies about 80% of the entire energy consumption for CO_2 capture process.[42]

The MEA process primarily consists of an absorber, a heat exchanger, and a stripper. The CO_2 in flue gas (Flue Gas) enters to the bottom of the absorber and the MEA solvent (Cold Lean MEA) enters to the top of the absorber. The MEA solvent selectively absorbs the CO_2 via exothermic reaction. The CO_2 rich solvent (Cold Rich MEA) drains the bottom of the absorber and passes through the heat exchanger for preheating. The preheated rich solvent (Hot Rich MEA) enters to the top of the stripper and desorbs the CO_2 at high temperature condition. The CO_2 is captured at top of the stripper and CO_2 lean solvent (Hot Lean MEA) drains the bottom of the stripper. After the lean solvent is cooled by passing through the heat exchanger and a cooler, the cold lean solvent (Cold Lean MEA) is recycled and enters to the top of the absorber.

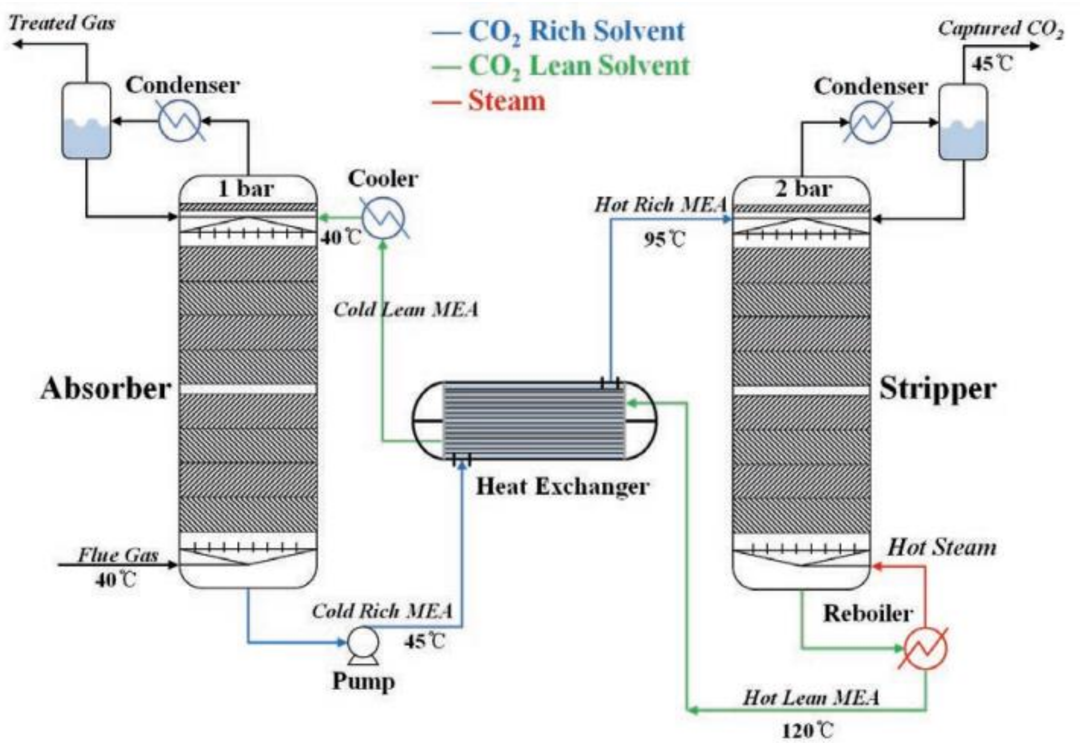


Figure 2.8 - Amine scrubbing using Monoethanolamine process [42]

Presently, the scrubbing methods in use consume a significant amount of energy, making them economically inefficient. Enhancing CO_2 capture technology requires addressing two primary shortcomings of amine scrubbing: firstly, the energy-inefficient process of regenerating at elevated temperatures, and secondly, the management of waste generated from the deteriorated solvent containing amines.[145]

2.4.1.3 Calcium looping

Calcium looping (CaL) technology – also known as the regenerative carbon cycle (RCC) – removes carbon dioxide (CO_2) from the flue gases using a calcium oxide (CaO) sorbent. The process relies on two reversible chemical reactions: carbonation and calcination.[46][47]

During carbonation, the sorbent reacts with the CO_2 in the flue gas to form calcium carbonate ($CaCO_3$). The $CaCO_3$ is then fed into a calciner, where it is heated to about 850°C-950°C, causing it to decompose into an almost pure CO_2 gas stream and solid CaO. The CO_2 is removed and further purified, before being sent either for geological storage or onward use. The solid CaO can be sent back for reuse in the process to capture more CO_2. [48]

2.4.1.4 Oxyfuel combustion

In the oxy-fuel combustion process, oxygen is employed to burn the fuel, resulting in the production of primarily CO_2 (approximately 75% to 80%) and water vapor (H_2O) in the exhaust. Thanks to the high purity of the CO_2 generated, it can be separated from the steam using techniques such as distillation or cooling towers.[49][50]

Oxy-combustion offers several advantages, including the ability to retrofit it into existing power plants, a smaller physical footprint, and, most importantly, the capability to produce CO_2 that's ready for capture without the need for extensive post-separation processes, as long as highly pure oxygen is used during combustion.

However, there are some challenges associated with oxy-combustion. The high temperatures in the boiler necessitate the use of heat-resistant materials, which tend to be more expensive and have shorter lifespans. To address this issue, a portion of the combustion products is often recycled back into the boiler. This helps dilute the reaction system, lower boiler temperatures, and reduce temperature variations within the boiler, mitigating the problem of high-temperature operation.[51]

The selection of the optimal CO_2 capture process involves careful evaluation of several key factors. These factors include the type of emission source, the volume or rate of CO_2 emissions, the concentration of CO_2 in the emissions, as well as the economic and energy costs associated with the separation process.

Among these criteria, the composition of the flue gas is of paramount importance. This is because the CO_2 content in flue gases can vary significantly depending on the source of stationary power generation. For instance, the typical CO_2 content in flue gases ranges from 3% to 5% for natural gas turbines, but it increases to a range of 10% to 15% for pulverized coal-fired power plants. In the case of integrated gasification combined cycle (IGCC) plants, the

CO_2 content can be even higher, ranging from 40% to 60% after the water gas shifting process. Therefore, understanding and considering the specific composition of the flue gas is crucial when determining the most suitable CO_2 capture process.[52]

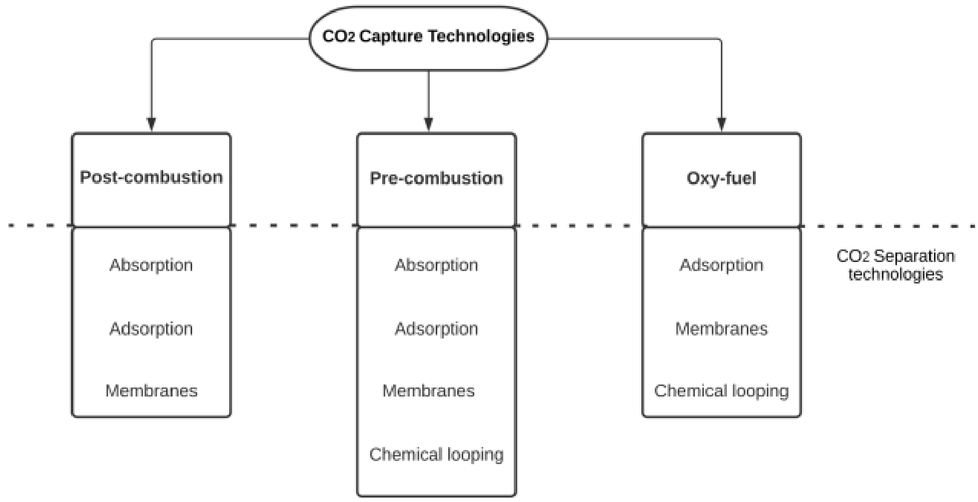


Figure 2.9 - CO_2 capture technologies [53]

2.4.2 Transportation:

Pipelines are preferred for transporting large amounts of CO_2 for distances up to around 1,000 km, for amounts smaller than a few million tonnes of CO_2 per year or for larger distances overseas, the use of ships, where applicable, could be economically more attractive. Shipping of CO_2, analogous to shipping of liquefied petroleum gases, is economically feasible under specific conditions but is currently carried out on a small scale due to limited demand. CO_2 can also be carried by rail and road tankers, but it is unlikely that these could be attractive options for large-scale CO_2 transportation.

CO_2 can be transported in gaseous, liquid or, rarely, solid phase. Commercial-scale transport is based on tanks, pipelines, and ships for gaseous and liquid CO_2.

Key Parameters Impacting Transport Cost Components:

- Method of transport (pipeline, ships, truck, railway)
- Distance
- CO_2 volume
- Monitoring/Regulatory Requirements (policy barriers and incentives)
- Cost structures (finance, capital, labor)

2.4.2.1 Pipelines

Pipeline transport offers the benefit of providing a consistent and uninterrupted flow of CO_2, eliminating the requirement for temporary storage at various points along the transmission route. Furthermore, it is worth noting that up to 90% of the overall cost of the Carbon Capture and Storage (CCS) process is attributed to the expenses associated with compression.[54][55]

The circumstances when transporting CO_2 in gas form become beneficial are when the amount of gas is relatively small and the travel distance short. This means a flow rate of up to 16,5 Mt/y with a distance of 100 km is beneficial for gas as well as resulting in low material cost for the pipelines due to their small thickness.

A comprehensive network of pipelines will be necessary to establish a transportation infrastructure capable of carrying carbon dioxide in significant quantities for effective climate change mitigation. As the demand for such infrastructure grows, securing rights-of-way for pipelines may become increasingly challenging, especially in densely populated areas that are major carbon dioxide producers.

When gas is transported at close to atmospheric pressure, it occupies a large volume, necessitating the use of extensive facilities. However, if the gas is compressed, its volume decreases, enabling transportation through pipelines. Further volume reduction can be achieved through techniques such as liquefaction, solidification, or hydration. Liquefaction, already a well-established technology used in the transportation of liquefied petroleum gas (LPG) and liquefied natural gas (LNG) by ship, can also be applied to the transportation of liquid carbon dioxide. Leveraging the existing knowledge and experience from these industries can facilitate the implementation of liquid CO_2 transport.

2.4.2.1.1 Existing CO_2 pipelines

Most of the CO_2 pipelines are in North America, where there is over 30 years of experience in carrying CO_2 from mostly natural sources to oilfields as part of CO_2 EOR (Enhanced Oil Recovery) operations through an extensive CO_2 pipeline infrastructure. In 2018 they extended over more than 2500 km in the western USA, where they carry 50 $MtCO_2$ per year from natural sources to enhanced oil recovery projects in the west Texas and nearby states. In table 2.10, are presented some examples of CO_2 pipelines across the globe.

Table 2.9 - Existing CO_2 pipelines [146]

Pipeline	Location	Capacity ($MtCO_2$/year)	Length (Km)	Origin of CO_2
Cortez	USA	19,3	808	McElmoDome
Sheep Mountain	USA	9,5	660	Sheep Mountain
Bravo	USA	7,3	350	Bravo Dome
Canyon Reef Carriers	USA	5,2	225	Gasification plants
Val Verde	USA	2,5	130	Val Verde Gas Plants
Bati Raman	Turkey	1,1	90	Dodan Field
Weyburn	USA & Canada	5	328	Gasification Plant

In the case of Cortez Pipeline, it passes through two built-up areas, Placitas, New Mexico (30 km north of Albuquerque, New Mexico) and Edgewood/Moriarty, New Mexico (40 km east of Albuquerque). The line is buried at least 1 m deep and is marked within its right of way. Near houses and built-up areas, it is marked more frequently to ensure the residents are aware of the pipeline locations. The entire pipeline is patrolled by air every two weeks, and in built-up areas is frequently patrolled by employees in company vehicles. The public education program includes the mailing of a brochure describing CO_2, signs of a leak and where to report a suspected leak, together with information about the operator and the "one-call" center.[56]

2.4.2.1.1.1 In Portugal

It was studied by the Global CCS Institute the possibility of selecting a route of **CO_2 pipelines in Portugal**, the methodology was implemented in the COMET FP7 project. The viable pipeline connections between source and sinks develop mainly along the coastal region, where the main CO_2 sources are located. Although the majority of the network develops onshore, in some COMET scenarios offshore pipelines may be required to connect to the offshore cluster S42 in the Algarve basin. Moreover, when the storage capacity in S05 becomes exhausted the alternative storage is the offshore S03 cluster, in the north Lusitanian basin, with a short offshore pipeline connecting to the injection sites in S03.

In the next table there is a list of viable pipeline corridors and characteristics, some of the corridors represent alternative connections between the same locations.[57]

Table 2.10 - Possibility of selecting a route of CO_2 pipelines in Portugal [57]

Pipeline	Origin	End	Length (Km)	Booster stations		Investment costs (M€/m diameter)
				Quantity	Distance (Km)	
PD_C69-C68	Setubal	Lisbon	70,8	1	70,8	112,5
PD_C71-C69	Sines	Setubal	74,4	1	74,4	181,7
PD_C71-S42	Sines	Algarve	153,8	1	153,8	321,2
PD_C73-C70	Porto	Leiria	107,6	1	107,6	162
PD_C73-S03	Leiria	Viana do C.	64	0	64	188,6
PD_C73-S05	Nazaré	Lusitanian Onshore	10,5	0	10,5	15
PD_C74-C73	Leiria	Nazaré	72,4	1	72,4	103
PD_C74-S05	Nazaré	Lusitanian Onshore	10,5	0	10,5	15
PD_C76-S42	Faro	Algarve	56,5	0	56,5	175,8
PD_C77-C68	Lisbon	Caldas	59,9	1	59,9	88,9
PD_C77-C71	Sines	Caldas	189,8	2	94,9	280,8
PD_C77-C74	Caldas	Nazaré	60,8	1	60,8	91,2
PD_C77-C75	Santarém	Caldas	68,2	1	68,2	105,3
PD_C77-S05	Caldas	Lusitanian Onshore	49,6	0	49,6	77,8

2.4.2.1.2 CO_2 specifications and conditions

The most efficient state of CO_2 for pipeline transport is as a dense-phase liquid, allowing high density of fluids without risk of phase change, which corresponds to a lower pressure drop along the pipeline per unit mass of CO_2 when compared to the transportation of the CO_2 as a gas or as a two-phase combination of both liquid and gas. In this 'supercritical' mode, captured CO_2 has to be compressed to a pressure above the critical pressure prior to transport, which occurs at a pressure higher than 73,8 bar and a temperature of more than 31,1°C for pure CO_2. It is important for operators to maintain single-phase flow in CO_2 pipelines by avoiding abrupt pressure drops, from a cost and efficiency point of view, in particular if the pipeline requires intermediate boosting stations. In a two-phase flow, two physical phases are present in the pipeline simultaneously (e.g., liquid and gas, or supercritical fluid and gas), which creates problems for compressors and other transport equipment, increasing chances of pipeline failure.[58]

It Is known that dry carbon dioxide does not corrode the carbon-manganese steels generally used for pipelines, if the relative humidity is less than 60% and this conclusion continues to apply in the presence of N_2, NOx and Sox contaminants. The water solubility limit in high-pressure CO_2 (500 bar) is 5000 ppm at 75°C and 2000 ppm at 30°C. Methane lowers the solubility limit, and H_2 S, O_2 and N_2 may have the same effect. [58]

If the CO_2 cannot be dried, it may be necessary to build the pipeline of a corrosion-resistant alloy ('stainless steel'). However, the cost of steel has greatly increased recently, and this may not be economical.

The composition of the CO_2 stream will depend on the source and technology for capturing the CO_2. These processes may generate different types and amounts of chemical components in the CO_2 flow, such as CH_4, H_2O, H_2S, SO_x, NO_x, N_2, O_2, Glycol and others.

Table 2.11 - Example of CO_2 specifications by Seller or Seller's representative to Buyer at the Canyon Reef Carriers Delivery Meter [59]

Component	Specification	Reason
Carbon Dioxide	Product shall contain at least ninety-five mole percent (95%) of Carbon Dioxide as measured at the SACROC delivery meter	To maintain dense phase
Water	Product shall contain no free water, and shall not contain more than 0.489 m^{-3} in the vapour phase	To avoid corrosion
Hydrogen Sulphide	Product shall not contain more than fifteen hundred (1500) parts per million, by weight, of hydrogen sulphide	Health and safety considerations
Total Sulphur	Product shall not contain more than fourteen hundred and fifty (1450) parts per million, by weight, of total sulphur	Foul odour in product
Temperature	Product shall not exceed a temperature of 48,9 °C	To protect pipeline external coating

Table 2.11 - Example of CO_2 specifications by Seller or Seller's representative to Buyer at the Canyon Reef Carriers Delivery Meter [59]

Component	Specification	Reason
Nitrogen	Product shall not contain more than four mole percent (4%) of nitrogen	To maintain dense phase of product
Hydrocarbons	Product shall not contain more than five mole percent (5%) of hydrocarbons and the dew point of Product (with respect to such hydrocarbons) shall not exceed –28.9 °C.	To maintain dense phase of product
Oxygen	Product shall not contain more than ten (10) parts per million, by weight, of oxygen.	Catalyst for other internal corrosion components. H_2S and O_2 form elemental sulfur in EOR piping
Glycol	Product shall not contain more than 4 x 10^{-5} L m^{-3} of glycol and at no time shall such glycol be present in a liquid state at the pressure and temperature conditions of the pipeline	Glycol damages pump seals.

Table 2.12 - Composition of CO_2 streams [57]

	Coal fired power plant			Gas fired power plant		
Component	Post-combustion	Pre-combustion	Oxy-fuel	Post-combustion	Pre-combustion	Oxy-fuel
$Ar/N_2/O_2$	0,01	0,03-0,6	3,7	0,01	1,3	4,1
H_2S	0	0,01-0,6	0	0	<0,01	0
H2	0	0,8-2,0	0	0	1	0
SO2	<0,01	0	0,5	<0,01	0	<0,01
CO	0	0,03-0,4	0	0	0,04	0
NO	<0,01	0	0,01	<0,01	0	<0,01
CH_4^+	0	0,01	0	0	2,0	0
Amines	-	-	-	-	-	-
Glycol	-	-	-	-	-	-

2.4.2.1.2.1 Purity grades

CO_2 has a wide variety of uses in industry with differing requirements for purity. Eleven different grades of CO_2 are listed by Praxair (2012) ranging from 99,9% to 99,9995% purity. An American measurement specialist, CO_2Meter Inc. (2019), lists nine grades associated with specific end uses, see table 2.15. Where grades have the same value for CO_2 purity, the specifications may differ in the impurity profiles, which may result from different source or purification processes. This may be important for certain uses, for instance beverage use, where trace impurities may strongly affect taste or smell. In the USA it seems there is a difference between beverage grade and food grade CO_2, with the latter not intended for consumption but used in packaging, processing, etc. This distinction is not made in Europe.[60]

Table 2.13 - Grade of purity for different usages

Grade Purity	%
Research	99.999
Super-critical Fluid	99.998
Beverage	99.9
Industrial	99.5

2.4.2.1.3 Design

When designing a pipeline, the first thing that is to be considered is the route of the pipeline. The aim is to design the route as straight and short as possible while avoiding any obstacles such as significant topographic features, water crossing, cities or other inhabited areas in addition to minimizing ecological damage.[61][62] Topography may include mountains, river and stream crossings, and for offshore pipelines, the differing challenges of very deep or shallow water, and uneven seabed[57].The local environmental data need to be included, as well as the annual variation in temperature during operation and during construction, potentially unstable slopes and seismic activity. Also included are water depth, sea currents, biological growth, aquifers, and other environmental considerations such as protected habitats.

Constructing a pipeline involves excavating channels and correctly placing the pipe within them. The cost of excavation is heavily influenced by the characteristics of the terrain and the depth of the channel. The typical depth of a pipe channel can vary and raising it from 1 meter to 1,5 meters would lead to an increase in the amount of material that needs to be removed. This increase in excavation volume results in a significant cost escalation. Consequently, the goal should be to minimize the depth of the excavated channels while ensuring compliance with all the necessary protocols for CO_2 pipelines. Typically, onshore pipelines are buried at a depth of 1 meter, while offshore pipelines are generally buried in shallow water. In the case of deeper water pipelines, those narrower than 400 mm are often trenched and sometimes buried to provide protection against potential damage caused by fishing equipment.

CO_2 pipelines may be more prone to longitudinal running fractures compared to pipelines carrying hydrocarbon gas. To ensure safe operation, long-distance CO_2 pipelines are equipped with monitoring instruments at approximately 500-meter intervals to enable continuous monitoring. The elements of a pipeline control system encompass a range of sensors for measuring parameters like flow, pressure, temperature, and composition. Additionally, there are actuators, such as valves, and remote terminal units (RTUs) that establish local communication with the sensors and actuators. They also communicate with a central supervisory control and data acquisition (SCADA) system situated at a remote location. The SCADA system collects, processes, and presents pipeline data to individuals responsible for overseeing the pipeline operations from a central control room. These individuals, using the SCADA system, issue commands that are relayed back to the RTUs, which in turn control the actuators.[147]

The system incorporates redundancies to prevent operational capability loss in the event of component failures. Pipelines are cleaned and inspected by 'pigs', piston-like devices driven along the line by the gas pressure. Pigs have reached a high level of sophistication, and can measure internal corrosion, mechanical deformation, external corrosion, the precise position of the line, and the development of spans in underwater lines.[64]

The optimum diameter is the minimum calculated internal diameter for which the pipeline is able to operate under the adequate flow rate and volume.[65] A limit of 6 m/s for liquid CO_2 has been set to avoid erosion, vibrations and damaging of the pipeline and above 0,5 m/s to ensure that the CO_2 flows.[66][67]The minimum thickness of a pipe should be at least 1% of the outer diameter.[68]

Typically, oil pipelines are constructed using steel or plastic tubes with an inner diameter ranging from 4 to 48 inches (100 to 1,220 mm). To determine the optimal diameter for CO_2 pipelines, it was necessary to refer to the standard diameter information provided in table 2.14. The Nominal Pipe Size (NPS) is a set of standard sizes used in North America for pipes designed to handle high or low pressures and temperatures. The term "nominal" is used to indicate that the pipe size is identified by a non-dimensional number, representing the diameter of the hole.

Table 2.14 - Nominal diameter of pipelines [69]

NPS	Outside diameter (inches)
2	2,375
2 1/2	2,875
3 1/2	4,00
4 1/2	5,00
6	6,625
8	8,625
10	10,750

2.4.2.1.4 Right-of -way in Portugal

There are no Portuguese regulations for the design, construction and operation/maintenance of CO_2 piping networks; however, various codes and standards may be considered, namely:

- The Decree-Law No. 140/2006[70], consisting of 14 Chapters and 4 Annexes, establishes the legal regime for transport and underground storage of natural gas, as well as for liquefied gas and for distribution of natural gas.
- ISO 13623:2017 – Petroleum and Natural Gas industries – Pipeline transportation Systems[71]

Particularly for CO_2 onshore pipelines and for an integrity management planning, the requirements of the recommended practice DNV-RP-J202 – Design and Operation of CO_2 Pipelines can be followed, for the type of data to be collected and for threads and hazards identification[72].

2.4.2.1.4.1 Case study: Pipeline Routeing in the UK with the Pipeline Code PD 8010 [73]

- Individual Risk Transects

The risks posed by a drifting toxic CO_2 cloud led to individual risk curves that exhibit a distinct shape compared to curves produced for a flammable fluid like natural gas. Figure 2.10 illustrates this difference, where individual risk values are plotted against the distance along a line perpendicular to the pipeline, forming what is known as a "risk transect." For a typical high-pressure natural gas pipeline and a large diameter, thick-walled dense phase CO_2 pipeline, the risk transects show contrasting patterns.

Specifically, the risk associated with the toxic hazard from the CO_2 pipeline decays much more slowly with distance from the pipeline, whereas the risk linked to the thermal hazards from the natural gas pipeline decreases relatively rapidly.

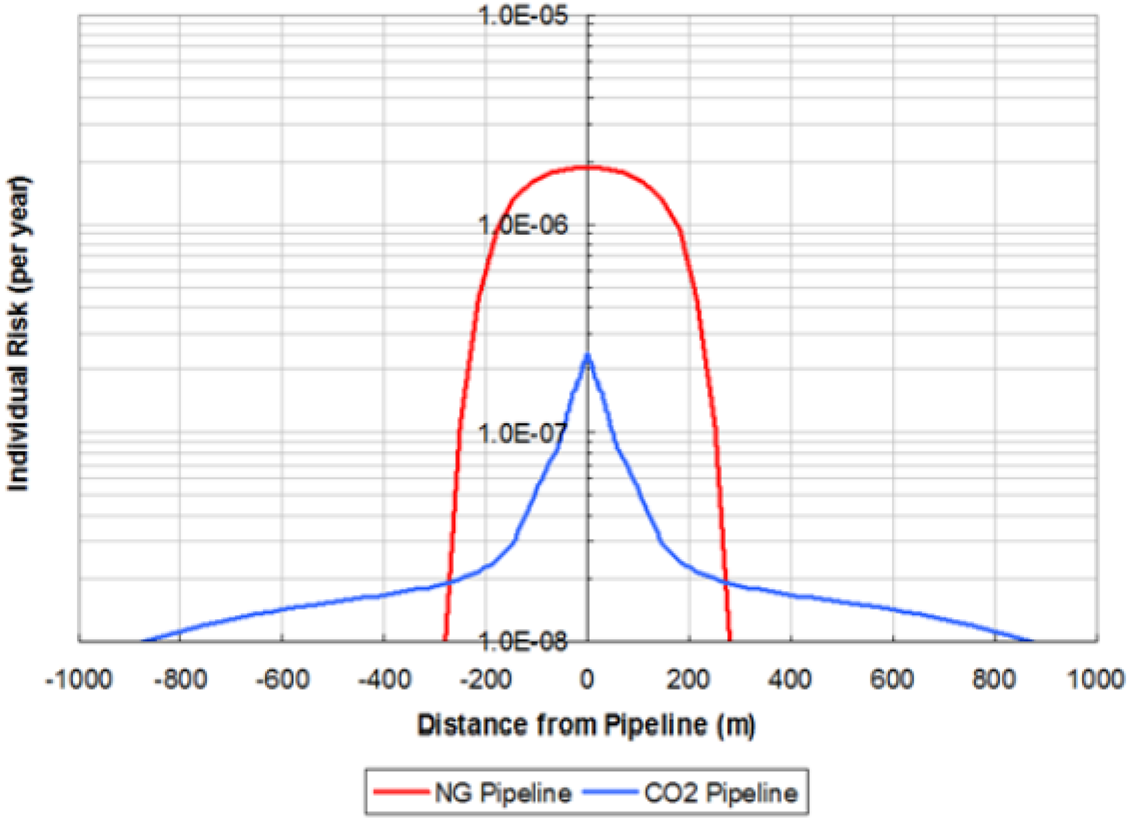


Figure 2.10 - Relation between individual risk and distance from pipeline for natural gas and CO_2 [73]

The difference in the risk transects' shape arises from the fact that the thermal hazard distances from a natural gas pipeline are less affected by changes in atmospheric conditions, wind speed, and topography compared to the dispersion distances associated with a drifting cloud of CO_2. This sensitivity leads to a "long tail" in the individual risk transect for CO_2 pipelines. Additionally, the magnitude of the risk near the pipelines differs because thick-walled CO_2 pipelines have lower failure frequencies, resulting in relatively low individual risk levels.

Consequently, the balance between individual and societal risk differs for CO_2 pipelines. Although individual risks are low, the potential for exposure to these low risks at extended distances from the pipelines necessitates consideration of societal risks, especially under unfavourable weather conditions when the hazardous cloud might drift to populations far from the pipeline. Moreover, the greater distance and longer time associated with the CO_2 hazard mean that various factors play a more significant role in modelling the risk compared to a natural gas pipeline.

These factors include the influence of source conditions and subsequent dispersion from the crater, population factors such as the density of people at greater distances from the pipeline, the time spent outdoors by individuals, escape and shelter assumptions, and the influence of isolation valves along the pipeline.

- Societal Risks

The analysis is conducted for various distances of separation and population densities, considering either one side or both sides of the pipeline. The model predicts the number of casualties for a 1-kilometer segment of straight pipeline, and FN (Frequency-Number) curves are generated. The results are then examined to illustrate the Expectation Value (EV) for the potential number of casualties per year, represented against the assumed separation distance (in meters). Figure 2.11 displays these results for a typical 914 mm outside diameter natural gas (NG) pipeline operating at 85 barg pressure and a 914 mm outside diameter dense phase CO_2 pipeline operating at 150 barg. The curves in figure 2.11 depict different representative values of population density beyond the separation distance.

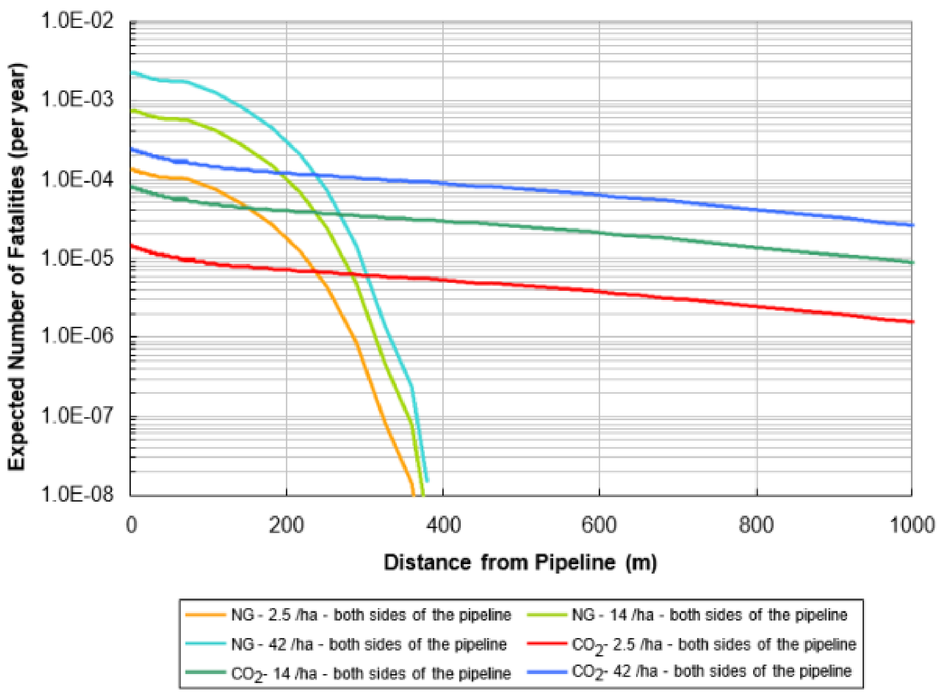


Figure 2.11 - Relation between expected number of fatalities per year and distance from pipeline for different population density [73]

2.4.2.1.5 CO_2 transport risk assessment

Safety of CO_2 onshore pipelines, concerning the impacts in individuals and society as well the impacts on the environment, resulting from hazards and risk exposure, shall be evaluated when planning the deployment of a CCS/CCU technological infrastructure.

In Portugal, and for the time being, there is no safety legislation regarding the transport of CO_2, and so, no practical guide exists to recommend a particular risk assessment methodology. Nevertheless, a robust experience in the design, construction and operation of natural gas transport pipelines exists, and the normally used methodology can be considered.

HAZOP technique is normally used, in natural gas infrastructure projects, to address the first query. The following main events, or risk elements, should be considered in a Risk Analysis for an onshore CO_2 pipeline:

- Leakages,
- Blowouts,
- Loss of soil stability.

The safety regulation for the transportation of natural gas (Portaria 142/2011)[74] can serve as a valuable reference. According to the requirements outlined in EN 1594/2009 [75] - Gas supply systems - Pipelines for maximum operating pressure over 16 bar, the Portuguese safety regulation mandates the implementation of a Pipeline Integrity Management Program (PIMS). This program is designed to assess risks based on collected data, in accordance with the guidelines specified in ASME B31.8S - Managing system integrity of gas pipelines[76] , as well as the European specifications CEN/TS 15173:2006 - Gas supply systems, which provide a framework for pipeline integrity management systems (PIMS), and CEN/TS 15174:2006 - Gas supply systems, which offer guidelines for safety management in natural gas transmission pipelines.

Table 2.15 - Risks for any pipeline and for CO_2 pipelines [76]

Risks (Threads and hazards)	Typical to any pipeline	Specific for CO_2 pipelines
Time dependent		
External corrosion	x	
Internal corrosion	x	x
Stress corrosion cracking/ Hydrogen induced cracking	x	
Fatigue	x	x
Degradation of materials	x	x
Manufacturing exposed to CO_2		x
Welding exposed to CO_2		x
Equipment defects exposed to CO_2		x
Stable		
Manufacturing not exposed to CO_2	x	
Welding not exposed to CO_2	x	
Time independent		
Third party damage	x	
Incorrect operations	x	
Weather/ outside force	x	
Equipment defects not affected by CO_2	x	
Equipment failure	x	x
On-bottom stability	x	x
Operational		
Repair/ Welding issues		x
Shut in		x
Blow Down/ Depressurization		x

The CO2RISKMAN Joint Industry Project (JIP) was initiated specifically to develop industry guidance that provides a reference source to assist the emerging CCS industry to appreciate, understand, communicate, and manage the issues, challenges and potential hazards associated with handling CCS CO_2 streams.

Some ways to reduce the risks for CO_2 pipelines will include:[148]

1. Adding a corrosion inhibitor to the CO_2 stream. It's important to note that when incorporating corrosion inhibitors, compliance with the London Convention and London Protocol should be ensured, as certain chemicals may not be permitted for sub-sea CO_2 storage.
2. Coating the interior surfaces of the pipeline with an appropriate corrosion-resistant lining. Special consideration should be given to the solubility of the lining in dense-phase CO_2 and the potential for dense-phase CO_2 to infiltrate the lining/steel interface, leading to explosive decompression when the fluid pressure decreases.
3. Specifying materials that can limit corrosion to safe levels throughout the equipment's lifespan, such as ASTM 304 and 316. However, if duplex steel is chosen to prevent stress corrosion cracking (SCC), it offers significantly greater corrosion resistance than these materials.
4. Selecting thick pipe and vessel walls with a corrosion safety margin that's sufficient to minimize the risk of corrosive breaches. However, it's important to be aware of the potential downstream issues that corrosion products might cause, such as valve blockages or pore blocking in the formation.
5. Implementing active monitoring when necessary to replace corroded components before they lead to Loss of Containment (LOC) incidents.

2.4.2.1.6 Costs

There is limited available data on the costs of CO_2 pipelines, however, natural gas pipelines can serve as a helpful reference for understanding the fundamental cost elements. These cost components generally encompass capital expenses and operational expenses. Capital expenditures involve the costs associated with constructing the pipeline, including materials, labour, acquiring rights of way, and miscellaneous expenses such as site surveys, engineering, supervision, contingencies, taxes, administration, and so on. Operational expenditures comprise both fixed and variable costs related to pipeline maintenance and associated equipment. This includes expenses for booster stations, the pipeline control system, electricity consumption, and other relevant operational costs.

Heddle's model used natural gas pipelines as an analogy for estimating the cost of CO_2 transport via pipeline. Both face similar construction costs that are sensitive to distance and scale, though CO_2 pipelines may cost slightly more due to greater pipeline thickness needed for transporting CO_2 at higher pressures. The diameter of a pipeline is determined by the flow rate of CO_2. Figure 2.12 illustrates the relationship between these two factors, demonstrating that as the CO_2 flow rate increases, the pipeline diameter also increases. [77]

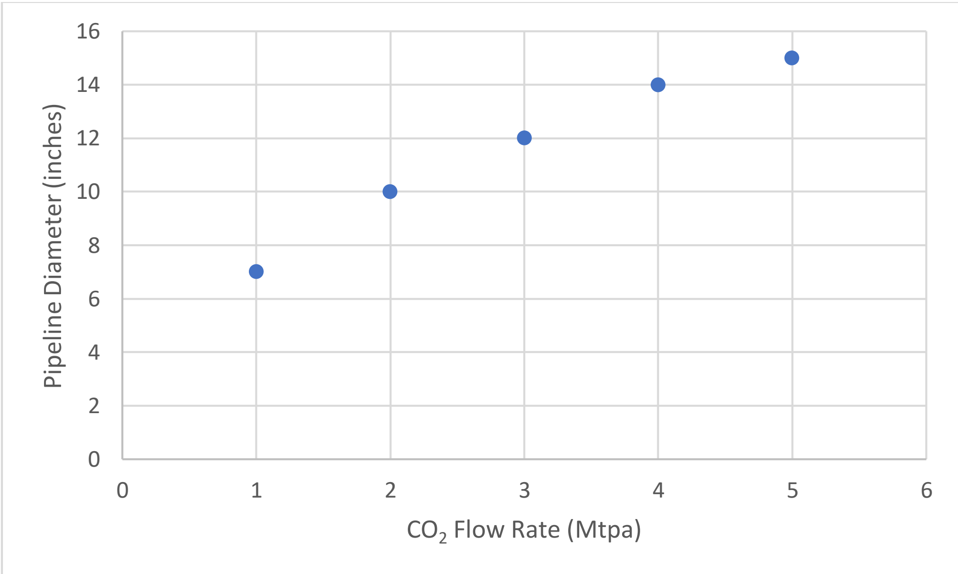


Figure 2.12 - Relation between pipeline diameter and CO_2 flow rate. Adapted: [77]

Moreover, it was also possible to create a relationship between the flow rate and the cost in $/t$CO_2$ for a certain distance, 100 miles, as shown in figure 2.13, where for the same distance the cost will diminish as the amount of CO_2 transported Increase.[77]

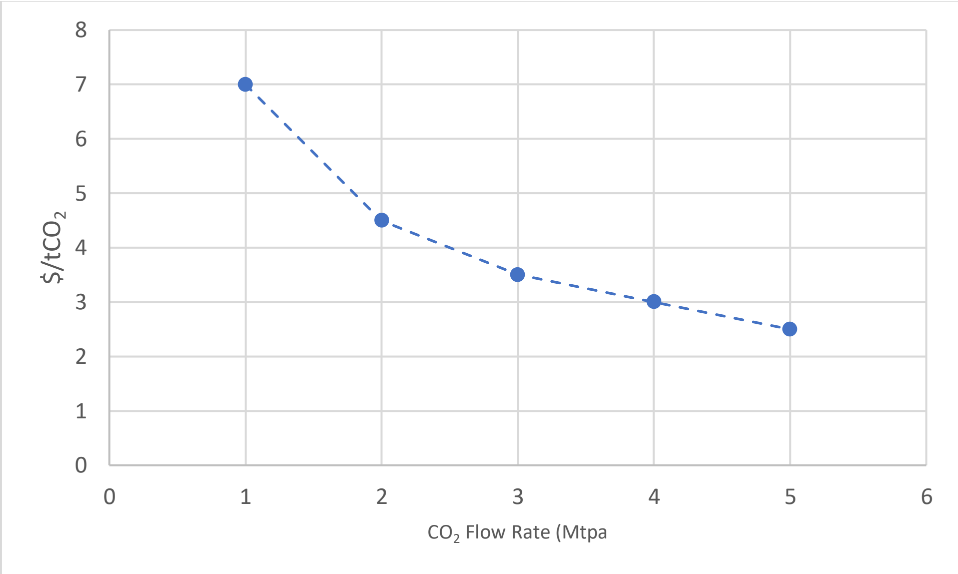


Figure 2.13 - Average pipeline construction costs in 2019$/mile as a function of CO_2 Flow Rate. Adapted: [77]

The material cost calculations include the material for the pipelines, and the application of coating and cathodic protection. X52 is a steel grade that is commonly used today for gaseous CO_2 and X70 for transportation of liquid CO_2.

Table 2.16 - Material for the pipelines. Adapted: [149]

Steel quality (US standard)	Steel quality (EU standard)	Yield stress (MPa)	Steel costs ($€_{2010}$/Kg)	Steel costs ($€_{2021}$/Kg)
X42	S275M	275	1,17	1,24
X52	S355M	355	1,20	1,27
X65	S460M	460	1,37	1,45
X70	S500QL	500	1,49	1,58
X80	S550QL	550	1,51	1,60
X90	S620QL	620	1,53	1,62
X100	S690QL	690	1,54	1,63
X120	S890QL	890	1,79	1,90

Operational and maintenance cost (O&M) is generally expressed as a percentage of the capital/investment cost. It was compared 15 different methods of cost estimations for CO_2 pipelines and the results were that 9 out of 15 use a percentage ranging between 1,5% and 4% to estimate the annual O&M cost [66][68], the rest of the methods have the annual cost as a function of the pipeline length. The O&M cost is in many cases excluding the cost of the electricity price of the compressor. [78]

Due to the significantly lower flow rate of CO_2 emissions, a comparison with figure 2.13 was not feasible. Therefore, further research was conducted to find values that are in a similar order of magnitude. This comparison was achieved by analysing the following case study:

2.4.2.1.6.1 CO_2 Pipeline Cost Analysis Utilizing a Modified FE/NETL CO_2 Transport Cost Model Tool

A modified FE/NETL CO_2 Transport Cost Model [79] was utilized to derive costs and specifications for various large-scale CO_2 pipeline scenarios. The NETL Cost Model, designed for point-to-point pipelines, takes into account inputs such as length, CO_2 capacity, pressure, project financing, and other parameters. It then calculates capital and operating costs, as well as technical specifications like pipeline diameter and the number of pumping stations required. A table was generated, containing all the input data along with the corresponding capital expenditure (CAPEX) and operating expenditure (OPEX) values for different distances and diameters, as shown:

Table 2.17 - Modified FE/NETL CO_2 Transport Cost Model CAPEX and OPEX. Source: [79]

Length (miles)	Number of pumps	Annual CO_2 (Mt/year)	Pipeline inner diameter (in)	CAPEX				Annual O&M ($k)
				Material ($M)	Labor ($M)	ROW ($M)	Misc. ($M)	
3,5	1	0,14	4	0,3	1,7	0,2	0,4	112
8,6	1	1,06	6	0,8	3,7	0,6	0,9	320
14,7	1	0,3	4	1,1	5,8	0,8	1,1	236
17,9	1	0,12	4	1,3	7	0,9	1,3	231
31,9	2	0,98	6	2,8	12,9	2,1	3	683
91	3	0,71	8	9,9	38,5	7,8	10,7	1 218

2.4.2.2 Truck

In this study was also considered truck for the transport of CO_2, where tanks are used as containers. To optimize the transport of CO_2 and keep the transportation at zero emissions the cargo type should be either pressure-type or semi-refrigerated to keep prevent any phase changes in the CO_2 during transportation. Moreover, it was considered to possibilities:

- **Electric trucks**
- **Diesel trucks**

A battery-powered electric truck is a type of vehicle used for transporting goods, carrying specialized loads, or performing utilitarian tasks. These trucks use electricity instead of internal combustion engines, resulting in reduced noise and pollution compared to traditional trucks. Electric trucks are highly efficient and have fewer components, leading to lower ownership and operational costs compared to diesel trucks. [80] They can operate silently and accelerate efficiently without burning fuel while idle. Electric trucks are also quieter, allowing them to operate in cities during nighttime when other heavy vehicles are restricted. This makes businesses more efficient by enabling trucks to be on the road during low-traffic periods, facilitating faster and easier deliveries. The silent operation of electric trucks allows them to approach delivery points more closely, further enhancing productivity. For drivers, electric trucks provide a better working environment with reduced vibrations and quiet operation. [81][82][83] Vehicle models released in recent years have been shown to produce emissions that are at least 63% lower over their lifetime compared to diesel vehicles. This significant reduction holds true even when these vehicles are charged using the European Union's average electricity grid mix, which is not entirely composed of renewable energy sources.[84][85] However, it is important to note that the grid mix is expected to become increasingly renewable during the lifespan of these vehicles. Projections suggest that a remarkable 92% reduction in emissions can be achieved when using 100% renewable electricity. [86]

There are several limitations to the amount of CO_2 that can be transported at a time by trucks. One of the limitations is the load capacity class of the roads and another one is the size of the trucks. The assumption is made that trucks are driven any time of the day, working hours could be used as a limitation. In compliance with EU regulations, workers involved in road transport activities are required to work an average of 48 hours per week. A driver's maximum daily driving time is limited to 9 hours. However, it is permissible to extend the daily driving time to a maximum of 10 hours, but only on two occasions per week. The total weekly driving time for employees must not exceed 56 hours, and their cumulative driving time over a two-week period should not exceed 90 hours. Additionally, employees should not work for more than 6 consecutive hours without taking a break. If the working duration falls between 6 and 9 hours, a minimum break of 30 minutes is required. If the working duration exceeds 9 hours, a break of at least 45 minutes is mandated.[87]

2.4.2.2.1 Existing CO_2 transportation trucks

In Australia, the prevalent method of CO_2 transportation involves trucks, which are used to deliver small quantities to numerous industrial users. Moreover, for experimental purposes at the CO2CRC Otway site, the Callide Oxyfuel Project, backed by the COAL21 industry fund, opted to transport a small volume of CO_2 from Queensland to Victoria using trucks.

2.4.2.2.1.1 Existing companies that transport CO_2

ASCO offers a range of transportable CO_2 tanks in various sizes, which can be conveniently mounted on compatible trucks or trailers at the desired location. These transportable tanks present a cost-effective alternative to traditional road tankers, as the vehicle can be utilized for other tasks in addition to bulk CO_2 transportation. The tank itself is a self-contained unit that is mounted on a base frame, allowing for easy removal and installation with the assistance of a crane when it is empty and as per requirements.[88][89]

Figure 2.14 - ASCO CO_2 truck [88,89]

TOMCO$_2$ Systems has developed CO_2 transportation equipment specifically designed to be mounted on trucks or trailers, prioritizing high-quality materials and considering the daily operations of operators. Their transportation equipment offers a range of options, allowing for versatile configurations that can accommodate various applications and adapt to different climates.[90]

Figure 2.15 - TOMCO$_2$ Systems truck [90]

To ensure a flexible and customer-oriented service, **ACP (Air Products Company)** utilizes tankers for the transportation and storage of liquid CO_2 at customer locations. ACP maintains a significant fleet of these trucks to meet customer demands, allowing for short delivery periods and accommodating small quantities as needed. Additionally, ACP exclusively employs these trucks for CO_2 transport to eliminate any potential risks of contamination. To ensure the safe delivery of goods to customers, ACP provides specialized training to their tanker drivers and conducts regular refresher courses. Furthermore, ACP possesses an in-house technical department with extensive experience in designing, installing, and maintaining customer installations.[91]

Figure 2.16 - ACP (Air Products Company) CO_2 truck

2.4.2.2.2 CO_2 specifications and conditions

The process begins by capturing CO_2, which is then compressed and cooled until it transforms into a liquid state. This occurs at either 19 bar and 30°C or 7 bar and 50°C. The liquid CO_2 is transported in specialized ISO-tank containers with a capacity of 30 tCO2, maintaining a pressure of 22 bar and a temperature of -35°C. [92] A buffer tank is utilized to store the liquid CO_2 until it is pumped into the truck's tank using a pump filling unit. The complete truck transport operation is depicted in figure 2.17. In order to transfer the CO_2 from the buffer tank to the truck, a pump filling unit must be installed. A storage tank with a capacity of 3800 tons will have an approximate cost of $2,13 million, with an annual cost of $0,24 million.[93]

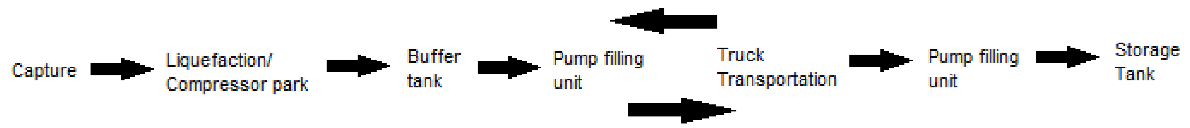


Figure 2.17 - Complete truck transport operation

2.4.2.2.3 Right-of-way

The trucks will be traveling on highly trafficked roads and be operated by personnel. It is therefore vital to try and prevent accidents from occurring which could expose danger to people and the surroundings. The personnel must have received training adapted precisely to their functions and responsibilities, focusing on the provisions of the regulations concerning the transport of dangerous goods. In cases where the transport of dangerous goods involves a multimodal transportation operation, the personnel must be aware of the provisions relating to the other modes of transport.

The purpose of the Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) is to establish regulations governing the transportation of hazardous materials across international borders via land routes.[94] According to Annex 1 of Regulation of the Transportation of Dangerous Goods by Road in Portugal, the carrier must ensure, in particular, that all information prescribed by the ADR (Accord Dangereux Routier) regarding the transport of dangerous goods has been provided by the shipper prior to transportation, that the prescribed documentation is on board the transport unit, or if electronic information handling techniques (TEI) or electronic data interchange (EDI) are used, that the data is available during transportation in a manner at least equivalent to that of paper documentation.[95]

2.4.2.2.4 CO_2 transport risk assessment

Common causes of pump failures include mechanical seal leakage, bearing problems, impeller wear, and coupling issues.

Mechanical seal leakage can occur due to various reasons, such as improper installation of seal rings, dry running, or thermal distortion. Vibration within the pump can also lead to component failures, including seal failures. Detecting external leakage is an indication of the problem, and in such cases, it is crucial to immediately shut down the pump to prevent the release of CO_2 into the atmosphere. [96][97]

Bearing malfunctions often arise from improper lubrication. Adequate lubrication plays a crucial role in protecting the contact surfaces of the bearing, which are involved in both rolling and sliding actions. It serves as a protective barrier, preventing direct metal-to-metal contact and reducing friction and heat generation. Proper lubrication also helps in preventing corrosion and effectively removes solid particles that may cause wear from the rolling contact surfaces.[98]

The **rotating impeller** is a critical component of the pump, and it can fail due to corrosion or cavitation. Corrosion is a common cause of failure, leading to deterioration of the impeller over time. Cavitation, on the other hand, occurs when the pressure of the liquid drops below the vapor pressure, resulting in the formation of bubbles in the low-pressure area. These bubbles then collapse or implode when they reach a high-pressure zone, exerting significant force on the impeller surface. This implosion can cause damage to the impeller and eventually alter its shape. Therefore, both corrosion and cavitation pose significant risks to the integrity and performance of the impeller in a pump system.[96]

One component of vehicles that experiences significant stress is the **front axle**. It undergoes fatigue loads caused by various factors, such as road bumps and vibrations due to its proximity to the engine. [99] Additionally, the high number of trips per truck, including the loading and unloading of heavy cargo, contributes to additional load cycles. These cumulative stresses can potentially lead to the formation of fatigue cracks in the load-bearing structures of the truck.[100]

Brake failure can have severe consequences, particularly when it occurs in a heavy truck weighing around 50-60 tons. When trucks decelerate, the brakes dissipate a substantial amount of energy in the form of heat within a matter of seconds. These rapid heat dissipation events significantly impact the lifespan of brake pads and disks, resulting in shorter durability compared to other axle components.[101] To mitigate the risk of brake failure, it is crucial to regularly inspect and maintain the brakes to ensure their proper functioning.

Tire blowouts or failures can lead to traffic accidents, especially if they happen in the front tires of a truck. In such situations, the truck becomes difficult to control, potentially resulting in multi-vehicle collisions or even truck rollovers. To prevent tire failures, it is essential to perform routine maintenance, including regular checks and timely replacement of worn-out tires. These proactive measures contribute to maintaining the safety and stability of the truck while on the road.[102]

2.4.2.2.5 Costs

2.4.2.2.5.1 Case Study: Sweden

In this study, the transportation of CO_2 from Högdalen to Värtan, covering 20 km, was examined. It is worth noting that longer distances would require increased fuel or electricity consumption, which not only incurs higher costs but also has a more negative impact on the environment. In Stockholm, there are specific regulations on the maximum allowable gross vehicle weight for roads. The gross vehicle weight refers to the combined weight of the vehicle itself and the load it carries. Additionally, different load classes have regulations pertaining to factors such as axle distances on the chassis. The limitations imposed on the container size are closely intertwined with the weight restrictions.

Given that the density of liquid CO_2 is approximately 1100 m^3/kg, the size of the container is constrained to a maximum of 30 m^3 when not completely filled. Comparatively, a typical diesel-powered truck weighing 50 tons has a load capacity of 30 tons. However, if the truck is electric, the estimated weight of the battery is around 10 tons, resulting in a gross vehicle weight of approximately 60 tons.[103]

Table 2.18 - Case study: input data [103]

Description		Value	Unit
Purchase price	Semi-truck	313 600	€
	Tank trailer	110 000	€
Estimated useful life of a truck		10	years
Truck capacity		30	Tons
One-way trip distance		20	Km

2.4.2.2.5.2 Maintenance and Repair Costs

Truck maintenance and repair (M&R) expenses play a significant role in the ownership and operation of trucks. The following table provides a comparison between electric and diesel trucks, highlighting various factors that should be considered.

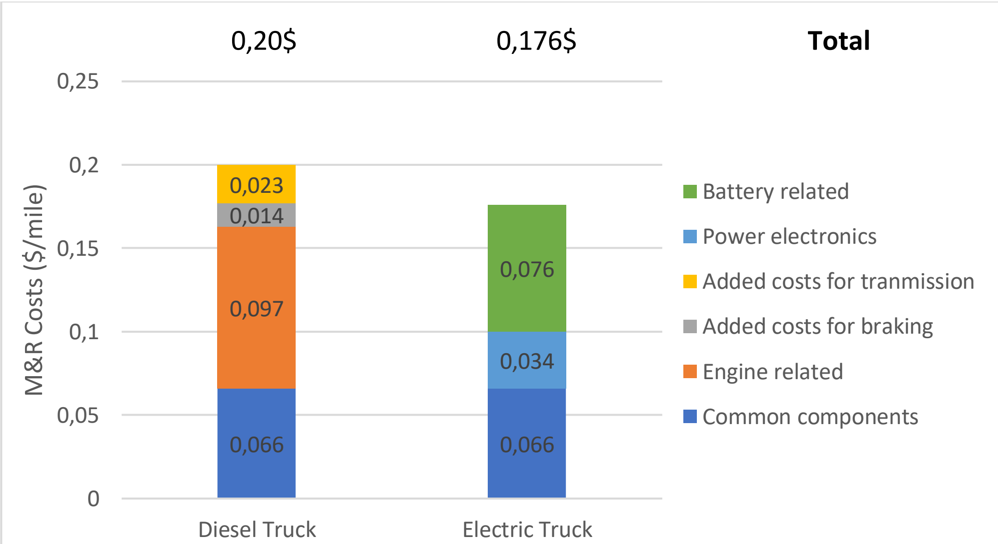


Figure 2.18 - Maintenance and Repair Costs comparison across Truck Technologies. Adapted: [104]

The diesel truck's overall M&R cost is 0,20$/mile and the electric truck's overall M&R cost is 0,176$/mile.[104]

2.4.2.3 Railway

Rail freight transportation and wagon rental offer numerous benefits compared to other transportation modes, enabling the efficient movement of substantial cargo over extensive distances. Like any mode of transport, rail has its advantages and disadvantages. Some of its benefits include:

1. Efficient transportation of large quantities of goods across long distances,
2. Enhanced transport security,
3. Reduced strain on roads due to freight being shifted to railways,
4. Lower CO_2 emissions, contributing to environmental sustainability,
5. Consistent and regular shipments,
6. Reduced vulnerability to weather conditions,

7. Precise adherence to departure and arrival schedules,
8. Relatively infrequent occurrences of faults or disruptions,
9. Cost-effectiveness of shipments.

2.4.2.3.1 Existing CO_2 railway transportation

Green Cargo, a Swedish transportation company, has a regular service for transporting carbon dioxide on behalf of AGA, a gas manufacturer, from Sweden to Norway. They utilize rail transport to deliver carbon dioxide to customers who collect it at the Rolvsoy terminal in Norway. Specially designed wagons are employed for this specific type of transportation. Multiple wagons depart weekly from Norrköping in Sweden, destined for Rolvsoy, situated outside Sarpsborg. The use of rail for CO_2 transportation contributes to a reduction of approximately 150,000 kg of carbon dioxide emissions annually.[105]

2.4.2.3.2 CO_2 specifications and conditions

If the current railway infrastructure connects the carbon capture facility with the storage site, utilizing specially modified tanks for transporting CO_2 via rail becomes a feasible choice. This method proves superior to using trucks, particularly when substantial quantities of CO_2 need to be transported.[106]

2.4.2.3.3 Right-of-way

For the past 25 years, the European Union has been actively promoting more efficient and sustainable transportation methods, particularly focusing on rail freight. As early as 1992, the European Commission prioritized rebalancing the usage of different transport modes as a key objective. In 2001, the Commission further emphasized the significance of revitalizing the railways and aimed to maintain a 35% market share for the rail freight sector in central and eastern European Member States by 2010. Subsequently, in 2011, the Commission set ambitious targets to transition up to 30% of road freight transported over distances greater than 300 km to alternative modes like rail or waterborne transport by 2030, with a long-term goal of surpassing 50% by 2050.

2.4.2.3.3.1 Routes and terminals in Portugal

There are a few terminals in Portugal as demonstrated in the appendix A.1. Freight trains are subject to length limits, as stated in the Network Directory, for each line/branch comprising the national railway network.

Table 2.19 - Length of trains for each line [150]

Line/ Branch	Section	Length	
		Basic (m)	Maximum (m)
Minho Line	Porto Campanhã-Nine	210	520
	Nine - V.Castelo		750
	V. Castelo - Valença		750
Braga Line	Nine - Tadim	415	520
Leixões Line	Contumil-Leixões	355	550
Douro Line	Ermesinde - Caíde	297	520
	Caíde - Pocinho		355
Norte Line	Lisboa Sta Apolónia - Entrocamento	340	550
Norte Line	Entroncamento - Pombal	340	630
	Pombal - Pampilhosa		500
	Pampilhosa- Cacia		680
	Cacia - Porto Campanhã		750
Beira Alta Line	Pampilhosa - Vilar Formoso	260	515
Ramal de Alfarelos	Bifurcação de Lares - Alfarelos	450	500
Oeste Line	Algualva-Cacém - Torres Vedras	295	385
	Torres Vedras - Fig. da Foz		500
Beira Baixa Line	Entrocamento - Abrantes	390	570
	Abrantes - Fundão		525
	Fundão - Covilhã		480
	Covilhã - Guarda		650
Leste Line	Abrantes - Elvas	355	600
Sintra Line	Campolide - Agualva-Cacém	230	330
Cintura Line	Braço de Prata - Ponte de Santana	305	550
	Ponte de Santana - Alcântara Terra		315

Table 2.19 - Length of trains for each line [150]

Line/ Branch	Section	Length	
		Basic (m)	Maximum (m)
Vendas Novas Line	Setil - Vendas Novas	475	605
Alentejo Line	Barreiro - Pinhal Novo	210	310
	Pinhal Novo - Poceirão		630
	Poceirão - Vendas Novas		595
	Vendas Novas - Casa Branca		750
	Casa Branca - Beja		505
Sul Line	Campolide - Pinheiro	260	630
Sul Line	Pinheiro - Ermidas-Sado	400	750
	Ermidas-Sado - Tunes	285	490
Sines Line	Ermidas-Sado - Porto de Sines	620	620
Évora Line	Casa Branca - Évora	745	750
Algarve Line	Tunes - Faro	395	395
	Faro - V.Real Stº António	130	200

2.4.2.4 Ship

Ship transport may be feasible when there is a need for transport over long distances or overseas, however, the location of anthropogenic CO_2 sources and suitable sinks is typically away from navigable waterways, so such scheme would still most likely require pipeline construction between CO_2 sources and port terminals.

2.4.2.5 Case study: Comparison between the train, pipeline and railway cost

To exemplify the computation of transportation costs, three viable project setups were chosen as case studies in the United States. The costs associated with transporting CO_2 via pipeline, truck, and rail for distances up to 200 km were assessed. Figure 2.19 displays the inverse correlation between pipeline and flowrate, whereas truck costs maintain a consistent value irrespective of the flowrate. Moreover, when considering rail transport, the unit cost for smaller flowrates is slightly elevated compared to higher flowrates. [107]

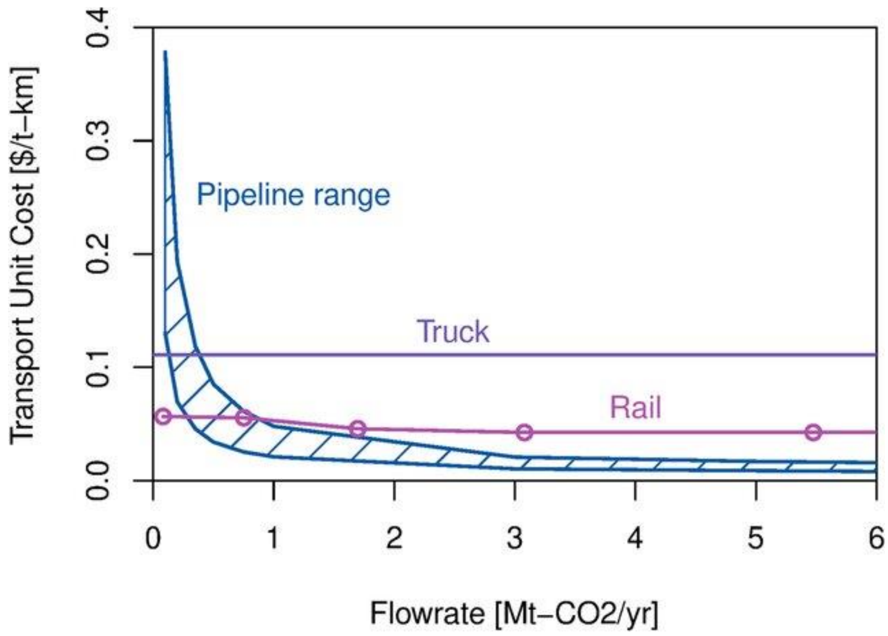


Figure 2.19 - Relation between transportation cost and flowrate for train, truck and pipeline [107]

2.4.3 Storage

CO_2 storage poses a great deal of uncertainty due to the quantification of storage potential, in the confirmation of outline assessments to a standard suitable for investment, the tracking verification and monitoring of injected CO_2, and finally the fail-safe retention of CO_2, so that a storage site can be transferred to government as a low-risk proposition for long-term care and maintenance. There are significant engineering challenges to ensure that the injected CO_2 remains in the subsurface for hundreds or thousands of years, however in general, an essential physical trapping mechanism is the presence of a caprock. The CO_2 is injected at high pressures deep underground; the principal storage sites are saline aquifers, depleted oil and gas fields, and deep coal seams. Most assessments of storage capacity consider that saline aquifers have the largest storage potential, while oil and gas fields offer the economic incentive of additional hydrocarbon recovery when the CO_2 is injected. [108] The combination of CO_2 storage with Enhanced Oil Recovery (EOR) or, potentially, Enhanced Coal Bed Methane recovery (ECBM) could lead to additional revenues from the oil or gas recovery.

In the next table it is possible to observe the maturity of each CCS component: capture, transportation, and storage.

Table 2.21 - Maturity of each CCS component: capture, transportation, and storage [138]

CCS component	CCS technology	Research phase	Demonstration phase	Economically feasible under specific conditions	Mature market
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			

2.4.4 Utilization

CO_2 utilization is a potential way to improve the economic feasibility of carbon capture by creating a revenue stream from captured CO_2. In some contexts, it can also compensate for a lack of readily available and accessible CO_2 storage sites; utilization may also serve to avoid social acceptance issues concerning CO_2 storage. [109]

There are several extant direct utilizations of CO_2, including in soft drinks, with foaming agents, in fire extinguishers, and as propellants. CO_2 can be used in enhanced hydrocarbon recovery (such as oil, gas or coal bed methane) and to produce fuels (methanol, hydrogen, syngas, bio-fuels via algae) or polymers.

The alternative to direct utilization is to transform the CO_2 into something that is more useful overall. This is indirect utilization, such as electrochemical conversion, and is typically not expected to directly remove CO_2 from the atmosphere. The goal of indirect utilization is to establish a sort of anthropogenic carbon cycle, wherein CO_2 can be converted to useful chemicals which will tend to eventually become CO_2 again. This CO_2 can be captured once more and transformed back into useful chemicals, without introducing new CO_2 into the atmosphere.[109] There are, however, two very important caveats in this regard. Firstly, the scale of CO_2 use applications is relatively small compared to the levels of CO_2 capture required this decade. Secondly, many utilization routes are not consistent with reaching net zero emissions, because the captured emissions are released back into the atmosphere in the short or medium term.[110] Captured CO_2 is currently used to a very limited degree in some goods in the beverage industry, and in ethanol, methanol, or fertilizer production. This is due to immature technologies that are also capital and energy intensive, they need to be in vicinity of capture plants to reduce transportation costs and have a commercial market.

2.4.4.1 CO_2 utilization for e-methanol production

Methanol is a highly versatile chemical mainly serving the chemical industry as a base material for a broad range of chemical products, such as polymer fibres for the textile industry, plastics for packaging, glues, adsorbents/nappies, paints, adhesives, and solvents, it also serves as a fuel or fuel additive. [112]

Globally, the reactions involved in the e-methanol formation are exothermal with a reduction of reaction mole number. It is thus favoured by temperature decrease and pressure increase.

There are two pathways for converting CO_2 to e-methanol. One pathway is to reduce CO_2 to carbon monoxide (CO) and then reduce CO with hydrogen to make methanol, which is a two-step process (equation 2.3A e B). The second pathway is direct hydrogenation of CO_2 with hydrogen over a heterogeneous catalyst through a one-step process that converts CO_2 directly to liquid fuels (equation 2.4). [111]

The technology can use CO_2 from multiple sources, such as direct air capture, point source capture, or other available biogenic sources like pulp mills and bio-waste to power plants. Depending on the CO_2 source, there may be a need to clean the CO_2 before it can be used for methanol synthesis. [113]

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad (2.3A)$$

$$CO + 2H_2 \leftrightarrow CH_3OH \quad (2.3\ B)$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad (2.4)$$

As the CO_2 reaction with H_2 derived from water electrolysis represents the sole viable approach for e-methanol production, our discussion will center on this method. In this context, the production of one metric ton of methanol necessitates approximately 1,38 metric tons of CO_2 and 0,19 metric tons of hydrogen. This reaction is carried out at temperatures ranging from 200°C to 300°C and pressures of 50 to 100 bar.

Table 2.22 - Existing or planned facilities for e-methanol production [152]

Country	Company	Start-up year	Capacity	Feedstock
Iceland	CRI	2011	4 000	Geothermal CO_2 and H_2 from water electrolysis
Germany	MefCO_2	2019	1 t/day	Power plant flue gas CO_2 and H_2 from water electrolysis
China	Dalian Institute of Chemical Physics	2020	1 000	CO_2 and H_2 from water electrolysis
Sweden	Liquid Wind	2023	45 000	Upcycled industrial CO_2 and H_2 from water electrolysis
Australia	ABEL	2023	60 000	Biogenic CO_2 and H_2 from water electrolysis
Norway	Swiss Liquid Future/ Thyssenkrupp	-	80 000	CO_2 from ferrosilicon plant and H_2 from water electrolysis

2.4.4.1.1 Cost of production

The most established and scalable approach involves first using water electrolysis to generate hydrogen (H_2) and then employing catalytic methanol synthesis with CO_2. The cost of e-methanol produced through this method is significantly influenced by the costs of its primary ingredients: CO_2 and hydrogen.

Moreover, the cost of hydrogen is intricately connected to the expense of the electrical power required for its production. To manufacture one metric ton of e-methanol, roughly 10-

11 megawatt-hours (MWh) of electricity are necessary, with a substantial portion allocated to the electrolysis process.[110]

Table 2.23 - Cost of producing methanol in different regions [110]

Methanol from natural gas	Europe	USD 300/t
	North America	USD 100/t
Methanol from Coal	China	USD 150-250/t

2.4.4.1.1.1 E-methanol

In 2007 a review evaluated the cost of production for CO_2 based methanol as being between USD 500-670/t. In the 2013 IRENA report, the production cost using CO_2 captured either from glue gases or the atmosphere was estimated at USD 570-1000/t. A summary of these cost estimates is presented in table 2.23, revealing that overall, the production costs for e-methanol are approximately between USD 300 and USD 1000 per ton, depending on the plant's capacity, which ranges from 4 000 tons per year to 1,8 million tons per year. For each tonne of methanol produced 1,5 t of oxygen are generated from the electrolysis of water. The sale of this oxygen could thus offset some of the costs of e-methanol production in the short term.[110]

Table 2.24 - Cost estimates for different carbon sources [110]

Carbon source	Electricity source for electrolysis	Cost of electricity (USD/kWh)	Cost of CO_2 (t/year)	Capacity (t/year)	Capital cost (USD million)	Capital cost (USD/t/year)	OPEX (USD million/year)	OPEX (USD/t)	Methanol cost (USD /t)
Biogas/ammonia	Grid/wind	3,5-16,2	0-3,3	4 000-10 000	16-30	1 680-4 700	2,6 - 12,3	510 - 1 270	680 - 1 610
DAC	Wind	-	-	65 000	222	3 330	-	-	830 - 890
Purchased	Grid	2,4 - 7,3	59	100 000	134	1 340	-	-	365 - 826
Flue gas	Hydropower	-	-	100 000	333-555	3 330-3 890	-	-	890- 1 000
Ethanol plant	Wind	-	-	32 000	30	944	-	-	405-1 070

The cost of e-methanol can also be estimated from the cost of hydrogen and CO_2, which in large e-methanol plants will represent most of the production cost. The cost of CO_2 will depend on the source from which it is captured (biogenic, DAC, Industrial). The cost of hydrogen is strongly correlated with the cost of electricity used to produce hydrogen and the utilisation rate of the electrolyser units and electrolyser cost. [110]

Table 2.25 - Cost of green hydrogen today and in the future [110]

	Historical progress	Where we are heading		Where we should be	
	2015-2018	2030	2050	2030	2050
Cost (USD/Kg H_2)	4-8	2,5 - 5	1,6 - 3,3	1,8 - 3,2	0,9 - 2

Table 2.26 - Estimated cost of CO_2 from different sources [110]

Source or technology	CO_2 concentration in exhaust (%)	Estimated cost of CO_2 (USD/t CO_2)	
		Today	2050
Coal power plant	12-14	43-97	46-55
Coal power plant with oxy-combustion	Close to 100	52-75	52
Natural gas power plant	3-5	80-89	43
Iron and steel	20-30	55-77	40-65
Cement	15-30	35-125	20-103
DAC	-	300-600	50-150
BECCS/BECCU	Close to 100	20-400	-

Table 2.26 also shows that carbon credits can have a large impact on the cost of the renewable methanol produced. A carbon credit of USD 100/t CO_2 can reduce the cost of methanol by USD 172/t compared to no credit at all. As carbon credits are expected to become more prevalent in the future, this could play a significant role in making renewable methanol more competitive, since it is expected to reach levels of USD 250-630/t without CO_2 credits. At first relatively inexpensive CO_2 sources including bioethanol and biogas production will be used, however, these sources have limited availability. Therefore, as the production of CO_2 derived fuels and materials such as e-methanol Increases, costlier options will have to

progressively used. These include pulp and paper, waste-to-energy plants, biomass combustion and DAC.

Table 2.27 - Estimated cost with and without carbon credits [110]

		Estimated cost in		
		2015-2018	2030	2050
Cost of green hydrogen (USD/t H_2)		4 000-8 000	1 800-3 200	900-2 000
Cost of CO_2 (USD/tCO_2)		10-50	15-70	20-150
Cost of methanol (USD/t MeOH)	With no carbon credit	820-1 620	410-750	250-630
	With a credit of USD 50/tCO_2	730-1 540	320-660	160-550
	With a credit of USD 100/tCO_2	640-1 450	240-580	70-460

The costs of producing bio-methanol are inferior to the costs of producing e-methanol ate the moment. In the future, when technology is more mature, the costs will be more similar.

2.5 Tax credits and incentives

Formulating appropriate policies and incentives plays a vital role in achieving objectives related to reducing carbon emissions, ensuring energy security, promoting sustainability, and enhancing the overall quality of life.

2.5.1 Section 45Q Credit for Carbon Oxide Sequestration

Introduced in 2008, Section 45Q of the United States Internal Revenue Code offers a tax credit to promote CO_2 storage, encouraging the implementation of carbon capture, utilization, and storage (CCUS) projects across various types. In 2022, the US government passed the Inflation Reduction Act, which expanded and prolonged the 45Q tax credit, providing substantial incentives for CCUS investment. The updated policy grants up to USD 85 per tonne of CO_2 stored permanently and USD 60 per tonne of CO_2 used for enhanced oil recovery (EOR) or other industrial purposes, given clear proof of emissions reduction. For direct air capture (DAC) projects, the credit amount increases significantly to USD 180 per tonne of CO_2 permanently stored and USD 130 per tonne for utilized CO_2. [114]

Additionally, the capacity requirements for eligible projects have been reduced: power plants need to store at least 75% of the captured CO_2 and have a capacity of 18,750 tonnes per year, while other facilities and DAC facilities require capacities of 12,500 tonnes per year and 1,000 tonnes per year, respectively. Moreover, the 2022 changes extend the qualification period for the tax credit by seven years, allowing projects until January 2033 to commence construction.

2.5.2 European Investment Bank (EIB) Project Development – NER 300

The NER 300 programme will help early-stage, innovative, low-carbon projects which are preparing for the commercial launch of a product. The support will speed up and increase the size of demonstration projects. The free financial advice will improve the bankability of projects while increasing the chances of getting funding from the European Investment Bank and other European financing initiatives. The support is available immediately and will run until the end of 2023.[115]

They focus on innovative projects in renewable energy, carbon capture use and storage, smart energy systems, and energy storage plans that increase the capacity, generation or use of renewable electricity. The projects can involve many technologies and sectors, including wind, solar power, geothermal, ocean, hydropower, bioenergy, battery storage, smart energy distribution systems, renewable fuels or heating and cooling.

2.5.3 European Commission Innovation Fund (ECIF)

The Innovation Fund is one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies. Below are some projects that are granted by the ECIF [116] in the cement and lime industry:

Table 2.28 - Examples of projects funded with ECIF [116]

Location	Project summary	Percentage of the grant
Germany[117]	The Carbon2Business project will deploy an innovative carbon capture technology at Holcim Germany's cement plant in Lägerdorf, Germany, and provide the captured CO_2 as a raw material to different industries in the region. Holcim will build a new kiln line, using an innovative second generation oxyfuel process and a downstream Compression and Purification Unit (CPU). By implementing this highly innovative technology, there will be a reduction of the greenhouse gas (GHG) emissions of its cement production by 128%, calculated over the first ten years of operation.	1,8%
Sweden	Project Air, coordinated by the Perstorp Group, and its partners Fortum and Uniper. The project is a combination of a carbon capture and utilisation (CCU) process for converting CO_2, residue streams, renewable hydrogen and bio-methane is used to create the first-of-a-kind, large-scale production of sustainable methanol. The project is expected to lead to a relative decrease of 123% in greenhouse gas (GHG) emissions avoidance in comparison with conventional methanol synthesis. Project Air will also contribute to Renewable	38%
Sweden	Energy Directive (RED II) targets, as well as the REPowerEU Plan. Further, Project Air's methanol production is far more energy efficient than conventional processes, contributing to the Energy Efficiency Directive (EED) targets.	38%
France	The K6 Program plans to modernize a current cement production site. The project will integrate the rotary kiln system - the central unit of the cement clinker production process - with a very efficient CO_2 capture system. It will also put in place a complete chain of carbon capture, liquefaction, transport and storage at full industrial scale. The main innovation of the project is the installation of the most energy efficient Oxyfuel technology in a cement plant at full scale, in combination with the cryogenic capture and membrane separation technology developed by Air Liquide (CryocapTM). The project also supports the development of the Carbon Capture Utilisation and Storage sector, one of the main priority objectives of the European Strategic Technology Plan (SET Plan). The K6 Program is in line with the new Circular Economy Action Plan in Europe, as it will reduce the water use.	60%

2.6 Carbon credits

Carbon credits, alternatively called carbon offsets, function as licenses permitting individuals or organizations to release a specific quantity of carbon dioxide or other greenhouse gases into the atmosphere. Each credit corresponds to the emission of one ton of carbon dioxide or its equivalent in other greenhouse gases. Companies can buy carbon credits to address emissions they cannot completely eliminate. These credits serve as certificates representing the amount of greenhouse gases that have either been prevented from entering the atmosphere or removed from it. Though carbon credits have been employed for many years, the voluntary market for them has experienced substantial growth in recent times.

The United Nations' Intergovernmental Panel on Climate Change (IPCC) developed a carbon credit proposal to reduce worldwide carbon emissions in a 1997 agreement known as the Kyoto Protocol. This Protocol divided countries into industrialized and developing economies. Industrialized countries, collectively called Annex 1 operated in their own emissions trading market. If a country emitted less than its target number of hydrocarbons, it could sell its surplus credits to countries that did not achieve its Kyoto level goals, through an Emissions Reduction Purchase Agreement (ERPA).

2.6.1 Emissions Reduction Purchase Agreement (ERPA)

An Emissions Reduction Purchase Agreement (ERPA) [118] is a legal contract between entities who buy and sell carbon credits. Emitting more than the assigned limit will result in a penalty for the violating country in the form of a lower emissions limit for the following period. However, if a country wants to emit more GHG than its allowed limit (without penalty), then it may participate in carbon trading using an ERPA. It identifies responsibilities, rights, and obligations to manage project risks. It also defines the commercial terms of the project including price, volume, and delivery schedule of emissions reductions. The standards for ERPAs are outlined by the International Emissions Trading Association (IETA), a nonprofit organization created in 1999 to serve businesses engaged in trading carbon credits.

2.6.2 United Nations Carbon Offset Platform

It's an e-commerce platform where a company, an organization or a regular citizen can purchase units (carbon credits) to compensate greenhouse gas emissions or to simply support action on climate. The main feature of this platform is to display UNFCCC-certified climate friendly projects that reduce, avoid or remove greenhouse gas emissions from the atmosphere. These projects are implemented in developing countries around the world and are rewarded with Certified Emission Reductions (CERs) for each tonne of greenhouse gas they help reduce, avoid or remove.

2.6.3 EU Emissions Trading System (EU ETS)

The EU ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by the operators covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, operators buy or receive emissions allowances, which they can trade with one another as needed. The limit on the total number of allowances available ensures that they have a value. The price signal incentivises emission reductions and promotes investment in innovative, low-carbon technologies, whilst trading brings flexibility that ensures emissions are cut where it costs least to do so.

The EU ETS covers the following sectors and gases, focusing on emissions that can be measured, reported and verified with a high level of accuracy:

- carbon dioxide (CO_2) from
    - electricity and heat generation,
    - energy-intensive industry sectors, including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals,
    - aviation within the European Economic Area and departing flights to Switzerland and the United Kingdom;

In phase 3 of the EU ETS (2013-2020), the Union-wide cap for stationary installations decreased each year by a linear reduction factor of 1,74%. In phase 4 of the EU ETS (2021-2030), the cap on emissions continues to decrease annually at an increased annual linear reduction factor of 2,2%.[119]

Operators in the EU Emissions Trading System (ETS) must surrender annually the number of allowances corresponding to their emissions in the preceding year. For each tonne of emissions for which no allowance is surrendered in due time, there is a penalty of EUR 100. This is on top of the cost of surrendering allowances due. [120]

2.6.4 In Portugal

In the Decree-Law No. 12/2020 of April 6th in Article 12 - Rules for granting emission licenses free of charge is stating that the granting of emission licenses free of charge to electricity producers, CO_2 capture facilities, CO_2 transport pipelines, or CO_2 storage sites is prohibited, except in heat or cold production, the granting of licenses free of charge should benefit urban heating and highly efficient cogeneration, as provided in Decree-Law No. 68-A/2015, dated April 30th, in its current wording.

Emission licenses that are not granted free of charge and are not included in the market stability reserve established in Decision (EU) No. 2015/1814 of the European Parliament and of the Council on October 6, 2015, as amended by Directive (EU) No. 2018/410 of the European Parliament and of the Council on March 14, 2018, shall be subject to auction for sale.

The installation operator whose annual emissions exceed the emission limit value set for that year shall be subject to the payment of a penalty. The penalty consists of the arithmetic average of the price of emission licenses sold at auction, with the revenue going to Portugal, for the year to which the emissions relate, for each ton of emitted CO_2 equivalent above the respective emission limit. An operator who fails to return, by April 30th of each calendar year, the emission licenses corresponding to the emissions verified in the previous year shall be subject to the payment of a penalty for the excess emissions. The penalty amount is €100 per ton of emitted CO_2 equivalent for the installation for which the licenses were not returned.

2.6.4.1 Voluntary Carbon Market

Voluntary carbon markets, by generating economic incentives to reduce emissions or increase carbon sequestration, reinforce the cost-effectiveness of greenhouse gas mitigation measures, and promote innovative solutions and technologies. They constitute a tool that supports the achievement of national objectives in climate action, accelerating the transition to a carbon-neutral society and strengthening the commitment to the United Nations' "Sustainable Development Goals" of the 2030 agenda.

The creation of a voluntary carbon market in Portugal allows for the involvement and participation of various stakeholders, at the individual or corporate level, whether public or private. On the supply side, it promotes projects that reduce emissions or sequester carbon, generating carbon credits. On the demand side, it enables the acquisition of these credits to offset residual emissions or provide financial contributions to climate action. This market not only facilitates collaboration among different agents but also catalyses private sector investments, complementing public efforts to accelerate and promote mitigation actions within the national territory.

With the implementation of the voluntary carbon market, and according with what already happens in other countries in the world, Portugal intends to anticipate an issue that is being discussed within the European institutions (Proposal for a European Regulation establishing a Union certification framework for carbon removals): that is, the regulation of the voluntary carbon markets that already operate in practice, outside the space occupied by the mandatory carbon market.[122]

The rules where subject to public consultation until 10th of April of 2023 refer to the creation of the voluntary market: participants are not obliged to purchase permits nor are they limited to a number of carbon emissions. Differently, the incentives to participate in the voluntary market are often reputational in a perspective of *Green marketing* and corporate social responsibility. [121]

There are two legal types of Carbon Credits:

a) **Future Carbon Credits (FCC):** credits generated at the project's zero moment (prior to its implementation) based on an estimate validated by an independent auditor, in an amount not exceeding 10 % of the total credits expected to be generated during the life of the project; this percentage may not be sufficient to contribute to the viability of the initial investment.

b) **Verified Carbon Credits (VCC**) generated after an effective GHG emission reduction or carbon sequestration by the project duly verified by an independent auditor.
The draft Decree-Law also contemplates the figure of Carbon Credits +, i.e. those resulting from projects that besides carbon sequestration include "significant additional benefits at the level of biodiversity and natural capital" - it is not, however, clear what advantages are associated with these Carbon Credits +.

3

METHODOLOGY

In this chapter, we delve into the methodology employed in this study, a critical phase that forms the backbone of my research. This chapter will detail the systematic approach we followed to identify various sources of carbon dioxide (CO_2) emissions, establish diverse scenarios, devise formulas for calculating the associated costs, and ultimately determine the most optimal means of transporting CO_2. As a pivotal tool for visualizing the methodological process, it is possible to see figure 3.1. This flowchart will offer a clear, structured overview of the approach, aiding in the understanding of the intricate steps involved in the study. Through this chapter, I aim to provide a solid grasp of the research framework, setting the stage for the subsequent analyses and findings.

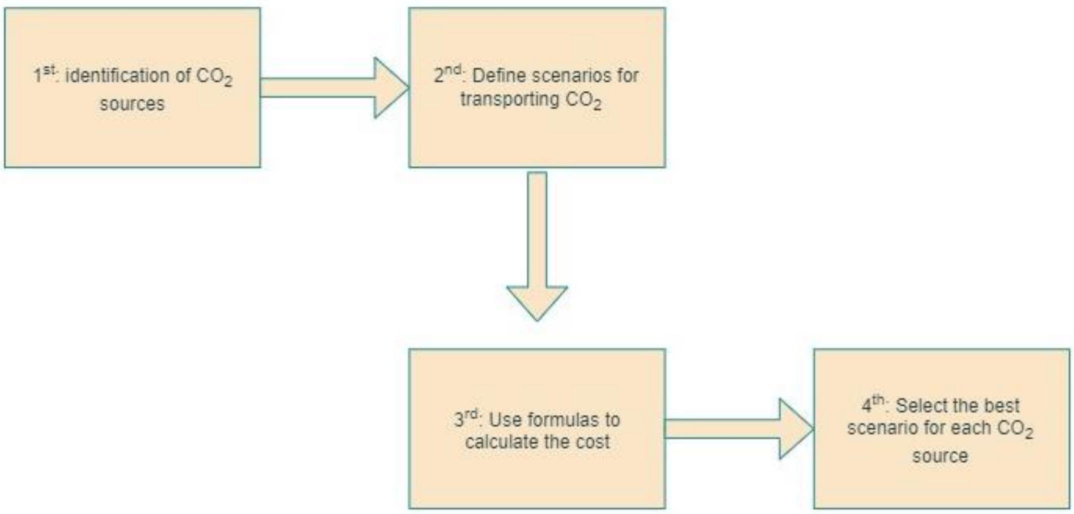


Figure 3.1 - Flowchart of the methodology

3.1 Identification of scenarios and relevant data

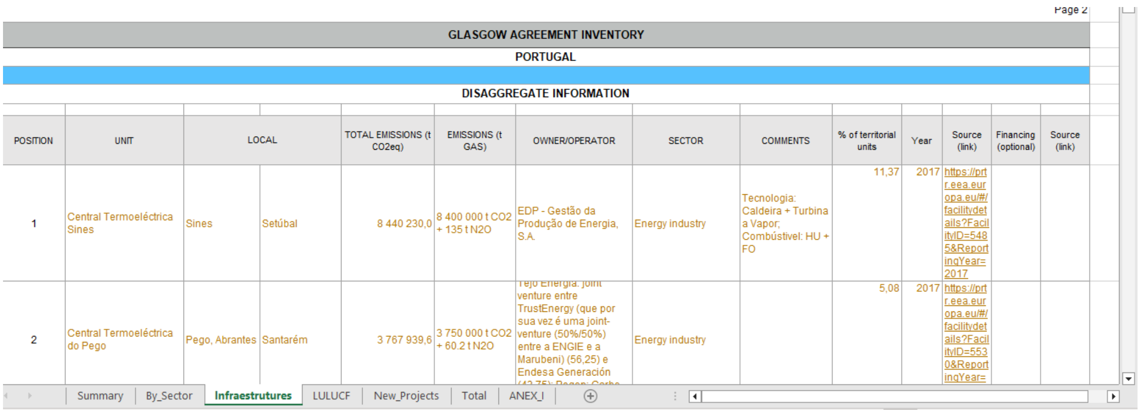
In order to identify the possible scenarios for CO_2 transportation is essential to know the key point sources of the Portuguese GHG emissions and the CO_2 emissions from selected major sources. In November 2020, the collective Climaximo and the Student Climate Strike signed the Glasgow Agreement, and they committed themselves to develop the following inventory accessing all the sectors emitting CO_2 emissions and the respective infrastructures. [123]

The information included in figure 3.2 relates to the exercise of spatial distribution by Municipality of estimated emissions of atmospheric pollutants and greenhouse gases, respectively, within the scope of the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC). The spreadsheet is divided into 14 categories, namely: public power, industry, combustion, fugitive emissions, solvents, road transport, shipping, international and domestic aviation, rail transport, waste disposal on land and biogas burning, enteric fermentation, agriculture, and forest fires. With this information, it was possible to determine the areas in Portugal with the highest CO_2 emissions and present them in a map.

			CO2
Concelho	**GNFR**	**Ano**	**kton**
Águeda	A_PublicPower	2019	-
Águeda	B_Industry	2019	5,394
Águeda	C_OtherStationaryComl	2019	11,399
Águeda	D_Fugitive	2019	0,000
Águeda	E_Solvents	2019	0,927
Águeda	F_RoadTransport	2019	63,856
Águeda	G_Shipping	2019	-
Águeda	H_Aviation	2019	-
Águeda	I_Offroad	2019	1,938
Águeda	J_Waste	2019	-
Águeda	K_AgriLivestock	2019	-
Águeda	L_AgriOther	2019	0,077
Águeda	M_Other	2019	-
Águeda	N_Natural	2019	10,940
Águeda	**Total**	**2019**	**94,530**

Figure 3.2 - CO_2 emissions per municipality and by sector

Furthermore, Figure 3.3 allowed us to gain insights into the facilities responsible for higher CO_2 emissions in Portugal, particularly within the Leiria region.



Page 2

GLASGOW AGREEMENT INVENTORY

PORTUGAL

DISAGGREGATE INFORMATION

POSITION	UNIT	LOCAL		TOTAL EMISSIONS (t CO2eq)	EMISSIONS (t GAS)	OWNER/OPERATOR	SECTOR	COMMENTS	% of territorial units	Year	Source (link)	Financing (optional)	Source (link)
1	Central Termoeléctrica Sines	Sines	Setúbal	8 440 230,0	8 400 000 t CO2 + 135 t N2O	EDP - Gestão da Produção de Energia, S.A.	Energy industry	Tecnologia: Caldeira + Turbina a Vapor; Combústivel: HU + FO	11,37	2017	https://prtr.eea.europa.eu/#/facilitydetails?FacilityID=5485&ReportingYear=2017		
2	Central Termoeléctrica do Pego	Pego, Abrantes	Santarém	3 767 939,6	3 750 000 t CO2 + 60.2 t N2O	Tejo Energia: joint venture entre TrustEnergy (que por sua vez é uma joint-venture (50%/50%) entre a ENGIE e a Marubeni) (56,25) e Endesa Generación	Energy industry		5,08	2017	https://prtr.eea.europa.eu/#/facilitydetails?FacilityID=5530&ReportingYear=		

Summary | By_Sector | Infraestrutures | LULUCF | New_Projects | Total | ANEX_I

Figure 3.3 - Excel with all the CO_2 sources in Portugal for 2021

Since the aim of these work is to access the costs of different means of transportation CO_2 from various sources of CO_2 emissions to Pataias (Leiria), where will be located the methanol plant, the major sources of CO_2 emissions chosen where located near Leiria.

After selecting the main sources of CO_2 emissions, the following step is to determine the distance between the source and the methanol plant by each mean of transportation: truck, pipeline and railway. There are three scenarios:

- Scenario 1: Truck
- Scenario 2: Pipeline
- Scenario 3: Railway + Truck

It will be presented the methodology applied to each of the scenarios. It is essential to understand the various approaches used to accurately assess their effectiveness and reliability. Transparency in the modelling process is paramount, ensuring that the obtained results are as accurate and representative as possible.

For each model, careful consideration was given to selecting appropriate forms and implementing a systematic methodology. These chosen forms take into account specific variables and factors relevant to the respective model's purpose and scope. Detailed explanations of the forms and methodologies used promote transparency and facilitate a deeper understanding of the models' results.

3.1.1 Pipeline

To estimate pipeline transport costs, this model estimates: CAPEX (Capital Expenditures) and OPEX (Operational Expenditures), based on the amount of CO_2 emissions, the distance between the source and the destination and the outside diameter.

Before calculating the CAPEX and OPEX it is necessary to calculate the diameter, as following:

$$Q = A \times v \quad (3.1)$$

$$A = 2\pi r^2 \quad (3.2)$$

where,

Q = flow rate in m^3/s

A = cross sectional area in m^2

v = CO_2 velocity m/s

With the following input data:

Table 3.1 - Input data for determining the diameter

Property	Value	Unit
Density (350K and 8MPa)	164	Kg/m^3
Supercritical CO_2 velocity	4	m/s

The diameter obtained was round up to the closest standard CO_2 pipelines diameter.

The costs associated with building pipeline infrastructure (CAPEX) can be separated into three groups:

1. Total installed costs: [124]

The total installed cost for various pipelines (TIC_{pipe}) were developed from historical construction cost projections for over 20,000 miles of natural gas, oil, and petroleum product pipelines in 893 projects in the US over 13 years to produce an acceptable equation estimating costs of the construction a pipeline of a given length and diameter.

$$\text{TIC}_{\text{pipe}} = \text{Material cost} + \text{Labor cost} + \text{Miscellaneous cost} + \text{Right-of-way cost} \quad (3.3)$$

1. Materials cost

This method resulted in the following equation for materials costs. The average percent error is 31,4%.

$$\text{Materials Cost (\$)} = [330{,}5 \times \text{dia}^2 + 687 \times \text{dia} + 26\,960] \times \text{length} + 35\,000 \quad (3.4)$$

where,
dia = diameter of the pipeline, in inches
length = length of the pipeline, in miles

2. Labour Cost

The average percent error for the estimated costs is 49,4%. The labour cost proves to be difficult to describe with only the pipeline length and diameter.

$$\text{Labour Cost (\$)} = [343 \times \text{dia}^2 + 2\,074 \times \text{dia} + 170\,013] \times \text{length} + 185\,000 \quad (3.5)$$

where,
dia = diameter of the pipeline, in inches
length = length of the pipeline, in miles

3. Miscellaneous

Miscellaneous costs are all costs not included in labour, material, or right of way. They generally include surveying, engineering, supervision, contingencies, allowances, overhead, and filing fees.

The minimum average percent error equation for the miscellaneous construction cost is the following equation with an average percent error of 58,6%.

$$\text{Miscellaeous Cost (\$)} = [343 \times \text{dia}^2 + 2\,074 \times \text{dia} + 170\,013] \times \text{length} + 185\,000 \quad (3.6)$$

where,
dia = diameter of the pipeline, in inches
length = length of the pipeline, in miles

4. Right-of-way

The right of way portion of the total construction cost is not easily described by the pipeline diameter and length alone. In some cases, pipelines were laid next to existing lines resulting in low to zero right of way cost. In other cases, the right of way is expensive due to the location.

The average percent error is 83,6%, not a good fit. Since the right of way cost is a small fraction of the total cost, this error does not translate into a big error for the total cost estimate.

$$\text{Right-of-way Cost (\$)} = [577 \times \text{dia}^2 + 29\,788] \times \text{length} + 40\,000 \qquad (3.7)$$

where,
dia = diameter of the pipeline, in inches
length = length of the pipeline, in miles

2. Total capital Investment: [124]

Once the TIC_{pipe} is calculated, the total capital investment of pipeline (TCI_{pipe}) can be determined by adding the indirect costs. TCI is the CAPEX at the beginning of a project and can occur over several years depending on how long it takes to design & procure equipment, deliver it to a project site, and construct the project.

$$\text{TCI}_{\text{pipe}}\ \text{(Capex of pipeline)} = \text{TIC}_{\text{pipe}} + \text{Indirect costs (\%)} \qquad (3.8)$$

3. Indirect costs:

The indirect costs used in this technical brief are based on established literature and are detailed below:

- Site preparation = 5% of TIC;

Encompassed within are the acquisition of land, the levelling and excavation of the premises, the establishment and connection of electrical, water, and sewer infrastructure, and the construction of internal roads, pathways, and parking areas.

- Engineering & Design = 10% of TIC;

Incorporated within are the remuneration and operational expenses for the engineering, drafting, and project management staff engaged in the project.

- Project Contingency = 10% of TIC;

A provision is included to account for unforeseen events, encompassing project risks and uncertainties. These unforeseen circumstances may encompass time delays caused by storms and strikes, minor design alterations, and unexpected fluctuations in prices.

- Permitting = 3% of TIC;

The expenses associated with obtaining the required approvals for designing and installing control equipment are referred to as permitting costs. These costs vary depending on the specific site and may not directly correspond to those of another facility. Nonetheless, it is important to include permitting costs in the overall assessment of expenses due to the potential for delays, redesigning requirements, and other relevant factors.

The costs associated with pipeline operations (OPEX) include:

Here is included labour costs and other fixed operation and maintenance costs as shown.

$$\mathrm{OPEX_{pipe}}\left(\frac{\$}{\mathrm{y}}\right)=\mathrm{Total\ labour_{pipe}}\left(\frac{\$}{\mathrm{y}}\right)+\mathrm{Fixed\ O\&M_{pipe}}\left(\frac{\$}{\mathrm{y}}\right) \tag{3.9}$$

- <u>Total labour cost:</u>

$$\mathrm{Total\ labour\ pipe}\left(\frac{\$}{\mathrm{y}}\right)=\mathrm{Direct\ labor_{pipe}}\left(\frac{\$}{\mathrm{y}}\right)+\mathrm{Fixed\ O\&M_{pipe}}\left(\frac{\$}{\mathrm{y}}\right) \tag{3.10}$$

  - <u>Direct labour cost:</u>

In Portugal the average labour rate is 13$ per hour.

$$\mathrm{Direct\ labour_{pipe}}\left(\frac{\$}{\mathrm{y}}\right)=\mathrm{Annual\ hours}\left(\frac{\mathrm{hours}}{\mathrm{y}}\right)\times\mathrm{Labor\ rate}\left(\frac{\$}{\mathrm{hour}}\right) \tag{3.11}$$

$$\mathrm{Annual\ labour\ hours}\left(\frac{\mathrm{hours}}{\mathrm{y}}\right)=8320\times\left(\frac{\mathrm{x}}{100\ 000}\right)^{0,25} \tag{3.12}$$

where,
x = average pipeline use (Kg CO_2/day)

  - <u>Indirect labour cost</u>

It is used to consider the cost of overhead (i.e. head office, personnel).

$$\text{Indirect labour}_{\text{pipe}}\left(\frac{\$}{\text{y}}\right)=\text{Direct labour}_{\text{pipe}}\left(\frac{\$}{\text{y}}\right)\times\text{Indirect labour factor}(\%) \quad (3.13)$$

where,

$$\text{Indirect labour factor} = 50\%$$

- <u>Fixed O&M costs:</u>

The fixed operation and maintenance (O&M) costs, excluding labour, are determined as a proportion of the Total Capital Investment (TCI) to account for the higher maintenance expenses associated with larger and more intricate projects. In the case of transmission pipelines, this amounts to 4% of the TCI. [125] These costs can be further categorized as follows:[128]

  - Insurance
  - Property tax
  - Licensing and permitting
  - Operating, maintenance and repairs

$$\text{Fixed O\&M}_{\text{pipe}}\left(\frac{\$}{\text{y}}\right)=\text{Insurance}(\frac{\$}{\text{y}})+\text{Property tax}(\frac{\$}{\text{y}})+\text{Permitis}(\frac{\$}{\text{y}})+\text{O\&M}(\frac{\$}{\text{y}}) \quad (3.14)$$

- **<u>Pumping:</u>**

When CO_2 is in its gaseous state, compression necessitates the use of a compressor. However, when CO_2 transitions to the liquid/dense phase, pressure can be increased using a pump. The critical pressure of CO_2, which is 7,38 MPa, is considered the 'cut-off' pressure ($P_{cut\text{-}off}$) for switching from a compressor to a pump. Consequently, a compressor will be employed in the pressure range of 0,1 to 7,38 MPa, while a pump will take over from 7,38 to 15 MPa (or any desired final pressure). Since the costs of compression are not considered for any transportation mode, the focus will be solely on the expenses associated with the pumps and the electricity required to operate them.

- Pumping power

To calculate the pumping power requirement for boosting the CO_2 pressure from $P_{cut\text{-}off}$ (7,38 MPa) to P_{final} (15 MPa), the following equation has been adapted from:

$$W_p = \frac{1000 \times 10}{24 \times 36} \times \frac{m \times (P_{final} - P_{cut\text{-}off})}{\rho \times \eta} \quad (3.15)$$

where,

m= CO_2 mass flow rate in tonnes/day

ρ= 630Kg/m^3

η=0,75

100=# of kilograms per tonne

24=# of hours per day

10=# of bar per MPa

36= # of m^3 x bar/hr per kW

The capital cost of the pump can be calculated based on the following equation:

$$C_{pump} = 1{,}11 \times 10^6 \times \frac{W_p}{1000} + 0{,}07 \times 10^6 \quad (3.16)$$

The total electric power costs of pump (E_{pump}) is calculated by multiplying the total power requirement by the capacity factor (CF) of 0,80 and price of electricity.

$$E_{annual} = E_{pump} = p_{electricity} \times W_p \times CF \times 24 \times 365 \quad (3.17)$$

Pipeline Levelized Cost

The simple definition for the Levelized cost of CO_2 for pipeline transport ($LCOCO_{2pipe}$) is as follows:[129]

$$\text{LCOCO}_2\left(\frac{\$}{KgCO_2}\right) = \frac{\text{Annualized capex}_{\text{pipe}}\left(\frac{\$}{y}\right) + \text{CAPEX}_{\text{pump}}\left(\frac{\$}{y}\right) + \text{OPEX}_{\text{pipe}}\left(\frac{\$}{y}\right) + \text{OPEX}_{\text{pump}}\left(\frac{\$}{y}\right)}{\text{Availability}_{\text{pipe}}(\%)\times\text{Capacity}_{\text{pipe}}\left(\frac{KgCO_2}{day}\right)\times 365\left(\frac{day}{y}\right)} \quad (3.18)$$

where,

$$Annualized\ \text{capex}_{\text{pipe}}\left(\frac{\$}{\text{Y}}\right) = \text{TCI}_{\text{pipe}}(\$)\times\text{Capital recovery factor (CRF)} \quad (3.19)$$

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (3.20)$$

where,
i – Discount rate (%)
n – Pipe lifetime

Table 3.2 - Input data do calculate CRF

Pipe lifetime	50 years
Discount rate	0,08

The annualized Total Capital Investment (TCI) transforms the initial capital investment, typically made at the project's inception, into an annualized expenditure. This enables a fair comparison with other annual expenses, such as non-energy operating expenses (OPEX).

Availability refers to the proportion of time in a year that an asset, such as a pipeline in this context, can operate effectively. By multiplying the availability factor with the pipeline's design capacity, the daily transportation capacity of CO_2 can be determined. In the case of large transmission pipelines, it is assumed that they need to be taken offline for maintenance or experience unplanned outages for only a few weeks per year, which accounts for approximately 10% of the time. Therefore, the availability is calculated as 100% minus 10%, resulting in an availability of 90%.

All economic assumptions used to calculate, and the results are presented in chapter 4.

3.1.2 Truck

As it was done for pipeline, for truck it was calculated the CAPEX and the OPEX, as following:

The costs associated with initial investment (CAPEX) is the purchase of trucks (diesel and electric), tank trailer, storage tank in site and loading arms.

First it was determined the number of trucks necessary to purchase for each trip, assuming that the loading capacity is 25 ton of CO_2.

$$\text{Number of trips per year} = \frac{\text{Total } CO_2 \text{ emissons (ton)}}{\text{Truck capacity (ton)}} \tag{3.21}$$

$$\text{Number of trips per day} = \frac{\text{Number of trips per year}}{365} \tag{3.22}$$

Secondly, it was determined the time needed to make a round trip with the loading and unloading time, which is presented in chapter 4.

According to the Portuguese law, drivers can only drive for a period of 10h straight for the safety of all personal in the road.

$$\text{Number of trips possible for a truck per day} = \frac{10\ (h)}{\text{Time need for round trip (h)}} \tag{3.23}$$

With this information it is possible to calculate the number of trucks needed for each route (equation 3.24).

$$\text{Number of trucks} = \frac{\text{Number of trips per day}}{\text{Number of trips possible for a truck per day}} \tag{3.24}$$

Knowing the cost of trucks (diesel and electric) and tank trailer, as shown in table 3.3, it was possible to calculate the total capital cost, using the following equation:

$$\text{CAPEX (€)} = \text{Number of trucks} \times (\text{cost of truck} + \text{tank trailer} + \text{loading arm}) + \text{cost of storage tank} \tag{3.25}$$

The Capital Recovery Factor was calculated as was done with pipeline, equation 3.20, for a lifetime of 10 years.

$$\text{Annualized capex}_{\text{truck}}\left(\frac{€}{y}\right) = \text{CAPEX}\times\text{Capital Recovery Factor} \tag{3.26}$$

The costs associated with truck operations (OPEX) include:

Table 3.3 - Input data with costs associated with OPEX

License fees and taxes	CO_2 tax	94,88	€/y
	Vehicle tax	368	€/y
Average consumption	Electricity	1,06	kWh/km
	Diesel	0,2492	L/ km
Loading time	1,5		h
Fuel price	Diesel	1,473	€/L
	Electricity	0,10173	€/kWh
Labour rate per hour	13		€/h

Apart from this, it was also determined the tolls cost through Via Verde estimation platform for each route.

The cost per mile for maintenance and repair of trucks (diesel and electric) are presented in the next table:

Table 3.4 - Cost per mile for maintenance and repair of trucks (diesel and electric) [104]

Type of truck	Value	Unit
Diesel	0,2	$/mile
Electric	0,175	$/mile

The OPEX was then calculated by the following equation:

$$\begin{aligned}\text{OPEX}\left(\frac{€}{y}\right) = {} & \text{Tolls}\times2\times\text{Number of trips per year}+\text{Cost of diesel per trip}\times \\ & \text{Number of trips per year} + \text{Maintenance and repair per year} + \\ & \text{CO}_2\text{tax}+\text{Labor work per year}+\text{Vehicle tax per year}\end{aligned} \tag{3.27}$$

The results for multiple scenarios are presented in chapter 4.

The simple definition for the Levelized cost of CO_2 for truck transport ($LCOCO_{2truck}$) is as follows:

$$LCOCO_2\left(\frac{€}{tonCO_2}\right) = \frac{Annualized\ \mathrm{capex_{truck}}\left(\frac{€}{y}\right) + OPEX_{truck}\left(\frac{€}{y}\right)}{\mathrm{CO_2 emissions}\left(\frac{ton\ CO_2}{year}\right)} \quad (3.28)$$

3.1.3 Railway

In order to calculate the costs associated to the transportation of CO_2 by railway, the costs were divided in OPEX and CAPEX. Before calculating those costs, it was determined the number of wagons per year and total length of the wagons, using the following equations:

$$\text{Number of wagons per year} = \frac{\mathrm{CO_2 emissions}}{\mathrm{CO_2}\ \text{Density} \times \text{Wagon Capacity}} \quad (3.29)$$

where,

CO_2 density = 630Kg/m^3

Wagon Capacity = 88 m^3

$$\text{Length of the wagons per year} = \text{Number of wagons per year} \times \text{length of one wagon} \quad (3.30)$$

where,

1 wagon = 15 m

$$\text{Number of trips per year} = \frac{\text{length of the wagon per year}}{\text{max length of train}} \quad (3.31)$$

In order to be able to make the trips in this region, the maximum length of the train is 500 m.

$$\text{Number of wagons in one trip} = \frac{\text{Number of wagons per year}}{\text{Number of trips per year}} \quad (3.32)$$

The costs associated with initial investment (CAPEX) is the purchase of a storage tank in site and loading arms. For CO_2 storage next to the e-methanol plant, there is a storage tank with a capacity of 3800 m^3, which costs 2,07 million €. Moreover, to load the CO_2 into the wagons, loading arms are used, with a cost of 7,200 € each.

In OPEX there were included the costs associated with the infrastructure usage, labour, and wagon rental.

- Infrastructure Usage Fee

To calculate the infrastructure usage fee, some considerations had to be defined, such as the type of goods to be transported, the operating line that will be used, traction utilized and the period of the day, according to this formula:

$$IUF = \sum_{i=1}^{n} T_i \times CK_i \tag{3.33}$$

where,

IUF - Infrastructure Usage Fee - Fee charged for the provision of services included in the minimum access package when using a time slot by a railway composition.

i - Operating Line

T_i- Base tariff - defined for each operating line, depending on the type of traction and use of platforms, train schedule, and market segment.

CK_i- Distance effectively traveled by a railway composition on each of the operating lines.

The calculation of the tariffs to be established for the minimum access package follows the formula:

$$T_i = DUC \times P_1 \times C_{2i} \times C_3 \times C_4 \times F \tag{3.34}$$

where,

T_i- Tariff for section i

DUC - Direct Unit Cost

P_1 - Cost Modulation Component for train traction and/or platform usage

C_{2i} - Line Demand Component

C_3 - Train Schedule Component

C_4 - Market Segment Component

F - Implementation Factor

The Direct Unit Cost, or DUC, is calculated by dividing the directly attributable costs by the effectively used capacity, on a network scale, thus representing the applicable average value. Based on the calculation using the actual costs and utilized capacity of the reference period, in accordance with Implementation Regulation (EU) 2015/909, the CUD is equal to 1,77 €/ck.

The component - Use of catenary and platform infrastructure (P_1) - reflects the differentiation of cost allocation to cks performed by trains with or without electric traction, using or not using station platforms.

Table 3.5 - Catenary and platform infrastructure [150]

P_1	Differentiation
Electric traction with platform utilization	Allocation to the average CUD (Chargeable Usage Distance) of costs directly attributable to the use of the catenary and platforms
Electric traction without platform utilization	Allocation to the average CUD (Chargeable Usage Distance) of costs directly attributable to the use of the catenary and platforms, and deduction from the average CUD of costs directly attributable to the use of platforms
Diesel traction with platform utilization	Deduction from the average CUD (Chargeable Usage Distance) of costs directly attributable to the use of the catenary
Diesel traction without platform utilization	Deduction from the average CUD (Chargeable Usage Distance) of costs directly attributable to the use of the catenary and platforms

The component - Line Demand (C_{2i}) - is organized into three categories related to the volume of traffic in cks and the length of tracks on each line, resulting in the following distribution:

Table 3.6 - Line Demand [150]

Category	Lines
Lines A	Core lines of the National Rail Freight Network with higher demand/value
Lines B	Lines with mixed passenger and freight consumption, complementing the traffic of type A lines
Lines C	Residual consumption lines mostly used by regional railway companies for freight and passenger transport

The component - Train Schedule (C_3) - For tariff purposes, the accounting time is the scheduled departure time.

Table 3.7 - Train Schedule [150]

Train departure schedule	Weekdays	Saturdays, Sundays, and official holidays
Low	00h00 - 05h59 20h45 - 23h59	00h00 - 05h59 20h45 - 23h59
Regular	10h00 - 16h30	06h00 - 20h44
Peak	06h00 - 09h59 16h31 - 20h44	NA

The component - Market Segment (C_4) - categorizes the existing offer based on the type of channel available. Some of the currently considered segments for tariff purposes are presented in the table below:

Table 3.8 - Market Segment [150]

Market segment	Definition for tariff purposes
Urban	Urban trains encompass all regular services that serve commuter flows of passengers within urban centres and between these centres and their respective suburbs.
International	Regular passenger trains that cross at least one border and operate beyond the first station of the neighbouring network.
Freight	Trains dedicated to the transportation of goods.

The following table presents the parameters applied to the tariffs listed in this Network Directory:

Table 3.9 - Parameters applied to the tariffs [150]

Components of the fare	Allocation parameter	Value of the parameter
Direct unit cost	single value	1,77
Use of catenary and platforms infrastructure	Electric traction with platform utilization	1,03
	Electric traction without platform utilization	1,02
	Diesel traction with platform utilization	0,90
	Diesel traction without platform utilization	0,89
Line demand	A	1,00
	B	0,90
	C	0,85
Train schedule	Peak	1,00
	Regular	1,00
	Low	0,85
Market segment	Urban	1,25

Table 3.9 - Parameters applied to the tariffs [150]

Components of the fare	Allocation parameter	Value of the parameter
Market segment	International	1,00
	Freight	1,00

For the transportation of CO_2 according to the source and destination, it was selected the criteria in table 3.10, as resulted in 0,956 €/ck.

Table 3.10 - Components of the fare chosen [150]

Components of the fare	Allocation parameter	Value of the parameter
Direct unit cost	single value	1,77
Use of catenary and platforms infrastructure	Electric traction without platform utilization	1,02
Line demand	C	0,85
Train schedule	Low	0,85
Market segment	Freight	1,00

The OPEX (Operational Expenditure) includes the cost of wagon rental, which amounts to 203€ per wagon, considering that each wagon has a capacity of 88m^3 and a length of 15m.

- Wagon rental

$$\text{Rental of wagons per year}\left(\frac{€}{\text{y}}\right) = \text{Numberof wagons}\times \text{rental wagon} \times \text{number of trips per year} \tag{3.35}$$

1 wagon rental = 203€

According to figure A.1 in appendix A.1, there is a restriction on the maximum train length for the Oeste Line (where Pataias is located), with a maximum allowable length of 500m, allowing for a maximum of 33 wagons.

Additionally, it is also included the labour cost, which depends on the time spent per trip plus the loading and unloading time as presented in the following table:

Table 3.11 - Time of transport for each scenario [151]

Location	Time of transport by railway (min)
Maceira, Secil	4
Marinha Grande, BA Glass	13
Marinha Grande, Gallo Vidro	13
Marinha Grande, Santos Barosa	13
Figueira de Foz, Verallia	68
Marinha Grande, Crisal	13
Pinheiros, RESPOL Resinas	23
Figueira da Foz, Navigator	48
CCGT Lares	68
Vila Nova de Famalicão	138

- Labour

$$\text{Labour (€)} = \text{time transport} \times \text{number of trips per year} \times \text{Labor rate per hour} \quad (3.36)$$

where,

Labour rate per hour = 13€/h

In some instances, the CO_2-emitting factory is not located near the railway station, resulting in a cost associated with transportation by truck.

4

Analysis and Discussion of Results

In this chapter, all the results are presented, and a detailed analysis of these results is also conducted to comprehend the models and means of transport proposed in this dissertation and assess their viability from a perspective standpoint.

4.1 Identification of scenarios and relevant data

In order to identify the possible scenarios for CO_2 transportation is essential to know the key point sources of the Portuguese GHG emissions and the CO_2 emissions from selected major sources, from 2021.

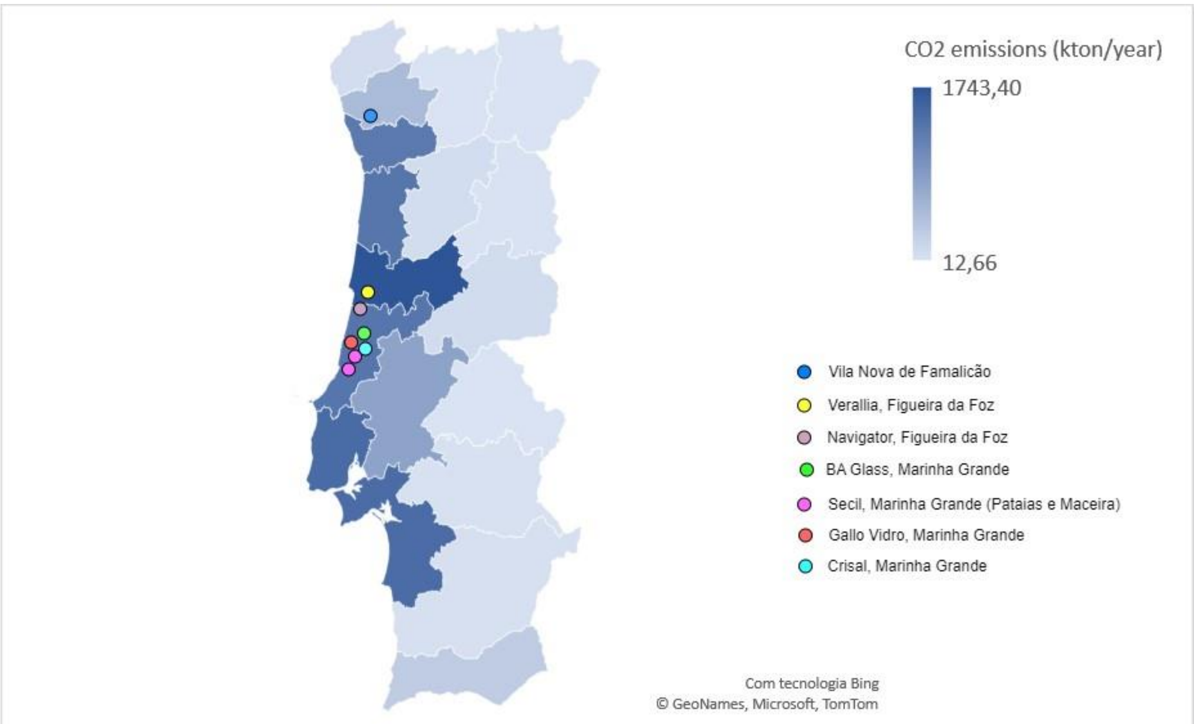


Figure 4.1 - Map with major CO_2 emissions sources

The aim of these work is to access the costs of different means of transportation CO_2 from various sources of CO_2 emissions to Pataias (Leiria), where will be located the methanol plant.

In table 4.1 there are the sources were selected for the purpose of this study since they are in the same region as the methanol plant, which is Leiria, Marinha Grande and Figueira Foz.

Table 4.1 - Various sources of CO_2 emissions next to Leiria based on fig.3.3

Sector	Location	Unit name	CO_2 emissions (tCO_2/year) in 2021	CO_2 emissions (tCO_2/h) in 2021
Cement	Pataias	Secil	273 000	32,5
Cement	Maceira	Secil	354 069	42,15
Glass	Marinha Grande	Ba Glass	88 572	10,54
Glass	Marinha Grande	Gallo vi-dro	80 650	9,6
Glass	Marinha Grande	Santos Barosa	153 476	16,12
Energy	Lares	CCGT	1 245 769	148,3
Ceramics	Figueira da Foz	Verallia	88 515	10,1
Ceramics	Marinha Grande	Crisal	38 816	4,43
Energy	Leiria	Repsol, Resinas	158 000	18
Paper and Pulp	Figueira da Foz	Naviga-tor	827 000	94,4

After selecting the main sources of CO_2 emissions, the following step is to determine the distance between the source and the methanol plant by each mean of transportation: truck, pipeline and railway. There are three scenarios:

- Scenario 1: Truck
- Scenario 2: Pipeline
- Scenario 3: Railway + Truck

The distances are presented in table 4.2:

Table 4.2 - Distances between Pataias and other sources from different scenarios [151]

Source	Scenario 1	Scenario 2	Scenario 3	
Secil - Maceira S.A.	9,6 km	7,7 km	6 km [1]	5,5 km
BA Glass, Marinha Grande	12 km	10,6 km	10 km [2]	0,9 km
Gallo Vidro, Marinha Grande	13 km	11,8 km	10 km [2]	3 km
Santos Barosa, Marinha Grande	12 km	10,4 km	10 km [2]	0,5 km
Verallia, Figueira da Foz	78 km	55,9 km	85 km [3]	17 km
Crisal, Marinha Grande	15 km	8 km	10 km [2]	4 km
Repsol Resinas, Leiria	33 km	21,7 km	25 km [4]	6 km
Navigator, Figueira da Foz	62 km	46,4 km	55 km [5]	8 km
CCGT, Lares	78,5 km	55 km	85 km [3]	20 km
Vila Nova de Famalicão	237 km	200 km	310 km*	-

1 – Regional Martingaça
2 – Regional Marinha Grande
3 – Regional Verride
4 – Regional Leiria
5 – Regional Louriçal
* - the exact location of the plant is not defined

In the next sub-chapters, there will be presented the total cost of capture and transportation for each mean of transport.

4.1.1 Pipeline

Based on the equations described in chapter 3, and on the distances in table 4.2 for scenario 2 in km and since the equations where needed in miles it was used a correlation between both units and resulted in table 4.3.

Table 4.3 - Convertion of distances from km to miles for scenario 2

Sources	Distance (km)	Distance (miles)
Maceira, Secil	7,7	4,81
Marinha Grande, BA Glass	10,6	6,63
Marinha Grande, Gallo Vidro	11,8	7,38
Marinha Grande, Santos Barosa	10,4	6,50
Figueira de Foz, Verallia	55,9	34,94
Marinha Grande, Crisal	8	5,00
Pinheiros, RESPOL Resinas	21,7	13,56
Figueira da Foz, Navigator	46,4	29,00
CCGT Lares	55	34,38
Vila Nova de Famalicão	200	125,00

After it was used equations 3.1 and 3.2 to calculate the diameter of the pipeline based on the cross-sectional area and the average velocity for critical CO_2 and based on table 2.14, it was possible to choose the standard diameter that is closest to the one calculated, as seen in table 4.4

Table 4.4 - Converting pipeline diameter in inch to standard pipeline diameter

Sources	Pipeline Diameter (inch)	Standard Pipeline Diameter (inch)
Maceira, Secil	4	4
Marinha Grande, BA Glass	2	4
Marinha Grande, Gallo Vidro	2	4
Marinha Grande, Santos Barosa	2	4
Figueira de Foz, Verallia	2	4
Marinha Grande, Crisal	2	4
Pinheiros, RESPOL Resinas	2	4
Figueira da Foz, Navigator	4	4
CCGT Lares	6	6
Vila Nova de Famalicão	2	4

To calculate the total installing cost based on the equation 3.3, it must include the material cost, labour cost, miscellaneous cost and right-of-way cost, which is presented in the next table.

Table 4.5 - Results of each component of CAPEX

Sources	Material (M$)	Labour (M$)	Misc. (M$)	ROW (M$)
Maceira, Secil	0,20	1,07	0,29	0,23
Marinha Grande, BA Glass	0,27	1,40	0,37	0,30
Marinha Grande, Gallo Vidro	0,29	1,54	0,40	0,33
Marinha Grande, Santos Barosa	0,26	1,38	0,36	0,29
Figueira de Foz, Verallia	1,26	6,61	1,53	1,40
Marinha Grande, Crisal	0,21	1,10	0,30	0,24
Pinheiros, RESPOL Resinas	0,51	2,68	0,65	0,57
Figueira da Foz, Navigator	1,05	5,52	1,28	1,17
CCGT Lares	1,51	6,88	2,08	1,78
Vila Nova de Famalicão	4,41	23,16	5,22	4,92

In order to calculate the capital cost of pumps it was necessary to calculate the pumping power for each flow rate, presented in the table 4.6, using equation 3.15.

Table 4.6 - Results of the pumping power for each flow rate

Sources	Pumping power (kW)
Maceira, Secil	181
Marinha Grande, BA Glass	45
Marinha Grande, Gallo Vidro	41
Marinha Grande, Santos Barosa	69
Figueira de Foz, Verallia	45
Marinha Grande, Crisal	20
Pinheiros, RESPOL Resinas	81
Figueira da Foz, Navigator	423
CCGT Lares	637
Vila Nova de Famalicacão	102

The total installation cost (direct and indirect) is presented in the following table.

Table 4.7 - Results of the total installation cost

Sources	CAPEX pipe (M$)	Indirect CAPEX (M$)	Pump (M$)	Total CAPEX (M$/y)
Maceira, Secil	1,8	0,50	0,27	2,6
Marinha Grande, BA Glass	2,3	0,65	0,12	3,1
Marinha Grande, Gallo Vidro	2,6	0,72	0,12	3,4
Marinha Grande, Santos Barosa	2,3	0,64	0,15	3,1
Figueira de Foz, Verallia	10,8	3,02	0,12	13,9
Marinha Grande, Crisal	1,8	0,52	0,09	2,5
Pinheiros, RESPOL Resinas	4,4	1,23	0,16	5,8
Figueira da Foz, Navigator	9,0	2,53	0,54	12,1
CCGT Lares	12,3	3,43	0,78	16,5
Vila Nova de Famalicão	37,7	10,56	0,18	48,4

To calculate the OPEX for pipeline is included the direct and indirect labour as well as operation and maintenance, based on the equations 3.9 to 3.13 and 3.17.

Table 4.8 - Results of the OPEX for each source

Sources	Direct labour (M$/y)	Indirect labour (M$/y)	O&M (M$/y)	Electricity costs (M$/y)
Maceira, Secil	0,19	0,10	0,05	0,14
Marinha Grande, BA Glass	0,13	0,07	0,06	0,04
Marinha Grande, Gallo Vidro	0,13	0,07	0,07	0,03
Marinha Grande, Santos Barosa	0,15	0,08	0,06	0,05
Figueira de Foz, Verallia	0,13	0,07	0,28	0,04
Marinha Grande, Crisal	0,11	0,05	0,05	0,02
Pinheiros, RESPOL Resinas	0,16	0,08	0,11	0,06
Figueira da Foz, Navigator	0,24	0,12	0,23	0,33
CCGT Lares	0,26	0,13	0,32	0,5
Vila Nova de Famalicão	0,17	0,08	0,98	0,08

In order to calculate the annualized CAPEX in M$ per year it was necessary to calculate the capital recovery factor based on equation 3.20.

Table 4.9 - Result of the CRF

CRF	0,082

Based on equation 3.18 it was also possible to calculate the Levelized cost in $ and € per ton of CO_2, which is shown in the next table.

Table 4.10 - Results of the Levelized Cost of pipeline

Sources	OPEX (M$/y)	Annualized Capex (M$/y)	Pipeline Levelized Cost ($/ton CO_2)	Pipeline Levelized Cost (€/ton CO_2)
Maceira, Secil	0,5	0,21	2,00	1,82
Marinha Grande, BA Glass	0,33	0,25	6,61	6,02
Marinha Grande, Gallo Vidro	0,33	0,28	7,56	6,88
Marinha Grande, Santos Barosa	0,37	0,25	4,60	4,19
Figueira de Foz, Verallia	0,67	1,14	20,44	18,60
Marinha Grande, Crisal	0,25	0,20	11,73	10,67
Pinheiros, RESPOL Resinas	0,47	0,47	6,00	5,46
Figueira da Foz, Naviga-tor	1,05	0,99	2,46	2,24
CCGT Lares	1,38	1,35	2,19	1,99
Vila Nova de Famalicão	1,84	3,96	24,80	22,57

The findings of this study were visualized through figure 4.1, revealing the correlation between the quantity of CO_2 emissions and two key variables: the distance between the source and destination of the pipeline, and the levelized cost in euros per ton of CO_2. It is possible to observe the levelized cost due to the dimension of the bubble. Figure 4.1 illustrates that shorter distances combined with minimal CO_2 emissions result in higher levelized costs compared to shorter distances with the same emission levels. Conversely, when the distances are relatively equal, higher quantities of CO_2 emissions are associated with lower levelized costs. This observation suggests that there is an inverse relationship between distance, CO_2 emissions, and the corresponding levelized costs, thereby highlighting the significance of these factors in the context of pipeline transportation.

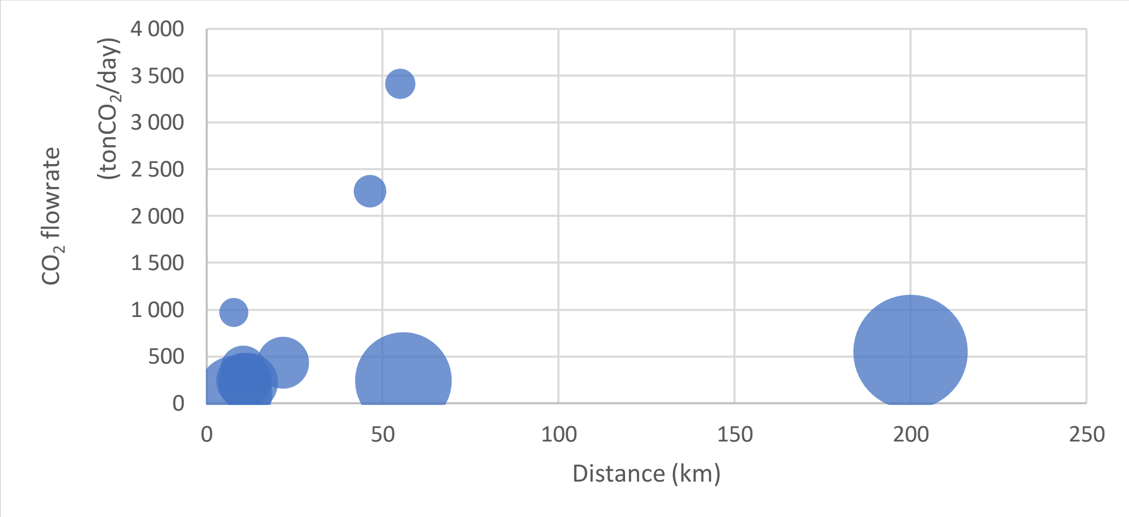


Figure 4.2 - Relation between CO_2 flowrate, the distance and the levelized cost

When conducting research, one of the crucial steps is to compare your findings with existing literature in the field. This process allows me to evaluate the validity and significance of your results, identify any gaps in current knowledge, and contribute to the broader scientific understanding.

Using the data from the case study: CO_2 Pipeline Cost Analysis Utilizing a Modified FE/NETL CO_2 Transport Cost Model Tool, shown in table 2.17 we could calculate the annualized CAPEX and the levelized cost of CO_2 using the equations 3.8 to 3.20 and the same CRF, as shown in the table 4.11.

Table 4.11 - Results of levelized cost of pipeline for the data obtained with modified FE/NETL CO_2 transport

Length (km)	CO_2 flowrate (kg/day)	Annualized CAPEX	Levelized Cost ($/ton CO_2)	Levelized Cost (€/ton CO_2)
5,6	383 562	0,21	2,32	2,11
13,8	2 904 110	0,49	0,77	0,70
23,5	821 918	0,72	3,19	2,90
28,6	328 767	0,86	9,10	8,28
51	2 684 932	1,71	2,44	2,22
145,6	1 945 205	5,49	9,44	8,59

When comparing both, it was possible to observe that the relation between the literature and my calculations where aligned, as presented in figure 4.3, suggesting that there is an inverse relationship between distance.

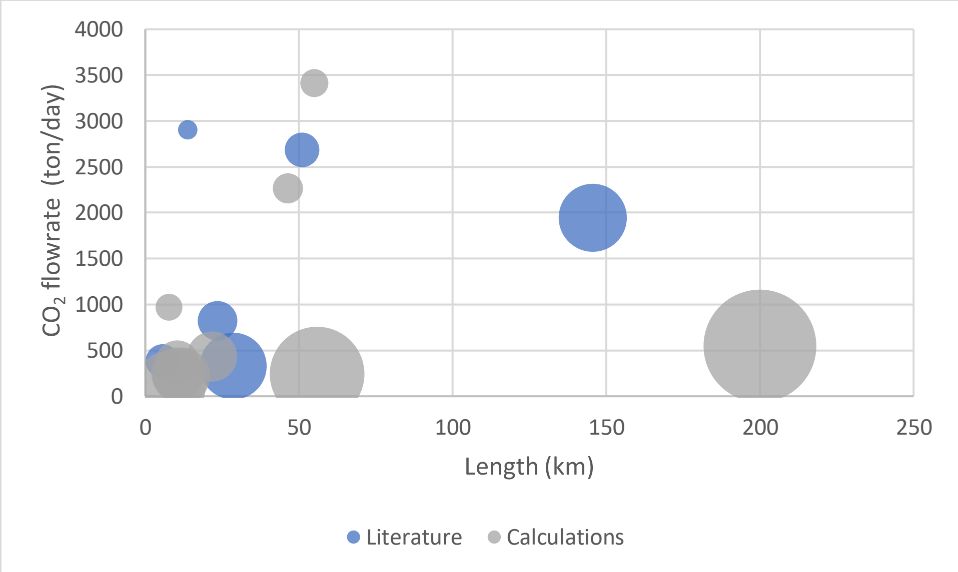


Figure 4.3 - Comparison between literature [79] and the results obtained. The size of the bubbles means the Levelized cost of CO_2

4.1.2 Truck

As mentioned in chapter 3, based on the equations 3.21 to 3.24, it was possible to determine the number of trips per year and the number of trips per day, as shown in the following table.

Table 4.12 - Number of trips per day and the total time per trip

Sources	Nº of trips per year	Nº of trips per day	Time per travel (h)	Total time (h)	Trips a truck can make per day	Number of trucks
Maceira, Secil	11802	32	0,22	3,22	3	11
Marinha Grande, BA Glass	2952	8	0,25	3,25	3	3
Marinha Grande, Gallo Vidro	2688	7	0,30	3,30	3	3
Marinha Grande, Santos Barosa	4516	12	0,27	3,27	3	5
Figueira de Foz, Verallia	2951	8	0,72	3,72	3	3
Marinha Grande, Crisal	1294	4	0,20	3,20	3	2

Table 4.12 - Number of trips per day and the total time per trip

Sources	Nº of trips per year	Nº of trips per day	Time per travel (h)	Total time (h)	Trips a truck can make per day	Number of trucks
Pinheiros, RESPOL Resinas	5267	14	0,37	3,37	3	5
Figueira da Foz, Navigator	27567	76	0,63	3,63	3	26
CCGT Lares	41526	114	0,75	3,75	3	38
Vila Nova de Famalicão	6667	18	2,20	5,20	2	10

In CAPEX it is included the cost for Semi trucks (diesel and electric) plus the tank trailer, for the amount of trucks needed for each trip. In order to calculate the Levelized cost it was necessary to annualize de CAPEX for diesel and electric trucks. Both are presented in the following table:

Table 4.13 - Results of the CAPEX for diesel and electric trucks

Sources	CAPEX diesel (M€)	Annualized CAPEX diesel (M€/y)	CAPEX electric (M€)	Annualized CAPEX electric (M€/y)
Maceira, Secil	4,99	0,41	7,3	0,61
Marinha Grande, BA Glass	1,36	0,11	2,0	0,17
Marinha Grande, Gallo Vidro	1,36	0,11	2,0	0,17
Marinha Grande, Santos Barosa	2,27	0,19	3,3	0,28
Figueira de Foz, Verallia	1,36	0,11	2,0	0,17
Marinha Grande, Crisal	0,91	0,08	1,3	0,11
Pinheiros, RESPOL Resinas	2,27	0,19	3,3	0,28
Figueira da Foz, Navigator	11,80	0,98	17,2	1,45
CCGT Lares	17,24	1,43	25,2	2,12
Vila Nova de Famalicão	4,54	0,38	6,6	0,56

Another important aspect to consider is the operation and maintenance cost. In OPEX it is included the cost of tools, vehicle taxes, maintenance, and repair of tires and of the truck itself and the fuel. It is presented a table for diesel trucks and for electric trucks.

Table 4.14 - Results of the components of OPEX for diesel truck

Sources	Tolls per year (€/year)	Cost of diesel per year (€/year)	Labour (€/year)	Maintenance and repair cost diesel (€/year)	OPEX diesel (€/year)
Maceira, Secil	0	83 180	25 628	503 682	612 952
Marinha Grande, BA Glass	0	26 010	8 014	138 791	173 278
Marinha Grande, Gallo Vidro	0	25 657	7 905	140 927	174 951
Marinha Grande, Santos Barosa	0	39 784	12 257	232 505	285 009
Figueira de Foz, Verallia	39389	168 955	52 055	158 720	419 582
Marinha Grande, Crisal	0	14 248	4 390	91 104	110 205
Pinheiros, RESPOL Resinas	11587	127 594	39 312	239 623	418 578
Figueira da Foz, Navigator	264640	1 254 749	386 588	1 344 733	3 251 173
CCGT Lares	554367	2 393 132	737 324	2 028 488	5 713 774
Vila Nova de Famalicão	256333	1 159 946	357 380	493 480	2 267 602

Table 4.15 - Results of the components of OPEX for electric truck

Sources	Tolls per year (€/year)	Cost of electricity per year (€/year)	Maintenance and repair cost electric (€/year)	Labour (€/year)	OPEX electric (€/y)
Maceira, Secil	-	24 436	26909	503682	551 038
Marinha Grande, BA Glass	-	7 641	8414	138791	153 852
Marinha Grande, Gallo Vidro	-	7 537	8300	140927	155 788
Marinha Grande, Santos Barosa	-	11 687	12870	232505	255 347
Figueira de Foz, Verallia	39 389	49 634	54658	158720	293 919
Marinha Grande, Crisal	-	4 186	4609	91104	99 521
Pinheiros, RESPOL Resinas	11 587	37 483	41277	239623	323 655
Figueira da Foz, Navigator	264 640	368 605	405918	1344733	2 318 543

Table 4.15 - Results of the components of OPEX for electric truck

Sources	Tolls per year (€/year)	Cost of electricity per year (€/year)	Maintenance and repair cost electric (€/year)	Labour (€/year)	OPEX electric (€/y)
CCGT Lares	554 367	703 025	774191	2028488	3 935 093
Vila Nova de Famalicão	256 333	340 755	375249	493480	1 405 430

In order to compare the cost of CO_2 transportation for different means, the cost was levelized ($LCOCO_{2\text{truck}}$) as follows, and for each type of truck is presented in table 4.16:

Table 4.16 - Levelized cost of transporting CO_2 for diesel and electric trucks

Sources	Truck diesel Levelized Cost (€/ton CO_2)	Truck electric Levelized Cost (€/ton CO_2)
Maceira, Secil	2,9	3,3
Marinha Grande, BA Glass	3,2	3,6
Marinha Grande, Gallo Vidro	3,6	4,0
Marinha Grande, Santos Barosa	3,5	3,9
Figueira de Foz, Verallia	6,0	5,2
Marinha Grande, Crisal	4,8	5,4
Pinheiros, RESPOL Resinas	3,8	3,8
Figueira da Foz, Navigator	5,1	4,6
CCGT Lares	5,7	4,9
Vila Nova de Famalicão	13,2	9,8

4.1.3 Railway

As mentioned in chapter 3, based on the equations 3.29 to 3.32, it was possible to determine the number of wagons per year, the total length of the wagons per year and number of trips per year, as shown in the following table:

Table 4.17 - Results of the number of wagons and total trips per year

Location	Number of wagons per year	Total length of the wagons per year	Nº of trips per year	Nº of wagons in one trip
Maceira, Secil	6 386	95 798	192	33
Marinha Grande, BA Glass	1 597	23 964	48	
Marinha Grande, Gallo Vidro	1 454	21 821	44	
Marinha Grande, Santos Barosa	2 443	36 655	73	
Figueira de Foz, Verallia	1 596	23 949	48	
Marinha Grande, Crisal	700	10 502	21	
Pinheiros, RESPOL Resinas	2 849	42 749	85	
Figueira da Foz, Navigator	14 917	223 755	448	
CCGT Lares	22 470	337 059	674	
Famalicão	3 607	54 113	108	

In table 4.20 are the results of the OPEX, CAPEX and levelized costs for railway.

Table 4.18 - Results of the OPEX, CAPEX and levelized costs for railway

Location	OPEX (M€/year)	CAPEX (M€)	CAPEX (M€/year)	Railway Levelized Cost (€/ton CO_2)
Maceira, Secil	1,30	2,08	0,175	4,16
Marinha Grande, BA Glass	0,32			5,64
Marinha Grande, Gallo Vidro	0,30			5,84
Marinha Grande, Santos Barosa	0,50			4,96
Figueira de Foz, Verallia	0,33			5,69
Marinha Grande, Crisal	0,14			8,17
Pinheiros, RESPOL Resinas	0,58			4,78
Figueira da Foz, Naviga-tor	3,06			3,91
CCGT Lares	4,63			3,86
Vila Nova de Famalicão	0,77			4,74

In addition to the costs presented in the previous table, it will be necessary to add trucking costs as the CO_2 needs to be transported from the station to the factory, these costs are in the following table:

Table 4.19 - Distance from source of CO_2 to the nearest railway and combined levelized cost

Location	Distance for truck (Km)	Truck diesel + railway Levelized Cost (€/ton CO_2)	Truck electric + railway Levelized Cost (€/ton CO_2)
Maceira, Secil	5,5	7,13	7,39
Marinha Grande, BA Glass	0,9	8,57	9,11
Marinha Grande, Gallo Vidro	3	9,15	9,70
Marinha Grande, Santos Barosa	0,5	8,19	8,74
Figueira de Foz, Verallia	17	9,37	9,61
Marinha Grande, Crisal	4	12,65	13,45
Pinheiros, RESPOL Resinas	6	7,78	8,15
Figueira da Foz, Navigator	8	7,47	7,40
CCGT Lares	20	7,97	7,46
Vila Nova de Famalicão	6	9,58	10,07

4.2 Best scenario

Based on the levelized costs determined for all the scenarios and for each CO_2 source, it was possible to analyse and define the best mode of transport for each situation. To summarise, all the costs are presented in table 4.20:

Table 4.20 - Summarized results and selection of the best scenario for each source

Sources	CO_2 flowrate (t CO_2/year)	Distance (km)	Truck diesel Levelized Cost (€/ton CO_2)	Truck electric Levelized Cost (€/ton CO_2)	Pipeline Levelized Cost (€/ton CO_2)	Truck diesel + railway Levelized Cost (€/ton CO_2)	Truck electric + railway Levelized Cost (€/ton CO_2)
Maceira, Secil	354 069	9,6	2,9	3,3	1,82	5,59	5,85
Marinha Grande, BA Glass	88 572	12	3,2	3,6	6,02	7,07	7,61
Marinha Grande, Gallo Vidro	80 650	13	3,6	4,0	6,88	7,64	8,20
Marinha Grande, Santos Barosa	135 476	12	3,5	3,9	4,19	6,69	7,23
Figueira de Foz, Verallia	88 515	78	6,0	5,2	18,60	8,50	8,75
Marinha Grande, Crisal	38 816	15	4,8	5,4	10,67	11,15	11,95
Pinheiros, RESPOL Resinas	158 000	33	3,8	3,8	5,46	6,38	6,75
Figueira da Foz, Navigator	827 000	62	5,1	4,6	2,24	6,41	6,34
CCGT Lares	1 245 769	78,5	5,7	4,9	1,99	7,11	6,60
Vila Nova de Famalicão*	200 000	237	13,2	9,8	22,57	9,75	10,25

* - the exact location of the plant is not defined

4.3 Variation of cost

4.3.1 Pipeline

As depicted in figure 4.4 is possible to visualize the connection between the cost of CO_2 transportation, the amount of CO_2 in tons, and the distance between the source and destination. The aim was to gain a clearer comprehension of their relationship.

Figure 4.4 demonstrates that regardless of the pipeline's size, the levelized cost decreases as the total amount of CO_2 emissions transported increases, thanks to economies of scale. Moreover, it is evident that cost discrepancies are more significant when dealing with small CO_2 emissions compared to cases involving more than 500 000 tons of CO_2.

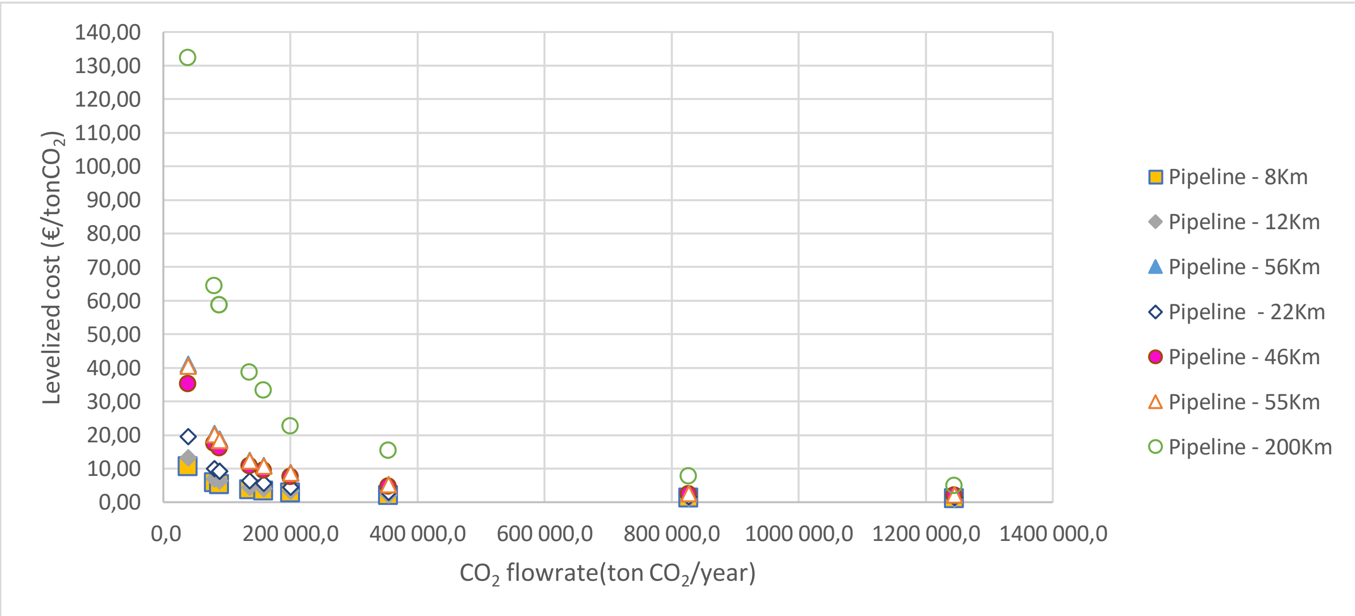


Figure 4.4 - Relation between levelized cost and the CO_2 flow rate for pipeline

4.3.2 Truck

The variation in distances covered by trucks does not show a substantial difference, unlike pipelines, as evident from both graphs (diesel and electric). Moreover, it is noticeable that the levelized cost values are higher for diesel trucks compared to electric ones.

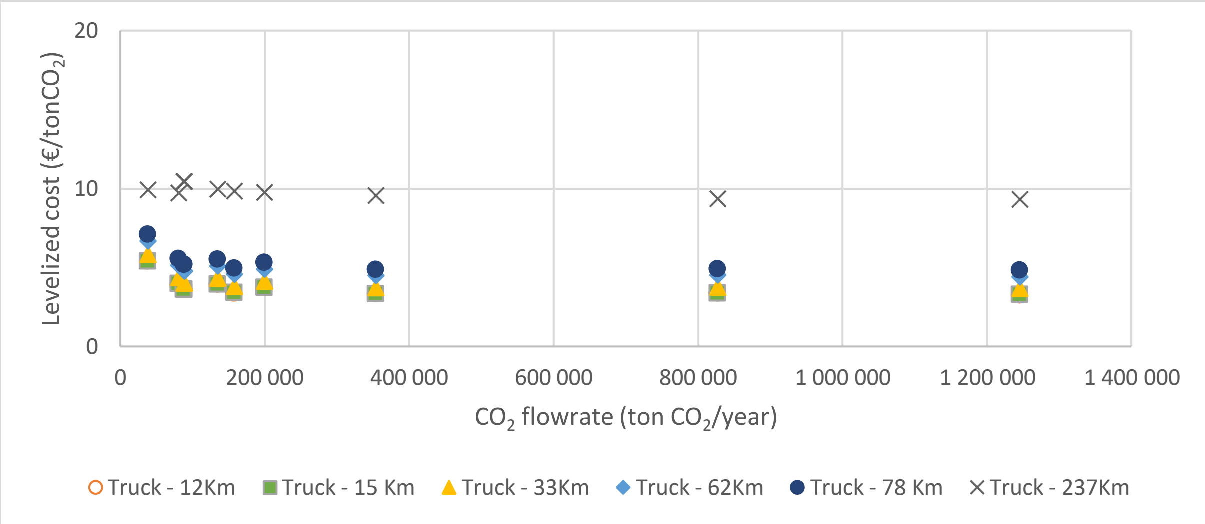


Figure 4.6 - Relation between levelized cost and the CO_2 flow rate for electric truck

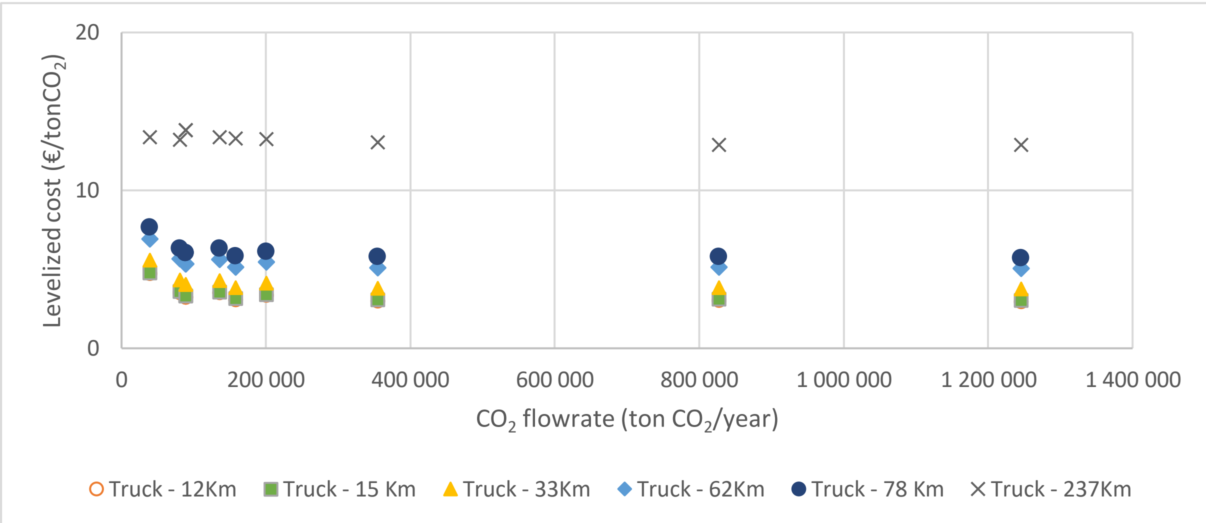


Figure 4.5 - Relation between levelized cost and the CO_2 flow rate for diesel truck

4.3.3 Railway

The correlation between the levelized cost and the quantity of CO_2 emissions transported follows a pattern similar to that of a pipeline with distance, which can be attributed to economies of scale. Moreover, once the quantity of CO_2 transported exceeds 800 000 tons, the levelized cost stabilizes at a constant value.

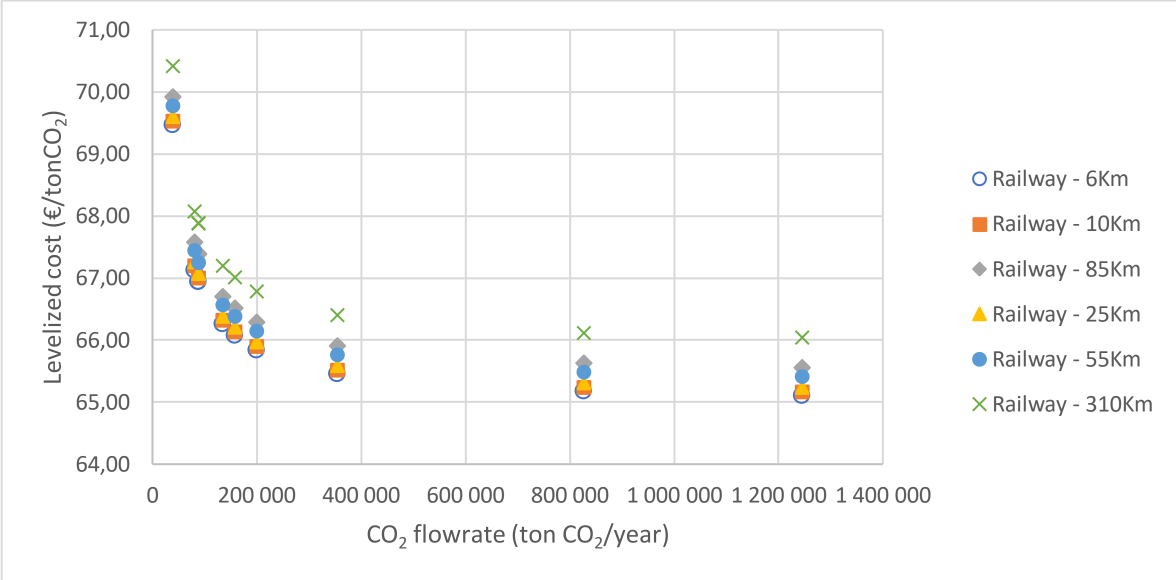


Figure 4.7 - Relation between levelized cost and the CO_2 flow rate for railway

4.3.4 Comparison between means of transportation

To enable more streamlined comparisons between different transportation methods, calculations were performed to determine the cost of CO_2 transportation per ton and per kilometre, the results are presented in the following table:

Table 4.21 - Comparison between different means of transportation

Means of transportation	Levelized Cost (€/km.ton CO_2)
Pipeline	0,55
Truck (diesel)	0,22
Truck (electric)	0,25
Railway	0,26

4.3.5 Cost structure

The purpose of conducting the cost structure is to comprehensively assess the potential impact of variations in key parameters on the overall costs of each mean of transportation. This analysis is crucial for identifying which factors have the most significant influence on the model's predictions and which are relatively less impactful.

4.3.5.1 Pipeline

Materials costs account for approximately 11% of the total construction costs on average. Labour, right of way, and miscellaneous costs make up 60%, 13%, and 16% of the direct cost on average, respectively.

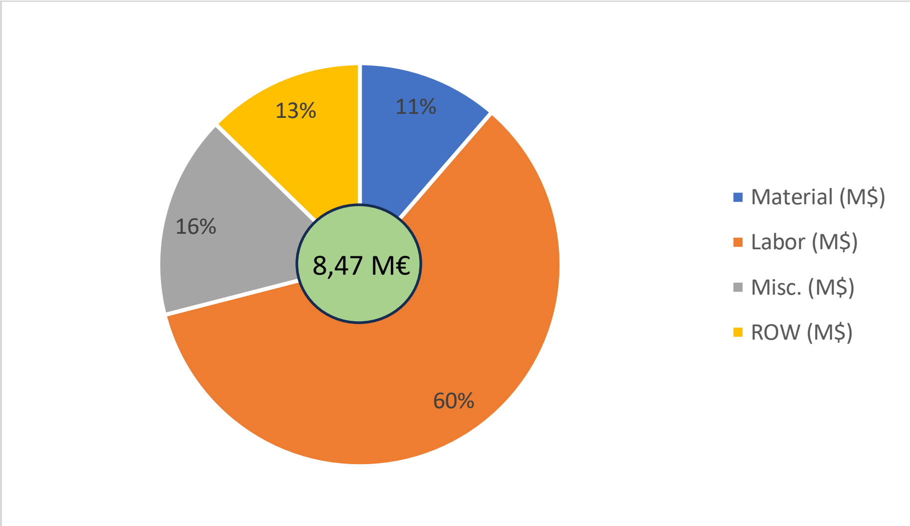


Figure 4.8 - Cost structure for CAPEX of pipeline

Direct labour accounts for approximately 38% of the total OPEX costs on average. Indirect labour and operation and maintenance costs make up 19% and 14% on average, respectively. The electricity for pumping accounts approximately 28%.

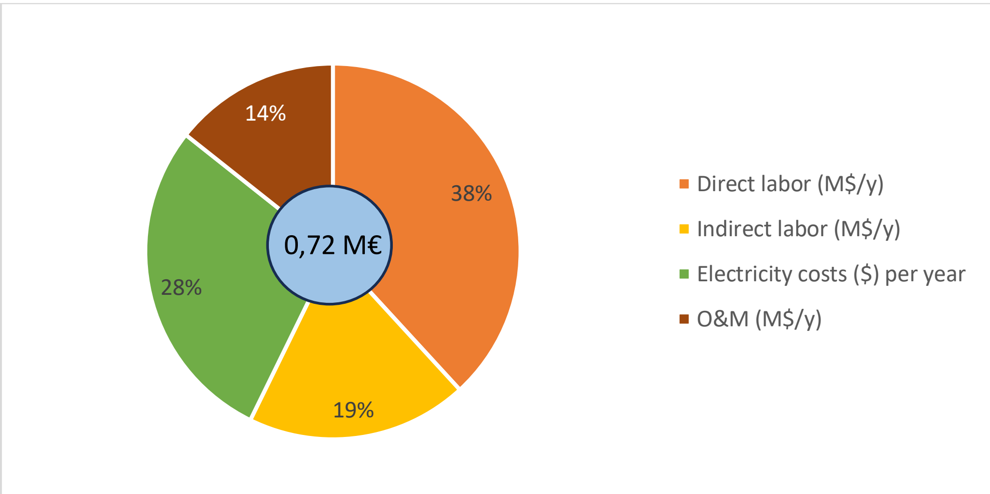


Figure 4.9 - Cost structure for OPEX of pipeline

4.3.5.2 Truck

The maintenance and repair expenses make up 18% of the overall OPEX costs in electric trucks, with tolls, electricity, and labour constituting 12%, 16%, and 57%, respectively.

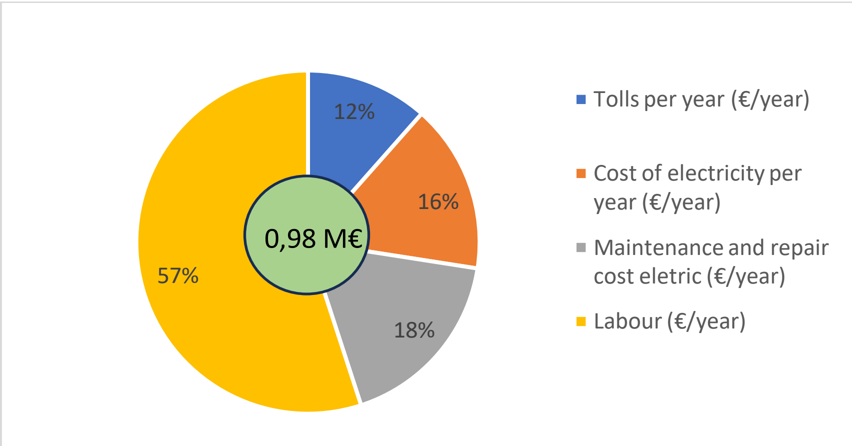


Figure 4.10 - Cost structure for OPEX of electric truck

The maintenance and repair expenses make up 12% of the overall OPEX costs in diesel trucks, with tolls, diesel, and labour constituting 8%, 39%, and 40%, respectively.

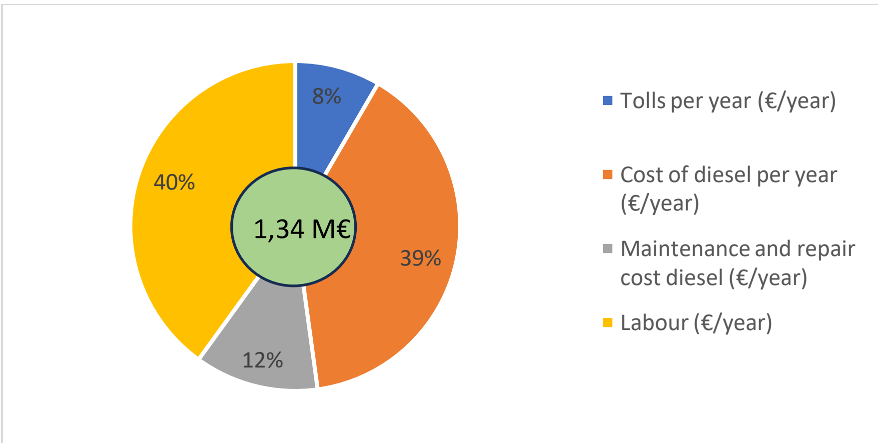


Figure 4.11 - Cost structure for OPEX of diesel truck

The distinction in capital expenditure (CAPEX) between diesel trucks and electric trucks lies in the expense associated with purchasing either a semi-truck that runs on electricity or one powered by diesel fuel. This is primarily because the cost of acquiring an electric truck is nearly twice that of procuring a diesel truck.

4.3.5.3 Railway

The cost of wagons makes up 90% of the overall OPEX costs in railway, with labour, and Infrastructure Usage Fee constituting 9%, and 1%, respectively.

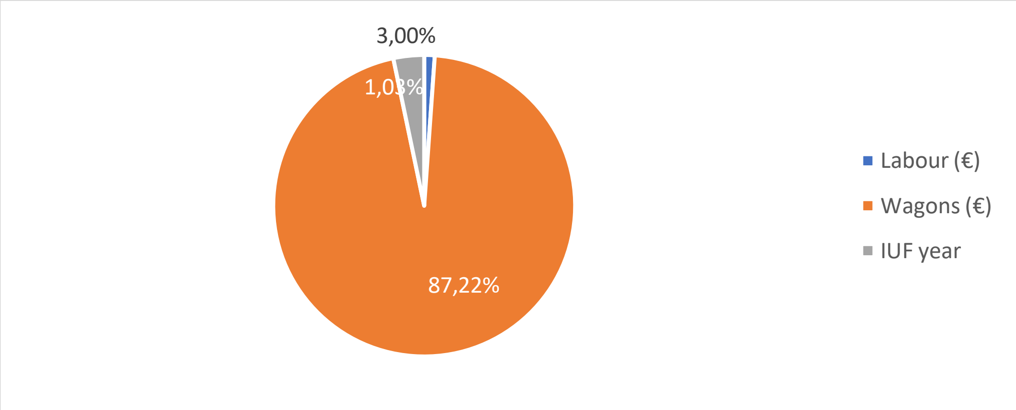


Figure 4.12 - Cost structure for OPEX of railway

The capital expenditure (CAPEX) remains constant irrespective of distance, as it encompasses the expenses associated with storage tanks and loading arms, which are essential across all scenarios. However, the size of the tanks may vary based on the quantity of CO_2 that needs to be stored.

4.3.6 Impact of CO_2 transportation in e-methanol production costs

The transportation of CO_2 plays a significant role in influencing the production costs of e-methanol. However, the cost-effectiveness of e-methanol production is intricately tied to the efficient sourcing and transportation of CO_2 feedstock. The proximity of CO_2 sources to production facilities and the efficiency of transportation networks directly impacts the overall cost structure. High transportation costs, whether due to long distances or complex logistics, can result in increased operational expenses for capturing and delivering CO_2. Therefore, optimizing the transportation logistics and exploring innovative solutions for CO_2 sourcing and delivery are pivotal in ensuring that e-methanol remains competitive in the transition towards greener energy solutions.

4.3.6.1 Impact of CO_2 transportation in e-methanol cost production for 2015-2018

As shown in figure 4.12, it is possible to see that some means of transportation have a bigger impact on the total cost of e-methanol. Additionally, pipeline is the mean of transportation that has the smallest impact and electric truck has the highest impact when comparing values with the smallest distance, up to 9 Km.

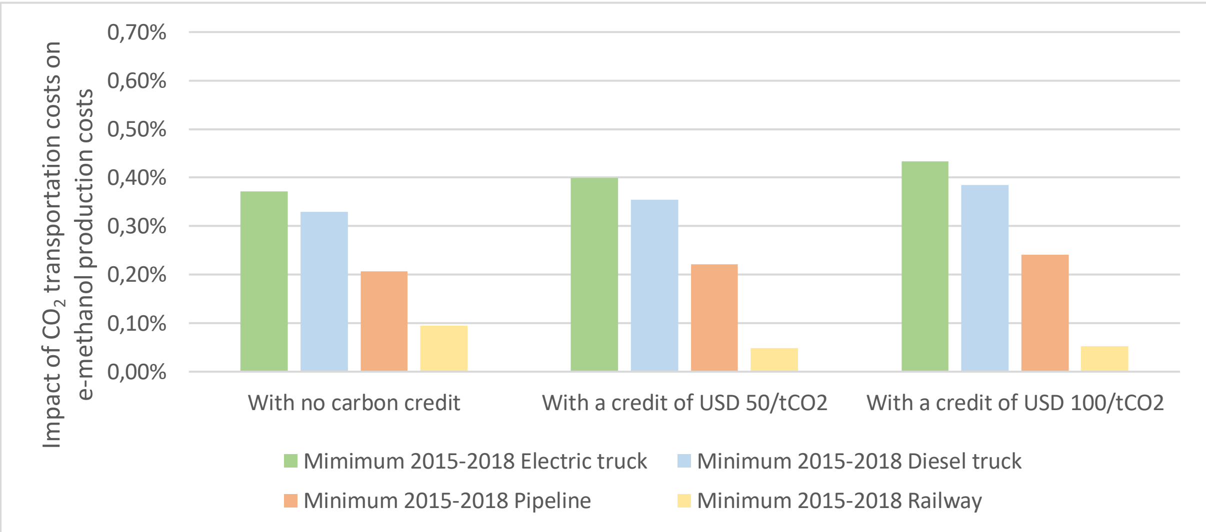


Figure 4.13 - Impact of CO_2 transportation cost on e-methanol production - short distance for 2015-2018

When evaluating average distance values (figure 4.13), it is evident that the transportation method exerting the most substantial influence on the production cost of e-methanol is diesel truck (regardless of the presence of carbon credits). Moreover, the effect of transporting CO_2 within e-methanol costs using all modes of transportation rises proportionally with distance, owing to the escalation in CO_2 transportation expenses. Furthermore, when distances fall within the range of over 10 km but under 33 km, the mode of transportation that has the least significant effect is railways. Overall, the impact of CO_2 transportation costs on e-methanol production is less than 1%.

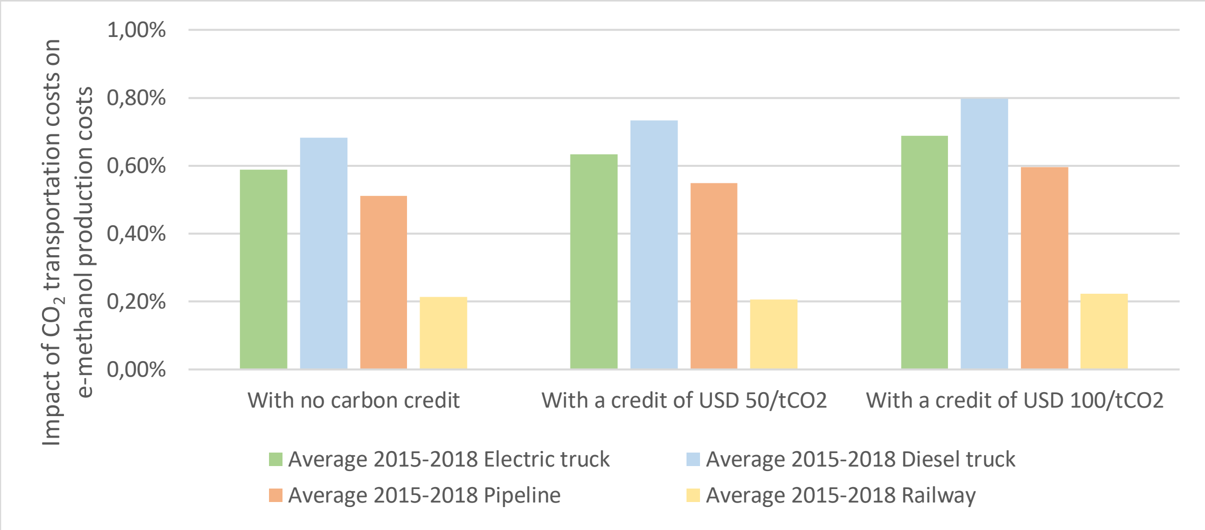


Figure 4.14 - Impact of CO_2 transportation cost on e-methanol production - average distance for 2015-2018

As shown in figure 4.14, it is possible to see that for the maximum distance, up to 200 Km the mean of transportation that has the smallest impact is also railway, followed by electric truck and diesel truck. The mode of transport that has the biggest impact is pipeline because CAPEX is mostly dependent on the distance between the source of CO_2 and the destination.

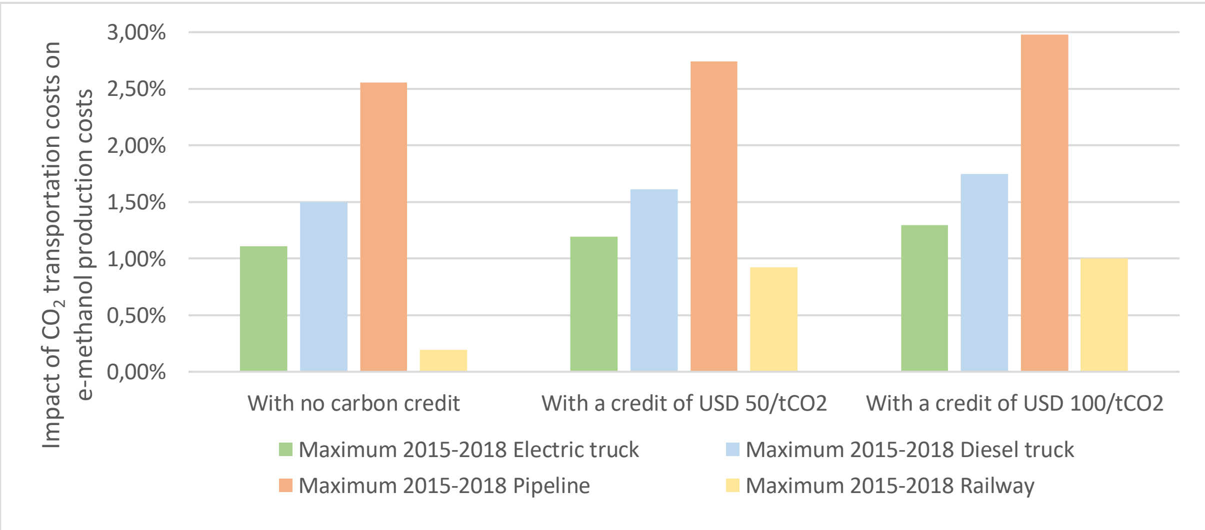


Figure 4.15 -Impact of CO_2 transportation cost on e-methanol production - long distance for 2015-2018

4.3.6.2 Impact of CO_2 transportation in e-methanol cost production for 2030

Illustrated in figure 4.15, it becomes apparent that the variance in total e-methanol cost impact among transportation methods is almost negligible. Furthermore, when examining values within the shortest distance range of up to 9 km, the impact of transportation on total cost reveals that pipelines have the slightest influence, while electric trucks (similarly to diesel trucks) exhibit the greatest impact. This relationship in terms of total e-methanol cost impact remains consistent regardless of the presence of carbon credits. When juxtaposing the year 2030 with the timeframe spanning from 2015 to 2018, the influence is more significant, owing to the anticipated reduction in e-methanol production costs resulting from the maturation of technology.

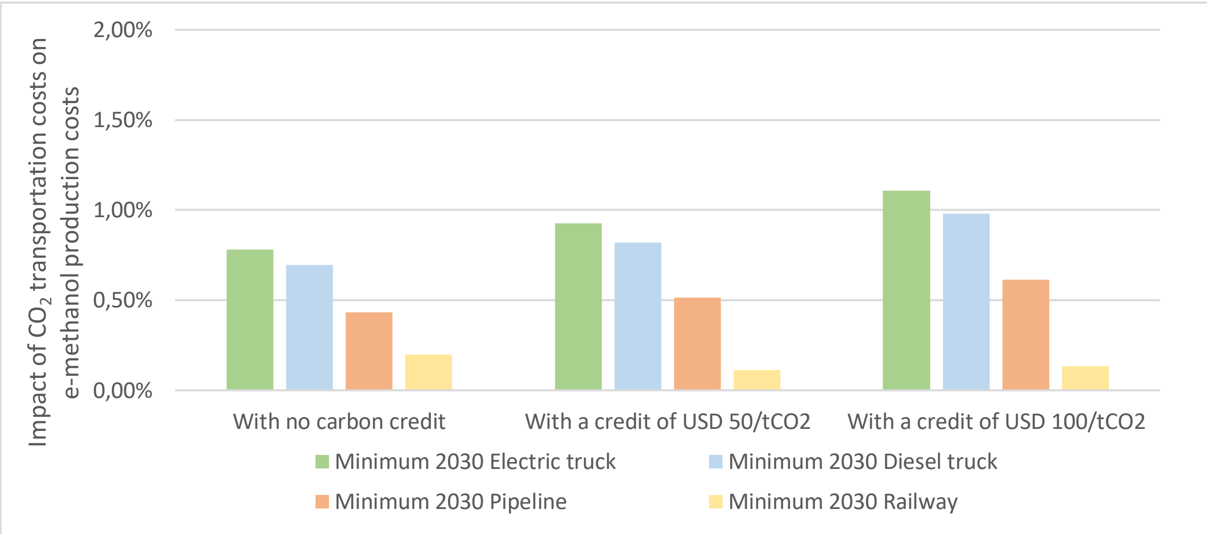


Figure 4.16 - Impact of CO_2 transportation cost on e-methanol production - short distance for 2030

Analysing the data of average distance values (as depicted in figure 4.16), it's clear that the transportation approach that holds the most significant sway over e-methanol production costs is the diesel truck, irrespective of carbon credit considerations. Additionally, the impact of CO_2 transportation expenses on e-methanol costs grows proportionately with distance across all transportation modes, due to the increasing expenses related to CO_2 transport. Moreover, when distances fall within the range of over 10 km but under 33 km, railways emerge as the transportation mode with the least noteworthy impact.

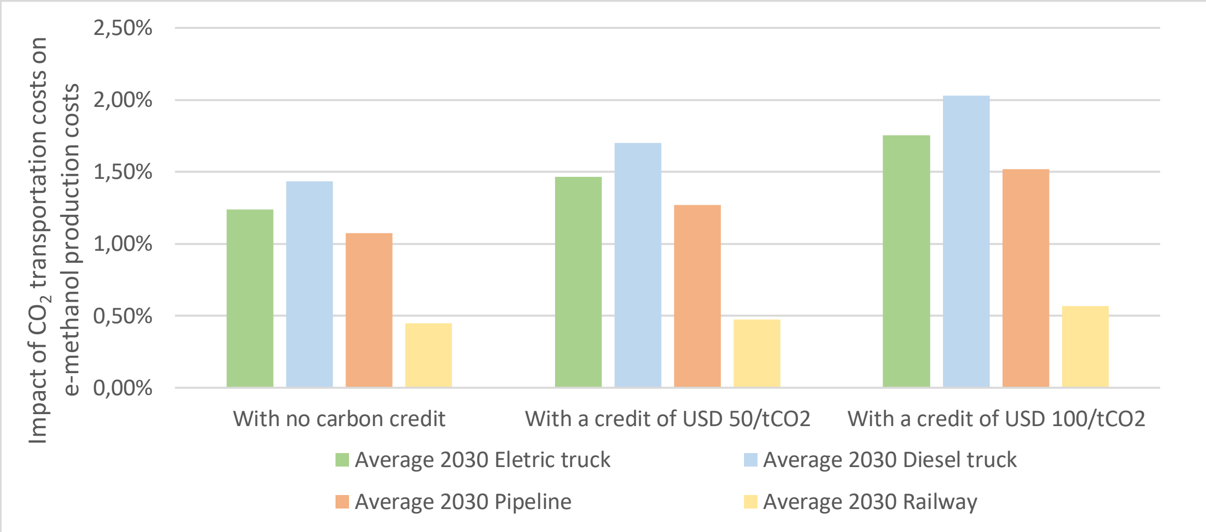


Figure 4.17 - Impact of CO_2 transportation cost on e-methanol production - average distance for 2030

Illustrated by the data presented in figure 4.17, it becomes apparent that, within the range of distances up to 200 km, the transportation method yielding the least pronounced influence is railways, succeeded by electric trucks and diesel trucks. Conversely, the mode of transportation with the most substantial impact is pipelines, largely due to CAPEX being predominantly contingent on the span between the CO_2 source and the endpoint. Consequently, longer distances translate to elevated costs.

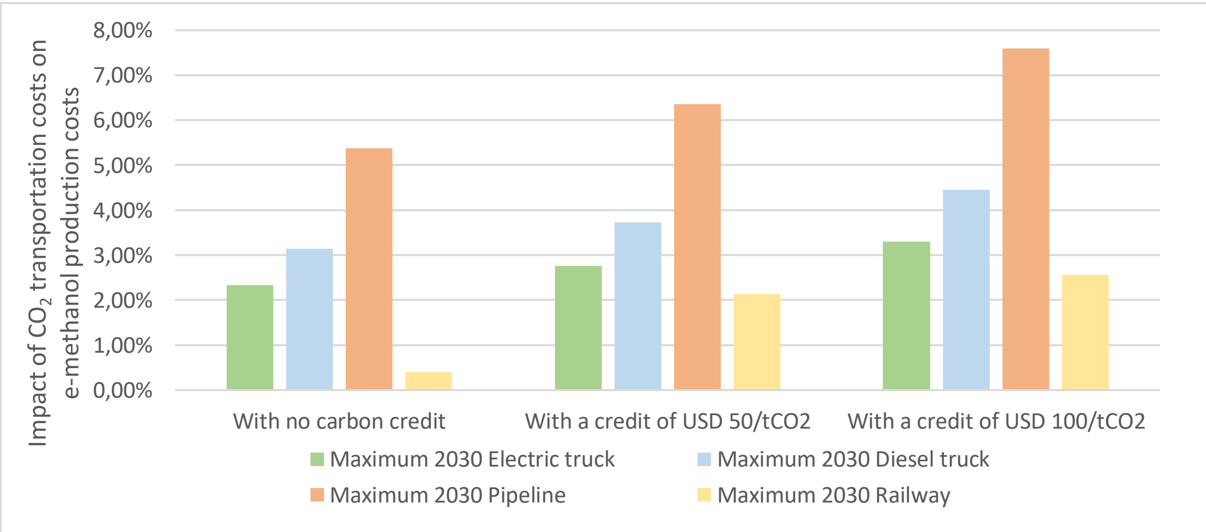


Figure 4.18 - Impact of CO_2 transportation cost on e-methanol production - long distance for 2030

4.3.6.3 Impact of CO_2 transportation in e-methanol cost production for 2050

As previously noted in prior years, in cases of shorter distances, the transportation mode with the least influence on e-methanol production costs is pipelines, closely followed by railways. The effects associated with trucks are more substantial for shorter distances because, in terms of OPEX, the costs for storage tanks and loading arms remain consistent for both short and long distances. This is a contrast to other transportation methods where such uniformity doesn't apply.

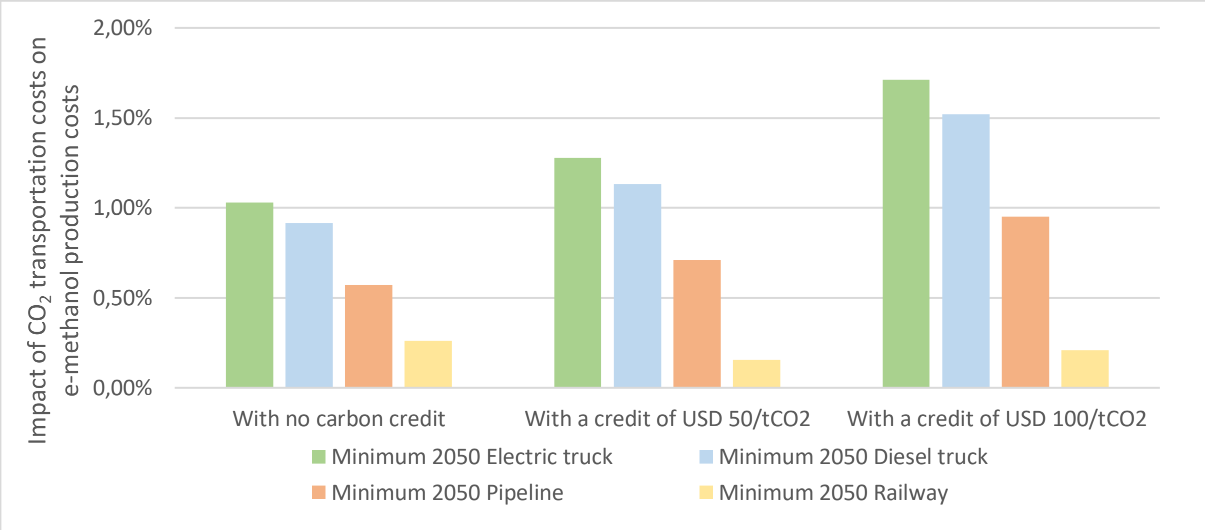


Figure 4.19 - Impact of CO_2 transportation cost on e-methanol production - short distance for 2050

Upon scrutinizing the average distance data (as depicted in figure 4.19), it becomes apparent that the production cost of e-methanol is most significantly impacted using diesel trucks, regardless of the inclusion of carbon credits. Additionally, the impact of CO_2 transportation costs in the context of e-methanol expenses grows linearly with distance across all transportation modes, attributed to the increasing CO_2 transportation expenditures. Furthermore, when distances fall between the range of over 10 km but under 33 km, railways emerge as the transportation mode with the least pronounced impact. Moreover, when juxtaposed with the data from the previous year, this graph demonstrates an escalation in the influence of CO_2 transportation costs on e-methanol production expenses. This is attributed to the diminishing e-methanol production costs resulting from the maturation of technology.

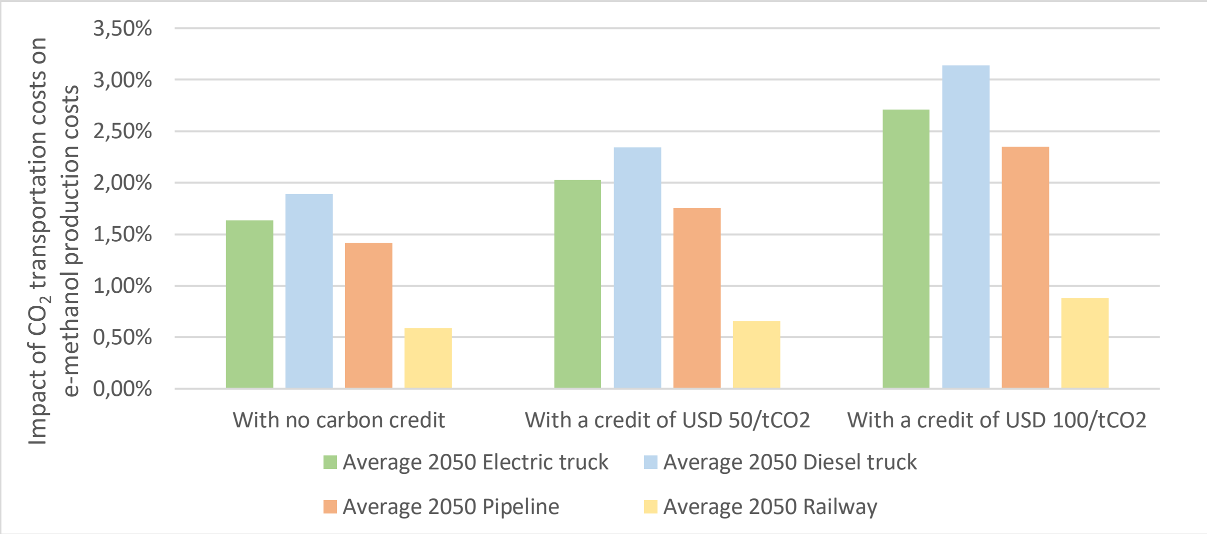


Figure 4.20 - Impact of CO_2 transportation cost on e-methanol production - average distance for 2050

Evident from the information showcased in figure 4.20, for distances up to 200 km, railways exhibit the least significant effect as a transportation method, followed by electric trucks and diesel trucks in succession. On the other hand, pipelines stand out as the mode of transportation having the greatest impact, primarily due to the dependence of CAPEX on the distance between the CO2 source and destination. As a result, greater distances lead to increased costs.

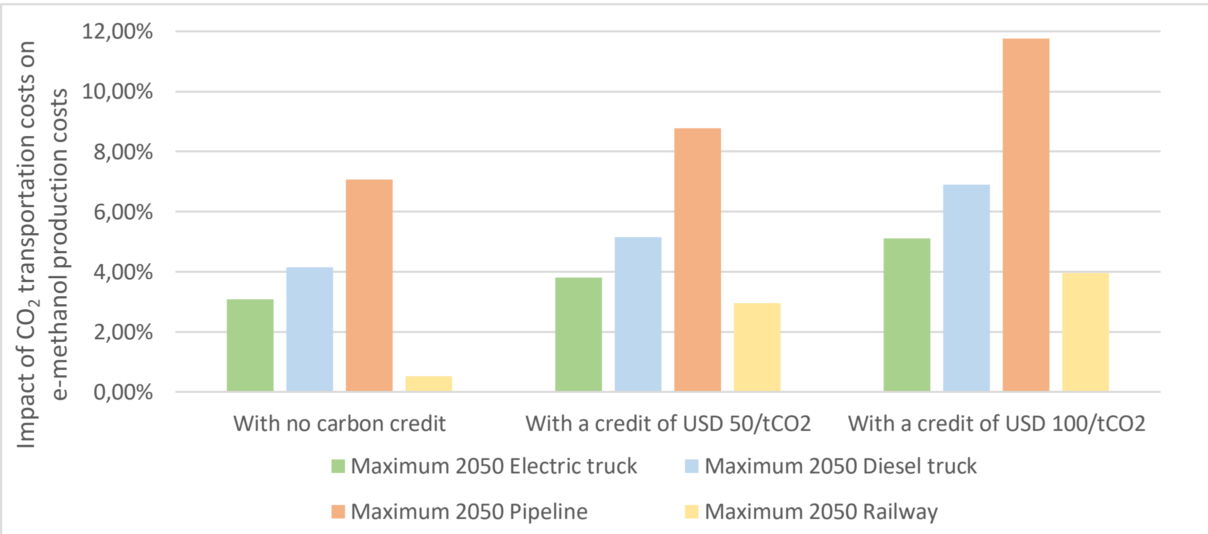


Figure 4.21 - Impact of CO_2 transportation cost on e-methanol production - long distance for 2050

When conducting this analysis, it becomes feasible to contrast the expenses associated with CO_2 transportation using literature [14] from various years. Nonetheless, even though the cost of producing e-methanol has undergone alterations, the assumption was made that the expenses for CO_2 transportation remained static. This assumption is rather improbable, as costs related to diesel, electricity, materials, and other factors can readily fluctuate, either rising or falling.

5

CONCLUSION AND FUTURE WORK

The growing concerns regarding the increasing concentration of CO_2 in the atmosphere, which leads to climate change, have prompted the development of various environmental goals, such as the Paris Agreement and the European Green Deal. These initiatives aim to mitigate the potential issues associated with global warming.

The adoption of these goals, both at the level of the European Union and Portugal, and their implications for decarbonization strategies, have led industrial companies to embark on research and the adoption of new procedures or technologies. The goal is to lower their emissions and enhance their efficiency.

This work was developed with the purpose of assessing the costs associated with the transportation of CO_2, one of the raw materials for e-methanol production. Within this context, this study involved the examination of the expenses, risks, and storage conditions pertaining to various modes of carbon dioxide transportation, such as truck, pipeline and railway.

This study's primary focus is to evaluate the expenses and logistical considerations associated with CO2 transportation within the glass, cement, and ceramic industries in the central and northern regions of Portugal. To sum it up, the research identifies the most cost-efficient mode of transportation for different scenarios: for shorter distances, pipelines prove to be the most economical option (costing approximately €1,82 per ton of CO_2 at flowrates around 900 tons of CO_2 per day); for moderate distances, both diesel (costing €5,6 per ton of CO_2 for flowrates ranging from 240 to 3 000 tons of CO_2 per day) and electric trucks (costing €4,9 per ton of CO2 for flowrates between 240 and 3 000 tons of CO_2 per day) are advantageous choices; and for longer distances (up to 200 km), railways are the optimal selection (costing €3,63 per ton of CO_2 for a flowrate of approximately 550 tons of CO_2 per day). However, it's important to note that the cost of transporting CO_2 from railway lines to the final destination is not taken into account, which can sometimes be significant due to the distance involved.

Throughout this study, certain assumptions were made. For instance, in the case of pipelines, the utilized formulas were derived from years of experience in natural gas pipeline operations. It's important to note that these formulas might not align with those employed for transporting supercritical CO_2 through pipelines (which is the best way to transport CO_2 by pipeline). At present, the possibility exists to repurpose a natural gas or oil pipeline into a CO_2 gas pipeline. However, it's imperative to consider safety aspects. CO_2 gas pipelines should not operate at pressures exceeding 1,070 psi for safety reasons. This pressure limit comfortably falls within the operational range of numerous existing natural gas and oil pipelines. Consequently, even if a pre-existing natural gas or oil pipeline lacks the strength to transport supercritical CO_2 fluid, it could likely be employed for CO_2 gas transport. Furthermore, it's important to note that all the formulas employed for computing OPEX and CAPEX were originally devised for the United States and not Europe. Consequently, there exists the potential for alterations in right-of-way costs.

Another presumption taken into account within this research concerning trucks was exclusively the procurement aspect, excluding any contemplation of potential leasing options. Furthermore, the acquired cost data originated from entities situated in Sweden, not Portugal. Therefore, for future reference, it would be prudent to engage with a more extensive range of companies situated in Portugal. This could lead to reduced expenses related to importation, a factor that was not considered in the current analysis.

In the case of rail transport, a base value for wagon rental was assumed, however, this value is not specific to CO_2 transport, as such information couldn't be obtained. Some companies in Portugal were contacted, but no response regarding the cost was received. Regarding the wagon selection, there are various types suitable for CO_2 transportation, therefore, it is recommended to thoroughly examine this information and choose the option that best fits each scenario. A value for labour costs was determined, but these costs would solely cover train operation. I assume that these costs are included in a comprehensive package offered by transportation and logistics companies, for instance, in Portugal, companies like CP and Medway provide such services.

In summary, it was feasible to determine the most suitable mode of transportation for each scenario: for shorter distances, pipelines exhibit the lowest cost, for intermediate distances, either diesel or electric trucks are preferable, and for longer distances (up to 200 km), railways emerge as the optimal choice. This is due to the existing infrastructure of railway lines and the substantial investment required for right-of-way when building pipelines.

My work holds significant importance as it addresses critical issues related to the transportation of CO_2 within the glass, cement, and ceramic industries in Portugal. This research not only sheds light on the costs and logistics associated with this crucial aspect of industrial operations but also offers valuable insights into the most cost-effective transportation modes for different scenarios. In a world increasingly focused on sustainability and carbon emissions reduction, my work provides practical information that can help these industries minimize their environmental footprint while optimizing their operations. Moreover, by identifying cost-effective transportation solutions, it contributes to the broader discussion of sustainable practices in industrial processes, highlighting the role of efficient logistics in achieving environmental goals. My efforts assist Madoqua in fostering environmentally conscious practices within their operations, demonstrating their dedication to sustainability in a world that is growing increasingly environmentally aware.

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A
DATA - RAILWAY ROUTES IN PORTUGAL

The figure A.1 displays the length of railway routes in Portugal provides a straightforward visual representation of the country's railway network. It offers a clear overview of the extent and coverage of railroads throughout Portugal, serving as a valuable reference for transportation planning and infrastructure development.

Figure A.1 - Railway routes in Portugal

2023

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Comparative cost analysis of different CO2 Capturing, Storage and Transport

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