Impact of financing cost on large-scale multi-modal CO2 transport cost: a European long-term perspective

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Alexandru Stefan Stefanescu

Student number: 5232929

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Graduation committee

Chairperson	: Prof.dr.ir. Andrea Ramirez Ramirez, Section E&I
First Supervisor	: Prof.dr.ir. Andrea Ramirez Ramirez, Section E&I
Second Supervisor	: Dr. Geerten van de Kaa, Section ETI
External Supervisor	: Prof. Dr. Bjarne Steffen, Climate Finance and Policy Group, ETH Zurich
External Supervisor	: Katrin Sievert, Climate Finance and Policy Group, ETH Zurich

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Contents

Executive summary

Decarbonisation is at the core of energy transition and climate change policies of the past years. The Glasgow Pact recognised for the first time the need to hold the increase of global temperature to 1.5 °C, and in order to do that the level of CO2 emissions emitted in the atmosphere needs to be drastically reduced. While there have been significant advances in renewable energy technologies, there are still glaring issues in terms of flexibility and reliability and fossil fuel is still the most utilised source of energy generation in the world. Apart from issues of energy security, there are also "hard-to-abate" sectors such as the cement and steel industry where the temperatures needed for operation can only be reached in a cost-efficient way with processes of fossil fuel combustion. In order to allow these sectors to transition in a sustainable way, CO2 capture technologies are crucial and have been acknowledge in every scenario where Net Zero emissions are reached by 2050. For CO2 capture technologies like DAC and CCS to develop at a large scale, infrastructure needs to be set up to allow for CO2 to be transported from source to sink in a reliable way.

CO2 transport costs have been studied before in literature, but there have been almost no studies where large scale multi-modal transport is considered. Furthermore, while the technical costs have been calculated in several studies, there has been no research on the potential sources of financing that the infrastructure could be based on and on the impact that different sources can have on the price. Therefore, this research looks at the different forms of financing available for each CO2 transport asset and assesses the impact that financing structures have on the cost of development of a CO2 transport infrastructure. The study considers a European cross-border case study (from Basel, CH to Bergen, NO) and it focuses on development of large scale transport, therefore the timeline is from 2030 onwards.

Firstly, a literature review is undergone in order to identify suitable financing structures for CO2 transport infrastructure and to collect data of technical costs of transport for the different assets. The financing structures identified are public investment, public-private partnerships, regulated private investment and (unregulated) private investment. These structures are characterised by different financing costs, with public funding typically being cheaper than private funding, but also in operational specificities and in the operational efficiency of each structure. Apart from the financing structures, data is gathered on financial parameters for each of the asset analysed, in order to calculate the cost of capital, and inputs for the calculation of technical costs are gathered from literature.

Secondly, a financial model is set up where the technical costs of transport for each of the transport assets are calculated and the costs are merged with the calculations of the cost of capital. Through this model, a levelized cost of transport for each transport mode and financing structure is identified and different scenarios of transport distance and capacity are modelled. The results are then discussed in a set of semi-structured interviews (n=4) in order to get validation on the financial inputs and to gather inputs for the technical costs of barge transport, which are missing in literature.

The results highlight how the cost of capital can influence the financing of CO2 transport at any scale of transport. As expected, pipelines are the most influenced by financing costs since the investment is very capital-intensive and subject to substantial economies of scale. The financing costs of pipelines built through private investment can reach as high as 48% of the total transport costs. Switching from a corporate finance model to a regulated corporate finance can save 10% of the costs, while financing from the government leads to almost 30% decrease in costs. On the other hand, public ownership of infrastructure is associated with operational inefficiencies which have not been quantified in the model, but public involvement in the financing structures is key in order to reduce the commercial risks associated with the development of the infrastructure and bring down the costs of capital. The results show how the threshold of investment into different transport assets changes when private or public financing are chosen for pipelines, showing that there are specific cases where transport by truck, rail, barge or ship is preferred over pipeline transport. For the Basel-Bergen case study, integrated onshore and offshore pipeline transport becomes the cheapest option from volumes of CO2 transported of 2 MtCO2/year when the project is financed publicly, however this value increases to 3 MtCO2/year when the pipeline is financed

through corporate transport.

Results highlight the need for a European framework for CO2 transport infrastructure which defines clearly how the infrastructure will be regulated and how its construction will be incentivised. In the interviews it became clear that until now the development has been slow because private actors do not want to commit to fund the infrastructure with private investment when there could be a possibility of regulation in the future, since funding the infrastructure privately and receiving regulated returns ex-post is economically inefficient. Since CO2 transport infrastructure is critical for the energy transition, public bodies need to speed up the pace and adopt a regulatory and financial framework which incentivises the development of CO2 capture technologies.

The research is subject to a number of limitations. Both the technical and the financial inputs can be expanded and a number of assumptions were made in order to stay within the scope of the thesis. The model does not take into account debt repayment schedules, refinancing or tax shields and the technical parameters used can be developed more in-depth: some transport modes have been calculated with one input for CAPEX, and this analysis should be made more granular in order to understand the different costs that go into the CAPEX. The number of interviews undergone is limited and more interviews should be done in order to have a robust dataset. Further research should focus on developing a model based on a network of CO2 transport hubs and introduce more thorough technical calculations to pair with the financial model.

Nomenclature

β_{asset}	Unlevered beta
β_{equity}	Levered beta
η_x	Energy efficiency of x
ρ_x	Density of x
τ_i	Depreciation time of asset i
C_x	Cost of component x
CA	Corrosion allowance
$CAPEX_x$	CAPEX of asset x
CoC_i	Cost of capital of asset i
d_x^y	distance travelled for x component and y asset
DM	Debt margin
E/V	Market risk premium
F	Corrosion factor
FL_{ti}	Full load of asset i at time t
K_d	Cost of debt
K_e	Cost of equity
L	Pipeline length
$LCOT$	Levelized cost of transport
m_i	Mass of CO2 transported in scenario i
m_x	Mass of CO2 transported with asset x
OD	Outer diameter
$OPEX_x$	OPEX of asset x
P_x	Pressure at stage x
R_F	Risk-free rate
S	Design factor
T	Corporate tax rate
t	Thickness
W_x	Power capacity of x

Chapter 1

Introduction

Anthropogenic climate change has caused widespread adverse impacts which are projected to exponentially intensify if action is not taken (Becattini et al., 2022) (IPCC, 2018). The need to hold the increase of global temperature to 1.5 °C has been internationally recognised in order to reduce further projected damages, and reaching net-zero emissions by mid-century is crucial to achieve the goal (UNFCCC, 2022). All of the scenarios where net-zero emissions are likely to be achieved by 2050 include the use of Carbon Dioxide Removal (CDR) technologies like Direct Air Capture (DAC), as well as emission-reducing technologies like Carbon Capture and Storage (CCS) (IPCC, 2022).

CCS research has been going on for decades and there is a recognised need to implement the technology in order to mitigate emissions of "hard-to-abate" industries, such as cement or steel manufacturing, where it is infeasible to reduce emissions from a technological or economical point-of-view. The development of CCS technologies has been lagging in the past decade, although CO2 capture and geological storage is already mature technology for gas processing and enhanced oil recovery (EOR) (IPCC, 2022). CCS deployment at a global scale is far behind the scenarios to limit global warming to 1.5°C or even 2°C (IPCC, 2022). Alongside CCS, during the last years, carbon capture research has also been dedicated to how to use carbon capture for negative emissions technologies, such as direct-air carbon capture and storage (DACCS) (Fasihi et al., 2019) or bioenergy with carbon capture and storage (BECCS) (Gough & Upham, 2011). The main driver for the uptake of carbon capture technologies is a high enough carbon tax which makes it more beneficial to invest in a capture plant than to continue emitting and paying for the CO2 released. In the past, the carbon tax has not brought the desired effect in spurring investment (Wang et al., 2021), however, this is due to the historically low prices that CO2 has had; for the past year the average carbon price for the ETS has been 80 €/tCO2, with highs of 96 €/tCO2, compared to prices of under 30 €/tCO2 for the years before (Trading Economics, 2022). The trend of increasing prices for the carbon tax is likely to continue.

Lupion and Herzog (2013) have analysed why European projects for CCS have failed to obtain funds for demonstration of the project under the NER300 funding scheme. Among the main reasons they have found are the low ETS carbon price, a system of tight public funds and a lack of comprehensive climate policies in most member states. The paper analysed carbon capture and emphasizes the need for clear signalling at a European level in order to drive down risks and complexity. The conclusions from Lupion and Herzog (2013) are echoed in Heffron et al. (2018), who argue that coordination to support transboundary CO2 transport at a European level is necessary in order to drive down the risks. Development of CCUS at a large scale depends on reducing the risks while at the same time providing the expectation for financial returns (Wang et al., 2021). Wang et al. (2021) find that the main features of a successful CCS project are the business-driven market possibilities, which reduce the hazard rate by 55%, followed by tax credit policies at 52%. A business-driven market turns CO2 from waste to commodity and gives it intrinsic value; on top of that, tax credits lower the investment needed and incentivise commercial players to participate in the system (Wang et al., 2021). Carbon taxes are found to not have a significant effect on the project's hazard, however, the research of Wang et al. (2021) was conducted during a period of low CO2 prices. On the other hand, the biggest factor which increases the hazard rate is increasing the capacity of the projects by large numbers annually: the argument made is that large scale deployment should happen gradually (Wang et al., 2021). Lau et al. (2021) identify the development of regional CCS corridors as an essential enabler to reduce the overall costs of the technology and take advantage of economies of scale in order to reduce the high capital expenditure needed to develop CO2 transport infrastructure. Over the past year, the ETS price has increased substantially (Trading Economics, 2022) and public investment in the energy transition is constantly increasing (Bloomberg, 2022), which makes it crucial to understand the development of CO2 transport.

In order to allow the development of such technologies, a CO2 transport infrastructure needs to be set up in order to link carbon sources with carbon sinks. The development of such an infrastructure is subject to the following challenges (ZEP & CCSA, 2022):

- Infrastructure development is capital-intensive and does not offer an immediate revenue stream in case the carbon capture technology is not yet widespread;
- Infrastructure has the potential for large economies of scale, therefore the development of clusters is more cost-effective than multiple point-to-point infrastructures;
- There are technical and financial risks associated with the ownership of carbon transport infrastructure, which makes liability an issue.

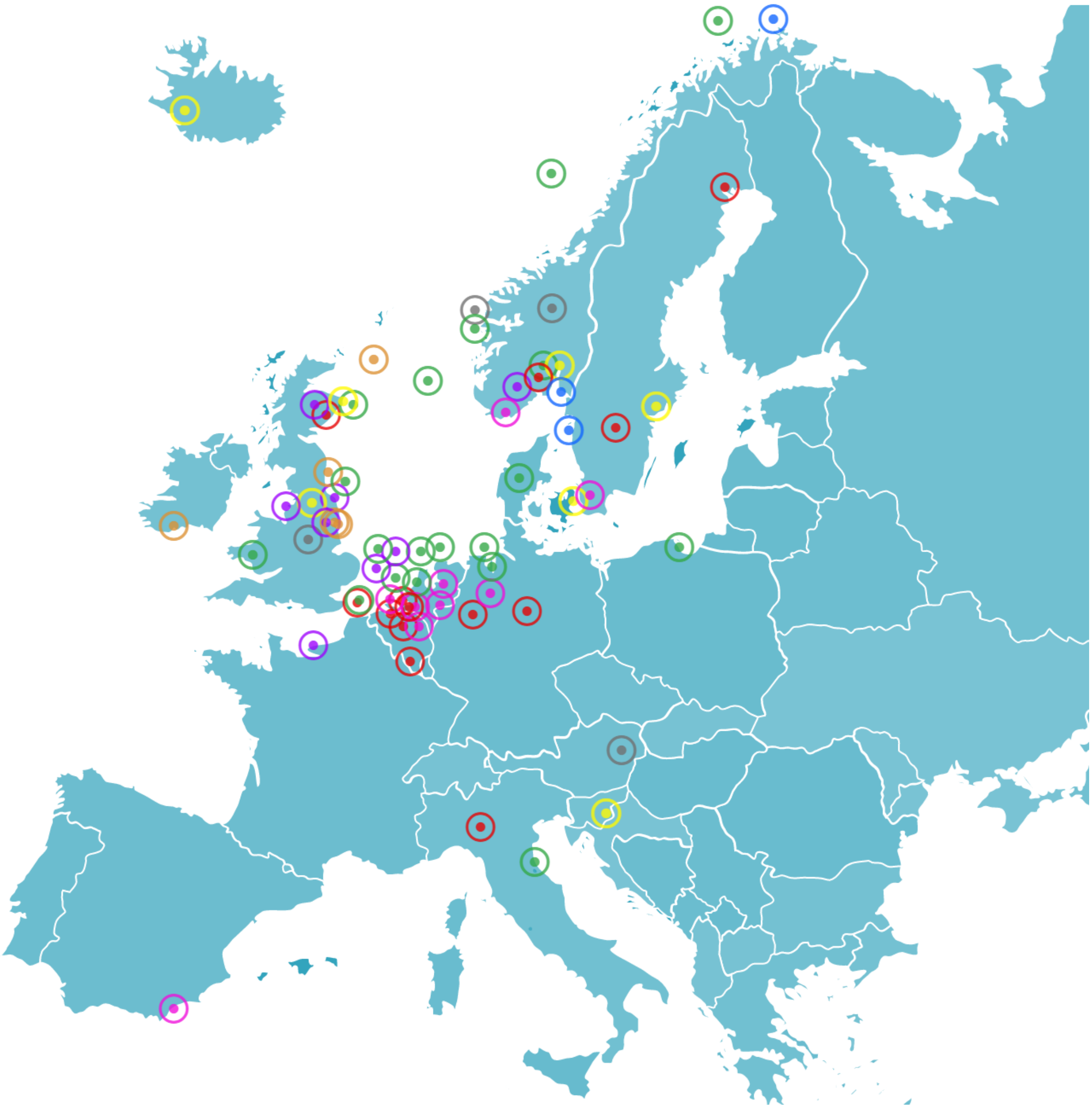
In Europe, CCS pilot projects are widespread, particularly in the countries surrounding the North Sea. Figure 1.1 shows the current CCS/CCU projects which will be ready for commercial delivery by 2030. Green dots show the projects for transport and storage of CO2: out of 66 projects, 19 deal with transport and storage. Apart from one project in Italy which is still at the stage of pre-feasibility study, all of the T&S projects for CO2 have been undergone in the area surrounding the North Sea. Notable projects include:

- Northern Lights, a CO2 transport and storage project on the coast of Norway which is in an advanced development stage, with operations scheduled to start in 2024 (Equinor, n.d.-b);
- Porthos, a CO2 transport and storage project for the port of Rotterdam, with a CO2 hub planned in the port of Rotterdam and transport to an offshore storage site by pipeline. The system is scheduled to start in 2024/2025 (Porthos, n.d.);
- CO2-Netz, a CO2 transport project sponsored by OGE planning to build a greenfield pipeline network in Germany linking all of the main industrial clusters, with potential transport of up to 18.8 million tons of CO2 (OGE, n.d.).
- Fluxys-Equinor CO2 transport project, a newly announced major infrastructure project planning to deliver an offshore pipeline connecting Belgium to Norway with capacities of 20-40 MTCO2 per year (Equinor, n.d.-a).

CO2 transport and storage (T&S) networks have gained importance from a socio-political standpoint in the past years, and important progress has already been made in terms of regulations for the development of a European transport infrastructure: the London Protocol has been amended for the cross-border transport of CO2 (International Energy Agency, 2020) (ZEP & CCSA, 2022), which means CO2 can now be transported outside of national boundaries. Furthermore, CO2 networks have been made eligible for different European funding mechanisms such as the Innovation Fund and Connecting Europe Facilities (ZEP & CCSA, 2022). In the next few years, the projects currently underway for carbon transportation systems (e.g. Porthos, Northern Lights) can provide valuable information and establish standards for the transportation of CO2 with different carriers (European Commission, 2019).

Until now, research on carbon transport has mostly been focused on assessing the costs and feasibility of different transport methods by road, rail, water or pipeline. However, there is a lack of research in the field of investment mechanisms and the evaluation of financial risks. It is projected that by 2030 a small-scale network will be set up and standards for carbon transport will be implemented at a European level (D'Aprile et al., 2020). The next step would then be to scale up this infrastructure, which will need different forms of financing than the ones which are being used now. At the moment, all projects dealing with carbon capture or carbon transport are very small-scale demonstration projects which have gathered funds through research projects, public funding or industry R&D spending: this type of financing structures are not feasible to develop the infrastructure at a large scale. This research seeks to define the financing options of the carbon transport infrastructure at a European level in 2030 and beyond, as well as assess the impacts of these financing options on the costs of carbon transport.

Figure 1.1: Map of CCS/CCU projects in Europe compiled by Zero Emissions Platform (2022)



Orange dots indicate full-chain CCS projects; green dots indicate CO2 transport and storage projects; Red dots indicate CCS projects for industry; Yellow dots indicate energy production and CCS projects; Purple dots indicate low-carbon hydrogen production; Grey dots represent test centres

1.1 Research approach

The research will focus on analysing CO2 transport asset cost from a technical and financial standpoint. A mixed methods approach is used in order to combine quantitative insights from techno-economic calculations with qualitative insights from financial structures and historical tendencies in financing large-scale infrastructure assets. As a first step, a structured literature review is undergone in order to assess the state-of-the-art knowledge on CO2 transport and financing structures. Through the literature review, the knowledge gaps are substantiated and a data collection process is undergone. The aim of the review is to get inputs on the calculation of CAPEX and OPEX of each of the assets considered, as well as an estimation of the cost of capital and other operational features of different financing structures. After the data collection phase, an Excel model is set up in order to estimate the impact of different financing structures on the cost of carbon transport. Finally, as a validation step for the research, a set of semi-structured interviews is undergone.

1.2 Research question

The research question is as follows:

How does the financing cost affect the levelized cost of CO2 transport assets in Europe?

This question can then be answered through the following sub-questions:

SQ1. What are potential options of finance for the different assets for carbon transport?

SQ2. What is the cost of capital of the financing options identified?

SQ3. What are the implications for the overall cost of carbon transport?

The novelty of this set of research questions is substantiated through the state-of-the-art literature review undergone in Chapter 2, where the knowledge gap is explained in detail.

1.3 Relevance with CoSEM

The research topic is of high relevance to the CoSEM field. Transport infrastructure for CO2 is a complex socio-technical system: it combines a modular and cross-border technical system with a multi-actor governance system which entails financing and operation at different institutional levels. Research into financing needs seeks to combine the profile of investors and the investment needs of the carbon transport infrastructure. The financial model built in this thesis seeks to explain the different risk profiles and investment capabilities of public and private actors by calculating the cost of capital, and through the expert interviews, these topics are further elaborated. On top of this understanding of the social aspects of investment, a technical understanding of the different transport methods is needed, as well as the engineering resources for the calculation of carbon transport processes and costs. Finally, an in-depth understanding of financing large-scale infrastructure is essential in order to apply investment methods to carbon transport.

The thesis will be structured as follows. Firstly, the state-of-the art literature review will be outlined, starting with a description of core concepts, analysing the knowledge gap in current CO2 transport costs and diving into the financing structures identified. Secondly, the methods section explains how the research was undergone with a mixed-methods approach. Thirdly, the results show the cost of capital and its impact on the levelized cost of transport. Fourthly, the discussion analyses these results and finally the conclusion wraps up the thesis and presents recommendations for policy-makers and further researchers.

Chapter 2

Literature review

2.1 Core concepts

2.1.1 Carbon transport infrastructure

Carbon transport infrastructure is defined as the assets needed to transport CO2 from source to sink. Transport of carbon is feasible through trucks, trains, barges, ships or pipelines, differentiating in terms of cost based on distance from source to sink, the quantity of CO2 transported, frequency of transport, or capital intensiveness of the asset. For the scope of the research, transport infrastructure includes conditioning (compression or liquefaction) of CO2, assets to transport CO2 including potential loading/unloading facilities and buffer storage at intermediate locations or at the end location. The transport of CO2 inside the underground storage is not part of the research scope.

2.1.2 Levelized cost of transport (LCOT)

Estimating the levelized cost is an approach that aims to quantify the total costs of an asset over its lifetime. The levelized cost is a sum of the annualized capital and operational expenditures of an asset, divided by the annual capacity/product that it generates. The approach is extensively used to quantify the costs of electricity generation, through the levelized cost of electricity (LCOE). The main advantage of the approach for CO2 transport is the ability to compare different assets in terms of their cost of transport for 1 unit (1 ton) of CO2 transported.

2.1.3 Cost of capital

The cost of capital is defined as the revenue that the lending party needs to give back to all stakeholders, including equity investors as well as banks or other debt investors. The cost of capital is calculated as a percentage on top of the investment, and is composed of two parts:

- Cost of debt: the interest rate applied by the institutions who provide the debt investment;
- Cost of equity: the return on investment needed by the stakeholders who provide equity.

These cost components are calculated separately through methods described in section 3.4.1. The cost of capital is then calculated as the Weighted Average Cost of Capital (WACC), which takes into account the cost of debt, cost of equity and tax rate to determine the interest rate for the asset. All of these parameters are asset-specific and they can also be different based on the financing structure used.

2.2 CO2 transport infrastructure costs

The costs of building a CO2 transport infrastructure have been studied in the literature for a range of different transport assets and geographical regions. Smith et al. (2021) conducted a literature review on the cost of CO2 transport, compiled costs for different transport modes across the world and found that there are significant differences in costs depending on transport distance, scale and geographic region. The results are echoed by van der Spek et al. (2019), as both papers agree on the high degree of variability in transport costs depending on the geographic region, which makes the assumption of a fixed rate for transport erroneous. Smith et al. (2021) find that while the

CO2 transport cost assumption is usually 10 \$/tCO2, in reality, the value is anywhere between 4-45 \$/tCO2. In Europe, Knoope (2015) studied CO2 transport infrastructure extensively, including cost modelling, assessment of technical risks and comparing ships and pipelines in terms of flexibility. She conducts an optimization study of technical inputs for pipeline transport (Knoope et al., 2014) where she finds that transporting CO2 in the liquid state is cheaper than the gaseous state (1.2-1.8 €/tCO2 vs 3.0-3.8 €/tCO2 respectively), and that higher steel grade lowers the investment costs for an onshore pipeline transporting liquid CO2. Furthermore, her results indicate that oversizing is cost-effective depending on the availability of mass flows, and that building point-to-point pipelines can sometimes be more cost-effective if the capacity of the transport hub is not used fully for a certain period of time. The methods and results in Knoope et al. (2014) are considered the state-of-the-art in calculating CO2 pipeline costs and are used in other studies analysed in this literature review (Roussanaly et al., 2017) (Roussanaly et al., 2021). CO2 pipelines are also considered in Onyebuchi et al. (2018), who review the challenges of deployment of CO2 pipelines, including design, construction, operation and financing. He reports that pipelines for CO2 transport constitute about 21% of the capital investment cost of a full-chain CCS project. In the analysis, the capital assets are barriers to investment and the government is expected to play a leading role in the development of transport infrastructure. Focusing on the US market, Edwards and Celia (2018) build a techno-economic model to calculate the CO2 transport costs by pipeline and they assess whether it is possible to fund the infrastructure privately. They conclude that without government finance it is unrealistic to have a network with commercial rates of return.

The pipeline cost model developed in the research by Knoope et al. (2014) is used in Oeuvray (2022) as well, who models point-to-point CCTS chains for a waste-to-energy plant based in Zurich, Switzerland. The study assesses different transport modes towards two storage sites, Rotterdam, NL and Rong, NO. In the thesis, she gathers data for all modes of transport and compares the costs of transport of each of the modes. She finds that transport by barge tankers is the cheapest option in her case study. and that the full transport chain for transport from Basel to Rong is around 150 €/tCO2. The high figure is explained as she takes into account small-scale CO2 transport, with volumes under 1 MTCO2/year, therefore the costs of transport are inflated and there is no scope for economies of scale. Stolaroff et al. (2021) conduct another study where they compare different modes of onshore transport in the US, and they find that transport by rail or truck can be cost-effective in situations where there is no possibility of pipeline transport or when the volumes are too low.

Roussanaly et al. (2021) conducts a research study on the costs of CO2 transport by ship: his research focuses on comparing low-pressure ships that transport CO2 at -49 °C and 7 barg, to medium-pressure ships that transport CO2 at -30 °C and 15 barg. He finds that while medium-pressure shipping is the predominant method used today, low-pressure CO2 transport is cheaper than medium-pressure transport for all combinations of transport distance and volumes considered. The cost reductions become very significant (over 30%) for distances of about 1000 km and larger. Reductions of 15% are reported even in the short term, for transport at a smaller scale. In absolute numbers, this represents 5 to 10 €/tCO2 less for the 7 barg shipping option compared to the 15 barg option. The capital and operational expenditures for the estimation of CO2 shipping costs in Roussanaly et al. (2021) are taken from Element Energy Limited (2018), where costs are compiled from a few different studies into a regression analysis. The sources highlighted in the regression analysis for 7 barg shipping are:

- Seo et al. (2016), who assume the costs of a CO2 carrier are the same as an oil tanker;
- Gao et al. (2011), who look at an LPG carrier with a capacity of 4000 t in China;
- Kler et al. (2016), who conduct interviews with different industry experts and assess the costs of a concept CO2 carrier.

This highlights that the estimates for CO2 shipping at low pressure are few and they use estimates from the shipping of other commodities which are part of mature market segments with no novelty and fewer commercial risks attached to it. The study undergone by Element Energy Limited (2018) highlights the limited experience in large scale CO2 shipping as a limitation and mentions a risk premium attached to CO2, however, it argues that this risk premium will decrease quickly since this is what happened to other ships which introduced novel factors such as LNG-powered ships. They highlight the need for further research in assessing viable business models for shipping, including the definition of ownership structures and capital financing.

Roussanaly et al. (2017) also conducted a case study on the costs of CO2 transport by train in Czech Republic, comparing it with the transport of CO2 by pipeline. The study considers two scenarios for storage, national and European hub, and analyses the prices of transport and conditioning for both pipeline and train. Transport costs for trains are reported at 5 €/tCO2 for 50 km and 11 €/tCO2 for 200 km transport. Results show that depending on the method used for capturing CO2 transport by pipeline is cheaper than train for distances lower than 350 and 900 km. These cut-offs are based on Rectisol and low-temperature CO2 capture respectively, and the reason for the difference is in the properties of the CO2 captured and the conditioning needs of pipeline and train transport. Furthermore, the study considers a scenario where a shorter period is considered for the depreciation of conditioning and transport assets, in order to showcase more risk-averse behaviour: in those scenarios, the threshold for switching between pipeline and train becomes as low as 425 km for Rectisol capture and 175 km for low-temperature capture. However, the study considers smaller transport volumes (around 1.3 MtCO2/year) and data sources for transport costs are scarce. The estimates for CO2 transport by train of Roussanaly et al. (2017) are taken from Andersson et al. (2011), who estimate rail transport costs in Europe. Other studies estimating the costs of CO2 transport by train are Stolaroff et al. (2021) for the US and Gao et al. (2011) in China, with costs at around 11 €/tCO2 for 200 km and 13 €/tCO2 for 600 km respectively.

Through the studies considered, long-distance transport has been calculated through ships and pipelines, while the other modes of transport have served a better purpose for short and medium-distance transport. This is due to the very high operational expenditures that these modes occur when travelling long-distance, as well as their operational specificities which makes them hard to deal with over long distances and big quantities. The need for different modes of transport is highlighted in some studies (Stolaroff et al., 2021) (Roussanaly et al., 2017), but there has little research on multi-modal transport of CO2 where all modes of transport are considered, outside of the thesis from Oeuvray (2022). Table 2.1 shows the transport assets which have been analysed by the papers selected in this review. The table shows how current research has been mostly focused on pipelines and ships, with few studies on rail and truck and only one assessment of barge transport which was found for this literature review.

Table 2.1: Transport asset costs calculated in the analyzed CO2 transport sources

Paper	**Pipeline**	**Ship**	**Rail**	**Truck**	**Barge**
Kler et al. (2016)	*	*			
Element Energy Limited (2018)		*			
Knoope et al. (2014)	*				
Nie et al. (2021)	*				
Oeuvray (2022)	*	*	*	*	*
Roussanaly et al. (2017)	*		*		
Roussanaly et al. (2021)	*	*			
Seo et al. (2016)		*			
Stolaroff et al. (2021)	*		*	*	

2.3 Knowledge gap

Until now, research on CO2 transport infrastructure has been focused on estimating the costs of transport from a technical standpoint. All of the studies analysed assume a fixed discount rate and depreciate over the entire lifetime of the asset. The discount rate is assumed between 7 and 10% in most studies. There have been no scientific studies which assessed the influence of financing and risks for the different carbon transport methods and their costs. The studies which focus on financing of the carbon transport infrastructure are either qualitative in nature (Mahgerefteh et al., 2020) (BEIS, 2020), or outdated and limited in the consideration of transport methods (Chrysostomidis et al., 2009). One study has been found in the literature which assesses economic factors for the evaluation of transport costs (Nie et al., 2021), however, the study only considers two generalised financing options and does not provide a basis for the assumptions of the financing structures.

The need to study the cost of capital for CO2 transport assets is emphasized in multiple studies (Lau et al., 2021) (Onyebuchi et al., 2018) (Pale Blue Dot., 2018). Roussanaly et al. (2014) dedicates a section of the sensitivity analysis to examining how different discount rates affect the investment in pipeline transport and he acknowledges how public investment can lead to cheaper infrastructure costs than private investment, however, the difference is not quantified. The development of business models from governmental actors has focused almost exclusively on CO2 pipeline infrastructure, and there is a lack of research into CO2 shipping, road and rail transport (Mahgerefteh et al., 2020). This conclusion is shared by van der Spek et al. (2019), who also conclude that more research is needed into the costs of both early-stage and more mature T&S networks. Finally, the studies analysed until now fail to consider part of the complexity of CO2 transport by not taking into account multi-modal transport or by only talking about part of the transport assets. The only study found in this literature review which considers all modes of transport which are feasible and realistic for CO2 transport is Oeuvray (2022), with few studies considering more than one transport modality in the use-case related to climate change mitigation (Stolaroff et al., 2021)(Roussanaly et al., 2017). Finally, data on some transport modes (e.g. barges) is very scarce and new inputs need to be acquired in order to study the impact of the cost of capital on these transport modes.

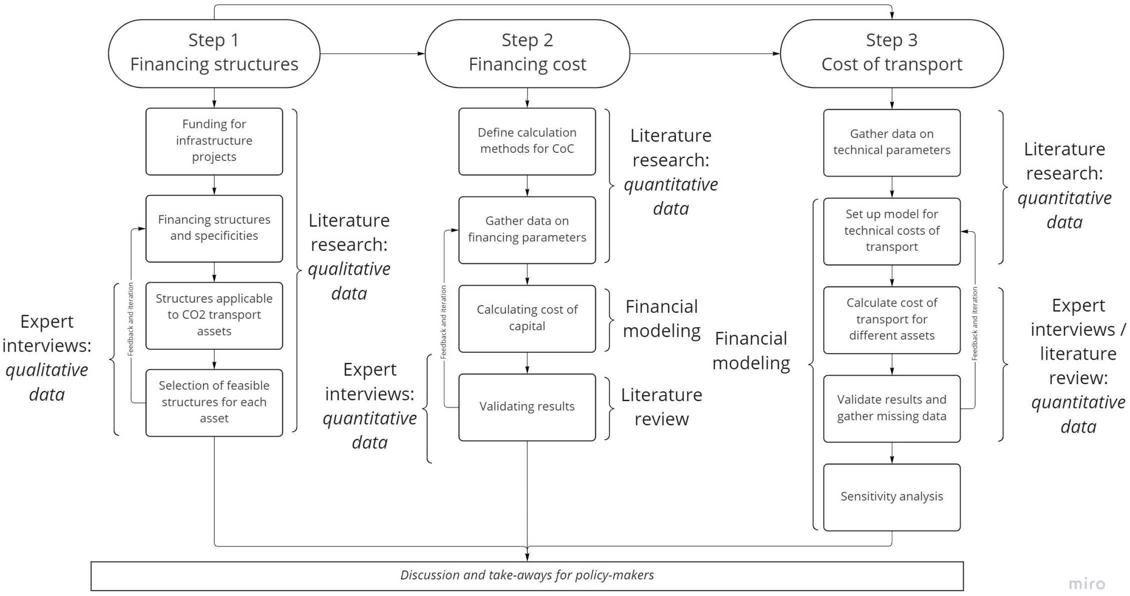
Chapter 3

Methods

3.1 Mixed methods

The main research questions concern determining an appropriate cost of capital for CO2 transport assets and evaluating the performance in terms of cost with different financing structures. This is exploratory research which combines technical and financial inputs with past experience, expectations and governance structures. Therefore, a mixed methods approach was chosen. Combining qualitative and quantitative research gives the opportunity to get both a broad understanding of the underlying events as well as a deep dive into a singular case (Johnson & Onwuegbuzie, 2016). Mixed methods design can be used to improve on simpler study designs in order to help answer research questions (Schoonenboom & Johnson, 2017). A mixed methods approach should be used when the research question has to be answered with different data types. In the context of infrastructure projects, quantitative methods such as technical and financial modelling have to be complemented by a study of financing expectations and risks associated with different assets. The approach to explanation contains an indication of the average effect of independent variables as well as a dive into individual cases (Mahoney & Goertz, n.d.).

Figure 3.1: Thesis flow overview



The approach is structured in three main methodological phases: a literature review (qualitative data), semi-structured interviews (qualitative data) and financial modelling (qualitative data). An overview of the research is presented in figure 3.1. The research is structured along the three sub-questions, tackling first the financing options, then the cost of capital, then the impact on the levelized cost of transport. The first step concerns mostly qualitative research, with the in-depth literature review being complemented by expert interviews: this methodology is needed in order to get information on financing structures and consolidating the information through the structures identified in current companies working with CO2 transport. The second step quantifies the financing structures identified in the literature review by looking at financial data from other studies and databases and validating that through interviews. The last step combines all of the information gathered beforehand into the financial model, compiles technical costs of CO2 transport from past literature and interviews, and calculates the levelized cost of transport for different distance and capacity requirements.

3.2 Case selection

This research project considers financing structures for large-scale multi-modal transport of CO2 for a case study between Basel and Bergen from 2030 onwards. The reasons for the choices made are as follows.

The *financing structures* selected are taken as a means of analysing the main structures of investment that can arise from public and private funding. The structures selected in this study are by no means exhaustive since theoretically there are endless possibilities of financing options in terms of the number of players involved, the rate of return required or the risks taken by each party. However, the structures identified are meant to explain the main differences between types of private, public and hybrid structures and what their differences are from a quantitative and qualitative standpoint.

Large-scale transport of CO2 is considered because financing structures play a more significant role when the infrastructure needs to be fully delivered and the investment needs are exponentially higher: pilot projects are already underway, and while there have been issues with financing for pilot projects as well (Lupion & Herzog, 2013), there are now projects which have been underway in Europe for years and large scale expansion is already planned (Equinor, n.d.-b) (OGE, n.d.). As has been discussed in the literature review, the development of large-scale infrastructure involves multiple stakeholders at different levels of governance (Glachant, 2012), which makes the study of financing structures crucial in order to maintain delivery and operational efficiency while safeguarding costs for users. The timeline considered is from 2030 onwards since that is when investment in CCS is projected to pick up and increase in scale (D'Aprile et al., 2020) (Haesen et al., 2017) (Bogdanov et al., 2019). Furthermore, the infrastructure considered is *NOAK* (Nth-of-a-kind). This leads to choosing a base case of 1 MtCO2 transported per year and increasing the amount transported until 10 MtCO2 in order to study the economies of scale that take place when increasing quantities transported for the same distances and for different transport assets.

Multi-modal transport of CO2 is considered in order to address the complexity of actors and assets that characterises the development of infrastructure at a large scale. Looking at oil and gas as mature sectors of chemical transport, multiple modes of transport have been used (Wetzel, 2019). The same is expected for CO2 transport as well: while the majority of the capacity is expected to come from pipelines and waterways networks, road and rail will be key for individual emitters or for onshore places where pipelines cannot be constructed (Stolaroff et al., 2021).

The research considers a *route from Basel to Bergen* as a case study which is representative of European transport of CO2, and the reason is two-fold. This route allows to take into account all of the transport modes: short-distance transport by truck or rail until Basel, inland shipping through the Rhein from Basel to Rotterdam, onshore pipelines from Basel to Rotterdam, offshore pipelines from Rotterdam to Bergen and shipping from Rotterdam to Bergen.

The research considers *greenfield* infrastructure only, without reuse of existing natural gas or oil transport infrastructure: this is due to the multiple uses that existing infrastructure could assume in the future, as CO2 would have to compete with hydrogen and other green fuels. Furthermore, it is less reliable to estimate the costs of converting existing infrastructure since the operational lifetime of the assets would need to be estimated on a case-by-case basis.

3.3 Data gathering

3.3.1 Literature review

Firstly, a structured literature review was developed in order to define the knowledge gap and the research questions. Google Scholar was chosen since the database aggregates a vast collection of papers from different editors and facilitates the use of Boolean coordinators. The sources were then managed through Mendeley. The main key terms were based on the following strings:

"*CO2 transport*" OR "*Carbon transport*" AND "*financing*" OR "*cost*" AND "*CCS*" OR "*DAC*";
"*large-scale infrastructure*" OR "*CO2 infrastructure*" AND "*financing*" OR "*cost of capital*".

A focus has been made to limit the papers to the last 10 years and to limit the geographic region to Europe in order to get the most relevant papers for the research. Furthermore, all of the papers analysed are in English. A few of the papers analysed are older than 10 years: this is due to the relevance of the papers up to this day and to the lack of alternative research conducted since that date. This is the case for Andersson et al. (2011), whose values for rail transport are used in Roussanaly et al. (2017) for the calculation of the transport cost and no data that is more recent has been found on the subject.

A starting point for the research was also the master thesis of Oeuvray (2022), who calculates the cost of CO2 transport with all possible transport modes from Switzerland to Norway and Iceland. For this paper and other relevant papers found during the research, backwards snowballing techniques were applied in order to find highly relevant papers which were not in the selected results or timespan.

Through this first literature review, a set of core concepts were identified, as well as the main knowledge gap that the research is based on. A set of 136 papers have been analysed and categorised through Mendeley, of which a set of key papers were taken for the literature review in section 2. The focus on the analysis was on identifying the focus on the papers by scanning through the methods and results section. The list of papers needed to be shortened in order to get to the key papers to analyse for the review and the following requirements were applied for the scoping down:

- sources dealing with quantitative analysis of CO2 transport costs for Europe should be included;
- sources dealing with financing structures for a CO2 transport infrastructure should be included;
- sources dealing with specifics of financing structures for large-scale infrastructure should be included;
- grey literature should be used only when there is a lack of academic literature on the topic;
- literature on the qualitative assessment of risks should be excluded;
- literature on general CCS developments should be excluded.

Table 3.1 presents an overview of the key papers cited in the literature review. The majority of the works come from peer-reviewed academic papers (n=22), while the rest is a mix of government reports, grey literature from industry related to CCS, working papers from academic groups or MSc thesis (n=11). After identifying suitable sources, the aim was to verify what type of research has been already undergone in terms of CO2 transport calculation methods and what data was available, therefore an in-depth analysis of the methods and results of the academic papers was undergone. Another point of focus for the analysis of the papers was the discussion and recommendations for further research, in order to grasp what the perceived knowledge gaps were and how the thesis work could address them.

Table 3.1: Overview of the key papers used for the literature review.

Paper	**Year**	**Type**	**Category**	**Topic**
F. Egli et al. (2019)	2019	Academic paper	Cost of capital	Assumptions on cost of capital
Singh et al. (2022)	2022	Academic paper	Cost of capital	Cost of equity for regulated energy
Steffen (2020)	2020	Academic paper	Cost of capital	Cost of capital for renewable energy
Lupion and Herzog (2013)	2013	Academic paper	Financing	Funding for CCS pilot projects
Wang et al. (2021)	2021	Academic paper	Financing	CCS deployment failure
Lau et al. (2021)	2021	Academic paper	Financing	CCS deployment failure
Mahgerefteh et al. (2020)	2020	Grey literature	Financing	CO2 transport infrastructure deployment
BEIS (2020)	2020	Governmental paper	Financing	CCUS business models
Pale Blue Dot. (2018)	2018	Grey literature	Financing	CO2 T&S business models
Faure (2015)	2015	Academic paper	Financing	Private liability and infrastructure
Lord Oxburgh (2016)	2016	Governmental paper	Financing	CCS business model
Haas et al. (2021)	2021	Academic paper	Financing - other industries	Financing sustainable energy systems
Mete (2020)	2020	Academic paper	Financing - other industries	LNG subsidies and financing
Ruester (2015)	2015	Working paper	Financing - other industries	LNG financing
Perrotton and Massol (2018)	2018	Academic paper	Financing - other industries	Natural gas pipeline financing
Steffen (2018)	2018	Academic paper	Financing - other industries	Project finance and renewable energy
Leisen et al. (2019)	2019	Academic paper	Financing - other industries	Regulatory risk in the energy sector
Makovšek and Veryard (2016)	2016	Grey literature	Financing structure	Financing structures (RAB, PPP, Hybrid)
Stern (n.d.)	2013	Working paper	Financing structure	RAB and infrastructure financing
Stern (2012)	2012	Academic paper	Financing structure	Regulatory agencies and infrastructure
Newbery et al. (2019)	2019	Academic paper	Financing structure	Financing structure (Hybrid RAB)
Inderst (2013)	2013	Grey literature	Financing structure	Private infrastructure finance
Heffron et al. (2018)	2018	Academic paper	Regulatory and financing	CO2 transport network ownership
Smith et al. (2021)	2021	MSc thesis	Technical costs	CO2 T&S costs
Knoope et al. (2014)	2014	Academic paper	Technical costs	CO2 transport costs - pipeline
Oeuvray (2022)	2022	MSc thesis	Technical costs	Full CCS chain costs
Chrysostomidis et al. (2009)	2009	Academic paper	Technical costs	CO2 pipeline transport cost and financing
van der Spek et al. (2019)	2019	Academic paper	Technical costs	Guidelines for CCS cost estimation
Roussanaly et al. (2021)	2021	Academic paper	Technical costs	CO2 transport costs - shipping
Stolaroff et al. (2021)	2021	Academic paper	Technical costs	CO2 T&S costs
Element Energy Limited (2018)	2018	Grey literature	Technical costs	CO2 transport costs - shipping
Edwards and Celia (2018)	2018	Academic paper	Technical costs	CO2 transport costs - pipeline
Onyebuchi et al. (2018)	2018	Academic paper	Technical costs	CO2 transport costs - pipeline

3.3.2 Semi-structured interviews

Semi-structured interviews (SSIs) are the best fit for research when the sector presents novelties: this type of interview serves the scope of guiding the interviewee on the topics to be discussed while at the same time leaving space for divergences which could reveal insights that are not in the set of predefined questions (Adams, 2015). Moreover, since there is already an established body of work on CO2 transport costs, SSIs allow to steer the interview away from the consolidated part of the research.

Interviews are a key addition to the study in order to validate the results and get insights into uncertain inputs: since transporting CO2 is a novel technological field, there are still gaps in literature in terms of reliable estimates and in this case it is best to double-check the data with experts that are working towards expanding the sector already.

In total, 4 semi-structured interviews have been carried out. The interviews were fully anonymised, according to the Chatham-House rule (Chatham House, n.d.). While the interviewees personal data is kept confidential, the profile of the experts is shown in Table 3.2. All interviewees have demonstrated experience in parts of the CCS supply chain, with expertise in one or more of the transport assets analysed in this study. The topics of discussion were the same for all interviews: professional background of the interviewee, technical inputs for transport asset cost calculation, financing structure options and cost of capital. The questions asked were kept as similar as possible while acknowledging the different fields of expertise of each interviewee: for example, when validating inputs for technical costs, some interviewees had to validate the shipping inputs while others were shown the inputs for pipeline transport, depending on the profile. The interviews were effective in showing aspects of the complexity that goes into developing large-scale infrastructure, and they were especially helpful in showing the specificities of CO2.

Table 3.2: Overview of the interviewees, including the sector of interest of the company and the position that the interviewee covers in the company

Sector	**Transport asset**	**Country**	**Position**
CO2 T&S	Ships	Norway	Shipping Manager
CO2 T&S	Pipeline	Germany	CO2 Activities
CO2 Transport	Ships	Denmark	Business Development Manager
CO2 Transport	Barge	Belgium	Business Development Manager

The interviews were all conducted online and transcribed. The duration of the interviews was 45 minutes to 1 hour, and after each interview a follow-up e-mail was sent to clarify uncertain statements and to ask further questions. The questions asked throughout the interview were based on the following list:

1. *Introductory questions*
   - Since when have you been working in the industry?
   - From which perspective did you experience the industry?
   - How familiar are you with the financing side of CO2 transport assets (e.g. ships, barges)?
2. *Technical inputs*
   - What is your knowledge on costs of CO2 transport for *X asset*?
   - How does the CAPEX identified in this research compare to the actual newbuilding cost?
   - Do you expect any cost reductions on CAPEX and OPEX, and if so by how much?
3. *Financing options*
   - To what extent are the financing scenarios identified comprehensive?
   - Is *company Y* financed with project finance or corporate finance, and why?
4. *Validation of results*
   - How does the cost of capital calculated in the research compare to the cost of capital of *company Y*?
   - Is there a risk premium attached to the development of the CO2 assets? If so, how does it affect the costs?
   - How does the levelized cost of transport calculated in the research compare to the cost of capital of *company Y*?
5. *Closing questions*
   - Do you have any questions or comments on the interview?
   - Can you recommend other experts in the field to contact?
   - What is your outlook for a CO2 transport infrastructure network in the long term?

The interviews are used both for validation and for the provision of technical data, with a clear distinction between what needs to be validated and the data to be provided. Only one of the interviewees (barging company) is asked to provide technical data and for that interview the validation of the technical results is not asked; the interviewee in question is only asked to validate the financial inputs.

3.4 Data analysis

3.4.1 Financial model

In order to assess the quantitative data gathered throughout the first phase of the research, a financial model is built. The model calculates the technical costs of transporting CO2 for each of the identified assets and improves on the calculations undergone until now by evaluating multiple financial parameters and calculating the cost of capital for each asset based on the different financing structures identified in literature. All of the cost data analysed in this model is adjusted for inflation in EUR2021 and foreign currency is also exchanged to EUR2021.

Levelized cost of transport

In order to take into account the differences in financing costs, the levelized cost of transport is calculated for each asset and each cost of capital associated with the different financing structures. The method for calculating the LCOT is adapted from Schmidt et al. (2019), who calculates the LCOE for RE plants.

$$LCOT = \frac{CAPEX_i + \sum_{t=1}^{t=\tau} * \frac{OPEX_i}{(1+CoC_i)^t}}{\sum_{t=1}^{t=\tau} \frac{FL_i}{(1+CoC_i)^t}} \tag{3.1}$$

Where $CAPEX_i$ is the capital expenditure of the asset i, τ is the depreciation time of the asset (here considered as the lifetime of the asset), $OPEX_i$ is the operational expenditure of the asset i, CoC is the cost of capital of the asset i and FL is the full load capacity (in tCO2) of the asset at time t and for the asset i. The formula sums the capital expenditure to a discounted operational expenditure over time.

Furthermore, in order to estimate the percentage of the cost that is due to financing and interest rate repayment, the LCOT is estimated again but this time with no cost of capital, following the approach of Schmidt et al. (2019) and F. M. ; Egli et al. (2018):

$$\delta = LCOT - LCOT_{CoC=0} \tag{3.2}$$

Cost of capital

The Weighted Average Cost of Capital (WACC) approach is suitable for determining financing costs for long term investment decisions when there are multiple financing options for the delivery of the asset (Haas et al., 2021). It represents a weighted average of the equity capital and the cost of debt, and it can be calculated both before and after the application of taxes. The most common approach is after-tax WACC, since this determines the cost for the company while the pre-tax WACC is mostly used by regulators for tariff setting (Haas et al., 2021). In this research, the cost of capital is calculated through the after-tax WACC:

$$COC_i = K_d \frac{D}{V}(1-T) + K_e \frac{E}{V} \tag{3.3}$$

Where K_d is the cost of debt, D/V is the debt share, T is the corporate tax rate, K_e is the cost of equity and E/V is the equity share.

For each financing scenario, the parameters to calculate the $WACC_{nom}$ need to be calculated separately. The only constant value is the tax rate, since the taxation environment remains the same across financing options.

The private cost of debt is calculated following past literature on energy finance (Schmidt et al., 2019) (Donovan & Nuñez, 2012):

$$K_d = R_F + DM \tag{3.4}$$

Where R_F is the risk-free rate, which represents the long term return on investment on the government bond yields. For financial calculations, long term bond yields are taken as the baseline since they are the most secure type of investment in stable regulatory environments. DM is the debt margin, which is the premium added on debt from private parties based on the expectations of added risks on top of the risk-free bond investment. The values are referenced in Table 3.3. Public financing has no premium over the risk-free rate, PPPs use a share of public financing and a share of unregulated private financing and private investments either use regulated private financing or unregulated private financing. Therefore, the public cost of debt is assumed to be the same as the risk-free rate R_F, and the private cost of debt has a debt margin of 2.75% or 1%.

Table 3.3: Debt margin for public, private and regulated financing models (Makovšek & Veryard, 2016)

Financing	**Debt margin**
Public	0%
Unregulated private	2.75%
Regulated private	1%

For the calculation of the cost of equity, the Capital Asset Pricing Model (CAPM) is used. There are multiple ways of estimating cost of equity (Fernandez, 2006), however, the CAPM method is the most used since this is the most common method and also the one used in other literature on energy infrastructure (Donovan & Nuñez, 2012).

$$K_e = R_F + \beta_i(ER_M - R_F) \tag{3.5}$$

Where β_i is the return sensitivity of stock i to changes in market return, ER_M is the expected market return and $(ER_M - R_F)$ is the market risk premium. When comparing calculations between cost of equity and cost of debt, the main difference is the evaluation of β, which needs to reflect the market risk for the asset considered. In order to reach a reasonable assumption for the beta of a novel market, parallels are made with other industries which are likely to take care of the CO2 market. The market risk of a company's equity is influenced both by the type of asset, as well as by the financial risk of the company in terms of their leverage. Therefore, simply taking the beta from another company is not enough. The debt-to-equity ratio, also called leverage, of the financing structure also needs to be considered. In order to do this, two types of β are being considered (Clayman et al., 2012):

- β_{asset}, otherwise called unlevered beta, which is the return sensitivity considering the asset-only risk;
- β_{equity}, otherwise called levered beta, which is the return sensitivity of the financing structure, considering both the asset and the debt-to-equity ratio.

The relation between the two parameters is outlined in Equation 3.6.

$$\beta_{equity} = \beta_{asset}[1 + (1 - t)\frac{D}{E}] \tag{3.6}$$

The unlevered beta is taken from Damodaran (2022) from his analysis of financial parameters for different sectors and is shown in Table 3.4. The beta for pipeline transport is determined through the oil and gas distribution industry. This is due to the similar business model and to the fact that oil and gas companies are almost exclusively interested in funding the projects

Table 3.4: Unlevered betas from different sectors; averages of yearly estimations from 2017 to 2021, adapted from Damodaran2022

Sector	**Unlevered beta**
Shipbuilding and Marine	0.96
Oil and Gas distribution	0.75
Railroads	0.6
Trucking	0.47

The leverage is determined through literature and validated through interviews. Table 3.5 shows the leverage chosen for financing through project finance for each of the analysed assets. The leverage changes based on the asset and on the financing structure:

- public-private partnerships are considered with a standard 50/25/25 share between public debt, private debt and private equity;
- project finance is assumed to have a 10% higher leverage, based on examples provided in Steffen (2020) and Gatti (2018);
- for the regulated financing structures, a debt share of 5% higher is assumed due to the lower risks involved when there are government guarantees in terms of an allowed rate of return, which enables an increased share of debt funding.

3.4.2 CO2 transport costs

In order to answer the research question, a calculation of the cost of development of each transport asset needs to be undertaken. The aim is to have a parametrized cost structure where inputs such as electricity price, capacity and distance can be modified at will in order to conduct sensitivity analysis on the results. To compare the different transport costs equally, an annualised transport cost is calculated taking into account the lifetime of each asset and splitting between CAPEX and

Table 3.5: Leverage of the transport assets considering a project finance structure.

Asset	Leverage
Pipeline	70%
Truck	70%
Ship	80%
Barge	75%
Rail	75%
Conditioning	70%

For pipelines, the value is taken from the analysis of gas pipelines undergone by Mete (2020). Trucks, rail and conditioning values are taken from Damodaran (2022). Barge and ship leverage is provided through the interviews.

OPEX. In the following sub-chapters, a description of the main calculations and sources is given for each transport asset. The costs for CO2 transport have been calculated in past literature, and this research uses inputs from different past sources in order to calculate CAPEX and OPEX for each transport asset. The exception to this is inputs for the calculation of barge transport, which have been provided in one of the interviews since there is no available data on the costs of CO2 transport by barge. All of the cost inputs are adjusted for inflation through the Consumer Price Index to reflect EUR2021 values (ECB, 2022b).

Onshore pipeline

In order to calculate the costs of transport for pipeline, the specifics of the CO2 transported need to be decided. The CO2 is assumed to be in the liquid phase, at 15 °C and at pressures between 12 MPa and 8 MPa (Knoope et al., 2014). Pressure drop is assumed to be 40 Pa/m, which means that a new pumping station is needed every 100 km of onshore pipeline. For this study, onshore pipelines are assumed to be built in regular terrain with no altitude gain or loss. Different diameters are considered based on the capacity to be transported and a steel with resistance of X120 is chosen, as it is cited as the preferred long term solution for building the infrastructure (Knoope et al., 2014). All calculations are done adapting the inputs and formulas of Knoope et al. (2014) in order to get to the important parameters of CAPEX and OPEX, see Appendix C.1. Pressure drop and diameter values are taken from the optimisation work done by Knoope et al. (2014).

Offshore pipelines

Offshore pipelines are assumed to be built here only between Rotterdam and Bergen, therefore the asset is only considered for long-distance transport. As for onshore pipelines, the diameter changes with different capacities, and a steel with resistance X65 is chosen. Inputs and calculations are taken from Knoope et al. (2014) and adapted to fit the scope of the model (see Appendix C.1). The pressure drop here is 20 Pa/m, half of what was considered for onshore pipelines, which is considered realistic in (Knoope et al., 2014) for offshore pipelines. The CO2 is assumed to be in fluid form at 4 °C and at pressures from 15 to 8 MPa, therefore higher than for onshore pipelines. All of these measures are taken in order to reduce the amount of pumping stations needed during transport, which is a complex task for offshore pipelines since it involes constructing an offshore platform. In addition to onshore pipelines, offshore pipelines require extra equipment during construction which is introduced as a fixed cost of 40 million EUR2021 (Knoope et al., 2014) and the construction of offshore platforms when pumping is needed, where the cost is 69 million EUR2021 for each platform needed (van den Broek et al., 2010).

For both offshore and onshore pipelines the development of only 1 pipeline is considered, with the diameter changing based on the capacity to be transported. This is due to the quantities considered in the study: the base case is 1 MTCO2/year, with calculations going up to 10 MTCO2/year. These quantities can be transported through 1 trunkline.

Vehicle transport: batch and bulk

The concept of batch and bulk transport is introduced in Oeuvray (2022) for CO2 transport. *Batch transport* means that the CO2 is transported through liquid containers called isotainers: the isotainers are filled at the capture side, loaded onto the transport vehicle, moved from one vehicle to another if needed and unloaded at the storage site. The isotainers are then transported back empty to the capture site, where they are swapped for a full isotainer. *Bulk transport* means that the vehicles are purposefully built with a CO2 storage tank onboard, and the CO2 is loaded onto the vehicle from and unloaded onto an intermediate storage site, from which it is transported to the storage site.

Batch transport: ship, train, truck and barge
All of the barge transport modes are calculated using inputs and formulas from Oeuvray (2022). Since transport by isotainers has no novel aspects during the transportation part itself, she was able to get quotes of transport that carriers are charging today for the route selected. For train and ship transport, an additional cost is incurred to install loading and unloading facilities. Isotainer cost is calculated through inputs provided by the DemoUpCARMA project.

Bulk transport: ship, train and barge
Bulk transport costs for ships and trains are calculated using two different studies, Roussanaly et al. (2021) and Roussanaly et al. (2017) respectively. Inputs for ship are completed through cost estimates from Element Energy Limited (2018) and validated through interviews. The papers provide input data for capital expenditure, fixed operational expenditure and fuel costs. Inputs for barge transport are provided by a barging company interviewed and are presented in table 3.6. Calculations and inputs for ships, rail, truck and barge are shown in chapters C.2 to C.5 of the Appendix.

Conditioning

Three scenarios of conditioning were considered for the CO2 to be transported:

- Compression: pressurising CO2 at ambient temperature in order to transport it by pipeline; for onshore pipeline, the outlet pressure is 120 barg while for offshore pipeline the pressure is 150 barg. Compression estimates are taken from Roussanaly et al. (2017) and Carapellucci et al. (2019). Capital costs are calculated by taking a cost factor of 2.15 €/tCO2 for 1 MT/yr and scaling it for the required CO2 transported in the model (Roussanaly et al., 2017). Operational costs include a fixed OPEX of 5% (Carapellucci et al., 2019) and energy cost with an associated energy consumption of 68.5 kWh/tCO2, which takes into account compression up to 85 barg and pumping up to 150 barg (Roussanaly et al., 2017).

- Liquefaction at 7 barg: cryogenic CO2 conditioning at low pressure until the CO2 is liquified at around -50 °C in order to transport it by train, barge, truck, rail and ship;

- Liquefaction at 15 barg: cryogenic CO2 conditioning at low pressure until the CO2 is liquified at around -30 °C in order to transport it by train, barge, truck, rail and ship. For both methods, liquefaction estimates are taken from Roussanaly et al. (2021) and Deng et al. (2019). The capital costs are estimated by taking a cost factor of 4 €/tCO2 and scaling it with an exponent factor of 0.85 (Roussanaly et al., 2021). To the operational expenditure, an additional fee compared to compression is added for cooling water in €/tCO2 (Deng et al., 2019).

The inputs and calculations are shown in Appendix C.6.

Bulk barge inputs

Since inputs for barge shipping of CO2 could not be found in literature outside of the calculations done in Oeuvray (2022), inputs were needed to calculate the CAPEX and OPEX of barges. The required inputs were provided by one of the interviewees and are shown in Table 3.6. The capacity of the barge is considered to be the maximum feasible capacity to transport over the Rhein river, but for other rivers in Europe higher capacities could be considered. While the inputs provided show that CO2 can be transported at different pressures and temperatures, low-pressure transport is chosen (-50 °C, 7 barg) in order to keep the same CO2 characteristics as the other liquified CO2 transport assets.

Table 3.6: Inputs for calculating the transport cost for bulk barges.

Parameter	**Figure**	**Unit**
CAPEX	16,300,000	€
Capacity ship	3,177	tCO2
OPEX	7.4%	-
Fuel consumed diesel	10.49	g/tCO2/km
Fuel cost	500	€/t
Harbor fees	0.26	€/tCO2
Loading/unloading time	12	h
Average sailing	11.9	km/h
Average capacity	65%	% or tonnes
Operating hours	8,520	h
Asset lifetime	30	yr
Pressure	7 to 20	bar
Temperature	-50 to -20	°C
Density	1050,0	kg/m^3

Data provided during interviews with a barging company

Chapter 4

Results

4.1 Financing structures

4.1.1 Financing in the energy sector

Haas et al. (2021) analyse the financing of the energy sector and identifies that most long term investments are located in a strictly regulated environment which allows no degree of freedom for the choice of financing parameters. This is due to the cap on the allowed rate of return that still characterises a lot of network operators. Sector liberalisation has brought a duality of competitive market segments and regulated businesses. This type of regulatory framework affects risks in two different ways: it has a direct impact on revenues due to price setting (feed-in tariffs or tax exemptions) and it establishes regulations for market entry (Leisen et al., 2019). Leisen et al. (2019) conduct interviews with participants in the energy sector and find that a stable market framework is preferred to an unregulated competitive environment; this is due to the characteristics of the sector, which has natural monopoly tendencies. Therefore, while competitiveness can make the generation of energy more efficient, transmission and distribution are still happening in a tightly regulated environment in order to avoid redundancies. In terms of generation, Steffen (2018) conducts an analysis of financing for renewable energy projects and finds that project finance is key for renewables in countries with low investment risk (e.g. Germany), since it allows choosing a higher debt ratio than feasible under corporate finance and it lets companies separate the commercial risks related to variable energy production from their traditional business model.

Financing in the (liquefied) natural gas sector

LNG and CO2 infrastructure are similar in terms of very capital-intensive upfront investments, as well as multiple interested parties and vested interests (Ruester, 2015). The differences between LNG and CO2 are of a technological and financial nature: firstly, CO2 transport technology is still developing and the assets have a higher degree of novelty than the mature LNG market; secondly, LNG is a commodity and the cash flow comes predominantly from the value of the product, while CO2 has no intrinsic value and can be considered as waste. Since LNG transport is capital-intensive, the shipbuilder needs to be assured of a rate of return that allows him to recover the sunk capital into building a new ship. In order to do that, long term contracts are signed prior to the building of the ship, which guarantee a period of 15 to 25 years (Neumann & Rüster, 2015) of operations and allow depreciation of the asset during that time frame. During the construction phase, the shareholders have liability towards the lending parties; in the operation phase, this recourse ceases to apply (Ruester, 2015). Due to these operational and technical characteristics, LNG transport infrastructure is mainly financed with project finance (Ruester, 2015). With project finance, lending parties evaluate the project based on how the risk impacts the expected cash flows. Debt ratio increases with the proportion of a project's capacity sold under long term sales-and-purchase agreements (Ruester, 2015). While LNG shipping can be privately owned and operated without the need for economic regulation, pipeline transport is subject to exponentially higher capital investments and economies of scale (Perrotton & Massol, 2018); this means that pipelines can become natural monopolies which need to be regulated in order to avoid market failures (Perrotton & Massol, 2018)(Glachant, 2012).

4.1.2 Financing options

In order to assess the discount rate (or cost of capital) of CO2 transport infrastructure in a detailed way, an assessment of financing structures needs to be made. Financing options for large-scale infrastructure has been subject to a previous research. The sources analysed all agree on four main types of financing (Makovšek & Veryard, 2016) (Stern, 2012) (Newbery et al., 2019) (BEIS, 2020):

- *public procurement*, where infrastructure is publicly owned, operated by a public network operator and constructed through public procurement procedures;
- *public-private partnerships (PPPs)*, where the project is partly owned by the government and long term contracts are awarded to a private party to design, build, finance, maintain and operate (DBFMO);
- *private regulated*, where the asset is entirely owned by a private party who acts as the infrastructure manager but the revenue stream is handled by an economic regulator whose most important task is to set an allowed rate of return, otherwise called regulated asset base (RAB);
- *private unregulated*, where the asset is entirely owned by a private party and the rate of return is decided by market competition only.

Makovšek and Veryard (2016) provide a comparison between traditional public procurement, RAB and PPPs. The comparison is based on four stages of the project life-cycle: quality and delivery approach, delivery efficiency, operational efficiency and operational flexibility. Through the paper, it is found that in the traditional model the public sector retains most of the risks of cost and time overruns, which leads to inefficient delivery of the assets. The RAB model improves the efficiency of delivery since the assets are privatised, however, it can lead to excessive capital expenditures in order to inflate the base of returns, which is also stated in Stern (2012) and Newbery et al. (2019). The PPP model, on the other hand, has a more rigid contract structure and renegotiating the contract is less structured than in RAB; however, the costs of delivery of the asset are theoretically minimized since the projects are awarded on a public procurement basis. This is debatable, and it has been reported that the required rates of return can be an issue with PPP financing structures even when there is bidding for the project (Makovšek & Veryard, 2016). Furthermore, PPP projects are complex and they are based on long term contractual commitments which leads to inherent uncertainty. In order to address the issues with PPP and RAB, Newbery et al. (2019) and Makovšek and Veryard (2016) propose a ”Project RAB Finance” model which pairs the bidding structure and financing of PPPs with the economic regulator structure of RABs. In order to understand the importance of considering different financing structures for CO2 transport infrastructure delivery, parallels to the electricity and gas sector can be made and the key features of those mature sectors are looked at in the next two sections.

Mahgerefteh et al. (2020) and Pale Blue Dot. (2018) provide guidelines for technical and economic development of CO2 transport network. While exploring financing structures, two options for T&S are proposed: the Regulated Asset Base (RAB) model, and public ownership. These options are in line with what is proposed in BEIS (2020), which adds that a hybrid model should also be considered.Lau et al. (2021) highlight the importance of long term PPPs in order to encourage the sharing of risks, socialization of costs and protection from political risks. In order to understand the differences between these models, literature on large-scale infrastructure financing is assessed. The literature focuses on pipeline transport, however, the need to study the financing of shipping and transport by road and rail has also been identified in the literature by Mahgerefteh et al. (2020). When considering the whole CCS chain, the type and intensity of risk in capture, transport and storage are vastly different: with such a profile, applying different financing for each part of the chain works best to minimize financing costs while protecting against the possible risks(Heffron et al., 2018). The need for coordination at a European level is highlighted in order to achieve an equal regulatory field. Heffron et al. (2018) argue that if government takes more of the risks, investments from private parties will be encouraged.

Based on the state-of-the art literature on infrastructure financing, four main types of financing structures are identified as suitable for large scale CO2 infrastructure projects: public, public-private, regulated private and unregulated private. Each of the financing structures is suitable for different transport assets, depending on parameters such as CAPEX-intensity, capacity and distance of transport or status quo (status quo meaning the known practices that are being done now). An overview of the financing structures is given in Table 4.1.

Table 4.1: Overview of the main financing structures and their economic and operational

	Government	Public-Private	Private	
			Regulated	Unregulated
Structure	Government ownership, construction and operation	Government tenders for long term DBFMO* contracts	Private company acting as infrastructure manager Economic regulator handles revenue stream	Private ownership, construction and operation
Operations specifics	Historical issues with operational efficiency	Operations agreed ex-ante	Flexibility in operational regulations	Most efficient in incentivizing competition
Cost efficiency	Potentially inefficient construction and operation costs	Efficient in minimizing capital	Potentially inefficient capital expenditure	Efficient cost allocation, but at a higher price

Public funding

Public financing and ownership are considered to be the traditional model of financing for infrastructure projects (Makovšek & Veryard, 2016) (Newbery et al., 2019). In public financing, the government is the sole owner of the infrastructure and can fund it entirely through public debt; there is also the option of funding through public equity, however, this is not considered in this study. During the process, the government puts out tenders for construction and after the construction is completed a public infrastructure manager is selected. This form of financing has been in use for decades for public financing under the assumption that public goods need to be managed at a governmental level to avoid inefficiencies. However, throughout the last two decades the approach changed drastically.

Public-private partnership

Financing through PPPs requires the government to request bids for a Design-Build-Finance-Maintain-Operate (DBFMO) contract. The consortium that wins the bidding is given long term control over all facets of the design, from building, financing and operation including revenue models, under the terms established in the contract established ex-ante. PPPs are renowned for being effective in reducing capital expenses and completing projects on schedule. However, since the responsible private party also carries the full risks for the project, which are considerable in novel initiatives with intrinsic uncertainties, the cost of funding of PPPs can be significant. Moreover, since the PPP contracts include performance standards and charges for the full operating time which are agreed upon prior to the construction phase, it is also seen as very rigorous during the operation phase. This type of contract is difficult to define and enforce when it comes to setting up an infrastructure taking into account new things

Private investment

Private investment means that a private company takes on the risks of the investment, gathers equity and debt and takes on the project for all of its development, construction and operation phases without public intervention. Private investment can be either based on project finance or corporate finance:

- Corporate finance is the traditional way of handling new projects, whereas companies use company equity and debt from investors and develop the project as a part of the company, with profits and losses flowing through the balance sheet of the company. This system is beneficial when the company is in a stable financial situation because it lowers the cost of debt that investors will ask, however, if the project makes a loss the whole company value goes down (Steffen, 2020).

- With project finance, the company creates a special purpose vehicle (SPV) which acts as a separate entity and is outside of the balance sheet of the company. This helps to fence off the project risk from interfering with the rest of the company's operations and allows for a higher debt share compared to corporate finance (Steffen, 2020). The downside is that all the debt needs to be repaid from the operations of the asset so a stable return needs to be assured for the whole duration of the depreciation period in order to decrease commercial risk (Mete, 2020).

In corporate finance, the actors investing in the projects are either the company itself or the debt providers of the company, which for grid operators are usually financial institutions and public sponsors. For project finance, the investors could also be industrial sponsors who see the project as linked to their business model or the contractual sponsors themselves, who build and operate the asset and want to participate in the initiative by also providing equity (Gatti, 2018).

Regulated private investment

Regulated private financing involves private ownership and investment into the infrastructure assets combined with underlying regulations and incentives provided by institutional actors. The private body is an infrastructure manager that collects income from users and/or subsidies in order to pay for operations and recoup investment expenses. The infrastructure manager is under regulation to safeguard issues such as market entry, fair pricing mechanism and unbundling, and in return for abiding by these regulations, the public economic regulator takes on commercial risks and ensures a suitable and stable return on the asset investment. Regulated financing structures can be set up in different ways: in this review, the focus is put on the Regulated Asset Base (RAB), which has been analysed in-depth for infrastructure financing (Newbery et al., 2019) (Makovšek & Veryard, 2016) and proposed as a structure for CO2 transport as well (ZEP & CCSA, 2022). In principle, the RAB model works both for traditional corporate finance and for project finance, depending on the field in which the company works in and the other assets owned by the company.

4.1.3 Validation from interviews

During the interviews (see Appendix D) a series of questions were asked on the financing structure of the company in question and of which structures were deemed feasible by the stakeholders. This provided insight into how the CO2 shipping and pipeline transport industry are shaped at the moment and what is the expectation for the future. Combining the insights from literature with the expert interviews, a set of financing structures is defined as suitable for each of the transport modes selected (Table 4.2). Funding pipelines is feasible with all of the financing structures identified: one interviewee mentioned how the intention of the company is to build a pipeline network entirely with corporate finance and the literature talks about project finance, PPPs or even direct public investment (Mete, 2020). Furthermore, pipeline transport in Europe has been regulated when private investment was concerned (Ruester, 2015). For rail transport, the financing structures are all similar as well, since rail infrastructure has been historically financed publicly and a lot of transportation companies are still fully or partially operated by the state (Casullo, 2017), and there is scope for both private investment and regulated investment. Ships and barges have been financed with project or corporate finance almost exclusively in the past, and the interviews have validated this for the CO2 sector. Interviewees addressed how they are interested in getting financed through green bonds, however, those are emitted by private financial institutions and do not need the involvement of the state. All interviewees agreed that regulated financing is unlikely to happen for ships and barges. Public financing is considered for all transport assets because of the relative simplicity of the structure where all of the investment is funded by debt through government bonds.

Table 4.2: Financing structures suitable for each of the transport modes.

	Public	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**
Pipeline Onshore	*	*	*	*	*	*
Pipeline Offshore	*	*	*	*	*	*
Rail	*	*	*		*	
Truck	*		*		*	
Ship	*	*	*		*	
Barge	*		*		*	

4.2 Cost of capital

The cost of capital for the different financing structures is presented in table 4.3 for pipeline and table 4.4 for truck. The cost of debt is assumed to be different between financing structures but equal between the transport assets. The only difference in the cost of capital stems from the risk-free rate: when the asset lifetime is 20 years or more, a 20-year government bond yield rate is calculated, while for shorter lifetimes a 10-year government bond yield rate is calculated. This can be seem looking at pipeline and truck transport. The average for the period 2010-2022 of the yield rate is 1.05% for the 10-year bond and 1.59% for the 20-year bond (ECB, 2022a). The difference in cost of capital comes when taking into account cost of equity: using the CAPM method, cost of equity is calculated taking into account the levered beta for the investment, which is asset-specific. This leads to significant differences of around 1% in the cost of capital of the different transport assets: in the tables below, the interest rate for corporate finance goes from 3.9% for trucks to 5% for pipelines. The values are lower than the discount rate calculated until now by other studies estimating costs of CO2 transport, where a discount rate between 7% and 10% is estimated (Knoope et al., 2014) (Oeuvray, 2022) (Stolaroff et al., 2021) (Roussanaly et al., 2017) (Roussanaly et al., 2021). Furthermore, another reason for these different cost of capitals is the different leverage applied for the transport assets. The leverage was taken from the database compiled by Damodaran (2022), who analyses markets across the globe and splits the financial parameters into industries. While the scenarios with public investment are standardised, corporate and project finance scenarios have varying leverage since each industry has different operating patterns and capital availability. Trucks and pipelines have similar leverage at 60%, while other transport assets have a higher leverage like ships at 70% (Damodaran, 2022).

Table 4.3: Cost of capital for pipeline transport under different financing structures.

Pipelines	**Public**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**
Public cost of debt	1.6%	1.6%	-	-	-	-
Public debt share	100%	50%	0%	0%	0%	0%
Private cost of debt	-	4.3%	4.3%	2.6%	4.3%	2.6%
Private debt share		25%	70%	75%	60%	65%
Cost of equity	-	8.1%	7.9%	8.1%	7.6%	7.8%
Equity share	-	25%	30%	25%	40%	35%
WACC	**1.6%**	**3.5%**	**4.7%**	**3.5%**	**5%**	**4%**

Public cost of debt is taken as the 20-year government bond (ECB, 2022a). Private cost of debt is calculated with the debt premium cited in Makovšek and Veryard (2016), while the cost of equity is calculated with data from Damodaran (2022) and Fernandez et al. (2020). The leverage is taken from Mete (2020).

Table 4.4: Cost of capital for truck transport under different financing structures.

Trucks	**Public**	**Project finance**	**Corporate finance**
Public cost of debt	1%	-	-
Public debt share	100%	0%	0%
Private cost of debt	-	3.8%	3.8%
Private debt share		70%	60%
Cost of equity	-	5.2%	5%
Equity share	-	30%	40%
WACC	**1.1%**	**3.8%**	**3.9%**

Public cost of debt is taken as the 10-year government bond (ECB, 2022a). Private cost of debt is calculated with the debt premium cited in Makovšek and Veryard (2016), while the cost of equity is calculated with data from Damodaran (2022) and Fernandez et al. (2020). The leverage is taken from Damodaran (2022).

Validation of results: cost of capital

Since CO2 transport is a novel technology, the validation of the cost of capital could not happen through comparisons with existing firm-level data, which is the standard in financial calculations today. Instead, the assumptions and the corresponding WACC were validated during the expert interviews conducted with companies working in the field of CO2 transport, either directly or through integrated CCS business models. Out of the 4 interviews conducted, 3 of the interviews conducted were with companies which are project financed and owned at least in part by gas and oil network operators or distributors, and one of them was an inland waterway transportation company. They could not validate the publicly financed scenarios since they did not have experience with the structure but agreed on the cost of capital that has been calculated for the project financed and corporate financed structures. The key factors to validate with experts from the private sector were leverage and cost of equity since these were the parameters with the biggest uncertainty when looking at past data. The operators interviewed, which dealt with pipeline, ship and barge transport, all agreed on the numbers used for the cost of equity and provided their ranges of leverage used to finance their assets which are in line with the data gathered beforehand. The validation also extended to the financing structures chosen, and the input given of which financing structure was more suited for the transport mode in question has been integrated in table 4.2.

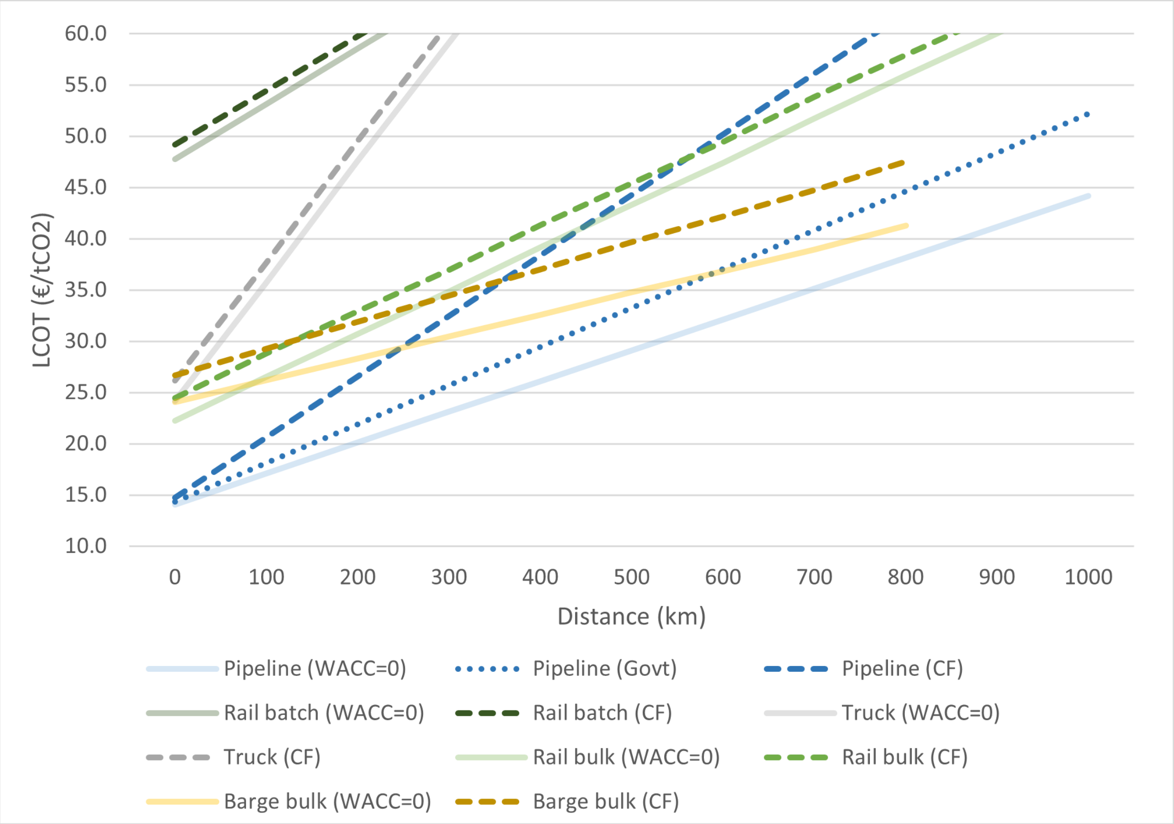
4.3 Levelized cost of transport

4.3.1 Distance selection

In order to validate the selection of the scale of transport for each of the methods, an analysis is undergone to see how transport costs scale at different distances. Figure 4.1 and figure 4.2 take into account the levelized cost of transport for 1 MTCO2/yr, with no financing cost, corporate finance or government financing for pipelines and ships. The reason that government financing is not looked at for other transport modes is that the influence of the cost of capital is not as high as for pipelines, therefore showing the costs through government finance would not change much from the no financing scenario.

The results include costs for conditioning of every transport mode, which is around 13 €/tCO2 for pipelines and 20 €/tCO2 for the other transport modes. Barge estimates reach until 800 km because it is not feasible to calculate for longer distances for the case of the Rhein river, where the data is taken from. The tables are split between onshore (figure 4.1) and offshore (figure 4.2) transport.

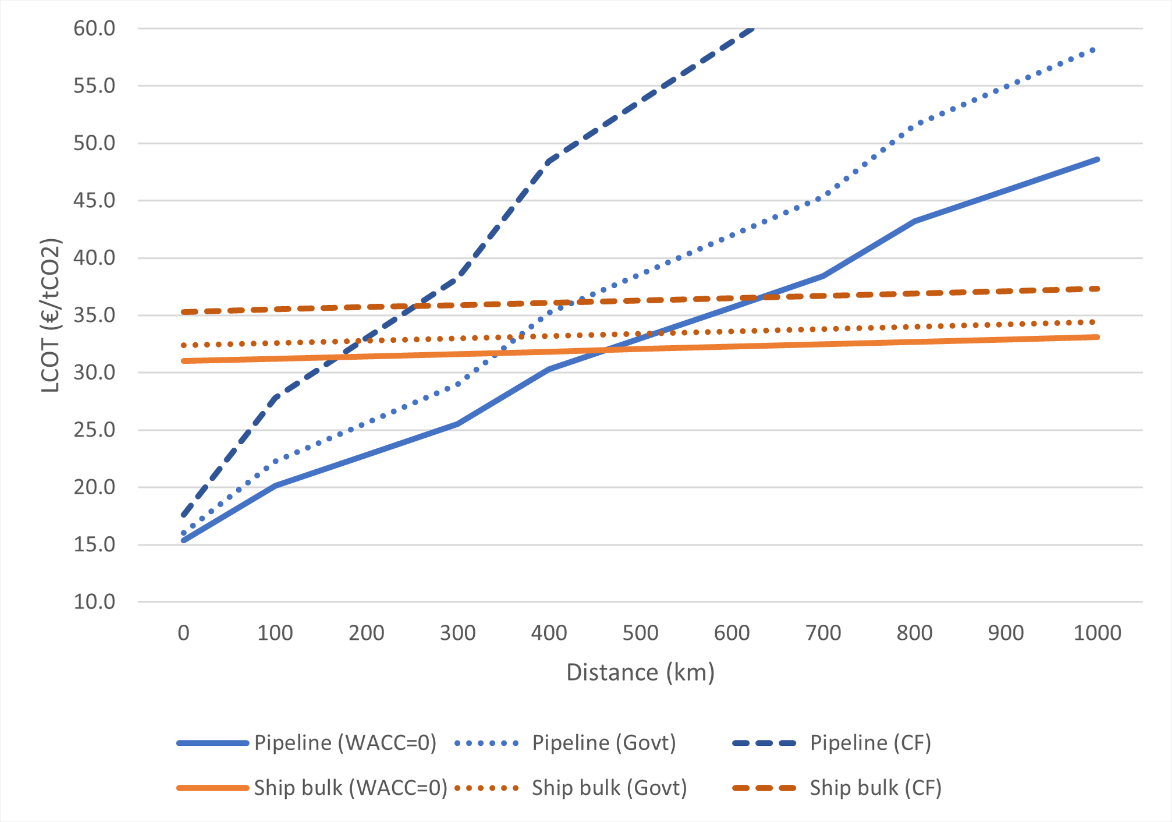
Figure 4.1: Impact of distance on the costs of transport (LCOT) for onshore transport modes with no financing costs and with corporate finance



All costs are estimated for transport of 1 MTCO2 per year. Costs include conditioning (compression or liquefaction). WACC=0 means no financing costs, CF means corporate finance and Govt means government finance

For the onshore part, the results show that without taking into account financing costs (straight line) pipelines are the cheapest option available at all distances. When financed by the government (dotted line) pipeline is still cheaper than all of the other transport modes financed privately. However, if the pipeline is financed privately, both barges and trains can become cheaper with enough transport distance; the cut-offs are at 350 and 550 km respectively. Aside from pipelines, trains are the cheapest option for short distance and barges become cheapest at around 100 km of distance. Batch transport is the most expensive option. Firstly, batch transport by rail has a very high cost even at low distances: this is due to the source of the data, which is taken from a quote of a rail transport agency who provides fixed rates for a whole route. Secondly, trucks are more expensive than rail or barge transport and the cost increase is the steepest for trucks, however at low distance (50 km or less) the cost is still in the same range as trains or barges: this is due to the limited capital expenditure needed for trucks, where more than 90% of the annualised cost comes from operational expenditures. This means that the costs of truck transport are linearly correlated with an increase in transport capacities and distance transported, making it a relatively cheap solution for small-scale, short-distance transport but very expensive for transport at larger scale, especially compared to CAPEX-heavy options like pipeline transport. From this table it can be seen that rail and barge transport could be an interesting option for both short distance and long distance inland transport, while truck is suitable for short-distance transport only.

Figure 4.2: Impact of distance on the costs of transport (LCOT) for offshore transport with no financing cost and with corporate finance



All costs are estimated for transport of 1 MTCO2 per year. Costs include conditioning (compression or liquefaction). WACC=0 means no financing costs, CF means corporate finance and Govt means government finance

For the offshore part, at this scale of 1 MtCO2/year pipelines are competitive with ships only for short- and medium-distance transport, while for longer distances ships become the preferred solution. This is due to the high capital expenditures needed for developing offshore pipelines, with fixed sunk costs which render it unfeasible to build a trunkline when the quantity to be transported is limited. Bulk ship transport for 1 MT or less is calculated with medium-pressure ships, as the technology for small-scale ship transport is already mature and the capital expenditure is lower compared to low-pressure ships. In this plot, the costs are highly inelastic to changes in distance since the calculations consider the construction of a 12500 t ship whose capacity is only partially used (for 100 km transport the capacity usage is 35%, while for 1000 km it is 66%), which makes the capital expenditure the main component of the cost. The results are clear: offshore pipelines are cheaper than ships until a certain threshold of distance, which varies vastly with the financing cost. Without financing cost, pipelines are cheaper until around 450 km; if pipelines are financed publicly and ships are financed privately, the threshold is quite similar at around 400 km, but if both assets are financed privately ships become the least expensive option already from 250 km. The line for offshore transport is not linear: this is due to the offshore platforms which need to be constructed in order to allow for pumping stations, and which are constructed every 350 km.

Figure 4.1 shows transport by barges and trains as effective solutions for long-distance and small-scale transport. Costs for batch transport by barge are excluded since they were calculated with data from specific start and end nodes and generalisation to different distances is not possible. Barge transport in bulk is the second cheapest option for inland transport when accounting for financing costs, however, the capacity of barges is limited (average capacity of 2000 t, compared to 12500 t for medium-pressure ships and 50000 t for low-pressure ships). At 1000 km and 1 MT/CO2 shipped per year, 11 barges are needed. This value scales linearly with increasing demand for CO2 transport. The Rhein river has limited transport space and transport of CO2 competes with other commodities, therefore the option is only available for small capacities (1 MT or less). Onshore pipelines are the cheapest option when considering transporting 1 MT of CO2 over all distances (100km or less), however, with such volumes, the costs still exceed 50 €/tCO2 for long distances. The reason for this is that the capital expenditure of pipelines is directly influenced by the length of the pipeline: at low volumes of CO2 transported, pipelines are cheap only for short distances and the costs increase substantially for long distances.

4.3.2 Conditioning units

Table 4.5 shows the costs of the conditioning units for compression and liquefaction and the impact that different financing structures have on the costs. The costs are considered at three different capacities transported in order to show the economies of scale that can be achieved at 5 MtCO2/year and at 10 MtCO2/year compared to the base case. Indeed, both liquefaction and compression costs decrease per unit of CO2 when bigger volumes are conditioned; this decrease is steeper for liquefaction since the capital expenditure for liquefaction is higher. However, the economies of scale are still small (max 3 €/tCO2 decrease) since liquefaction and compression are complex modular systems where the price increases almost linearly with the volume; hence why the cost scale-up factor is 0.85 in Appendix C.6. Compression units are largely unaffected by the change in cost of capital, while for liquefaction plants the financing structure can increase the costs by up to 2 €/tCO2, which is around 8% of the investment costs. The main cost factor for conditioning is the electricity price, calculated at 120 €/MWh (Eurostat, 2022): the cost factor is taken as the average non-household consumer electricity price for the EU-27 zone from 2010 until 2021. Electricity price heavily influences the LCOT for conditioning units (see Figure 4.11 in the sensitivity analysis section).

Table 4.5: Levelized costs for the conditioning units (€/tCO2)

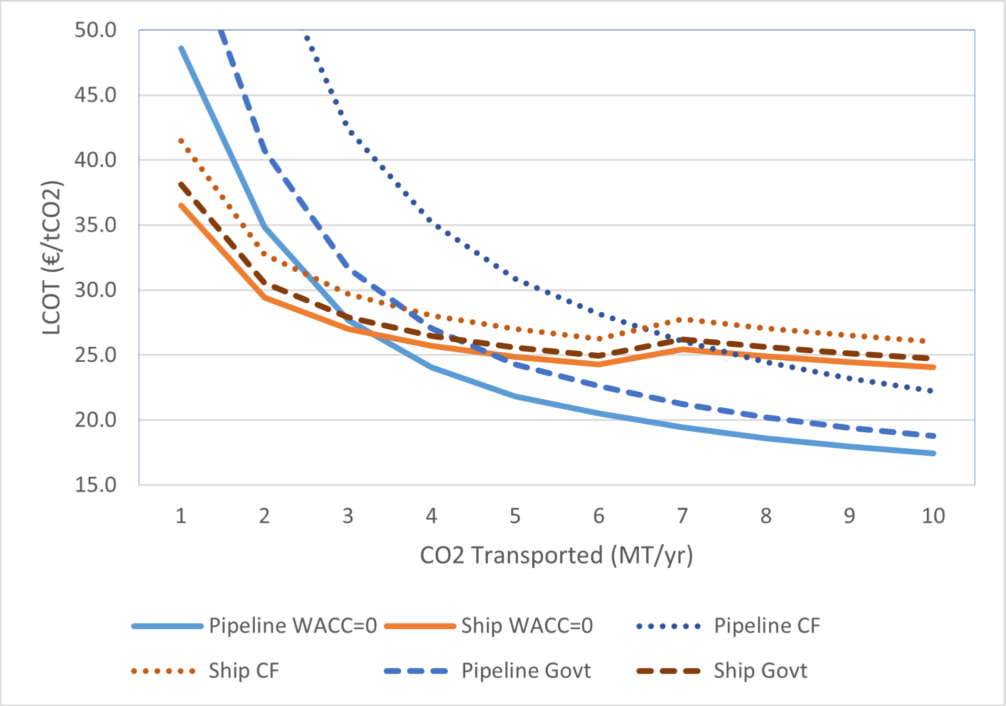
CO2 conditioned	**Conditioning unit**	**WACC=0**	**Full government**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**
1 MT/yr	*Compression*	13.9	14.1	14.4	14.5	14.3	14.6	14.4
	Liquefaction	21.7	22.4	23.1	23.6	23.1	23.7	23.2
5 MT/yr	*Compression*	13.0	13.2	13.3	13.5	13.3	13.5	13.4
	Liquefaction	19.6	20.1	20.6	21.0	20.6	21.1	20.7
10 MT/yr	*Compression*	12.7	12.8	13.0	13.1	13.0	13.1	13.0
	Liquefaction	18.8	19.3	19.7	20.1	19.7	20.1	19.8

Electricity price is 120 €/MWh, which is the average non-consumer household electricity price over the EU-27 from 2010 until the end of 2021 (Eurostat, 2022)

4.3.3 Offshore transport

Figure 4.3 provides a comparison between the costs of shipping and the costs of transporting by offshore pipeline. Both transport assets are calculated for 1000 km transport, which is the distance between Rotterdam and Bergen, and the capacity transported goes until 10 MTCO2/year in order to take into account the effects of economies of scale when distributing more CO2 for the same distance. The figure provides estimates without financing costs (WACC=0), with public financing (Govt) and with private corporate finance (CF). While financing impacts both transport assets, offshore pipeline costs increase substantially more than ship costs when the asset is financed privately compared to public financing. For ship transport, the price increase between 6 and 7 MT is related to the purchase of a second 50kt ship for the transport. If ships are privately financed, pipeline transport which is publicly funded becomes cheaper at around 4 MTCO2/yr and pipeline transport which is financed by corporate finance becomes cheaper at around 7 MTCO2/yr. Furthermore, pipelines have a steeper price decrease than ships and the difference in price becomes increasingly larger with the quantity of CO2 to be transported. This is due to the increased capital intensity of pipelines and the relatively higher operational expenditures for ships which increase linearly with the capacity to be transported.

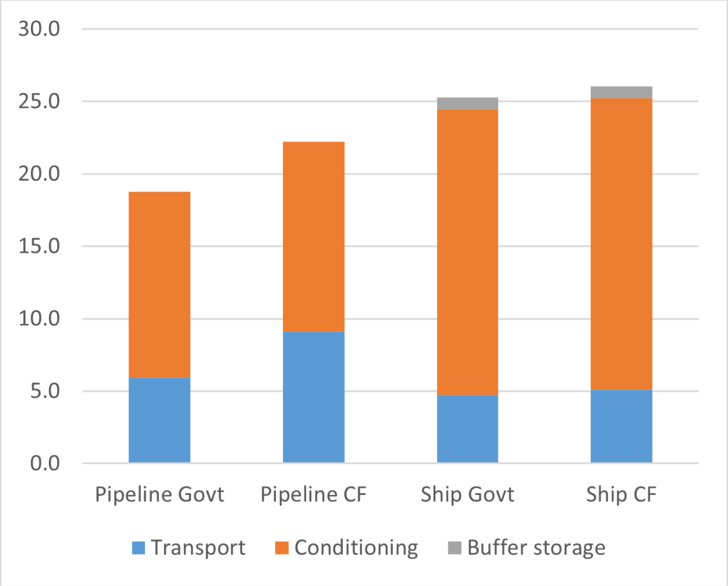
Figure 4.3: Comparison of LCOT of ships and offshore pipelines, including conditioning and buffer storage, for different financing structures for the Rotterdam-Bergen route (1000 km)



Blue lines represent offshore pipelines, orange lines represent ships. The costs include compression costs of around 12-13 €/tCO2 for pipeline and liquefaction costs of 19-22 €/tCO2 for ship (scaled depending on the amount of CO2 and financing structure). "WACC=0" refers to a scenario with no financing costs, "Govt" refers to public finaning and "CF" refers to private corporate finance.

Figure 4.4 shows that with large quantities of CO2 transported the main cost factor becomes the conditioning of the CO2: 80% of the cost of shipping is represented by liquefaction regardless of the financing structure, while for pipeline it varies between 60% and 70% depending on the financing structure selected. The numbers shown in Figure 4.4 are for transport of 1000 km and 10 MTCO2/yr.

Figure 4.4: Cost breakdown between offshore pipelines and ships at 10 MT/yr transported



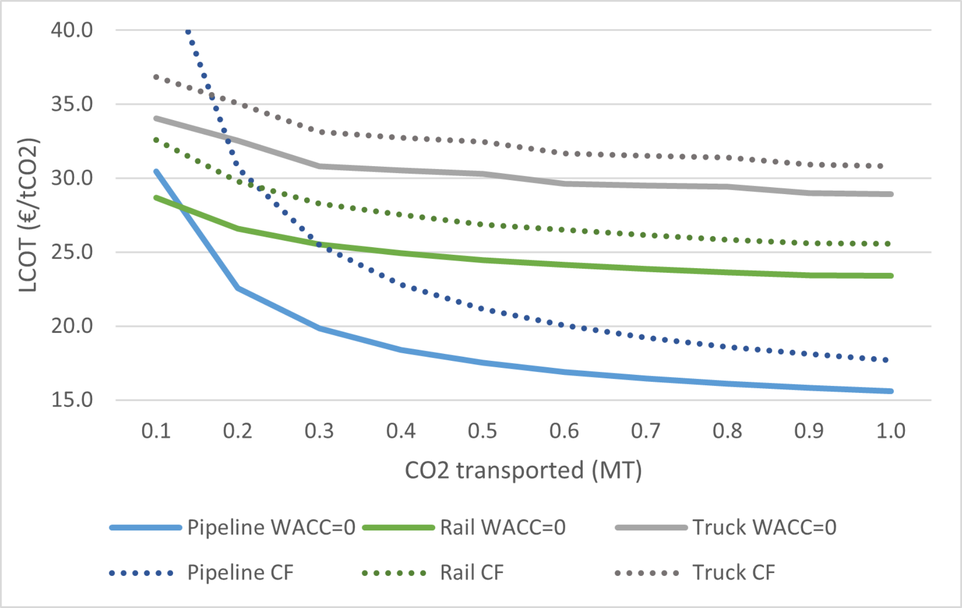
"Govt" refers to public finaning and "CF" refers to private corporate finance. "Conditioning" is different for pipelines and ships: for pipelines, it refers to compressing up to 85 bars and pumping up to 150 bars (Roussanaly et al., 2017) , while for ships the CO2 is liquified at -50 °C and 7 barg (Roussanaly et al., 2021). Buffer storage represents 150% of the total capacity of the ship (Element Energy Limited, 2018)

4.3.4 Inland transport

Short distance: pipeline, rail and truck

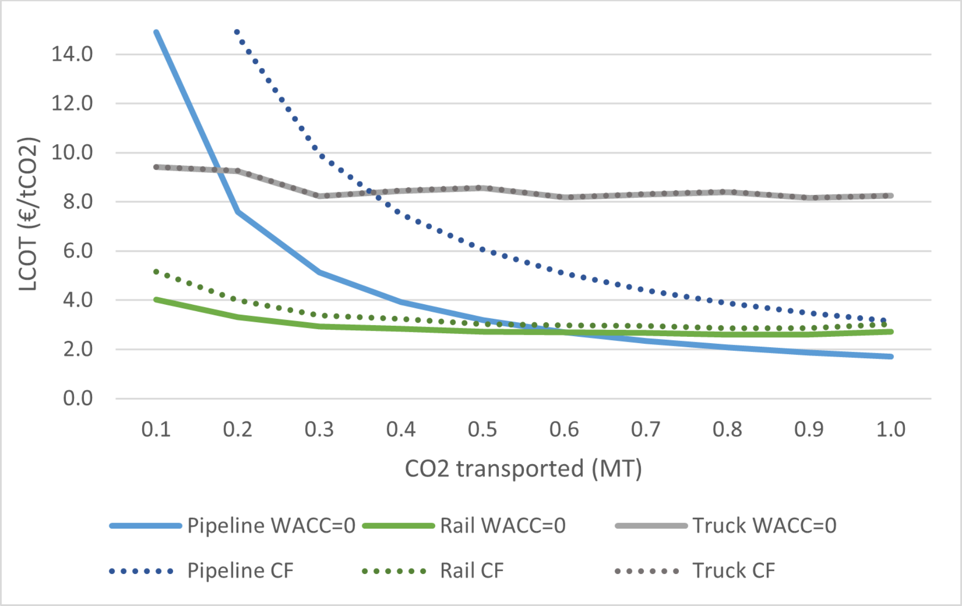
Figure 4.5 shows a comparison between pipeline, truck and rail for short-distance transport (50 km) in terms of LCOT (y axis, €/tCO2) and quantities of CO2 transported (x axis, from 100 ktCO2/year to 1 MtCO2/year). When excluding financing costs, truck is the most expensive option at all times. However, when the project needs to be financed with corporate finance, truck transport is cheaper than pipeline for small quantities of 100 or 200 kt per year. Due to the low distance and low volumes transported, capital expenditure for pipeline transport make up the majority of the investment which means that even a small change in financing costs has a significant impact on the LCOT of pipelines. The difference between rail transport and truck transport is around 5 €/tCO2 for all distances considered. Rail transport is the cheapest option until 200 to 300 kt per year and is subject to marginally better economies of scale compared to truck transport. These values include the full cost of conditioning, which should be spread around the whole transport distance.

Figure 4.5: Comparison of LCOT between pipeline, truck and rail for transport of 50 km, including conditioning.



Values on the x axis represent the CO2 capacity to be transported in 100kt (so the x axis goes from 100kt to 1 Mt), y axis is the LCOT (€/tCO2). Rail calculations also include intermediate storage. For rail and truck, liquefaction is done at 7 barg. "WACC=0" refers to a scenario with no financing costs, "Govt" refers to public finaning and "CF" refers to private corporate finance.

Figure 4.6: Comparison of LCOT between pipeline, truck and rail for transport of 50 km considering transport costs only.



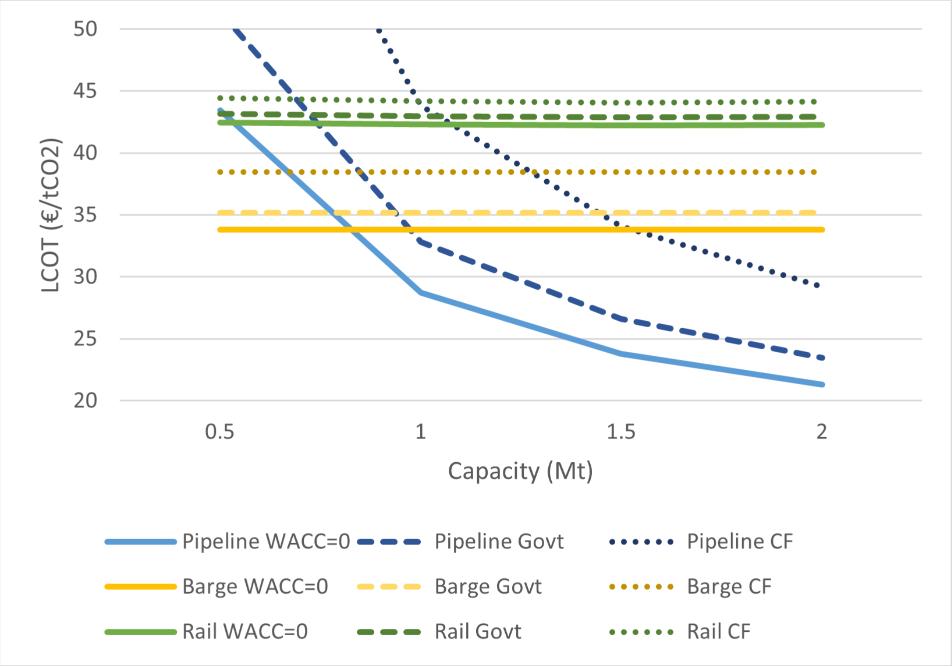
Values on the x axis represent the CO2 capacity to be transported in 100kt (so the x axis goes from 100kt to 1 Mt), y axis is the LCOT (€/tCO2). Rail calculations also include intermediate storage. "WACC=0" refers to a scenario with no financing costs, "Govt" refers to public finaning and "CF" refers to private corporate finance.

Figure 4.6 shows how the costs compare when conditioning is not considered and only transport costs are taken into account. Considering private finance, truck transport is cheaper than pipeline transport until around 350 kt per year, while rail is cheaper until 1 MT per year. At 1 Mt per year, the difference in cost between trucks and pipelines is around 6 EUR/tCO2.

Long distance: pipeline, rail and barge

Figure 4.7 compares transport between pipeline, rail and barge for distance travelled of 500 km, including conditioning costs. Rail and barge prices are inflexible to changes in capacities since the prices for transport scale linearly and there is little scope for economies of scale. Rail transport is unaffected by financing, while barge transport is 3.5 €/tCO2 more expensive with corporate finance than with government investment. The reason for this is the higher construction cost of barges than for trains. If pipelines are financed with corporate finance, rail transport is cheaper than pipeline transport until capacities of 1 MtCO2/year and for barges the threshold is 1.5 MtCO2/year. Public financing for pipelines reduces the thresholds by around 500 ktCO2/year, and decreases the cost of transport of pipelines by 5-10 €/tCO2 depending on the capacity. The range considered here is still considered small-scale for pipelines and the CAPEX is disproportionately high compared to OPEX, which makes financing costs very important for pipeline: with corporate finance, the financing costs make up 35% of the LCOT, while for barges the financing costs make up 18% of the LCOT. Aside from the cost, the feasibility of these scenarios is also driven by the amount of assets needed in terms of trains and barges: at the break-even point of 1 MtCO2/year, 4 locomotives are needed, each with 20 wagons, while at 1.5 MtCO2/year transported 13 barges are required.

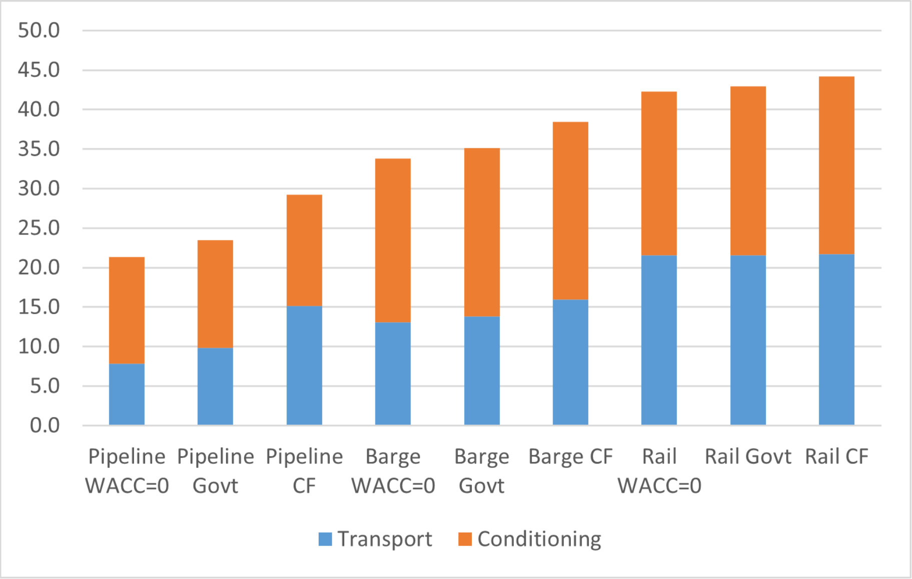
Figure 4.7: Comparison of LCOT between pipeline, rail and barge for transport of 500 km.



"WACC=0" refers to a scenario with no financing costs, "Govt" refers to public finaning and "CF" refers to private corporate finance.

As can be seen in figure 4.8, conditioning is a key factor in the transport costs outlined in figure 4.7. The values are taken for transport of 2 MtCO2/year. Here, it can be clearly seen how the pipeline transport costs are the main driver for the increase in financing costs for pipelines, with a difference of 5 €/tCO2 between public and private financing. For barges, the increase in cost with different financing options is due both to the CAPEX of the barges as well as to the CAPEX of the liquefaction plants. Without taking into account conditioning costs, barges would still be competitive with pipelines in this scenario.

Figure 4.8: Breakdown of costs for inland transport of 500 km at 2 MtCO2 transported per year

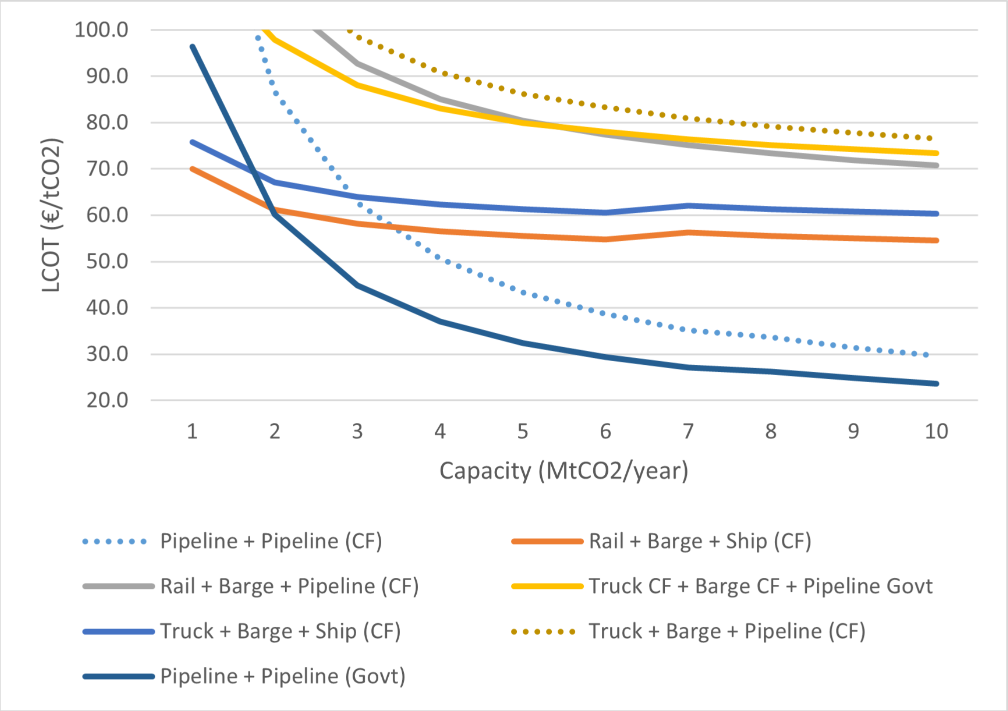


"WACC=0" refers to a scenario with no financing costs, "Govt" refers to public finaning and "CF" refers to private corporate finance.

4.3.5 Case study route

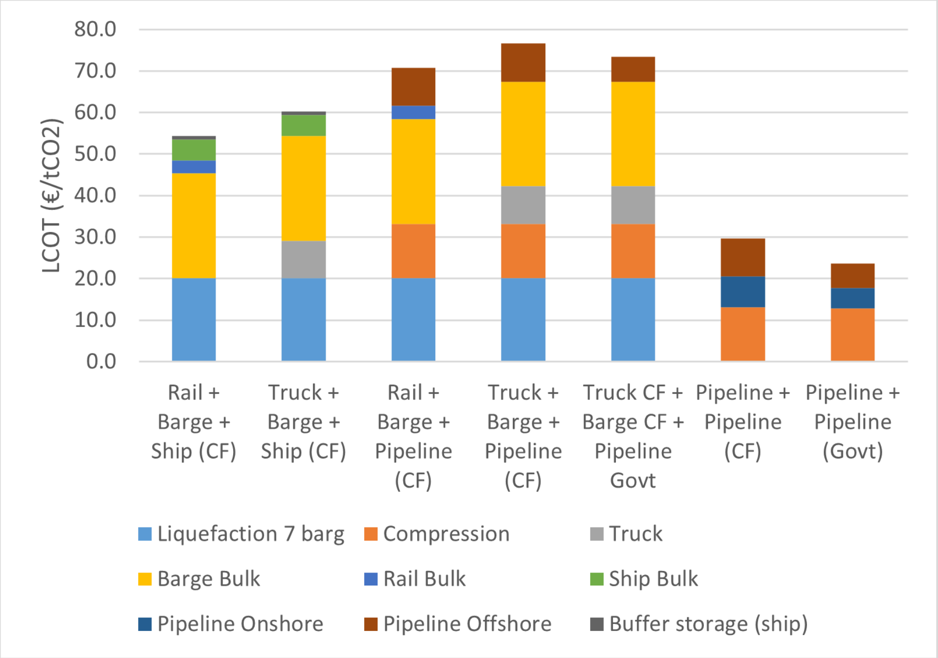
A combination of different transport modes is plotted for the route from Basel to Bergen in figure 4.9. As in the study undergone by Oeuvray (2022), the transport starts from a plant 58 km outside of Basel (JC Wildegg), in order to model with short-distance transport modes. Transport by rail and truck are considered for a distance of 58 km (from JC Wildegg to Basel); barge transport is for 852 km, from Basel to Rotterdam; ship and offshore pipeline transport is from Rotterdam to Bergen. Onshore pipeline is for transport of 1000 km. All transport modes are considered as being financed with corporate finance, which is the most likely scenario for all transport assets apart from pipelines; in the case of pipeline transport, public financing is also considered.

Figure 4.9: Comparison of LCOT of different combinations of transport assets for the route from Basel to Bergen.



The results show how full-chain pipeline transport compares to multi-modal transport. With public financing, a pipeline network becomes cheaper than all other combinations after around 2 MtCO2/year transported, while private financing pushes this threshold to 3 MtCO2/year. In both cases of public and private financing, pipelines are the only transport assets with enough capacity for economies of scale to drive the price down substantially at 10 MtCO2/year; however, private financing is 6 €/tCO2 more expensive than public financing, which means a 20% increase in the price. It is interesting to note how the multi-modal options that contain pipeline transport are the most expensive options: this is due to the higher conditioning cost associated with liquefaction for rail, barge and truck as well as compression for offshore pipelines. This can be clearly seen in the cost breakdown in figure 4.10, where for the transport modes which contain both pipelines and other assets the costs for conditioning get to more than 30 €/tCO2 due to the combination of compression and liquefaction. It is worth noting again that these prices are so high in big part because of the high electricity price taken into account (120 €/MWh).

Figure 4.10: Comparison of LCOT of different combinations of transport assets for the route from Basel to Bergen.



In terms of costs, the most suitable methods for large scale CO2 transport are also the most CAPEX-intensive ones, therefore the ones being influenced the most by different costs of capital. Financing does not influence each transport mode at the same rate. Tables 4.6 and 4.7 show the percentage of the cost that is due to financing costs, which comprises all expenses due to the interest rate. Each asset is considered individually, therefore the cost for the transport modes does not include conditioning, which has its separate entry in the tables. Depending on the capital-intensity of the asset, financing can take on a significant percentage of the levelized cost of transport. For pipelines, financing costs can be up to 50% of the investment if the investment is funded entirely by private funds. These costs are particularly high since capital-intensive projects which have no financial backing from the government can incur high losses. Barge and ship investments can also be capital-intensive, and while financing does not have as high of an impact as for pipelines, financing costs can still reach 18% of the levelized cost of transport. Trucks are not influenced by the financing structure in any of the scenarios modelled. This is due to the technical characteristics of truck transport, where capital expenditure and operational expenditure increase linearly with increasing CO2 capacities to be transported and there is no scope for scale-up factors. Furthermore, operational expenditure like maintenance and fuel costs are the vast majority of the truck costs, which means that factors affecting the capital expenditure are not as important.

Table 4.6: LCOT of different transport assets (10 MtCO2/year)

Calculation of LCOT per transport asset								
Distance	**LCOT**	**WACC=0**	**Public**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**
1000	*Pipeline Onshore*	6.5	8.1	10.3	12.0	10.4	12.5	11.1
1000	*Pipeline Offshore*	8.8	11.1	14.3	16.7	14.4	17.4	15.4
58	*Rail Bulk*	2.9	3.0	3.1	3.1	3.1	3.2	3.1
58	*Truck*	9.0	9.0	9.0	9.0	9.0	9.0	9.0
1000	*Ship Bulk*	4.6	4.7	5.0	5.1	4.9	5.1	5.0
852	*Barge Bulk*	20.7	21.9	24.0	25.0	23.9	25.2	24.2
	Compression	13.0	13.2	13.3	13.5	13.3	13.5	13.4
	Liquefaction 7 barg	19.6	20.1	20.6	21.0	20.6	21.1	20.7
	Buffer storage (ship)	0.7	0.7	0.8	0.8	0.8	0.8	0.8

Table 4.7: Impact of financing on the different transport assets (10 MtCO2/year)

Percentage of the cost that is financing						
LCOT	**Public**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**
Pipeline Onshore	19%	37%	45%	37%	47%	41%
Pipeline Offshore	20%	38%	46%	38%	48%	42%
Rail Bulk	3%	6%	7%	5%	7%	6%
Truck	0%	0%	0%	0%	0%	0%
Ship Bulk	3%	8%	9%	6%	10%	8%
Barge Bulk	5%	14%	17%	13%	18%	14%
Compression	2%	4%	5%	3%	5%	4%
Liquefaction 7 barg	3%	6%	8%	6%	9%	7%
Buffer storage (ship)	7%	14%	17%	13%	18%	14%

Cells are colored based on the percentage of financing for each asset and financing structure.

4.3.6 Validation of results

In order to validate the results for the calculated levelized cost of transport, the results from the financial model are compared to results in other literature studies about CO2 transport costs. Table 4.8 compares results in terms of €/tCO2 or €/tCO2-km between the calculations undergone in this research and previous results. Generally, results are in line with previous literature. The difference in results can be attributed in large part to the method used for calculating the costs in the financial model, which follows a less granular approach compared to the other studies analysed and does not optimise the transport costs for every distance and capacity required. Liquefaction is around 6 €/tCO2 more expensive in the model compared to calculations done in Roussanaly et al. (2021), which is mostly due to the electricity price jump from 80 €/MWh in Roussanaly et al. (2021) to 120 €/MWh in this study. The same reasoning can be applied to compression costs, which are also higher than in Roussanaly et al. (2017) by around 3.5 €/tCO2. Furthermore, the price increase in liquefaction and compression is also likely due to the different ways of introducing the discount rate into the LCOT calculation: without taking into account the discount rate, the values for CAPEX and OPEX for liquefaction are similar between the financial model and the papers by Roussanaly.

Costs for shipping are in line with Roussanaly et al. (2021). Costs for trucks are in line with Oeuvray (2022) and higher than Stolaroff et al. (2021), but Stolaroff et al. (2021) takes into account a US case study where transport costs can be different. The same reasoning can be applied to rail transport, where the figure calculated in my model is lower than Stolaroff et al. (2021) for the US but in line with the calculations by Roussanaly et al. (2017), who conducts a case study for the Czech Republic. For pipeline transport, the overall costs for onshore pipeline and compression are in line with Knoope et al. (2014) if adjusted for electricity price, however the offshore pipeline costs are lower in this study than in Knoope et al. (2014); this is likely due to an underestimation of the offshore pipeline costs.

Table 4.8: Comparison between transport costs calculated in the financial model and transport costs calculated in previous literature.

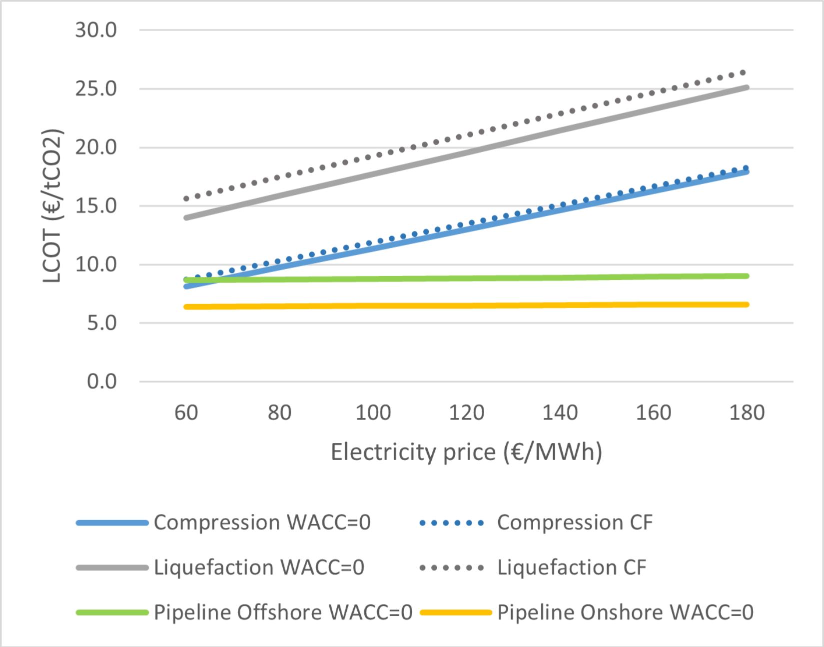
Asset	**Literature**	**Financial model**	**Unit**	**Source**
Liquefaction (7 barg 1 MT)	14.9	21.7	€/tCO2	Roussanaly et al. (2021)
Liquefaction (15 barg 1 MT)	14.0	20.7	€/tCO2	Roussanaly et al. (2021)
Ship + liquefaction (low pressure, 5 MT, 1000 km)	22.4	24.2	€/tCO2	Roussanaly et al. (2021)
Ship + liquefaction (medium pressure, 500kt, 1000 km)	42.5	42.1	€/tCO2	Roussanaly et al. (2021)
Compression	9.3	12.7	€/tCO2	Roussanaly et al. (2017)
Truck	0.2	0.2	€/tCO2-km	Oeuvray (2022)
Truck	0.1	0.2	€/tCO2-km	Stolaroff et al. (2021)
Rail (100 km)	6.4	4.8	€/tCO2	Stolaroff et al. (2021)
Rail (200 km)	10.8	9.5	€/tCO2	Roussanaly et al. (2017)
Pipeline onshore (100km, 3.2 MT)	1.8	2.1	€/tCO2	Knoope et al. (2014)
Pipeline onshore + compression (100km, 3.2 MT)	13.0	15.8	€/tCO2	Knoope et al. (2014)
Pipeline offshore (350 km, 9 MT)	4.9	3.9	€/tCO2	Knoope et al. (2014)
Pipeline offshore + compression (350 km, 9 MT)	15.9	17.1	€/tCO2	Knoope et al. (2014)

The costs in Stolaroff et al. (2021) are calculated for US transport. The truck costs in Oeuvray (2022) are taken with the assumption of salaries from Germany, which are the same values used in the financial model. The values in MT express the amount of CO2 transported yearly to get the results, while the values in km represent the distance of transport.

4.4 Sensitivity analysis

In order to verify the robustness of the results, a round of sensitivity analysis is conducted on electricity cost and depreciation. Firstly, figure 4.11 shows the impact that a change of +- 60 €/MWh has on liquefaction, compression and pipeline costs. The values are taken for a CO2 volume of 5MT/year, in order to account for the economies of scale due to higher volumes and study the impact of electricity prices exclusively. The impact on pipeline costs is minimal since electricity usage in pumping stations is only a small percentage of total pipeline investment, however, compression and liquefaction scale linearly and the price increases by around 1.6 €/tCO2 for every 20 €/MWh increase in electricity costs. The electricity cost is the main driver of the costs for conditioning of the CO2, which means that electricity also becomes an important cost factor when considering large scale transport: looking back at figure 4.10, conditioning takes up between 50% and 65% of the total cost of CO2 transport for all of the scenarios, therefore a change in electricity prices can drive down the LCOT substantially.

Figure 4.11: Impact of electricity price on liquefaction, compression and pipeline transport.



The values are calculated for 5 MT/year of CO2 transport and 1000 km of transport for onshore and offshore pipelines. Offshore pipeline is 8.7-9 €/tCO2 and onshore pipeline is 6.4-6.6 €/tCO2, scaling linearly with increased electricity price.

Secondly, depreciation of the assets is considered. Throughout the study, depreciation of the capital investment has been done for the entire useful lifetime of the asset, however, during the interviews shipping and barging companies have stated that they depreciate over a shorter timespan which is tied to the long term contracts that they can secure for the demand of the ship. For ships and barges, this timespan is 15-20 years, compared to a useful lifetime of 25-30 years for ships and barges respectively. The same findings are echoed in the literature about LNG shipping, where the investment into new ships are tied to the long term contracts secured ex-ante (see 4.1.1). Table 4.9 shows the impact of decreasing the financing timeline on the levelized cost of transport. Without taking into account financing costs, pipelines are the most affected by this change, with a price increase of 36% when the pipeline is depreciated over 30 years instead of 50 years. However, this impact decreases substantially when private investment is considered: the cost of capital difference has more impact than the depreciation time. For public financing of pipeline transport, changing the depreciation time from 50 years (asset lifetime) to 30 years sees an increase in LCOT of 28%, or 2.3 €/tCO2 in absolute numbers; by contrast, when the pipeline is financed through corporate finance that same difference in depreciation leads to an increase in LCOT of 13%, or 1.6 €/tCO2. Barges are more affected by depreciation than pipelines when corporate finance is considered, with an increase in LCOT of 15% when depreciating over 15 years. For ships the difference is modest (around 5%) since the lifetime of a ship is considered 20 years.

Table 4.9: Change in LCOT for pipeline, ship and barges with lower depreciation times and for different financing structures.

	WACC=0	*%increase*	**Full-government**	*%increase*	**Corporate finance**	*%increase*
Pipeline Onshore	6.4	-	8.0	-	12.4	-
Pipeline Onshore (40y)	7.3	13.59%	8.9	10.35%	13.0	4.61%
Pipeline Onshore (30y)	8.8	35.94%	10.3	27.66%	14.1	13.46%
Ship Bulk	4.6	-	4.7	-	5.1	-
Ship Bulk (15y)	4.9	5.92%	5.0	5.66%	5.4	4.83%
Barge Bulk	20.7	-	21.9	-	25.2	-
Barge Bulk (20y)	22.9	10.51%	24.0	9.74%	27.1	7.22%
Barge Bulk (15y)	25.0	20.68%	26.1	19.23%	29.0	14.74%

Depreciation is considered until 15 years for ships and barges and until 30 years for pipelines. Asset lifetime is 20 years for ships, 30 years for barges and 50 years for pipelines. Values for LCOT are taken for 5 MtCO2/year transport load, 1000 km of travel distance for ships and pipelines and 852 km of travel distance for barges.

Chapter 5

Discussion

5.1 Impact of financing structures

In the previous section, the quantitative impact that different financing structures have on the transport of CO2 was analysed. This impact is evident for pipeline transport, and the differences in how pipelines are financed also affect the development of the other modes of transport. While the results point towards pipelines as being the cheapest mode of transport for most of the scenarios identified, the results show that this is not always the case, especially when taking into account how the infrastructure is financed. Furthermore, the results show that there is scope for transporting CO2 with different modes of transport in specific cases and that transport by truck, rail or barge can be cost-effective when pipelines are not feasible. Since the capital investment required for rail, barge or truck is substantially lower than for pipelines, this type of transport can be used as a short-term solution until a pipeline network is built.

The results show how big of an impact financing plays for pipeline transport, with an average difference of around 10 €/tCO2 between public and private investment. In the interview undergone with the developer of a project about greenfield CO2 pipeline delivery, it was revealed that the pipeline would be financed exclusively through corporate finance, with leverage of 50-60%. While it is encouraging that the private sector is taking a leading role in transport infrastructure development and that companies are planning to develop a pipeline network entirely with private funds, this raises questions in terms of the costs of the infrastructure which will be developed. These increased costs will be borne by consumers, so mostly industry and power generation. This raises the threshold for industries which have to decide on whether to build a capture plant or not and raises the price of the finished goods which are sold to the population.

While in specific terms the costs of transport are only a small portion of technologies like CCS or DAC, this is because the assumption is that the transport infrastructure will be developed in a cost-efficient way through a network of multi-modal transport: if the burden of the infrastructure development is put entirely in private investment, the costs can increase significantly and the development slows down. The interviewee communicated that the expected cost of transport by onshore pipeline would be around 20 €/tCO2: this value is more than double what is being analysed in previous literature, as well as in this study. As shown in the results, the cost is largely driven by the corporate finance structure applied to the development of the project. A potential alternative to private infrastructure development is regulating the revenue through the Regulated Asset Base model or similar regulated financing structures: since the government takes on significant risk in this structure, the cost of funding decreases substantially (see 4.3). However, during the interview with the developer of the pipeline project, it was highlighted that companies in Germany do not desire a regulated financing model; this is said to be due to how the development of regulation of the hydrogen infrastructure was handled. Currently, Germany has a voluntary regulatory framework set in place for hydrogen operators which takes on issues of market access, unbundling and tariff setting. The issue is that this regulation is only meant as a transition period until the European Union decides on how to regulate the infrastructure and it does not provide any financial benefit in terms of a regulated asset base (CMS, 2022). When asked whether he sees a regulated framework developing in the long term, the interviewee said that it is possible but not desirable from a private perspective if the infrastructure is already built with private investment. Looking outside of Germany, the issue of private financing is less revelant: in the Netherlands, Gasunie is partially owned by the government (50%) and in Belgium, Fluxys is in a similar situation. Since the development of CO2 infrastructure has been mainly in the hands of gas network operators, this means that countries with publicly owned operators can potentially deliver the infrastructure at a lower cost.

The fact that capital expenditure plays a significant role was also made clear in all of the interviews with shipping and barging companies undergone during the study. All of the interviewees stressed the importance of ex-ante long term contracts in order to secure enough transport volume for a long enough depreciation time that would ensure the payback of the investment. Upon getting these contracts, companies are able to secure a high leverage rate for the projects (up to 85% for ships and 75% for barges) without having to pay for risk premiums because of the uncertainty of CO2 demand. One interviewee stated how shipping was a low-margin business, and consequently, it is important to have enough debt funding in order to finance new investments. While the involvement of government financing would lower the overall cost of capital and drive down risks and costs of the project on paper, the interviewees deemed that it was not something that would be expected considering the state of the market and the other commodities. Furthermore, the difference between public and private financing for shipping and barging is limited compared to pipeline infrastructure.

5.2 Government involvement

Developing a transport infrastructure for CO2 means dealing with a complex socio-technical system which is subject to both market failures in terms of natural monopolies, as well as social acceptance issues. The need for government intervention has been highlighted both in previous literature as well as during the interviews. In the interviews it was stressed that a clear framework for the transport of CO2 needs to be developed at an international level, defining standards in terms of CO2 transport specifics as well as the allowed modes of transport. CO2 transport projects which are now in feasibility study phase are waiting for indications from governmental bodies in order to advance to the development phase, as is the case with the pipeline network operator who was interviewed. Small-scale transport systems of shipping and barging are already developing but this is due to the flexible nature of the transport assets and large scale transport by ships has been shown to be substantially more expensive than pipeline transport. In order to reach large scale development of CO2 capture technologies, a cost-effective transport infrastructure needs to be developed.

Furthermore, when there is no clear signal from the government of what the long term plan for CO2 transport development is, private parties will be less inclined to invest because of the uncertainty of future government involvement. Since publicly delivered infrastructure can be built cheaper than with private investment, even private parties who believe in the development of technologies and want to invest in the infrastructure will wait until a final decision is announced by the government out of fear of making a loss on the investment. As mentioned previously, this argument was used by one of the interviewees to argue against government regulation for the operators.

5.3 Multi-modal transport of CO2

The study has shown that all of the transport modes identified have a use case when developing CO2 transport infrastructure. While rail and truck are expensive and unrealistic for long distances, they are crucial for transporting small quantities in places where pipeline development is not possible and in certain cases transport by rail or truck can be more cost-effective than building a pipeline, especially in the case of small emitters. Barge transport is similarly cost-effective and can be an option even for larger emitters of more than 1 MtCO2/year. A key driver of multi-modal transport is also the source of electricity for conditioning. Liquefaction plants are more expensive than compressors and more energy-intensive, and transport by rail, truck, barge and ship is most effective in a liquefied form. If liquefaction plants can be powered through cheaper sources of electricity, the competitiveness of these modes of transport increases substantially. In any case, CO2 transport hubs are needed in order to take advantage of the economies of scale of pipeline transport. Hubs can be strategically placed inland, close to the main industrial clusters in Europe in order to transport large quantities of CO2: this decreases the costs substantially and allows the emitters to plan for long term contracts with the transport option from the plant to the CO2 hub. Such hubs are already being planned in major points on the northern coast of Europe like Rotterdam and Gdansk, and more are being developed inland.

5.4 Evaluation of the methodological approach

The approach is subject to methodological limitations.

Firstly, taking a mixed methods approach inserts complexity into the study by combining qualitative and quantitative data. The risk is that the research produces data which cannot be validated or reproduced in different settings. In order to safeguard against this, the methods used are applied in an iterative manner in order to double-check all of the data acquired and calculated. The financing structures identified in the literature review and the levelized costs calculated in the financial model are cross-checked with expert interviews, and the results of the model are also cross-checked with past literature. All discrepancies found are substantiated and explained through the novel factors introduced in the research.

Secondly, semi-structured interviews with experts in the field can provide biased information, especially when the number of interviewees is limited (n=4). On top of that, interviews with experts in the field will always yield results which are hopeful in future developments and positive of the technology. This risk can be minimised by getting focused input on some targeted topics from each of the interviewees and presenting everyone with the same dataset. Furthermore, statements made by interviewees can be cross-checked with literature in order to ensure that there is no key difference between interview statements and literature knowledge. If that is the case, follow-up questions can be sent in order to clarify the salient points.

Thirdly, the study only considers one route and a set of financing options which are not exhaustive considering the European infrastructure financing landscape. Since this is an exploratory research, the case is considered exhaustive to examine the main effects that financing can have on the transport costs of the asset. In the future, the case selection could be expanded to include a European network of CO2 transport.

Finally, data availability is a concern for a novel industry such as CO2 transport infrastructure, which means that the research needs to rely on data which could be misleading and validation of results is not always possible through comparisons with current literature. This is especially the case when considering the financial calculations.

5.5 Limitations of the study

The results show that financing structures have a significant impact on the cost of infrastructure delivery and quantify this impact for different scales of transport. However, the study is subject to certain limitations and due to the duration and complexity of the research, some assumptions had to be made to limit the scope.

Firstly, the financial model developed has multiple assumptions in terms of financing structure. The model does not calculate debt repayment schedules and refinancing, assumes linear depreciation and does not account for tax shields in private investment. The model also does not take into account the nuances of debt and equity, leaving out hybrid instruments like mezzanine debt or convertible bonds (OECD, 2015). The model also does not take into account end-of-life costs and repurposing. Furthermore, from a qualitative perspective the model simplifies the financing structures and ignores the synergies that are present between different financing structures: public-private partnerships are a form of project finance where the government is also one of the sponsors, however this interaction is not studied.

Secondly, the technical costs are calculated making several assumptions on the capacity of the transport assets and on its technical characteristics. For pipelines, 3 diameter ranges were selected to satisfy requirements for transport between 1 MtCO2/year and 10 MtCo2/year. While the diameters satisfy the technical requirements of CO2 transportation pressure and speed, they might not be the optimal size for the considered distance and capacity. Furthermore, the calculations are made with the assumption that the pipeline runs on flat terrain outside populated centres. For ship and rail transport, the calculations follow inputs from sources which are either outdated or heavily contested. The figures for CAPEX of low-pressure ships are taken from Element Energy Limited (2018), a source which has been criticised by one of the interviewees dealing with medium-pressure ship transport as being too optimistic with the results on low-pressure ships; however, the same figures have been validated as realistic by another interviewee who deals with low-pressure ships. These disagreements could be born out of strategic behaviour, but what is sure is that cost values for the transport of CO2 are scarce, especially when trying to get reliable granular data. For trains, railways are assumed to be built and congestion is not taken into account. Lastly, the emissions during the transport of CO2 are not calculated but should be taken into account in order to make the analysis of the differences between transport assets more accurate.

Thirdly, the study assumes that the risk premium put on the novelty of CO2 infrastructure will not be there anymore in 2030: there have been reports that the risk premium on CO2 is already being taken away from shipbuilding companies (Equinor, n.d.-b), and projections indicate growth in demand and supply of CO2 during the next years (Bogdanov et al., 2019). However, there are multiple risks to take into account when financing. A risk assessm ent framework has been used to detail the risks for the CO2 transport infrastructure at the different stages of construction (Appendix A.1), however, due to the scope of the thesis the identified risks have not been quantified.

Chapter 6

Conclusion

This study has analysed how different financing options impact the costs of CO2 transport assets, and how this impact changes the threshold where one transport asset becomes more cost-efficient than another. The results show that financing costs can be a substantial part of the overall investment cost: for pipelines, an unregulated corporate finance structure leads to financing costs taking up 48% of the costs, while with public financing this value decreases to 19%. Financing costs are also significant for barge and ship financing, where they take up 18% and 10% of the costs respectively, while for rail transport this value decreases to 7% and truck transport is unaffected by financing. the results show how the involvement of public funding for infrastructure delivery can lower the costs of pipeline infrastructure substantially in regions with stable governments like in Europe.

Public ownership of infrastructure is documented to present inefficiencies in terms of capital expenditure and operational efficiencies, which could not be quantified in the model but should be taken into account when considering the results. However, public institutions have different ways of intervening in the financing phase without owning the infrastructure: regulated private financing has been studied in this model and in this study it is shown that using a regulated financing model can decrease the cost of capital by 1-1.5 %, which has a significant impact on the cost of infrastructure delivery and can decrease the impact of financing costs by 10% for pipelines. At a public level, CCS investments will have to compete with other energy transition or green technologies (e.g. nuclear power) in order to gain funds (Newbery et al., 2019): this makes it crucial to have a clear financing model set up and clear scenarios for deployment.

In light of these results, government policies should be focused on developing a common framework of CO2 infrastructure development at a European level and on providing guarantees for private investment. The carbon tax as a policy instrument is effective in putting a price on emissions, but unless there are cost-effective alternatives to lower emissions the only result of the tax will be the increase in consumer prices. The revenues from the EU ETS have already been invested in programs like the Innovation Fund, which promotes technologies to accelerate decarbonisation. However, all of the investment was focused on pilot and demonstration projects. The focus needs to shift from demonstration to large scale development, and developing the backbone infrastructure for CO2 transport in a cost-effective way will encourage CO2 capture technologies. The study has shown that with public financing, the delivery of long-distance and large scale pipeline infrastructure can get to around 21 €/tCO2, including conditioning of the CO2, while with private financing the cost increases to 30 €/tCO2.

Until now, development of long-distance transport of goods has only been envisioned for commodities such as natural gas, oil or electricity. Transporting CO2 is different since CO2 is waste, not a commodity: the only value that CO2 has is attached to a carbon tax system, which has not been stable until 2 years ago. The commercial risks involved in developing infrastructure for CO2 are higher than the risks which were historically attached to developing infrastructure for gas or oil. Natural gas developed with a bottom up approach, with initial infrastructure being built on a town basis for the distribution of gas produced from coking coal and used for lighting, power and heating purposed (Bouzarovski et al., 2015). This type of development is not feasible for CO2 infrastructure, since development of small-scale infrastructure is only feasible in a few places where storage sites are available: instead, CO2 transport infrastructure will need to be developed with a top-down approach, where big transmission lines are built at the same time (or before) the distribution grid.

While financing is an important part of the cost of transport, future development of the infrastructure will not necessarily be based on which decision makes most financial sense. Other factors such as technology maturity, perceived safety or capital intensity in the short term undermine this reasoning, therefore the study is not meant as a research into what will be developed. However, some of the issues which undermine cost-efficient development can be solved with an integrated financial structure: for example in terms of capital intensity, the government can provide initial grands for investment and then charge users a lower interest rate as a consequence. Still, this study is not meant as a guide on infrastructure development but on the opportunity in terms of costs of delivering a public infrastructure compared to a privately owned one.

6.1 Answering the research questions

SQ1. What are potential options of finance for the different assets for carbon transport?

This thesis has analysed different types of financing structures for infrastructure delivery and has outlined the main ones in section 4.1. The financing structures range from public to private, with hybrid options like PPPs and RAB also being considered. While all options are theoretically feasible for all transport assets, looking at past projects and taking cues from the interviews leads to the selection of fewer options based on the asset considered.

SQ2. What is the cost of capital of the financing options identified?

The research has quantified each financing structure through the cost of capital, taking into account differences between transport assets as well as the specificity of each financing structure. The costs of capital for ships, barges and pipelines have been validated through interviews. The cost of capital can range from 1.5% to more than 5%, depending on the asset and financing structure.

SQ3. What are the implications for the overall cost of carbon transport?

The results have shown that the cost of financing can have a substantial impact on the choice of CO2 transport assets. The competitiveness of truck and rail transport changes based on the financing structure applied to pipelines and the overall cost of transport can vary significantly. Low-cost financing can decrease the costs of large scale CO2 infrastructure delivery by as much as 10 €/tCO2.

6.2 Scientific relevance

This is the first study which analyses financing options for CO2 transport quantitatively: other reports have outlined some of the options available, however, there was no study which tried to quantify the difference between public and private investment when dealing with the development of new CO2 transport infrastructure assets. The thesis expands on the existing body of knowledge on CO2 transport infrastructure, taking cues from academic research, industry reports and government papers. The financing costs identified in this study can be used in other studies about CO2 transport infrastructure. The financial model developed can be refined and paired with a technical optimisation model in order to predict more accurate CO2 transport costs. As a by-product, the research provides new inputs for barge transport of CO2 and compiles the literature demonstrating the state of the art in CO2 transport in Europe. Most importantly, the study shows how the financing cost can impact the total infrastructure cost and future research can use these results as reference to where the discount rate matters and how much it matters. The study provides input for future scientific research in the field of CO2 transport by highlighting where the cost of capital leads to the highest impact and providing a methodical approach to calculate the cost of capital without assuming a fixed discount rate.

6.3 Societal relevance

CO2 capture and storage technologies are crucial in order to avoid climate disaster, and the importance of these technologies seems to be growing. Currently, it is unlikely that the world will be able to go away from fossil fuels in the short and medium term, especially with the new regulations that are beginning to be set in place. The European Union has voted natural gas a green energy carrier, which means that natural gas will be able to get more financing at cheaper rates through green bonds and it is likely that a new infrastructure lock-in will start with the development of large scale LNG infrastructure in the North Sea. If that is the case, CCS will become crucial to the complete decarbonisation of Europe and developing an efficient and cost-effective transport infrastructure is of great societal relevance to achieve this goal. Leaving the deployment of the infrastructure to the private sector can not only be more costly, but also less efficient in terms of space and materials if the development is not done with a network approach. The research has shown how different financing structures can affect the cost of the technology, which ultimately will reflect in the social welfare of the population which will pay for the increase in the price of goods such as cement and steel. Whether CO2 is considered waste or commodity, the burden of managing its transport and sequestration is relevant for the whole society; furthermore, developing large-scale infrastructure which passes through cities and crosses borders can not be done without some type of societal approval, be it through government mandates or through participatory decisions at a local level. Studying the costs of the infrastructure is crucial for getting societal approval, but also for getting more interest from the industry side: the carbon tax is not yet at the price needed to cover all CCS expenses, however, if the costs of development of the infrastructure are lowered, the opportunity cost will turn positive in a shorter timespan.

6.4 Future work recommendations

This study is meant as a first exploration of the topic of financing for CO2 transport infrastructure. Further studies should focus on the following points.

- Focus on expanding the geographical scope of the research to include all of the major industrial clusters in Europe and undergo a network analysis study to identify where CO2 transport hubs and infrastructure can be developed optimally taking into account national regulation and impacts on financing.
- Expand the technical calculations of the model by including more granular parameters and splitting CAPEX for transport assets into inputs like material cost, labour cost and other costs: this allows for more precise financial calculations and allows to control for uncertainties for things like an increase in steel cost.
- Develop the financing options in order to take into account payback schedules and refinancing costs, as well as consider different types of costs of capital outside the traditional cost of equity and cost of debt.
- More interviews with actors involved in the CO2 transport infrastructure are key in order to validate financial parameters and get more insights into the operation of different CO2 transport assets. Furthermore, this could help expand the data available for costs of transport assets where there is almost no research, like barges and trucks.

Reflection

As I come to the end of this master thesis, I can safely say that this project was one of my biggest challenges so far and it surpassed a lot of my expectations.

This project defied my expectations from the very start; after a semester in Zurich, I was planning to come back to Delft and conduct my thesis research there. However, during the last lecture at Zurich I was presented with the topic of this thesis (well, a slightly different version at least) by Prof. Tobias Schmidt, I really liked the concept and three months later I was starting my research in the Climate Finance and Policy group of ETH Zurich. I learned that doing your master thesis at one university and being graded by another university is not always easy and I was routinely behind schedule for TU Delft due to the different timelines for the thesis between Zurich and Delft. However, having the input of experts in financing from ETH Zurich and combining that with input of experts in engineering and CO2 infrastructure at TU Delft has in my opinion elevated this thesis to a level that none of the universities could have achieved alone.

From an academic perspective, this experience has taught me the importance of properly written methods sections and references. When gathering data for the financial model I was routinely coming across results which I did not know how to verify because the process of obtaining the result from the raw data was not properly explained. As I was starting to write my own methods section, I realised that I was doing the same mistake, which made me realize why it is crucial to have feedback from someone who was not into the project as I was. I also learned the importance of systems thinking, a pillar of the teaching of the CoSEM course. Studying financing does not just have an effect on the cost of the infrastructure, but it also impacts the stakeholders involved, the scale of the project and institutions at large. Comparing different transport assets is not just based on cost, but also on the feasibility of having tens of trains or barges transporting CO2 compared to one pipeline. I learned how to use the conceptual tools that I was taught in the first year in Delft outside of the controlled setting of a classroom and applied to a topic I had never studied before.

From a professional perspective, this project was also a lesson in organisation, time management and decision-making: this is the first time in my life being put in front of a project where there is no set goal and no predefined way to achieve this. This brought a lot of responsibility on myself, not just for deciding how to structure this project but for actually doing it, as well as changing the structure when needed. I learned that there is no sign when one stage of research is over and that I have to decide for myself when it was enough research and where I could dig deeper. Of course there is help, and I was lucky enough to have a lot of supervision throughout the thesis, but a lot of the decision-making process still needed to happen from my side. I had some good choices and some bad choices. A particularly bad choice was to postpone the start of the interviews; the reason for that was to consolidate the results further before consulting outside experts about them, but this could have been done while at the same time getting in touch with potential interviewees.

Looking forward to what is coming in my career, I am grateful for having been given the opportunity to work with such experts in the field and to learn from them. I will forever cherish the amount of things I have learned about the thesis and about myself.

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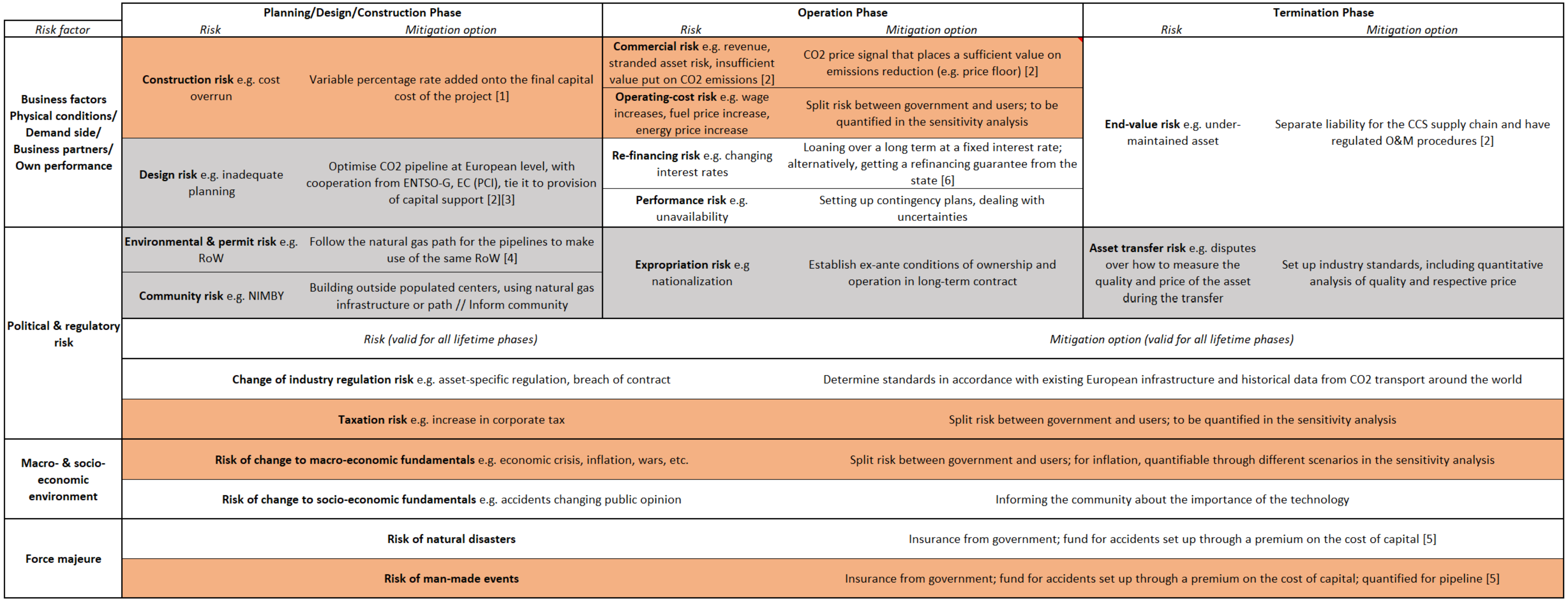
Appendix A

Risk assessment for CO2 transport

In order to aid with the analysis of the financing structures and quantification of risks, the risk framework from World Economic Forum (2015) is adapted for assessing project risks related to CO2 transport infrastructure. The framework was not integrated since data on quantifiable risks is very scarce in literature but it was important to assess how different financing structures can impact these risks. Table A.1 shows the results of the assessment.



	Planning/Design/Construction Phase		Operation Phase		Termination Phase	
Risk factor	*Risk*	*Mitigation option*	*Risk*	*Mitigation option*	*Risk*	*Mitigation option*
Business factors Physical conditions/ Demand side/ Business partners/ Own performance	**Construction risk** e.g. cost overrun	Variable percentage rate added onto the final capital cost of the project [1]	**Commercial risk** e.g. revenue, stranded asset risk, insufficient value put on CO2 emissions [2]	CO2 price signal that places a sufficient value on emissions reduction (e.g. price floor) [2]	**End-value risk** e.g. under-maintained asset	Separate liability for the CCS supply chain and have regulated O&M procedures [2]
			Operating-cost risk e.g. wage increases, fuel price increase, energy price increase	Split risk between government and users; to be quantified in the sensitivity analysis		
	Design risk e.g. inadequate planning	Optimise CO2 pipeline at European level, with cooperation from ENTSO-G, EC (PCI), tie it to provision of capital support [2][3]	**Re-financing risk** e.g. changing interest rates	Loaning over a long term at a fixed interest rate; alternatively, getting a refinancing guarantee from the state [6]		
			Performance risk e.g. unavailability	Setting up contingency plans, dealing with uncertainties		
Political & regulatory risk	**Environmental & permit risk** e.g. RoW	Follow the natural gas path for the pipelines to make use of the same RoW [4]	**Expropriation risk** e.g nationalization	Establish ex-ante conditions of ownership and operation in long-term contract	**Asset transfer risk** e.g. disputes over how to measure the quality and price of the asset during the transfer	Set up industry standards, including quantitative analysis of quality and respective price
	Community risk e.g. NIMBY	Building outside populated centers, using natural gas infrastructure or path // Inform community				
	Risk (valid for all lifetime phases)			*Mitigation option (valid for all lifetime phases)*		
	Change of industry regulation risk e.g. asset-specific regulation, breach of contract			Determine standards in accordance with existing European infrastructure and historical data from CO2 transport around the world		
	Taxation risk e.g. increase in corporate tax			Split risk between government and users; to be quantified in the sensitivity analysis		
Macro- & socio-economic environment	**Risk of change to macro-economic fundamentals** e.g. economic crisis, inflation, wars, etc.			Split risk between government and users; for inflation, quantifiable through different scenarios in the sensitivity analysis		
	Risk of change to socio-economic fundamentals e.g. accidents changing public opinion			Informing the community about the importance of the technology		
Force majeure	**Risk of natural disasters**			Insurance from government; fund for accidents set up through a premium on the cost of capital [5]		
	Risk of man-made events			Insurance from government; fund for accidents set up through a premium on the cost of capital; quantified for pipeline [5]		

Figure A.1: Risk framework developed for CO2 transport infrastructure assets

Appendix B

Cost of capital for other transport assets

Table B.1: Cost of capital inputs for ship transport

Ships	**Public finance**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**	*Source*
Public cost of debt	1.59%	1.59%	-	-	-	-	*(ECB, 2022a)*
Public debt share	100%	50%	0%	0%	0%	0%	*Mete (2020); interviews*
Private cost of debt	-	4.34%	4.34%	2.59%	4.34%	2.59%	*OECD (2016)*
Private debt share		25%	80%	85%	70%	75%	*Mete (2020); interviews*
Cost of equity	-	9.92%	10.12%	10.32%	9.72%	9.92%	*Fernandez (2020)*
Equity share	-	25%	20%	15%	30%	25%	*Mete (2020); interviews*
WACC	**1.59%**	**4.10%**	**4.66%**	**3.22%**	**5.22%**	**3.95%**	

Table B.2: Cost of capital inputs for barge transport

Barges	**Public finance**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**	*Source*
Public cost of debt	1.59%	1.59%	-	-	-	-	*ECB (2022)*
Public debt share	100%	50%	0%	0%	0%	0%	*Damodaran (2022); interviews*
Private cost of debt	-	4.34%	4.34%	2.59%	4.34%	2.59%	*OECD (2016)*
Private debt share		25%	70%	75%	65%	70%	*Damodaran (2022); interviews*
Cost of equity	-	9.92%	9.72%	9.92%	9.52%	9.72%	*Fernandez (2020)*
Equity share	-	25%	30%	25%	35%	30%	*Damodaran (2022); interviews*
WACC	**1.59%**	**4.10%**	**5.22%**	**3.95%**	**5.47%**	**4.29%**	

Table B.3: Cost of capital inputs for train transport

Trains	**Public finance**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**	*Source*
Public cost of debt	1.59%	1.59%	-	-	-	-	*ECB (2022)*
Public debt share	100%	50%	0%	0%	0%	0%	*Damodaran (2022)*
Private cost of debt	-	4.34%	4.34%	2.59%	4.34%	2.59%	*OECD (2016)*
Private debt share		25%	70%	75%	65%	70%	*Damodaran (2022)*
Cost of equity	-	6.80%	6.67%	6.80%	6.55%	6.67%	*Fernandez (2020)*
Equity share	-	25%	30%	25%	35%	30%	*Damodaran (2022)*
WACC	**1.59%**	**3.32%**	**4.31%**	**3.17%**	**4.43%**	**3.38%**	

Table B.4: Cost of capital inputs for conditioning

Conditioning	**Public finance**	**PPP**	**Project finance**	**Project finance RAB**	**Corporate finance**	**Corporate finance RAB**	*Source*
Public cost of debt	1.59%	1.59%	-	-	-	-	*ECB (2022)*
Public debt share	100%	50%	0%	0%	0%	0%	*Damodaran (2022)*
Private cost of debt	-	4.34%	4.34%	2.59%	4.34%	2.59%	*OECD (2016)*
Private debt share		25%	70%	75%	60%	65%	*Damodaran (2022)*
Cost of equity	-	5.84%	5.74%	5.84%	5.53%	5.64%	*Fernandez (2020)*
Equity share	-	25%	30%	25%	40%	35%	*Damodaran (2022)*
WACC	**1.59%**	**3.08%**	**4.03%**	**2.94%**	**4.19%**	**3.25%**	

Appendix C

Inputs and calculations for CO2 transport assets

C.1 Pipeline

Thickness:

$$t = \frac{OD * 1.1P_2}{2 * F * S} + CA \tag{C.1}$$

Where OD is the outer diameter, F is the corrosion factor, S is the design factor, CA is the corrosion allowance, P_2 is the outlet pressure and $1.1P_2$ is the maximum allowable operation pressure. The outer diameter has 3 different inputs based on the capacity to be transported, and only one pipeline is assumed since the maximum quantities modelled in the study is 10 MTCO2/year. *Steel cost:*

$$C_{Material} = t\pi * (OD - t) * L * \rho_{steel} * C_{steel} \tag{C.2}$$

Where $C_{material}$ is the material cost, t is the thickness, L is the pipeline lengths, ρ_{steel} is the steel pressure and C_{steel} is the cost of steel.

A fixed rate is calculated for labour, rights-of-way and other costs in order to calculate the remaining parameters of the CAPEX and OPEX for the pipeline (Knoope, 2015).

Operation and maintenance (O&M) costs are calculated as follows:

$$OM_{pipeline_{on}} = CAPEX_{pump} * 4\% + (C_L + C_R + C_{Material}) * 1.5\% \tag{C.3}$$

Where C_L is the cost of labour and C_R is the cost of the rights-of-way.

Total capital expenditure for the onshore pipeline is:

$$CAPEX_{pipeline_{on}} = CAPEX_{pump} + (L + R + M) * d \tag{C.4}$$

Operational expenditures include the cost of the energy for pumping and the cost for O&M:

$$OPEX_{pipeline_{on}} = W_{pump} * 8760 * C_{electricity} + OM_{pipeline_{on}} \tag{C.5}$$

C.1.1 Pumping stations

Energy consumption of the pump:

$$W_{pump} = \frac{P_2 - P_1}{n_{pump} * \rho} * m \tag{C.6}$$

Where W_{pump} is the capacity of the pumping station; P_2 is the outlet pressure (MPa); P_1 is the inlet pressure (MPa); n_{pump} is the efficiency of the pumping station; ρ is the density

Pumping cost:

$$CAPEX_{pump} = 74.3 * W_{pump}^{0.58} * n^{me} \tag{C.7}$$

C.1.2 Pipeline inputs

The inputs for the calculation of pipeline costs are shown in table C.1. Miscellaneous costs are related to the construction of the pipeline and reflect the added costs related to construction which are not related to steel cost and labour cost. OPEX is the sum of operational expenditures which repeat every year, including energy requirements for pumping and operating and maintenance costs for the infrastructure.

Table C.1: Inputs for the calculation of CO2 transport by pipelines.

CO2 specifics assumptions			
Inlet pressure onshore	MPa	12	Knoope (2014)
Outlet pressure onshore	MPa	8	Knoope (2014)
Temperature (onshore)	°C	15	Knoope (2014)
Density	kg/m3	865.4	
Inlet pressure offshore	MPa	15	Knoope (2014)
Outlet pressure offshore	MPa	8	Knoope (2014)
Temperature (offshore)	°C	4	Knoope (2014)
Pipeline onshore			
Steel cost (X120)	EUR/kg	1.987079	Knoope (2014)
Yield stress (X120)	MPa	890	Knoope (2014)
Outer diameter (OD) 100 kg/s	m	0.32	Knoope (2014) ->100 kg/s flow
Outer diameter (OD) 250 kg/s	m	0.51	Knoope (2014) ->250 kg/s flow
Labor costs	EUR/km	554221.8	Knoope (2014)
Rights-of-way fee	EUR/km	90909.9	Knoope (2014)
Miscelaneous	-	25%	Knoope (2014)
Lifetime	years	50	Knoope (2014)
Pressure drop	Pa/m	40	Knoope (2014)
Design factor		0.5	Knoope (2014)
Corrosion allowance	m	0.001	Knoope (2014)
Thickness safety margin	-	10%	Knoope (2014)
Pipeline offshore			
Steel cost (X65)	EUR/kg	1.520837	Knoope (2014)
Yield stress (X65)	MPa	460	Knoope (2014)
Thickness (offshore)	% of OD	3%	Knoope (2014)
Outer diameter (OD)	m	0.32	Knoope (2014) -><=100 kg/s flow
Outer diameter (OD)	m	0.61	Knoope (2014) ->100-300 kg/s flow
Outer diameter (OD)	m	1.06	Knoope (2014) ->>= 300 kg/s flow
Pressure drop	Pa/m	20	Knoope (2014)
Labor costs	EUR/km	554221.8	Knoope (2014)
Machinery premium	EUR	39823000	Austell et al. (2011); Knoope (2014)
Rights-of-way fee	EUR/km	0	Bureau et al. (2011); Knoope (2014)
Miscelaneous	-	25%	Knoope (2014)
Lifetime	years	50	Knoope (2014)
OPEX pipeline	%	1.50%	Knoope (2014)
Steel density	kg/mˆ3	7900	Knoope (2014)
Thickness safety margin	-	10%	Knoope (2014)
Offshore platform	EUR	69405800	Van de Broek (2010)
Pumping station			
Multiplication factor	-	74.3	Meerman et al. (2012); Knoope (2014)
Capacity	kWe	2000	Meerman et al. (2012); Knoope (2014)
Exponent factor	-	0.58	Meerman et al. (2012); Knoope (2014)
Pumps onshore	km/pump	100	Meerman et al. (2012); Knoope (2014)
Pumps offshore		0	Knoope (2014)
Lifetime	years	25	Knoope (2014)
Pump efficiency	-	75%	IEA GHG (2002); Knoope (2014)
OPEX pump	%	4%	Knoope (2014)

C.2 Truck

There are 3 main components to the CAPEX of the truck: isotainer cost, tractor cost and trailer cost. Calculations for CAPEX and OPEX follow (Oeuvray, 2022). Firstly, the duration of a roundtrip is calculated:

$$d_{rdtrip}^{truck} = 2d_{transport}^{truck} + d_{load}^{truck} + d_{unload}^{truck} + d_{break}^{truck} \tag{C.8}$$

From this, the number of trucks needed is calculated:

$$n_{truck} = \frac{m_i}{8760/t_{rdtrip}^{truck} * m_{isotainer}} \tag{C.9}$$

Where m_i is the yearly mass of CO2 to be transported and $m_{isotainer}$ is the capacity of an isotainer. The CAPEX is then:

$$CAPEX_{truck} = n_{truck} * (C_{truck} + C_{trailer} + C_{isotainer}) \tag{C.10}$$

In terms of OPEX, there is a component for each roundtrip, for each truck, and for salary of the drivers.

$$OPEX_{rdtrip_{truck}} = (c_{fuel} * C_{fuel} + C_{maintenance} + C_{insurance}) * 2r_{truck} * n_{truck} * \frac{8760}{d_{rdtrip}^{truck}} \tag{C.11}$$

Where c_{fuel} is the fuel consumption, C_{fuel} is the fuel cost, $C_{maintenance}$ is the maintenance cost, r_{truck} is the route travelled by truck one-way.

$$OPEX_{misc_{truck}} = (C_{insurance} + C_{administration}) * n_{truck} \tag{C.12}$$

Where $C_{insurance}$ is the insurance cost and $C_{administration}$ is the administration cost per truck.

The salary is calculated based on the amount of drivers needed and their yearly salary, where salary rates from Germany are assumed.

$$OPEX_{salary_{truck}} = \frac{n_{truck} * 8760}{d_{driver}} * C_{salary} \tag{C.13}$$

Where d_{driver} is the yearly working hours and C_{salary} is the yearly salary of a truck driver.

The total OPEX for transport by truck is therefore:

$$OPEX_{truck} = OPEX_{rdtrip_{truck}} + OPEX_{misc_{truck}} + OPEX_{salary_{truck}} \tag{C.14}$$

C.2.1 Truck inputs

Table C.2: Inputs for calculation of CO2 transport by truck.

	Isotainer		
Capacity	l	20000	HOYER; Oeuvray (2022)
Capacity	t	22	HOYER; Oeuvray (2022)
Max CO2 mass	t	20	HOYER; Oeuvray (2022)
Tara isotainer	t	8	HOYER; Oeuvray (2022)
Purchase cost	EUR	86625	DemoUpCARMA estimate; Oeuvray (2022)
Rental cost	EUR	28875	DemoUpCARMA estimate; Oeuvray (2022)
Lifetime	y	15	HOYER; Oeuvray (2022)
	Duration		
Short break (SB)	h	0.75	Oeuvray (2022)
Period between SB	h	4.5	Oeuvray (2022)
Long break	h	11	Oeuvray (2022)
Period between LB	h	9	Oeuvray (2022)
Loading/unloading	h	1	Oeuvray (2022)
	Costs of truck		
Tractor cost	EUR	145000	Oeuvray (2022)
Tractor	y	10	Oeuvray (2022)
Trailer cost	EUR	102000	Oeuvray (2022)
Trailer	y	10	Oeuvray (2022)
Fuel	l/km	0.3	Oeuvray (2022)
Fuel	EUR/l	1.5	Oeuvray (2022)
Maintenance	EUR/km	0.14	Oeuvray (2022)
Insurance and damages	EUR/y	13200	Oeuvray (2022)
Infrastructure	EUR/y	8660	Oeuvray (2022)
Administration	EUR/y	28440	Oeuvray (2022)
Tires	EUR/y	11000	Oeuvray (2022)
Salary (EU)	EUR/h	18	Oeuvray (2022)

C.3 Ship

Ship transport has been divided into batch and bulk. For batch transport, the only element which influences CAPEX is isotainer cost. The calculations for batch ship transport are taken from (Oeuvray, 2022).

$$CAPEX_{ship_{batch}} = C_{isotainer} * (\frac{m_i * d^{shipbatch}_{rdtrip}}{m_{isotainer} * 8760} + \frac{m_i}{m_{isotainer} * f_{ship} * 52}) \qquad (C.15)$$

Where $t^{shipbatch}_{rdtrip}$ is the roundtrip time for the ship and f_{ship} is the frequency in terms of trips per week for a ship. In terms of OPEX, a fixed fee for the travel cost is calculated for each transport route and for each isotainer, and a dangerous goods surcharge is added on top.

$$OPEX_{ship_{batch}} = (C_{ship} + C_{dangerous}) * (m_i/m_{isotainer}) \qquad (C.16)$$

For tanker shipping in bulk, estimates from (Roussanaly et al., 2021) and (Element Energy Limited, 2018) are taken. The costs are calculated for a low-pressure ship if the annual capacity to be transported is more than 1 MtCO2, while for 1 MtCO2 or less a medium-pressure ship is considered. This is due to the widespread use of medium-pressure ships for transport of small-scale CO2 at the moment and the predicted lock-in on the technology due to its maturity, regardless of the cost optimality.

For low-pressure ships, CAPEX is calculated based on a 50 ktCO2 ship at low pressure (7 barg) and temperature of -50 °C. For medium-pressure ships, CAPEX is calculated based on a 12.5 ktCO2 ship at medium pressure (15 barg) and temperature of -30 °C. The CAPEX includes the cost of construction of a loading and unloading facility for the liquified CO2.

$$CAPEX_{shipbulk} = n_{shipbulk} * C_{shipbulk} + m_i * C_{loading} \qquad (C.17)$$

Where $CAPEX_{shipbulk}$ is the investment cost, $n_{shipbulk}$ is the number of ships needed, $C_{shipbulk}$ is the construction cost of the ship (in EUR), $C_{loading}$ is the cost of the loading facility (in EUR/tCO2).

OPEX is a function of fixed operation and maintenance costs and fuel cost.

$$OPEX_{shipbulk} = d_{shipbulk} * m_i * c_{fuel} * C_{fuel} + C_{other} \tag{C.18}$$

Where $OPEX_{shipbulk}$ is the operational expenditure, $d_{shipbulk}$ is the distance travelled by the ship, c_{fuel} is the fuel consumption of the ship and C_{fuel} is the fuel cost.

C.3.1 Ship inputs

Table C.3: Inputs for calculation of ship transport.

CO2 Specifics			
Pressure	6.5	barg	Roussanaly et al. (2017)
Temperature	-50	°C	Roussanaly et al. (2017)
Ship transport			
Loading/unloading	15	h	Cato (2016); Element Energy Limited (2018)
Loading facility	2.63	€/tCO2	Roussanaly (2021)
OPEX loading	2%	€	Roussanaly (2021)
Port entry/exit	2	h	Seo et al. (2016); Element Energy Limited (2018)
Operating hours	8400	h	Roussanaly et al. (2021); Element Energy Limited (2018)
Speed	15	nm/h	Seo et al. (2016); Element Energy Limited (2018)
Speed km	27.78	km/h	Seo et al. (2016); Element Energy Limited (2018)
OPEX	5%	-	Roussanaly (2021)
Harbor fees	1.1	€/tCO2	Roussanaly (2021); Roussanaly (2013)
Lifetime	20	yr	Roussanaly (2021)
Low-pressure ships			
Pressure	7	bar	Element Energy Limited (2018)
Temperature	-50	°C	Element Energy Limited (2018)
Density	1150	kg/mˆ3	Element Energy Limited (2018)
Capacity	50000	tCO2	Element Energy Limited (2018)
CAPEX ship	83952000	€	Element Energy Limited (2018); Roussanaly (2021)
Fuel consumed	5.19	g/tCO2/km	Roussanaly (2021)
Medium-pressure ships			
Pressure	15	bar	Roussanaly (2021)
Temperature	-30	°C	Roussanaly (2021)
Density	1077	kg/mˆ3	Peace software (2022)
Capacity ship	12500	tCO2	Roussanaly (2021); Northern Lights interview (2022)
CAPEX ship	82797660	€	Roussanaly (2021)
Fuel consumed	6.67	g/tCO2/km	Roussanaly (2021)

C.4 Barge

CAPEX for barges is calculated as follows:

$$CAPEX_{bargebulk} = \frac{m_i}{\frac{d_{year}}{(d_{trip}*2)} * m_{barge} * M_{barge_{avg}}} * C_{barge} \tag{C.19}$$

Where $d_{year}/(d_{trip} * 2)$ is the amount of round trips per year, m_{barge} is the capacity of a barge, $M_{barge_{avg}}$ is the average capacity of the barge (in percentage) and C_{barge} is the cost of a barge.

Operational expenditure:

$$OPEX_{bargebulk} = CAPEX_{bargebulk} * c_{OPEX} + \frac{m_i * d_{barge} * c_{fuel}}{1000000} * C_{fuel} \tag{C.20}$$

Where c_{OPEX} is the percentage of operation and maintenance fee, d_{barge} is the distance travelled by barge, c_{fuel} is the fuel consumption in g/tCO2/km and C_{fuel} is the fuel cost (500 €/t).

The inputs are shown in the Methods section.

C.5 Rail

$$CAPEX_{rail} = n_{rail} * C_{locomotive} + n_{rail_{wagon}} + m_i * C_{wagon} + \frac{m_i}{365} * C_{storage} \tag{C.21}$$

Where n_{rail} is the number of locomotives needed, $n_{rail_{wagon}}$ is the number of wagons needed, $C_{locomotive}$ is the cost of a locomotive, C_{wagon} is the cost of a wagon, $C_{storage}$ is the cost of buffer storage unit.

$$OPEX_{rail} = d_{rail} * m_i * C_{OPEX_{full}} + d_{rail} * m_i * C_{OPEX_{empty}} + (\frac{m_i}{365} * C_{storage}) * C_{OPEX_{storage}} \tag{C.22}$$

Where d_{rail} is the distance travelled by train, $C_{OPEX_{full}}$ is the OPEX of the rail with full load, $C_{OPEX_{empty}}$ is the OPEX of the rail with empty load, $C_{OPEX_{storage}}$ is the percentage of operation and maintenance for buffer storage.

C.5.1 Rail inputs

Table C.4: Inputs for calculation of rail transport (adjusted for inflation to EUR2021).

	CO2 Specifics		
Pressure	6.5	barg	Roussanaly et al. (2017)
Temperature	-50	°C	Roussanaly et al. (2017)
	Train costs		
Scaling factor	0.85		Roussanaly et al. (2017)
Locomotive cap.	1250	ton	Roussanaly et al. (2017)
Locomotive cost	3774629	EUR	Roussanaly et al. (2017)
Wagons cost	4159.577	EUR/tCO2	Roussanaly et al. (2017)
Train speed	60	km/h	Roussanaly et al. (2017)
Time for load/unload	5	h	Roussanaly et al. (2017)
Max wagons	20		Roussanaly et al. (2017)
Capacity per wagon	240	tCO2	Roussanaly et al. (2017)
OPEX full	0.028356	€/tCO2/km	Roussanaly et al. (2017)
OPEX empty	0.014178	€/tCO2/km	Roussanaly et al. (2017)
Lifetime	25	years	Roussanaly et al. (2017)

C.6 Conditioning

All conditioning units have the same method of calculation.

$$CAPEX_{cond} = m_i * C_{cond} \tag{C.23}$$

Where C_{cond} is the specific cost of conditioning in €/tCO2. The cost is scaled throught the cost scale-up factor formula.

$$OPEX_{cond} = \frac{m_i * c_{elec}}{\eta_{cond}} * C_{elec} \tag{C.24}$$

Where c_{elec} is the energy consumption (kWh/tCO2), η_{cond} is the efficiency of the conditioning unit, C_{ele} is the cost of electricity.

C.6.1 Liquefaction input

Table C.5: Input table for liquefaction plants at 7 barg and 15 barg.

Liquefaction @ 7 barg, -50°C, pure CO2			
Base case capacity	t/y	1000000	Roussanaly (2021); Deng et al. (2019)
CAPEX	€/tCO2	4.2	Roussanaly (2021); Deng et al. (2019)
Fixed OPEX	-	6%	Roussanaly et al. (2017)
Lifetime	y	25	Deng et al. (2019)
Energy consumption	kWh/tCO2	96.3	Roussanaly et al. (2017)
Exponent factor	-	0.85	Roussanaly (2021); Deng et al. (2019)
Cooling water	€/tCO2	0.55	Deng et al. (2019)
Liquefaction @ 15 barg, -30 °C, pure CO2			
Base case capacity	t/y	1000000	Roussanaly (2021); Deng et al. (2019)
Base case cost	€/tCO2	4	Roussanaly (2021); Deng et al. (2019)
Fixed OPEX	-	6%	Roussanaly et al. (2017)
Energy consumption	kWh/tCO2	90.4	Roussanaly (2021); Deng et al. (2019)
Exponent factor	-	0.85	Roussanaly (2021); Deng et al. (2019)
Lifetime	y	25	Deng et al. (2019)
Cooling water	€/tCO2	0.66	Deng et al. (2019)

C.6.2 Compression input

Table C.6: Input table for compression units.

Compression			
Base case capacity	t/y	1000000	Roussanaly et al. (2017)
Base case CAPEX	€/tCO2	2.15	Roussanaly et al. (2017), Figure 8
Efficiency	-	0.8	Carapellucci et al. (2019); Oeuvray (2022)
Lifetime	y	20	Carapellucci et al. (2019); Oeuvray (2022)
Energy consumption	kWh/tCO2compressed	68.5	Roussanaly et al. (2017)
Exponent factor	-	0.85	Roussanaly (2021); Deng et al. (2019)
OPEX	-	5%	Carapellucci et al. (2019); Oeuvray (2022)

Appendix D

Interviews

The following sections show the main findings from the interviews carried with the 4 interviewees. The full interview transcript, as well as information given in the follow-up e-mails is available upon contact.

D.1 Interview 1: shipping

[. . .] We are approached by financiers, but what we often do is we are the charterers, so the ship owner needs to secure financing and provide us a full package, ETA time, charter level. So time charter, of course incorporates their finance and competitiveness, but it also incorporates their risk appetites. Risk appetite, meaning for example, the residual value risk of the ship if they're going to charter to us for seven, 10-15 years, do they depreciate the assets significantly over that period or do they think they can make use of the assets after the charter period is over and also, the time charter contracts has certain risk allocation on the operations of the ship.

[. . .] So there is only one source of ship price in all the papers coming from 2015-2016 from a South Korean research paper. I think it's incorrect. First of all, it's too old information and same information from same source almost now at 10 years old is being propagated and people start believing it hearing from so many reports, no one digs down into the source and they so it's been published just last year. [. . .] In addition, I think 50,000 cubic meter, completely new technology ship first of all kinds. There is no way you can get it at this price. I don't wanna put a price out there as COMPANY is not focusing on this at the moment. So our phase one is on medium pressure. Our first we should start at 7500 much smaller. Our second generation ships which will be on the water from 2026 onwards will be 12,000 cubic meters. Again medium pressure. Medium pressure being 13 to 18 bar, it's a bit more proven technology, although they are all gonna be the largest of their kinds in the world, so there's still some novelty in them, but as you can see, even us for us.

[. . .] Shipbuilding is typically very low margin, high volume business. They are very squeezed because they buy all the components from their suppliers, they integrate and then they have to commit to the performance of the ship that they haven't really produced themselves.

[. . .] Big, big, big price difference because these ships are again still first of a kind. It's so I can give you ranges. For example 7500 ship. Today you can get offers from 40 million to 75 million. Could be even outside the range. I mean this is probably 80-90% of the offers. For a 12,000 ship, you could get offers from 40 million to 90 million and again could be outside the range as well. So you can see the type of range, but also it shows that even at 12,000 medium pressure which is much less risky, much simpler ship than what you have, your 50,000 could be even more expensive than what you have for the 50,000.

[. . .] You understand, of course, why this (low pressure ships) is more novel right? Because you are so close to the triple points, this ship would have much more instrumentation to measure the cargo and manage the cargo in that in that critical area versus the type of ships we build medium pressure, it doesn't really manage the cargo. There is no cargo management at all. You just load it cold and low pressure and over the course of the journey just heats up and pressure builds up, but you just manage it by installation. So you don't have to really manage the cargo at all. Versus type of ships you have, you would have really perfection plans. So of measurements management. Much more technical, technologically advanced chips, so that's why there's a risk over there.

[. . .] in Northwest Europe we'll probably see two different asset classes. We will both see medium pressure and we will see low pressure as well. So if you look at the emitters in Northwest

Europe, there are many customers who are standalone. They are significant emitters, but well below 3,000,000 tons per annum, maybe even less than 1,000,000 tons per annum. I would say they are ranges between 400 ktpa to 1.5 million tons per annum type of range standalone customers and at this type of emission level they don't need large ships because the shipping distance to North Sea is so short they need small ships

[. . .] So our infrastructure is being built by to a large extent states funding, and they will contribute towards OPEX as well for the 1st 10 years to a certain ratio and the remaining funding will come from our parents, COMPANIES, a third each contributing for the rest. Of course they have their own way of financing their activities and initially until we get commercial customers, it's up front investments that would lose money for 10 years unless we secure customers. [. . .] Although state is giving significant supports, they are not owners. So company is owned a third each by the three companies. So there's no stake for the Norwegian state.

[. . .] So there is immense amount of interest from ship owners, which means financiers are also showing a lot of interest. We are really overwhelmed by interest. I mean, we have been approached by 30 plus ship owners in less than a year.

[. . .] We are receiving indicative very competitive charter rates from ship owners. Pleasantly surprised in this aspect. We are typically after 10 or 15 years of time charter type of agreements because we expect that our agreements with the customers will be either 10 or 15 years. So as a result, we would like to get ships from ship owners Charter to us for either 10 or 15 years and the rates are very competitive. So if I could quantify based on my, you know, back engineering off the offers you receive, it looks like if we assume they have 70% gearing on their offer, they're equity IRR is between 8 and 10%.

[. . .] So having seen and talked to these industrial customers, ship owners fully understand that there will be a CO2 shipping markets. They understand that although there is some level of novelty involved, it's not significantly different. So that's why I think they are very much willing to take risk on CO2 ships which is great for the development of the market for everyone.

[. . .] Most customers' emissions are peaking in winter, but at the same time, the North Sea is most difficult in winter. At the same time. So these ship-to-ship transfers offshore in North Sea will be not predictable in winter time and the customers need the highest level of service, the highest level of emissions and predictability in service level, and so forth. So there are of course challenges as such but so that's why this type of offshore injection only makes sense if it's really large scale.

D.2 Interview 2: shipping

[. . .] I'm glad that you're looking at low pressure because that's what we are mainly focusing on. We very much think that all of those looking at the medium pressure is you know long term it probably not the most optimal solution. So it's nice to hear that you are also finding low pressure as the most optimal solution when scale is the important part of it. But as to the CapEx, I think it's it's it's reasonable.

[. . .] We have had quotes for a 22,000 cubic meter low pressure design vessel at just around €60 million. So that extra 20 million, yeah, it seems reasonable to me that that's kind of the the the extra on top of it to going from a 22 to 50, it might be a bit more, but I'm not, I don't think you're off in that estimate. It seems reasonable to me.

[. . .] shipbuilding prices has increased 20%, something like that in the past year because of a steel prices and legal price and stuff like that. So that's, I mean we are hoping right now is kind of the tip of it. But I mean it could be here for the long term as well. So but you asked me a year ago, I would have said it was a lot cheaper, but yeah, that's just kind of the dynamics that plays into it.

[. . .] We consider 20k because we think it has the right size for the kind of the start of the industry. So that's 2025 and then we are looking at like 10 years on what's with that we also are working on the design of 50,000 cubic meters just as you mentioned here because you know long term volumes will increase, but it's just a reflection of where we see the market and the volumes are at everything that's smaller sizes.

[. . .] the main point that I would be looking for and kind of in the difference between low pressure medium pressure is obviously the amount of steel that you need. So going by medium pressure, high pressure is you know more steel that increases cost but also for the operations of it you are just moving more steel through water, you need more fuel. So kind of that whole you know calculation of not only the CAPEX but also the operations of it just looks worse with the medium pressure of course you have a bigger safety margin. [. . .] . I wouldn't say that that low pressure should be more expensive. I would actually say the contrary. There could be something in the innovation of the designs that medium pressure is more off the shelf so to speak. So there's some innovative cost in the ship design and that's perhaps what could be factored into that. But just you know on a like-for-like basis low pressure should offhand be cheaper than the medium or high pressure. [. . .]

So either we have ships that do very high pressure but not very much cooling or you have a lot of cooling and not that much pressure. And with CO2 we kind of need both. And that's also why there is the need for for this construction of new ships. [. . .] the technology is the same, all of the technology exists, you just need to kind of put it together for the first time. So there's nothing new in in that.

[. . .] So that I think what some important to keep in mind here what we are looking at when trying to compare it to other stuff is that this is basically waste disposal. So it we can't really like for like compared to the energy industry or other kind of yeah electricity as you mentioned as well. So it's kind of there are different dynamics in place that kind of drive this than we see from.

[. . .] what we're looking at is project finance for when we have to build these ships. So essentially as I alert to earlier we kind of wanted to separate it from our existing business. [. . .] one of the reasons were for kind of a marketing angle and trying to reposition ourselves as greener than we perhaps are. But another one was also in relation to the financing definitely because we think there is a potential for green financing in some sorts you know the people should want to invest in this to higher degree than should we say a regular gas carrier. So that was a very conscious decision to kind of server at the two. So that if you as a lender on investor or whatever.

[. . .] We built the ships and we own them and then we charter them out to to the customer and it depends very much you know project for project if we chatter it directly to the emitter or if you have a you know these storage and transport corporations that kind of would take them in and then have the responsibility of employing the ships we open for both and we see different approaches to it but essentially. It's based on us owning the ships and then we charter them out for 10 years or something like that.

[. . .] (on government subsidies) I don't think in the in the actual development of the ships, but I think it's very important and incentivizing the industry as a general. So I think especially the, I mean from the emitters point of view, government subsidies is very important or carbon taxes or some sort of you know mechanism that you know kind of penalizes you for having emissions. So that you create this incentive to actually do something about it instead of just you know, it has to be more expensive to. [. . .] So for the emitters I think it's very important. For us as a, you know, a transport provider, it doesn't really play that much of a role and I wouldn't really make that much of a difference. We will find the financing for this anyway.

[. . .] at the moment what we hear is about 27-28 months from the investment decision to the delivery of the ship and that space is if we build them in in Asia, of course you can, you know, get that down if you do it in Europe. But Europe is much more expensive. It's a discussion, but primarily we're looking at doing the shipbuilding in Asia because it's just much cheaper than we would rather have that month of sailing back to Europe and, you know, paying 10 millions more.

[. . .] we kind of need that first long period of 10 years and once that is secured then we are confident we can get the financing forward.

[. . .] Our insurance would essentially go in and cover that and just on a general note pursue too, we see it as file less risky than what we normally do. I mean it's not combustible. [. . .] So I think our seafarers would love to go with it because of the the the decreased risk essentially of doing it.

[. . .] We depreciate the ships quite steeply in most cases for the first contract period so that we essentially have no risk after that, but it also drives up the transport cost and for the emitter, which is also not desirable. [. . .] So that would be the first contract. So if it's a 10-year contract we're looking at, we would appreciate it to scrap over 10 years and that's very unusual for shipping. Normally you would do it over 20 or 25 years. So it's also I mean if people want to have a longer first contract and then we would extend the period over which we depreciate the asset. [. . .]So I guess for your purposes, we would not do the steep depreciation if we are looking in 2030 onwards, it's more right here, right now we are, we're looking at to kind of do it the Safeway and and and not really take any risk on.

[. . .] so starting with the debt share, we would expect 80 to 85% probably.

[. . .] And then in terms of the equity cost, I think you have a good point in you know in the comparison with our usual business or you know for from what we do internally and what it would require from us to do this is no different than what we would normally engage in.

[. . .] (on cost of equity) estimate initially it was 10%. So I mean it's nice to see that the calculations are basically the same. So what we have used especially in kind of early indications when we have to set this up and kind of provide cost quotes to customers then we use 10% for that. So yeah, I'd say that's pretty accurate.

[. . .] (on cost of capital) probably in all cases, try to keep it under 8%. That's kind of a, you know, the Max where it just destroys the calculations basically and that's kind of conservative [. . .] At the LNG industry 20 years ago, 30 years ago, when it started to kind of emerge and we are trying to take some lessons from that. It might not be clever, but at least that's what we're doing as ship owners, we look at other shipping segments and we think it's very much what we are trying to benchmark it against in terms of development, but also how the contracts were in the beginning of the LNG industry.

[. . .] (on the emissions of ships throughout the transport) in terms of automation that we're looking at, then when we look at methanolysis the few, then what our rough estimates is that it's about 2.5% of the cargo carried in a year, that's kind of the ship's emission.

D.3 Interview 3: pipelines

What I can at the moment say that we want to try that the overall average price for the transport will be around about €20 or less per ton. (for 20 million tonnes per year and transport only, no conditioning)

[. . .] So we need to look where have we have really large amounts we can transport from point A to point B for example, I guess a Switzerland has around about the potential of seven to 10 million tons. [. . .]We have to look that we get this large amounts and to look how many will be then in the end participate on it and we have to calculate which pipeline or on which route makes a pipeline sense or perhaps the barge or the train is for the first part or the last mile a better option.

[. . .] What all the standards are planning part and the building and construction is more or less the same that we expect at the moment. The real cost driver within the construction is the pipe itself, especially at the actual steel prices we see at the moment.

[. . .] I guess the steel factor can make more or less 40% of the costs.

[. . .] we do not expect that this year to infrastructure will be cost regulated in Europe because it's the moment it's not foreseen and when you follow the discussion around about the hydrogen way this time the decision should be, yeah, set in another direction so that they said OK, cost regulation will be not seen because there's speak companies from eye to eye on the same level more or less there will be nothing part that one company can, yeah, push the other company in a situation they have no free hands to do what they want that they saw in on the hydrogen level a little bit otherwise. [. . .] I guess in the first step will be on the private side the unregulated part and also the government or public private part because the countries like Netherlands or Belgium have a grid operators with Gazunie or Fluxys, their more or less owned by the government and there we see still that they have more or less the the order to also build a per year two infrastructure.

[. . .] (on the possibility of regulated financing after the infrastructure is set up) Then it could be possible that the government says they want to regulate it, but then is for the private investors are very unhappy situation. Because then we have uh the vice versa effect of the yeah, the risk takes these will be socialized and the amounts will be privatized and that would be the case around of this situation. What is not a stable situation for the future. So for us that is one of the parts that we set next year for example within the year 2 strategy of the government there they have to decide.

[. . .] When everything runs well, it should be run. Yeah, on our books. And also all on the books of our partners. Perhaps that is still open under discussion and not complete clear. But we see us more or less role as the main investor.

[. . .] (on the cost of capital) It will be higher because the market is not as developed as the oil and gas business because there, you know, all the risk. For oil and gas, you know what can happen on the user side and on the supplier side. And the transport is more or less developed we see here in the beginning and higher risk profile and so usually higher return on invest. [. . .] It is between one and a half and two at the moment I would say. (1.5 – 2 times higher WACC than in the slide: the slide had WACC 5%)

[. . .] (on the equity share) At the moment we calculate internally at the moment with a very high part of equity. They are our own money and not so much private debt share, but we calculate also situations up to 50% for the debt share to log with which effects this has on the web for example. But we have the situation that our shareholders have actually deep pockets and they have enough money and they're from very long term interest. So for them it's also possible to invest it the money directly because it's retirement firms and so stuff.

[. . .] (on the cost of equity) Uh especially, I guess over the whole industry that makes sense, but in their own or in the transport industry alone, the regulated transport industry, it is less at the moment. So in Germany, I guess we at the moment at around about 6%. [. . .] We have to raise the cost when it is unregulated because the risks are higher

[. . .] (on the extra cost of conditioning) So that is a part that we would offer an additional service to the customers that we liquified it for them. And at the moment we calculate their very roughly with additional €10 per ton.

[. . .] (on validation of pipeline transport cost) . Yeah, I can say the €9 you have there, it is when you work with the US amounts with 25% on top and perhaps you work with a long time. [. . .] for example calculate with natural gas there 55 years for the pipeline and then it is in the range, then you're around about this nine euro, yes. But if you say I want to get all my money back within of 20 years, for example, where no one knows what happened after 2045 with the grid when every single runs with green energy or so, and then you rise or push the price in another direction more or less. But that is also questions I said before. We need a clear framework from the government. What will be the market in the future? How long will it a stable market and how long it should it work?

[. . .] I also see in the long term a huge potential. So I guess we will need in the future cement we need calc, we need glass and we have a huge chemistry industry in Europe and they need CO2 as a resource and not so less CO2. The expectations we get from the German chemistry industry that they said they need to be between 15 and 45 million tons.

D.4 Interview 4: barging

[. . .] seeing the math volumes that we need to ship, we think that bulk transport is preferable.

[. . .] we are restricted to water levels. We are restricted to bridges. So lodges are quite small and therefore prices are higher than for the seagoing transport. [. . .] we really design a custom built boat depending on the restrictions that this customer has and of course emittors that are in the seagoing hubs are less restricted than, let's say, the industry in Basel.

[. . .] for the Swiss industry we had a March designed with the capacity of let's say around 3000 ton, but that is where the density of 1 because in our assumptions we we calculated with the density of 1. But I see in the in the interview in the reporting that you are calculating with the density of 1.15 and then we could take a maximum of 3200 or three 3300 metric tons. [. . .] we could go with batches up to 9000-10,000 tonnes, but that only applies to seaport areas or larger rivers – for the Rhine, that is too large.

[. . .] So a barge would take around seven days for a round trip. That means that we could do 50 to 52 trips and the average that the bot could load on the Rhine over the last seven years was about 2000 tons because there is some low water, some high water.

[. . .] in a more mature market than it maybe will also be the case for CO2 that within 10 years the results were spot market available. That would mean that the customer is looking for a ship available on the market tomorrow because of low water levels. And I need an additional ship then it can go on the spot market, he can just rent any shift from the market that is available.

[. . .] We just calculate the CapEx back to a day rate and then we know the OpEx on a day rate. So we have a division of CapEx and OpEx on the day rate which is I think it's 60% is CapEx and 40% is OpEx.

[. . .] This is a very general structure, but this is not what we can use. In the inland barging it's easy: You have 25% private equity, 75% is a financial institution. The the normal banks of the country will give us the credits. So we we can't use money from the governments. Not all not a mix in inland navigation you have to go. [. . .] We are in the unregulated private investment side, 25% regularly is private equity.

[. . .] (on the contract length) But we discussed it internally, everything between 10 and 15 years would be would be we we can bear a risk as well, of course. And it's a commercial risk that we want to take, but we'll also be of importance to the bank and the interest rate and the cost of capital, how long the ship will be time charted in the first place.

[. . .] (on the cost of capital) So we are at 4%, so I think 4.5 is OK.

[. . .] (on the cost of equity) Equity at 9% is okay, everyone wants 10% but let's keep it at 9.3%.

[. . .] (on the leverage) But in this scenario I have an equity share of 40% which is quite high. We never saw that before in all market. So you you can put there let let's let's do 30 and 70 because I'm actually banks are not really convinced of course they are convinced but there is no contract signed today. So it is it is still seen as risk capital because this market is not existing today and we tried to convince them. So if if you allow us to to have private debt share of 70 and equity of 30% and and in your mind.

[. . .] (depreciation and contract length) It will always be 15 years, 10 years is too short. [. . .] Our barges can last up to 25 years.

[. . .] And there is a big potential for badges for sure, because we can transport liquid and we can directly connect to an intermediate storage facility without pipeline and and and this intermediate storage can connect to seagoing ship. So we keep the whole loop liquid if we want.