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The Impact of Financing Structures on the Cost of CO_2 Transport

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The impact of financing structures on the cost of CO_2 transport

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Abstract

The economic operation of carbon capture and storage (CCS) facilities hinges on the availability of CO_2 transport infrastructure, and the financing structure of new transport assets will affect CO_2 transport cost. Building on economic studies of infrastructure finance in other sectors, we empirically calibrate the cost of capital and operational efficiency under different financing structures, considering CO_2 transport via pipelines, barges, trains, and ships in a levelized transport cost model. Our results show that the choice of financing structure can result in transport cost differences of up to 22% for pipelines, with smaller effects observed for the other transport modes. Generally, public finance emerges as the most cost-effective financing structure for all CO_2 transport modes; the advantages of a lower cost of capital compared to private finance options outweigh the associated operational efficiency disadvantages. While additional aspects beyond cost must be considered when selecting financing structures for new infrastructure assets, our ex-ante analysis underlines the importance of financing structures for the economic viability of CO_2 transport assets, and for CCS more broadly.

Keywords: Carbon capture and utilization, climate change mitigation, infrastructure investment, regulated asset base, cost of capital
JEL Codes: H54, L90, L95, Q40.

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1 Introduction

The Paris Agreement aims at limiting global warming to well below 2°C (IPCC, 2022). To keep this target attainable, the European Union (EU) and other regions have set a legally binding target of achieving net-zero greenhouse gas emissions by 2050 (European Commission, 2021). While the decarbonization of power generation and the electrification of road transport could yield substantial emission reductions, some energy-intensive industries cannot be economically electrified (Speizer et al., 2024). According to decarbonization pathways, carbon capture and storage (CCS) forms a core part of the mitigation technology portfolio for cement and clinker, pulp and paper, and the chemical sector (Bachorz et al., 2024; Bashmakov et al., 2023; Holz et al., 2021; Schreyer et al., 2024; van Sluisveld et al., 2021).

One region with high policy attention on CCS as part of the decarbonization portfolio is Europe. After a long period of hibernation since the early 2000s (Holz et al., 2021; Wang et al., 2021), CCS deployment is gaining momentum, targeting the very sectors where emissions are difficult or expensive to abate. To help achieve climate neutrality by 2050, the EU is facilitating the acceleration of CCS deployment through legislative and regulatory initiatives as part of the "Fit for 55 package". Specifically, in the Net Zero Act adopted in early 2024, the EU set a target to capture and store at least 50 million tons of CO_2 ($MtCO_2$) per year by 2030 (European Commission, 2024). As of November 2023, there are 119 commercial-scale CCS projects in Europe at various stages of planning or advanced development (Levina et al., 2023).[1]

To incentivize CCS investments, the availability of economical CO_2 transport options plays a crucial role. Commercial-scale CO_2 transport infrastructure is needed because European industrial CO_2 emitters are spread across the continent while potential underground storage sites are concentrated where geological formations are favorable (for example, around the North Sea; see Figure 1). Developing such infrastructure involves resolving several techno-economic issues, such as identifying which CO_2 transport modes are feasible, designing optimal transport routes, and estimating transport costs. Numerous techno-economic assessments and optimization studies of CO_2 transport networks have been performed for onshore transport modes (trucks, trains, barges, and pipelines) and offshore modes (ships, pipelines) (Alhajaj & Shah, 2020; Bjerketvedt et al., 2022; d'Amore et al., 2021a; Kalyanarengan Ravi et al., 2017; Knoope et al., 2014; Leonzio et al., 2019; Luo et al.,

[1] The cement and clinker sector is at the forefront of CCS adoption, with major projects announced in 2023 that are projected to reduce emissions by 6.3 $MtCO_2$ per year (Hunt, 2023). Key projects include Grand Ouest CO_2 in France (GRTgaz, 2023), IFESTOS in Greece (European Commission, 2023) and GeZero in Germany (Heidelberg Materials, 2023).

2014; Morbee et al., 2012; Oeuvray et al., 2024; Roussanaly et al., 2013, 2014, 2021). This research has offered valuable insights into potential CO_2 transport modes, routes, and costs. The question of how to finance the upfront investment cost, however, is typically out-of-scope. Yet it matters: Developing a transnational CO_2 transport network in Europe will require substantial initial investments, with estimates ranging from €8.2 billion to €11.6 billion (Tumara et al., 2024). Despite its importance, the issue of how to finance CO_2 transport infrastructure is hardly addressed in the literature. This may be because CO_2 transport in Europe is only developing and there is no historical data on financing of CO_2 assets required for CO_2 transport modes.

However, the financing structure of transport assets is an important determinant of transport cost: Financing conditions are critical for capital-intensive assets, where large parts of the life-cycle costs are incurred upfront and need to be financed. Compared to less capital-intensive solutions, capital-intensive assets are particularly sensitive to financing conditions (Borenstein, 2012; Steffen, 2020; Stocks, 1984). In the case of CO_2 transport, favorable financing conditions could lead to a lower total transport cost, potentially resulting in a shift from less to more capital-intensive transport assets, e.g., from barges to pipelines. It can also affect the economic attractiveness of CCS vis-a-vis other decarbonization options. However, it is the total life-cycle costs of transport, not just the financing part, that ultimately determines the trade-offs. This article, therefore, addresses the following question: *How do financing structures of transport assets impact the total cost of CO_2 transport?*

To address this question, given the absence of empirical data on CO_2 transport financing, our work presents an ex-ante model-based analysis of the impact of financing structures on CO_2 transport costs. We apply insights from the broader economic literature on infrastructure financing to the case of CO_2 transport. More specifically, we review the literature on economic ownership to identify the economic rationales that influences the choice of financing structures and to assess the impact of financing structures on the cost of capital and on operational efficiency. As for other infrastructure assets, several financing structures are available to provide capital for CO_2 transport assets: public finance, private finance, and regulatory asset base (RAB) finance.[2] In terms of financing models, new projects may be added to the balance sheet of an existing company (i.e., corporate finance), or alternatively, a dedicated entity with a separate balance sheet may be established specifically for the project (i.e., project finance) (Esty, 2004; Steffen, 2018). The general consensus in the literature is that financing structures vary by asset and that different financing structures can lead to

[2] In the RAB model, private firms manage, invest in, and operate infrastructure assets, funding their activities through user fees and subsidies. An economic regulator oversees these firms, capping prices and enforcing efficiency to prevent excessive pricing and ensure fair social outcomes (Makovšek & Veryard, 2016).

differences in cost of capital (Arrow & Lind, 1970; Fisher, 1973) and operational efficiency (Goldeng et al., 2008; Megginson & Netter, 2001; Nijkamp & Rienstra, 1995; Shleifer, 1998).

The model-based analysis contains three steps: First, we assess which financing structures are most suitable for the financing of assets required for each CO_2 transport mode by referring to analogous industries with similar asset types and risk profiles. Second, we estimate the financing structure– and transport mode–specific financing cost, namely, the cost of capital. Third, we calculate the levelized cost of transport, accounting for operational efficiency differences related to the different financing structures. We then break down the levelized cost of transport into its cost components to examine the costs attributable to financing.

Our results show that onshore and offshore pipelines are the lowest-cost transport modes regardless of the financing structure. In the onshore transport case (500 km, 1 $MtCO_2$/year), the levelized transport costs of pipelines range from 31 to 38 €/tCO_2 depending on the financing structure, which accordingly leads to a cost markup of 22%. For transport via barges (52-56 €/tCO_2) and trains (78-79 €/tCO_2) the effect of financing structures is smaller. In the offshore transport case (1000 km, 3 $MtCO_2$/year), the levelized transport costs of pipelines range from 30 to 37 €/tCO_2, with a similar effect of the financing structure, compared to 40-42 €/tCO_2 for transport via ships. Public finance emerges as the most cost-effective financing structure for all CO_2 transport modes; the advantages of a lower cost of capital (relative to RAB and private finance) outweigh the associated operational efficiency disadvantages.

We contribute to the existing techno-economic literature on CO_2 transport by adding an important economic aspect, namely financing structures of urgently required CO_2 transport assets. Given the need to develop CO_2 transport infrastructure to meet CCS policy targets in Europe, we hope that studying the impact of financing structures on cost will expand policymakers' attention beyond the question of the total investment required toward the issue of how the financing will be realized. The analysis can inform policymakers aiming to design regulations that attract both public and private investment in CO_2 transport infrastructure, CO_2 emitters evaluating their CO_2 transport options, and project financiers and financial intermediaries considering becoming involved in CO_2 transport finance.

The remainder of the paper is structured as follows. Section 2 bridges two bodies of literature by first examining previous techno-economic insights on CO_2 transport and then summarizing the economic ownership literature on financing structures, focusing on their impact on cost of capital and operational efficiency. Section 3 describes our methods and data. Section 4 presents and discusses our findings, and Section 5 concludes.

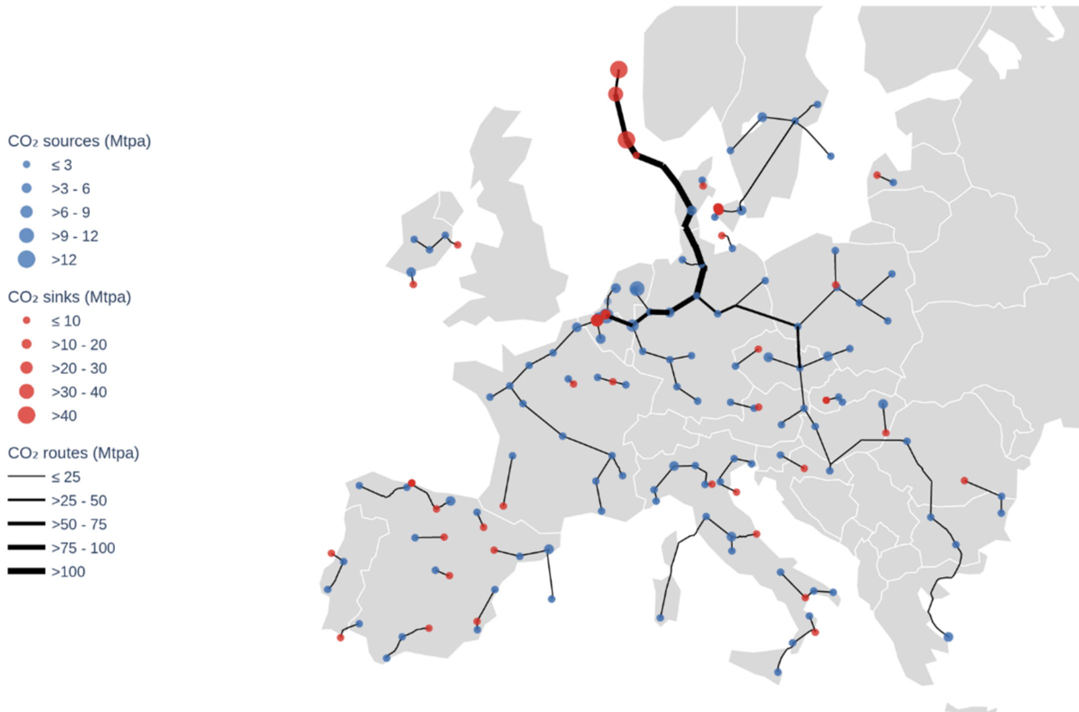

Figure 1: Potential CO_2 transport network in the EU beyond 2030. CO_2 source locations indicate the sites where CO_2 emitters are situated and where carbon capture technologies could be implemented; CO_2 sinks indicate potential storage sites. Own map based on data from (Tumara et al., 2024).

2 Context and financing structures for CO_2 transport assets

CO_2 transport infrastructure in Europe requires rapid development and substantial investment. Economic literature hitherto touches upon CO_2 transport infrastructure with respect to a number of aspects, such as transport cost as an element in the trade-off between CCS and CO_2 utilization (CCU) (Lamberts-Van Assche et al., 2023), the sizing of pipeline systems (Nicolle & Massol, 2023), or game-theoretic considerations concerning the value of transport assets for a group of emitters (Jagu Schippers & Massol, 2020; Massol et al., 2015). Financing structures of transport assets have not been addressed explicitly. In this section, we first review the techno-economic literature on CO_2 transport modes, optimal route design, and cost assessments (Section 2.1). Although this literature implicitly considers the cost of capital as discount rates, estimates of these costs often lack empirical support or clear justification and typically do not specify the financing structures assumed. This omission is relevant because the financing structure directly affects the cost of capital. To address this gap, we review the economic ownership literature, which discusses financing structures for infrastructure assets and their influence on cost of capital and operational efficiency (Section 2.2).

2.1 Previous techno-economic research on CO_2 transport

A large number of techno-economic studies evaluate CO_2 infrastructure. Previous research has identified potential inland transport modes (trucks, trains, barges, and pipelines) and offshore transport modes (ships and pipelines) (Knoope et al., 2014; Oeuvray et al., 2024; Roussanaly et al., 2013, 2014, 2021). For Europe, Oeuvray et al. (2024) suggest a phased approach: they propose initially utilizing container-based transport but transitioning in the medium to long term to dedicated transport via custom-built tanks in trains, barges, ships, and pipelines. Other studies have sought to determine optimal transport routes from emission sources to storage sites in Europe (Bjerketvedt et al., 2022; d'Amore et al., 2018; d'Amore et al., 2021a, 2021b; Elahi et al., 2014; Kalyanarengan Ravi et al., 2017; Knoope et al., 2014; Leonzio et al., 2019; Luo et al., 2014; Morbee et al., 2012; Zhang et al., 2020). Furthermore, several studies have performed levelized cost assessments for newly built CO_2 transport assets (d'Amore et al., 2021b; Knoope et al., 2014; Oeuvray et al., 2024; Roussanaly et al., 2013, 2014, 2021). The findings from this research stream highlight that, for inland transport, barges are the lowest-cost option in the medium term whereas pipelines become cost-competitive in the long term. For offshore transport, both pipelines and ships are projected to be cost-competitive in the long term (Oeuvray et al., 2024; Roussanaly et al., 2013, 2021).

The data used in the levelized cost assessments on CO_2 transport are inherently uncertain, as is typical of ex ante analyses. A notable knowledge gap remains with respect to the cost of capital (as reflected in the discount rate) specific to the financing of assets required for CO_2 transport. Previous CO_2 transport cost assessments have applied discount rates between 8% and 10% (Oeuvray et al., 2024; Roussanaly et al., 2013, 2014, 2021) (with a sensitivity range of 5% to 15%) (Knoope et al., 2014), without justifying these values or discussing the underlying financing structures. These omissions matter because the discount rate is a highly sensitive parameter in levelized cost assessments in general (Lonergan et al., 2023) and in CO_2 transport cost evaluations specifically (Knoope et al., 2014; Oeuvray et al., 2024;

Roussanaly et al., 2013, 2014). Particularly for capital-intensive transport assets such as pipelines, the cost of capital substantially impacts cost estimates, as seen in the sensitivity analysis provided by Oeuvray et al. (2024). Given the nascent stage of CO_2 transport in Europe, there is no historical precedent for financing structures or empirically grounded data on the cost of capital for CO_2 transport assets. Consequently, we revisit the economic ownership literature to identify appropriate financing structures for CO_2 transport assets and derive financing structure–specific cost of capital.

2.2 Financing structures for infrastructure assets

2.2.1 Public and private financing sources

Historically, infrastructure in industrialized countries has been both publicly and privately financed (Helm, 2010). Before the 1970s, infrastructure was primarily financed by the state because public financing allowed political and regulatory risks to be centralized and risk to be shared between taxpayers and customers (Helm, 2010). Public ownership was favored as a perceived safeguard against unregulated market power given the monopolistic character of infrastructure networks (Newbery, 2006). Public financing is characterized by government ownership of infrastructure (Shleifer, 1998), with funding coming from tax revenues and public borrowing (Feldstein, 1984). The government bears all project risks, including those related to investment, and operations (Greco & Moszoro, 2023).

Starting from the late 1970s, there was a noticeable shift toward privatization, with ownership and financing of infrastructure moving to the private sector (Helm, 2010). The goal was to reduce public capital expenditures (Helm, 2010) and transfer risk from public to private entities (Engel et al., 2014). Another key driver was the notion that privatization improves efficiency[3] through competition (Haque, 2000; Okten & Arin, 2006; Yarrow, 1986). Proponents argued that, despite the higher cost of capital associated with private financing, the resulting benefits—such as reduced expenditure and improved project design—would outweigh the costs (Boardman & Vining, 1989; Goldeng et al., 2008; Helm, 2010).

As privatization expanded, market liberalization led to the rise of regulated, privately owned and financed infrastructure utilities under the regulated asset base (RAB) model, whereby the private sector owns, finances, and manages assets under regulatory oversight. The RAB model emerged as a key approach to infrastructure regulation in Europe (Stern,

[3]Efficiency can refer to allocative and operational efficiency. Allocative efficiency is the effectiveness with which resources are allocated to produce the optimal combination of goods and services, thereby maximizing social welfare. In contrast, operational efficiency, or X-efficiency, refers to a firm's ability to improve productivity under competitive pressure (Frantz, 2020). This paper focuses on operational efficiency to compare productivity differences between public and private finance.

2014), applied primarily to the network infrastructure industries with characteristics of natural monopolies: water, energy, and rail. The idea behind the model is to combine the strengths of public and private finance by marrying the lower cost of capital of public financing with the greater operating efficiency of private financing (Christiansen, 2013).[4] Within the RAB model, economic regulation is designed to provide efficiency incentives to the infrastructure manager, which would otherwise operate much like a natural monopoly. These efficiency incentives for the private company arise from its competition with the regulator—the goal of the economic regulation is to simulate the incentives that would typically be generated by market forces (Makovšek & Veryard, 2016).

The transition to privatization and regulated private financing, however, has not settled the broader debate on efficiency and the cost of capital in public versus private financing. While the general consensus among economists is that private entities tend to be more efficient than public ones (Goldeng et al., 2008; Heald, 1997; Lowe, 2008; Megginson & Netter, 2001; Nijkamp & Rienstra, 1995; Shleifer, 1998), some authors caution that efficiency outcomes vary depending on project-specific factors such as management practices and contractual arrangements (Hoppe & Schmitz, 2010) and stress the importance of public oversight in aligning efficiency gains with broader socioeconomic objectives (Nijkamp & Rienstra, 1995).

Beyond efficiency, financing structures also matter for the cost of capital. Theoretical or generally more normative studies advocate a lower discount rate in the public than in the private sector (Arrow & Lind, 1970; Baumol, 1968; Fisher, 1973; Jorgenson et al., 1964; Solow, 1964), with Arrow and Lind (1970) and Fisher (1973) arguing that the public sector can better absorb risks and spread them over a larger number of individuals. Grout (2003) highlights that the inherently higher risks and market imperfections associated with private financing warrant a higher discount rate, and Greco and Moszoro (2023) underscore that publicly financed projects offer greater long-term benefits than privately financed ones, warranting a lower discount rate. Lind (1990) proposed using government borrowing rates as the default discount rate for publicly financed projects, a practice later adopted by three major US federal agencies (Spackman, 2004). Other scholars, however, advocate for a discount rate in the public sector that exceeds the government's borrowing rate, equaling both public and private discount rates. They argue that the government's low borrowing cost is attributable to its unique ability to avoid default and levy taxes, not necessarily to more efficient risk

[4] In terms of efficiency, the RAB model offers adjustable, high-powered incentives for operational efficiency such as detailed monitoring of regulated firms and regular reviews of price caps by regulators over the life of the infrastructure (Makovšek & Moszoro, 2018; Makovšek & Veryard, 2016). In terms of the cost of capital, the RAB model offers one of the lowest, with a cost of capital marginally above that of government bonds (Makovšek & Moszoro, 2018).

management (Baumstark & Gollier, 2014; Brealey et al., 1997; Drèze, 1974; Hirshleifer, 1964; Kay, 1993; Klein, 1997). Recent survey evidence indicates that, among professional economists, there is no consensus on whether the public discount rate should be based on the average cost of capital in the economy, sovereign borrowing costs, or the Ramsey rule, leading to disagreement over the appropriate public discount rate (Gollier et al., 2023).

While the normative literature is divided, with support for both a lower public-sector cost of capital and the view that publicly financed projects should be discounted at the same rate as privately financed ones (Greco & Moszoro, 2023; Lind et al., 2013), empirical evidence from various political systems over a long period suggests that the private sector faces a higher cost of capital than the public sector (Helm, 2010; Shaoul, 2005). For instance, a higher cost of capital for private versus public finance in the provision of infrastructure was observed in Germany as early as 1994 (Bach, 1994) and was recently discussed by the UK HM Treasury Department, concluding that private finance should only be used if it creates efficiency gains in delivery, as non-government lenders face higher cost of capital (UK HM Treasury, 2023). In practice, hence, public finance can lower the cost of capital for infrastructure assets.

2.2.2 Corporate versus project finance models

For private-sector actors, investing in a new project involves choosing a financing model. There are two main options: integrating the project into the existing balance sheet through corporate finance or establishing a separate financial entity using project finance (Esty, 2004; Steffen, 2018). Project finance, as an alternative to the classical way of corporate finance, originated with the development of American railroads in the 19th century. Its use grew during the 1970s to develop oil and gas fields and received further impetus in the 1980s to realize transport projects such as bridges and tunnels (Yescombe, 2014). Although it still represents only a minor portion of overall capital investment, project finance is predominantly employed in three key sectors: power generation, oil and gas, and transport infrastructure (Steffen, 2018).

Corporate finance involves financing projects through a combination of equity and debt on the sponsoring entity's balance sheet. Assets and cash flows from the existing entity are used to guarantee the credit provided by lenders. Under this model, investors and lenders assess risk based on the company's total assets and cash flows, which determines the cost of capital (Steffen & Waidelich, 2022). Therefore, the ability to finance new projects is linked to the strength of the balance sheet, with a strong balance sheet potentially lowering the cost of capital by indicating higher creditworthiness.

Conversely, project finance involves the creation of a new entity, a special purpose vehicle

(SPV), dedicated solely to the project. The SPV's debt and equity are structured to be serviced exclusively from the project's future cash flows (Gatti, 2019), thereby isolating the parent entity from the financial risks associated with the project (Steffen, 2018). As a result, the investment risk profile and associated cost of capital for each project are unique to that specific project (Krupa & Harvey, 2017). The debt share is typically higher under project finance, often ranging from 70% to 90% (Yescombe, 2014), which increases the importance of the cost of debt for the overall cost of capital.

Hence, the cost of capital is calculated differently for corporate finance and project finance because of the different risk characteristics of the respective investments (Steffen & Waidelich, 2022). Regarding operational efficiency, there is no evidence in the literature indicating a difference between corporate finance and project finance.

Taking into account the techno-economic data on CO_2 transport modes (Section 2.1) and insights from the economic ownership literature regarding the choice of financing source and model and its impact on cost of capital and operational efficiency (Section 2.2), in the following analysis, we propose suitable financing structures for five CO_2 transport modes to calculate the mode-specific levelized cost of transport.

3 Data and method

To study the impact of financing structures on the cost of CO_2 transport, we apply established financing structures to CO_2 transport, assuming that the financing structures used in industries with similar asset types or risk profiles are also suitable for CO_2 transport modes (see Section 3.1). Given comparable risk profiles, we can estimate the financing structure–specific cost of capital for each transport mode on the basis of analogue industries. Operational efficiency impacts are considered based on stylized evidence from other sectors. Building on previous CO_2 transport cost assessments (Deng et al., 2019; Oeuvray et al., 2024; Roussanaly et al., 2013, 2014, 2017, 2021), we then calculate the mode-specific levelized cost of transport considering financing structure–specific variations in the cost of capital.

This section is organized as follows. First, we identify suitable financing structures for the financing of assets required for each transport mode (Section 3.1). Second, we calculate the technology- and financing structure–specific cost of capital (Section 3.2). Third, we consider scenarios for the general interest rate level, which affects the cost of capital for all technologies and financing structures (Section 3.3). Fourth, we calculate the levelized cost of transport and conditioning (Section 3.4). Finally, we assess how financing impacts the levelized cost of transport (Section 3.5).

3.1 Assessment of financing structures for CO_2 transport assets

Our analysis focuses on the financing of assets required for CO_2 transport modes in Europe, where CO_2 transport infrastructure is not yet developing and historical financing data are lacking. In line with typical CCS rollout scenarios, we are interested in the financing of CO_2 transport assets in a commercial-scale CO_2 transport network in the mid-to long-term future (beyond 2030). Consequently, our analysis focuses on pipelines, barges, and trains as modes of onshore CO_2 transport and pipelines and ships as modes of offshore CO_2 transport. Truck transport is considered a short-term, transitional mode of CO_2 transport given its limited range and capacity (Oeuvray et al., 2024) and is therefore excluded from the analysis. From the literature review above, we know that infrastructure assets can be financed through public, private, or RAB finance and that projects may be structured under the corporate or project finance models. Drawing on comparisons with other industries that exhibit either the same asset type or a similar risk profile, we conclude which financing structures are most suitable for the financing of assets required for each CO_2 transport mode. Prior literature in energy financing has highlighted that different investments attract different financing sources, largely based on the investment's risk type (Mazzucato & Semieniuk, 2018; Polzin, Sanders, & Serebriakova, 2021; Polzin et al., 2017). These investment risks subsequently impact financing costs by affecting the investors' return expectations (Wiser & Pickle, 1998; Wüstenhagen & Menichetti, 2012). Thus, we identify industries with risks comparable to those of the different CO_2 transport assets, positing that similar risks suggest applicable financing structures.

For *CO_2 transport via pipeline*, we consider financing structures used for electricity grids and natural gas pipelines, as they share similar infrastructure and network management and face similar safety regulations, regulatory compliance and oversight, and economic regulation (Lu et al., 2020). For electricity grids, Steffen and Waidelich (2022) identify revenue risk as a substantial driver of the cost of capital; in particular, network regulation can impact revenue levels and introduce uncertainty. Additionally, technology and operational risks, alongside macroeconomic factors such as changes in general interest rates, impact the cost of capital. For CO_2 pipeline transport, the literature suggests that revenue risk is notably high because of regulatory uncertainty in the emerging industry (Knoope et al., 2015). This risk can be divided into near-term and long-term risks. Near-term risks, particularly concern the amount of CO_2 transported given uncertainties in CCS deployment projections (Holz et al., 2021; Koelbl et al., 2014; Onyebuchi et al., 2017). The long-term revenue risks for pipeline transport, similarly to those for electricity and natural gas, largely relate to network regulation. As the sector matures post-2030, earlier market risks such as infrastructure utilization uncertainty and safety concerns will likely decrease, bringing CO_2 pipeline risks into alignment with those of power and gas energy networks. Technology and operational risks for pipelines are considered low, but there are concerns about CO_2 pipeline corrosion (Onyebuchi et al., 2017) and operational failures that could lead to CO_2 releases (Koornneef et al., 2010). As is the case for the energy sector at large, the CO_2 transport sector is subject to the risk of rising general interest rates. In summary, market risks, technology and operational risks, and interest rate risks are pertinent for CO_2 transport, electricity grids, and natural gas pipelines alike.

For *CO_2 transport via barge, train, and ship*, we assume that the financing structures used for barges, ships and rolling stock in the transport of other heavy goods will apply, given the similar risks and structural characteristics of the assets involved.

3.2 Estimation of cost of capital

Having identified suitable financing structures, we estimate the financing structure– and asset–specific cost of capital for different transport modes.

For investments that use multiple types of capital, such as equity and debt, the total cost of capital is the combined cost of these components. The cost of debt is the interest paid on funds borrowed to finance a project, while the cost of equity is the dividend paid to project shareholders. The common expression of this total cost of capital is the weighted average cost of capital (WACC), where for this analysis, we follow the standard notation (Equation 1) and estimate the cost of debt, the cost of equity, and the debt share separately (Brealey et al., 2020). We use the after-tax WACC (Steffen, 2020):

$$\text{WACC} = \delta(1-\tau)C_{\text{d}} + (1-\delta)C_{\text{e}} \tag{1}$$

where C_{d} and C_{e} are the cost of debt and the cost of equity, respectively. τ represents the corporate tax rate, and δ is the debt share.

We calculate the cost of debt (C_{d}) by adding a debt margin (DM) to the risk-free rate r_{f} (Egli et al., 2018; Schmidt et al., 2019). The additional risk on top of the risk-free rate comprises the debt margin (DM), which reflects the greater risk and yield associated with corporate than with government bonds (Elton et al., 2001). For country-specific cost-of-capital calculations, previous research has added a default spread to account for country risk (Agutu et al., 2022). In our assessment of Western Europe, we use German government bond yields as the risk-free rate and omit a country risk premium because German government bond yields are commonly used as a benchmark in the European Economic and Monetary Union (Gruppe & Lange, 2014; Rodriguez Gonzalez et al., 2017; Tholl & Schwarzbach, 2022). We calculate the cost of debt (C_{d}) as:

$$C_\mathrm{d} = r_\mathrm{f} + \mathrm{DM} \tag{2}$$

The cost of equity (C_e) reflects an investor's expected return from investing in a company. The capital asset pricing model (CAPM) (Lintner, 1965; Sharpe, 1964) remains the predominant method used in corporate finance and financial advising (Baumstark & Gollier, 2014; Donovan & Nuñez, 2012). The cost of equity (C_e) is the sum of the risk-free rate (r_f) and the product of the market risk premium (MRP) and the asset-specific levered beta (β_equity) (Geddes & Goldman, 2022):

$$C_\mathrm{e} = r_\mathrm{f} + \mathrm{MRP} \cdot \beta_\mathrm{equity} \tag{3}$$

We estimate the transport asset–specific WACC in Equation 1 for five different financing structures: public finance (for all transport modes), RAB corporate finance and RAB project finance (for onshore and offshore pipelines), and private corporate finance and private project finance (for barges, trains and ships). The different logics for calculating the cost of capital help us quantify the differences in cost of capital.

3.2.1 Cost of capital in public finance

For *public finance*, we assume that all investments are financed entirely through long-term sovereign debt, eliminating the need to consider the cost of equity (δ=1). We approximate r_f using long-term German government bond rates. Economic principles suggest that using a uniform discount rate for evaluating public sector projects can lead to misallocations if the macroeconomic risk differs (Gollier et al., 2023), but there is no reason to expect that the link between economic growth and the social benefit of CO_2 transport assets differ between transport modes. For the base case, we set r_f to 1.8%, which aligns with the December 2023 rate for 10-year German bonds and reflects Germany's low-risk status that can serve as a benchmark for risk-free rates in Western Europe. Note that when the cost of capital for countries or regions other than Western Europe is assessed, a premium could be added to the risk-free rate to reflect country-specific risk.

3.2.2 Cost of capital in private RAB corporate finance

For *private corporate finance* and *RAB corporate finance*, we model investments as financed by the private sector with incorporation into the sponsoring entity's existing balance sheet. For *RAB corporate finance*, private financing is subject to government regulation. For the WACC (Equation 1), the tax rate τ is held constant at the average corporate tax rate in the euro area (January 2022–December 2023) at 23.8% (OECD, 2023). The debt share (δ), the cost of debt (C_d) and the cost of equity (C_e) are based on Damodaran (2024a). For pipeline assets, we use the debt share (δ) for the "Utility" sector, namely, 52.28%, to reflect the similarity in risk types with electricity grids and gas pipelines. For CO_2 transport via barges, trains and ships, we use the debt share (δ) for the "Transportation" sector, namely, a δ of 20.52%, to reflect our assumption that this mode is subject to the same risk as the transport of other goods via barges, trains and ships. For the cost of debt (C_d) and the cost of equity (C_e), we use the values from Damodaran (2024a) which are calculated based on aggregated debt and equity market values for the "Transportation" and "Utility" sectors in 2023. We convert the values from USD to Euro and take into account inflation (see details in Appendix A).

3.2.3 Cost of capital in private and RAB project finance

For *private project finance* and *RAB project finance*, we model investments as financed by the private sector through an SPV. In *RAB project finance*, private financing is subject to government regulation. We estimate the WACC (Equation 1) by quantifying the cost of debt (C_d (Equation 2)) and the cost of equity (C_e (Equation 3)).

For the WACC (Equation 1), the tax rate τ is held constant at the average corporate tax rate in the euro area (January 2022–December 2023) at 23.8% (OECD, 2023). The debt share (δ) is consistently held at 75% across all transport assets. This choice is supported by insights from expert interviews in the shipping and barge sectors and further validated for pipeline project financing through triangulation with oil and gas financing data (Kim & Choi, 2019).

For the cost of debt (Equation 2), the risk-free rate (r_f) does not differ between financing structures (Steffen, 2020) and is held constant at 1.8%, reflecting the 10-year German government bond rate as of December 2023, identical to the rate that we consider for public finance. The DM reflects the project- and region-specific risk associated with CO_2 transport. Given the absence of credit ratings for CO_2 transport companies, we adopt a synthetic rating approach based on the method in Damodaran (2024b). Here, we analyze financially rated European utilities to identify their long-term credit ratings. Utilities serve as proxies for CO_2 transport companies, given that companies in both sectors provide infrastructure services and utilities possess well-established credit ratings that are useful for financial analysis. As of 2023, the largest European utilities had an average Standard & Poor's (S&P) credit rating of BBB (see Appendix A, Table A2). For infrastructure companies and utilities, the estimated default spread for a BBB credit rating was 1.47% as of January 2024 (Damodaran, 2024c) (see Appendix A, Table A3). Consequently, the DM is 1.47%. This spread, added to the risk-free rate (r_f), determines the cost of debt for an entity.

For the cost of equity (Equation 3), the MRP represents the additional expected return from holding a risky market portfolio relative to that from holding a risk-free asset. For the Western European market, the MRP is set to 6.37%, as determined by Damodaran's (2023b) analysis as of July 2023. The levered beta (β_equity) reflects the asset-specific risk and the return required to compensate for that risk (Steffen, 2020). While levered betas are readily available for listed companies, deriving them for nonlisted companies requires comparison with similar listed companies (Clayman et al., 2012). However, these comparisons often overlook that project finance is typically associated with higher debt ratios than those observed in corporate finance (Steffen, 2020).

To address this discrepancy, we follow the approach of Angelopoulos et al. (2016, 2017) and Partridge (2018) and use market proxies to determine corporate risk through the unlevered beta (β_asset). These β_asset estimates are then adjusted to reflect the specific project debt, yielding the calculated levered beta (β_equity) for each transport asset. β_equity is thus calculated to capture the market sensitivity and inherent risk of the project (β_asset), considering the impact of the financing structure, particularly its debt-to-equity ratio (D/E), adjusted for the corporate tax rate (τ), as shown in Equation 4:

$$\beta_\mathrm{equity} = \beta_\mathrm{asset}\left[1 + (1-\tau)\frac{D}{E}\right] \tag{4}$$

To determine β_asset for the nascent CO_2 transport sector, we reference Damodaran's (2023a) sector-specific beta analysis. For pipeline assets, we use the unlevered beta of 0.45 for the "Utility" sector to reflect the similarity in risk types to electricity networks and gas pipelines. For CO_2 transport via barges, trains and ships, we use the unlevered beta of 0.68 for the "Transportation" sector to reflect our assumption of risk equal to that for transport of other goods via barges, trains and ships. These values are based on the averages of annual estimations from 2017 to 2021. We calculate the D/E ratio $\left(\frac{D}{E}\right)$ by dividing a company's total liabilities (debt) by its shareholder equity, based on the debt share (δ) from Equation 1.

3.3 General interest rate risk

The general interest rate level, typically mirrored by long-term government bond rates, is the risk-free rate (r_f). Thus, changes in the general interest rate level directly impact the cost of capital: An uptick in r_f leads to higher debt issuance rates, thereby increasing the cost of debt (C_d), as shown in Equation 2. This uptick in the r_f can similarly lead to an increase in the cost of equity (C_e), as shown in Equation 3.

For public finance and private project finance, we use the 10-year German government bond rate as a proxy for r_f in Western Europe. Figure 2 illustrates the trajectory from January 1974 to December 2023 of monthly 10-year German government bond rates, denominated in euros (OECD, 2024). The rates followed a downward trend, albeit with some fluctuations, until 2022, reaching a low of -0.65% in August 2019. The aftermath of the COVID-19 pandemic and its economic impact pushed the 10-year German government bond yield to 2.1% by December 2023 (OECD, 2024).

To assess how varying general interest rates affect the cost of capital across different transport assets, and subsequently transport costs, we examine three interest rate scenarios: In the base case scenario, r_f is set to 1.8%, reflecting the 2-year average of the 10-year German government bond rate from 2022 to 2023. In the moderate increase scenario, r_f is set to 4.9%, reflecting the 50-year average from 1974 to 2023. In the moderate decrease scenario, r_f is set to 0.5%, reflecting the 10-year average from 2014 to 2023.

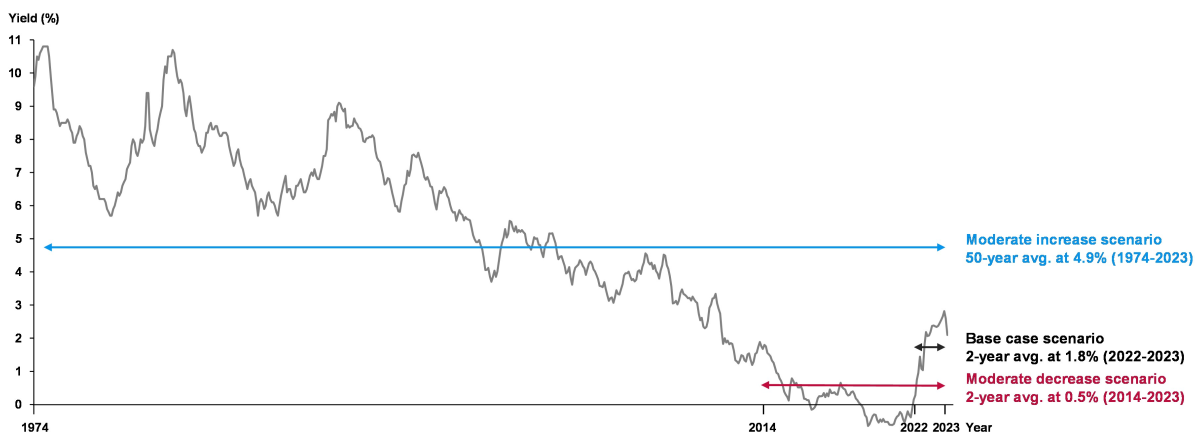

Figure 2: General interest rate level scenarios; historical development of 10-year German government bond yields and interest rate scenarios based on historical estimates; in the baseline scenario (black line), interest rates are kept constant at the 2-year average from 2022 to 2023 of 1.8%; in the moderate increase scenario (blue line), interest rates rise to the 50-year historical average from 1974 to 2023 of 4.9%; in the moderate decrease scenario (red line), interest rates fall to the 10-year average from 2014 to 2023 of 0.5%

3.4 Levelized cost of transport

To analyze the social cost of CO_2 transport, we require a metric that encompasses all cost components. While the time of day and location are irrelevant for CO_2 transport, different transport assets feature distinct cost components and asset lifetimes. Additional cost factors are the amount of CO_2 transported and the distance of transport. Therefore, to make the social costs of different transport assets comparable, we employ a levelized cost metric by aggregating each mode's lifetime investment and operating expenses into a single unit cost. This extends the traditional levelized cost of energy (LCOE) approach used for energy technologies to accommodate the varying lifetimes of projects (Friedl et al., 2023).

The levelized cost approach also accommodates variances in the cost of capital (reflected in discount rates), which affects the total cost. Realistic cost-of-capital rates are especially important for deciding between different technology investments (Borenstein, 2012; Hirth et al., 2016). Stocks (1984) was the first to propose using different discount rates for different energy technologies, noting that high discount rates disproportionately affect cost estimates for capital-intensive technologies. Hirth and Steckel (2016) and Schmidt (2014) demonstrate this by comparing the LCOEs for various power generation technologies at different cost of capital, showing that while all technologies show LCOE increases under rising cost of capital, the most capital-intensive ones display the greatest increases.

The reason for these variations is that different technologies exhibit different cost structures. In addition, different technologies have different risk profiles because of their differential exposure to policy risk and fuel price uncertainty, which also justifies the use of technology-specific cost-of-capital rates (Angelopoulos et al., 2016; Egli et al., 2018).

The levelized cost approach also accommodates variances in operational efficiency (reflected in the operational cost), which affects the total cost. This is important for comparing costs across financing structures. Scholars have argued that efficiency differs between financing structures (Heald, 1997; Megginson & Netter, 2001; Nijkamp & Rienstra, 1995; Shleifer, 1998). Goldeng et al. (2008) demonstrates this by showing a systematic efficiency gap between public and private entities, with public entities generally exhibiting higher operational costs.

We calculate the levelized cost of transport (LCOT) to assess the per-unit cost of CO_2 transport over the lifetime of the asset. We calculate the levelized costs for each transport mode i (onshore and offshore pipelines, barges, trains, and ships) and for the conditioning units, namely, liquefaction units for barges, trains and ships and compression units for pipelines.

$$\text{LCOT}_i = \frac{C_i^{\text{inv}} + \sum_{t=1}^{t=y} \frac{\eta C_{it}^{\text{op}}}{(1+r_i)^t}}{\sum_{t=1}^{t=y} \frac{Q_{it}}{(1+r_i)^t}} \tag{5}$$

where C_i^{inv} is the initial investment cost (capex) per ton of CO_2 capacity at $t = 0$. The operation and maintenance costs per ton of CO_2 capacity per year, denoted C_i^{op}, are constant from $t = 1$ to $t = y$, where y marks the end of the asset's lifetime. η reflects different cost efficiencies, where a publicly financed asset incurs an additional percentage markup on operational costs ($\eta_{\text{public finance}} = 1.05$ versus $\eta_{\text{RAB finance}}$ and $\eta_{\text{private finance}} = 1$). Q_{it} is the full capacity in tons of CO_2 per year transported by asset i from $t = 1$ to $t = y$ (constant). The discount rate r_i is specific to the technology and finance structure of each asset, $r_i = \text{WACC}_i$.

Table 1 lists the investment cost C_i^{inv} and operation and maintenance cost C_i^{op} parameters for the levelized cost of transport and conditioning for each transport mode, as per the operating models assumed in this study. For CO_2 transport via trains, it is assumed that investors purchase the wagons but rent the service. For CO_2 transport via barges, ships, and pipelines, investors are presumed to buy and operate the transport mode, covering all associated costs. Any transport mode receiving and delivering CO_2 requires CO_2 conditioning before transport. For pipelines, CO_2 conditioning before transport involves compression and pumping (Roussanaly et al., 2013). For barges, trains and ships, CO_2 conditioning before transport involves liquefaction (Deng et al., 2019; Roussanaly et al., 2021). Conditioning is financed solely through private corporate finance. This expectation is grounded in the assumption that these units will be operated by CO_2 emitters, such as cement and steel plants.

The equations and data used are adopted from existing techno-economic studies on CO_2 transport. Specifically, for trains, the calculations and data are based on Roussanaly et al. (2017) and Oeuvray et al. (2024); for barges, the calculations are based on Oeuvray et al. (2024), while the data are based on an interview with a barge transport provider; for ship transport, the calculations and data are based on Roussanaly et al. (2021), UK Department for Energy Security and Net Zero (2018) and Seo et al. (2016); and for pipelines, the calculations and data are based on van den Broek et al. (2010), Knoope et al. (2014) and Oeuvray et al. (2024). Detailed equations for the cost parameters are given in Appendix C, in accordance with Equation 5 and Table 1. The equation numbers listed in Table 1 correspond to those found in Appendices C and D.

The data for the cost input parameters are from a diverse range of sources, reflecting the specific transport and loading conditions of each transport mode. Detailed information on the transport and conditioning cost data, including associated references, is provided in Appendix E. The fuel cost data are obtained from informal sources and have been cross-referenced with prior academic studies on CO_2 transport costs. Similarly, the electricity cost data are acquired from Eurostat. The energy cost assumptions, along with the relevant sources, are listed in Appendix E. All values are given in $€_{2022}$ terms. Nominal values are converted to real $€_{2022}$ with the European consumer price index (ECB, 2023a).

Our analysis covers transport costs (divided into capital and operating costs and financing costs) and conditioning costs for two cases: a 500 km route with a capacity of 1 $MtCO_2$ per year (onshore) and a 1000 km route with a capacity of 3 $MtCO_2$ per year (offshore). Table 2 lists the resulting investment cost C_i^{inv} and operation and maintenance cost C_{it}^{op} for each transport mode. A detailed sensitivity analysis of the levelized transport and conditioning

Table 1: Transport and conditioning cost parameters (equation numbers refer to Appendices C and D)

Cost		**Onshore transport**			**Offshore transport**	
Terrain		Pipeline	Barge	Train	Pipeline	Ship
C_i^{inv}	Pipe	(C.1.1)			(C.1.1)	
	Pumping stations	(C.1.1.4)			(C.1.1.4)	
	Carrier		(C.2.1)			(C.4.1)
	Loading stations			(C.3.1)		(C.4.1)
	Wagon			(C.3.1)		
	Intermediate storage		(C.5.1)	(C.5.1)		(C.5.1)
	Compression	(D.1.1)			(D.1.1)	
	Liquefaction		(D.2.1)	(D.2.1)		(D.2.1)
C_{it}^{op}	Pipe	(C.1.2)			(C.1.2)	
	Pumping station	(C.1.2.2)			(C.1.2.2)	
	Loading stations			(C.2.1)		
	Fuel		(C.2.2)			(C.4.2)
	Transport/service			(C.3.2)		
	Harbor fee/other		(C.2.2)			(C.4.2)
	Intermediate storage		(C.5.2)	(C.5.2)		(C.5.2)
	Compression	(D.1.2)			(D.1.2)	
	Liquefaction		(D.2.2)	(D.2.2)		(D.2.2)

costs as a function of distance and capacity transported is available in Appendix F.

Table 2: Investment cost and operation and maintenance cost in €$_{2022}$ for each transport mode at 500 km and 1 $MtCO_2$/year for onshore transport and 1000 km and 3 $MtCO_2$/year for offshore transport

Terrain	**Onshore transport**			**Offshore transport**	
Transport mode	Pipeline	Barge	Train	Pipeline	Ship
Distance (d)		500 km		1000 km	
Capacity (m_i)		1 $MtCO_2$/y		3 $MtCO_2$/y	
$C_i^{\text{inv}}(d, m_i)$	301 M€	129 M€	61 M€	856 M€	164 M€
$C_{it}^{\text{op}}(d, m_i)$	4.8 M€/y	11.4 M€/y	39.9 M€/y	14.6 M€/y	19.1 M€/y

3.5 Impact of financing structures on the levelized cost of transport

Impact of cost of capital on levelized cost of transport

To assess the impact of the cost of capital on the levelized cost of transport, we follow the approach of Egli et al. (2018) in splitting the levelized cost into a capital and operating cost component and a financing cost component. We do so by estimating the levelized cost with a 0% cost of capital for each transport mode in each year.

We define the difference between the levelized cost estimated using the technology- and finance structure–specific cost of capital and the levelized cost estimated with the 0% cost of capital as the financing cost share δ^{f}, according to Equation 6:

$$\delta_i^{\mathrm{f}} = \mathrm{LCOT} - \mathrm{LCOT}_{\mathrm{CoC}=0} \tag{6}$$

Impact of ownership efficiency on levelized cost of transport

To assess the impact of ownership efficiency on the levelized cost of transport, we integrate efficiency differences between financing structures by incorporating an operational cost efficiency loss. To make it feasible to compare their operational efficiency, we assume that, in CO_2 transport, public and private companies operate in the same market with the same objectives. While economists generally agree that private entities tend to be more operationally efficient than public entities (Heald, 1997; Megginson & Netter, 2001; Nijkamp & Rienstra, 1995; Shleifer, 1998), empirical studies on this topic are limited. We draw on Goldeng et al. (2008), who test the effect of ownership type and financing source on firm performance using Norwegian company data. Their findings show an efficiency gap between public and private entities, with private entities typically being more cost-efficient. Specifically, the regression models indicate that private entities have a 4–5% lower operational cost share because of their higher operational efficiency. Based on this empirical evidence, we adjust the operational cost for publicly financed assets to include a 5% cost markup on operational costs C_{it}^{op} for each transport mode.

4 Results

4.1 Suitable financing structures

For *CO_2 transport via pipeline*, the financing structures used in electricity and natural gas networks are suitable given the similarity of the sectors' risk types, including their market, technology and operational and interest rate risks (see Section 3.2). These similarities with energy networks, often regulated as natural monopolies given the limited competition in their markets, support the case for public financing of pipelines to prevent monopolistic practices (Anuta et al., 2014; Jamasb & Pollitt, 2007). Moreover, in Europe, RAB-like financing is favored for infrastructure projects, including those for electricity and gas (Stern, 2014). In the UK, the RAB model was chosen as the preferred financing option for CO_2

pipeline projects, following a public consultation (UK Department for Business, Energy and Industrial Strategy, 2020). These points suggest that both public and RAB financing are practical choices for CO_2 pipeline investments.

For *CO_2 transport via barge*, barges have been financed through both public and private finance in Europe since the early 2000s (Załoga & Kuciaba, 2014). Hence, we consider that both public and private finance could be adapted for CO_2 barge transport. Given the lack of precedent for RAB financing in the barging sector in Europe, it is unlikely to be used to finance CO_2 shipping via barges.

For *CO_2 transport via train*, from 2015 to 2017, two-thirds of the financing of Europe's rolling stock, such as the trains used on railways, was public, and the remaining one-third was private (Dvorakova, 2019). Assuming similar financing sources, we consider that both public and private finance could be adapted for CO_2 rail transport. Given the lack of precedent for RAB financing of goods requiring dedicated tanks permanently integrated into trains in Europe, it remains unlikely that this financing structure will be used for CO_2 transport of this kind.

For *CO_2 transport via ship*, shipping finance in Europe generally relies on private sources, utilizing either corporate or project finance (Goulielmos & Psifia, 2006). However, for liquefied natural gas (LNG), the German Federal Ministry for Economic Affairs and Climate Action allocated €62 million to support the construction of three LNG bunker vessels by a consortium of shipping companies in an investment that combined public and private financing (German Federal Ministry for Economic Affairs and Climate Action, 2022). Hence, we consider that both public and private finance could be adapted for CO_2 shipping. Given the lack of precedent for RAB financing in the shipping sector in Europe, we deem it unlikely to be used to finance CO_2 shipping.

As a summary, Table 3 outlines the financing source and financing model that we consider suitable for the assets required for each CO_2 transport mode. For all transport assets, public finance is listed as an option. In addition, pipelines may be financed through RAB corporate finance and RAB project finance, while the other transport assets may be financed by private corporate finance and private project finance[5].

[5]We expect CO_2 conditioning (liquefaction and compression) to be financed solely through private corporate finance, on the basis of the assumption that these units will be operated by CO_2 emitters, such as cement and steel plants (see Section 3.4).

Table 3: Financing structures for CO_2 transport modes (✓indicates suitability for the respective transport mode)

Asset	**Public finance**	**Private corporate finance**	**Private project finance**	**RAB corporate finance**	**RAB project finance**
Pipeline	✓	-	-	✓	✓
Barge	✓	✓	✓	-	-
Train	✓	✓	✓	-	-
Ship	✓	✓	✓	-	-

4.2 Cost of capital under different financing structures

Based on the suitable financing structures identified for pipelines (public finance, RAB corporate finance, and RAB project finance) and for barges, trains and ships (public finance, private corporate finance, and private project finance), Figure 3 shows the WACC in our main interest rate scenario for CO_2 transport and conditioning assets. Across these different financing structures and transport assets, the estimated WACC ranges from 1.8% to 7.1%. Public finance consistently shows the lowest WACC at 1.8%, whereas corporate finance generally incurs a higher WACC than project finance for both RAB finance and private finance. Specifically, for pipelines, the WACC for RAB corporate finance is 0.7 percentage points higher than that for RAB project finance. For barges, trains and ships, the WACC for corporate finance is 1.5 percentage points higher than that for project finance.

An important factor driving the lower WACC in project finance is the higher debt share: a 75% debt share in RAB project finance versus 52.28% in RAB corporate finance for pipelines, and a 75% share versus 20.52% in project finance versus corporate finance for trains, barges, ships, and conditioning units. Debt is typically less expensive than equity and offers tax benefits (see Equation 1), which reduces the after-tax WACC. Despite the higher cost of equity in project finance (because of the perceived risk)—3 percentage points higher in RAB project finance than in RAB corporate finance and 6.9 percentage points higher in project finance than in corporate finance for the other transport assets—the larger share of cheaper, tax-deductible debt leads to a lower overall WACC in project finance than in corporate finance.

Figure 3 also shows that within private finance and RAB finance structures, the estimated WACC is lower for pipelines than for trains, barges, ships, and conditioning units. In corporate finance, the lower estimated WACC for pipelines is driven by the higher debt ratio in the capital structure: 52.28% compared to 20.52% for barges, trains and ships (see Appendix A, Table A1). This means that the cost of debt, reduced by tax deductibility, influences the estimated WACC more than the cost of equity. In project finance, while the cost of debt and the debt ratio are consistent across all transport assets, variations in the estimated WACC arise from differences in the cost of equity, which is impacted by the levered beta. The beta value for pipelines of 1.48 is lower than that of the other modes at 2.23, indicating lower systematic risk from the perspective of equity investors, which results in a lower cost of equity and, consequently, a lower WACC.

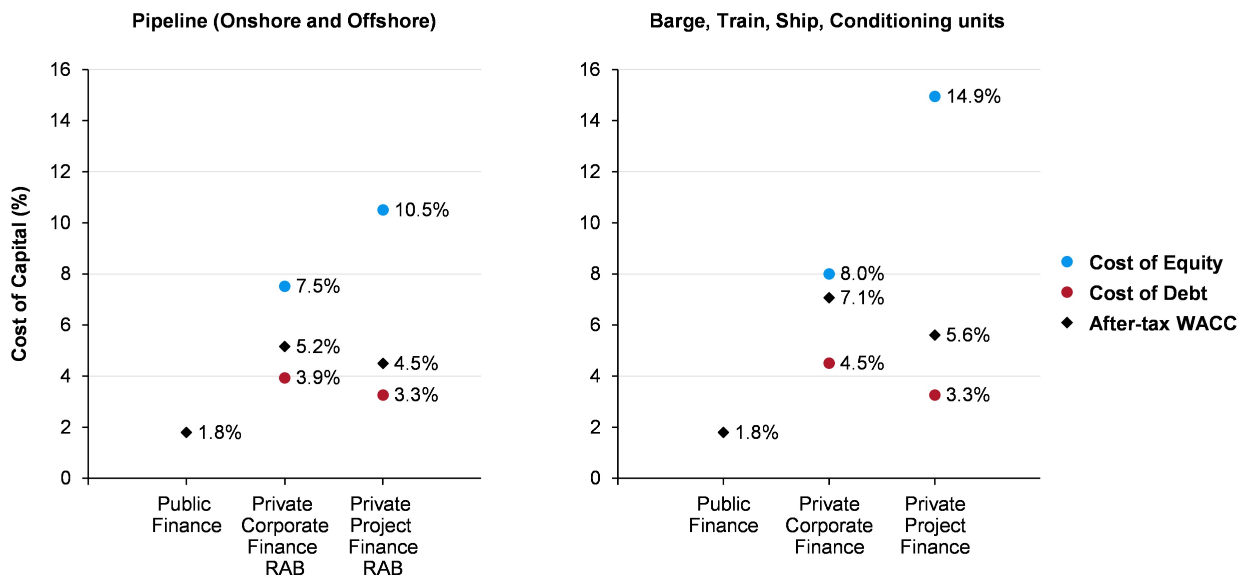

Figure 3: Technology- and finance structure–specific weighted average cost of capital of CO_2 transport assets in Europe in our main interest rate scenario ($r_f = 1.8\%$)

4.3 Impact of financing structures on CO_2 transport costs

Figure 4 shows the levelized cost of CO_2 transport across different financing structures. In the onshore transport case (500 km, 1 $MtCO_2$/year), our results show that onshore pipelines are the lowest-cost transport option regardless of the financing structure at 31-38 €$_{2022}$/tCO_2, which is 21-48 €$_{2022}$/tCO_2 cheaper than levelized cost of barges, and trains. More specifically, under public finance, transport and conditioning via onshore pipeline is 41% and 61% cheaper than that via barge and train (33% and 53% cheaper under project finance and 32% and 52% under corporate finance). This cost advantage is largely due to the lower cost of CO_2 compression over CO_2 liquefaction, with the compression costs being half the liquefaction costs. The results also show differences in levelized cost between the financing structures. Public finance results in the lowest combined costs for transport and conditioning across all transport modes despite incorporating an efficiency loss reflected in a 5% markup on operational costs. Public finance reduces the share of financing costs in total transport expenditure to 1–10%, in contrast to the 4–28% and 3–25% observed for corporate and project finance, respectively.

In the offshore transport case (1000 km and 3 $MtCO_2$/year), our results show that the cost patterns are consistent with those observed in the onshore case. Offshore pipelines are the lowest-cost transport option regardless of the financing structure at 30-37 $€_{2022}/tCO_2$. More specifically, under public finance, transport and conditioning via offshore pipeline is 25% cheaper than ship transport (13% cheaper under project finance and 11% under corporate finance). The costs associated with CO_2 conditioning in offshore settings mirror those for onshore transport, with the compression costs being half the liquefaction costs. The results also show differences in levelized cost between the financing structures. Public finance results in the lowest combined costs for transport and conditioning for both offshore pipelines and ships. Public finance reduces the share of financing costs in total transport expenditure to 1–10%, in contrast to the 6–28% and 5–24% observed for corporate and project finance, respectively.

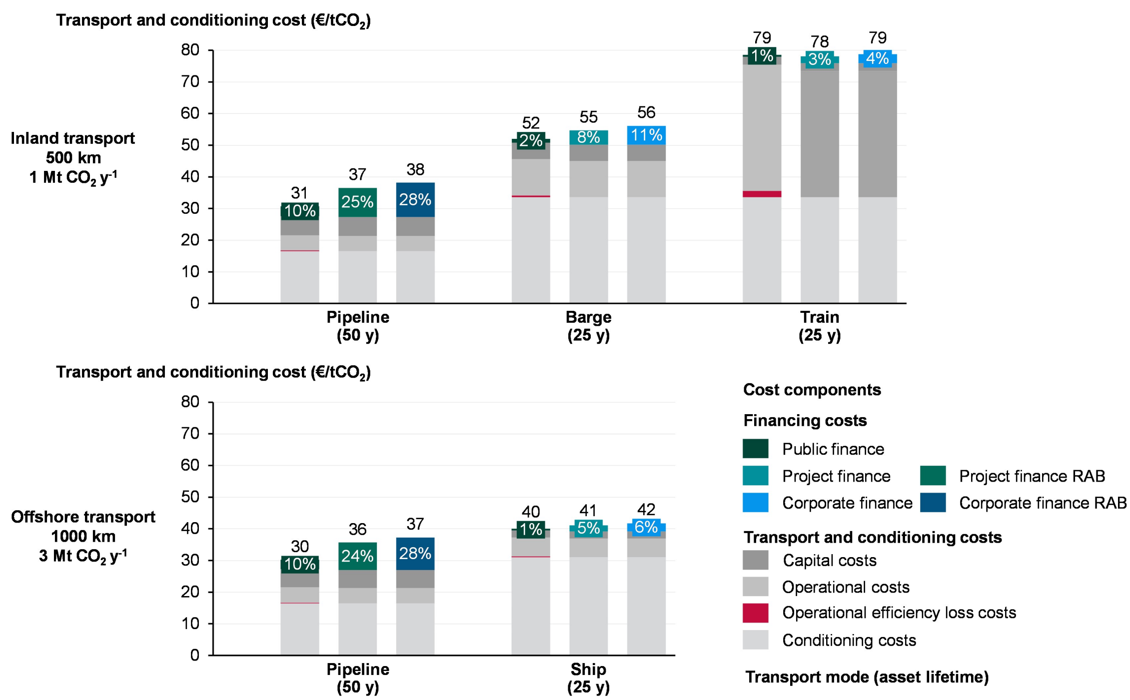

Figure 4: Levelized cost assessment of CO_2 transport and conditioning in $€_{2022}/tCO_2$ under different financing structures (conditioning includes CO_2 compression before pipeline transport and liquefaction before transport by barge, train, and ship; conditioning is always financed through private corporate finance).

Pipelines, both onshore and offshore, incur a higher proportion of financing costs than do other transport modes. However, they also exhibit the lowest combined transport and conditioning costs across all financing structures. The high share of financing costs for pipelines stems from their capital-intensive nature (e.g., upfront investment costs of 301 M€$_{2022}$ and annual operation cost of 4.8 M€$_{2022}$ for onshore pipelines; see Table 2). The long asset lifetime of 50 years also affects the financing costs. To assess whether pipelines maintain their cost-effectiveness with a hypothetical (unrealistic short) asset lifetime of 25 years, we adjust these parameters (see detailed analysis in Appendix G). The results show that pipelines continue to be the most cost-effective option for onshore transport. In offshore transport, while pipelines remain cost-effective under public finance, the levelized transport costs under project and corporate finance become comparable to those of ships.

4.4 Impact of different general interest rates

All CO_2 transport modes are sensitive to the general interest rate level. General interest rates directly impact financing costs, which in turn impacts the cost of capital-intensive assets (Schmidt et al., 2019). General interest rate dynamics are particularly relevant given the ten consecutive interest rate increases by the European Central Bank between July 2022 and October 2023 (ECB, 2023b).

To assess the impact of changes in general interest rates on levelized transport costs, we adjust the risk-free rate. Starting from a base case scenario with a risk-free rate (r_f) of 1.8%, we alter the rate by ±4 percentage points to calculate the effects on levelized transport costs, as shown in Figure 5. We compare two financing structures for each CO_2 transport mode: public finance, typically offering the lowest cost, and project finance, which is usually more expensive; this includes RAB project finance for onshore and offshore pipelines and private project finance for barges, trains, and ships.

Given their high financing costs, onshore and offshore pipelines are particularly sensitive to shifts in general interest rate levels. For onshore pipelines under public finance, a 4-percentage-point increase in r_f—from 1.8% to 5.8%—results in a 67% increase in the levelized cost of transport, which rises from 13.9 €$_{2022}$/tCO_2 to 23.3 €$_{2022}$/tCO_2. For RAB project finance, a 4-percentage-point increase in r_f—from 1.8% to 5.8%—results in a 44% increase in the levelized cost of transport, from 20 €$_{2022}$/tCO_2 to 28.7 €$_{2022}$/tCO_2. For RAB corporate finance, a 4-percentage-point increase in r_f—from 1.8% to 5.8%—results in a 44% increase in the levelized cost of transport, from 21.6 €$_{2022}$/tCO_2 to 31.2 €$_{2022}$/tCO_2.

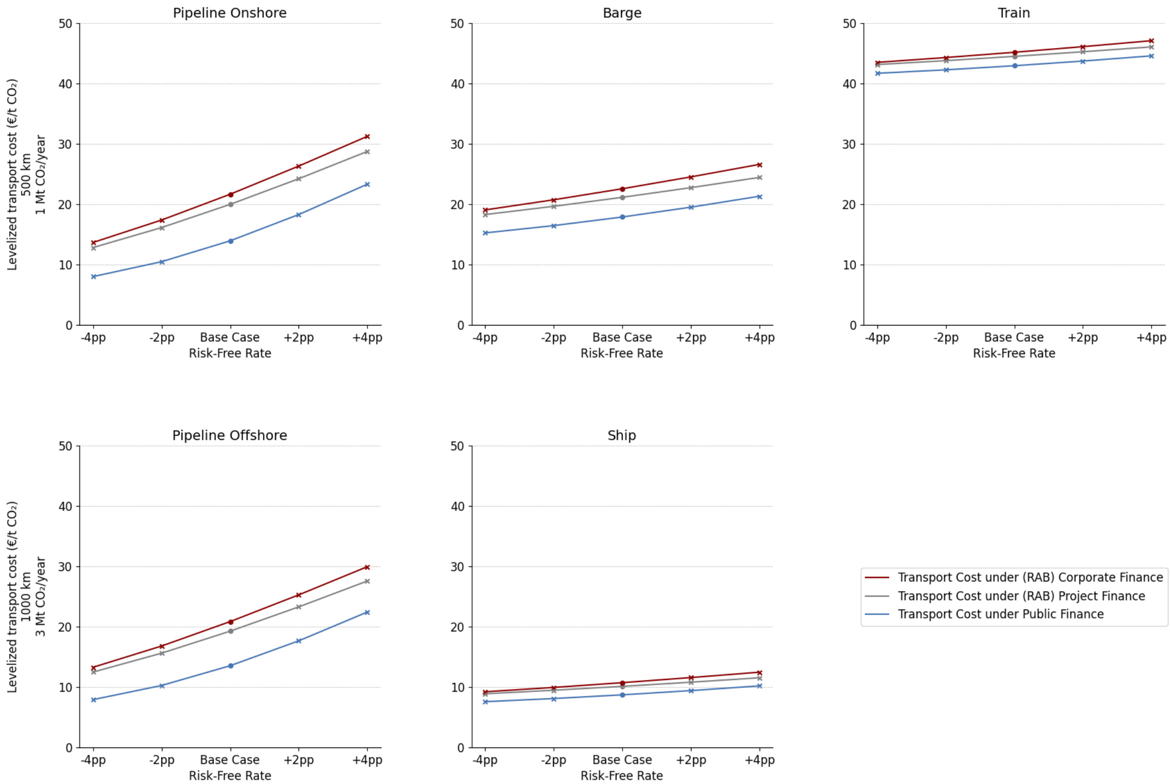

Figure 5: Sensitivity analysis of the levelized cost of CO_2 transport in our main interest rate scenario (r_f = 1.8%); The panels illustrate the impact of a ±4-percentage-point change in the risk-free rate on transport mode-specific costs under different financing structures; financing structures include public finance (blue), RAB project (grey) and RAB corporate finance (red) for onshore and offshore pipelines, and private project (grey) and private corporate finance (red) for barges, trains, and ships.

Given the substantial impact of general interest rate levels on the levelized cost of pipelines, we zoom in on the results for onshore pipelines. In Figure 6, we compare the levelized pipeline transport costs for public finance and RAB project finance under three long-term general interest rate scenarios: the base case of 1.8%, an increased rate of 4.9%, and a decreased rate of 0.5%.

Under public finance, the base case levelized transport cost is 14.2 €$_{2022}$/tCO_2, with the financing cost comprising 22% of this. An increase in the general interest rate to 4.9% triples the financing costs from 3.1 to 10.2 €$_{2022}$/tCO_2. This, in turn, increases levelized transport costs by 50%, with the total costs evenly split between financing and the sum of capital and operating costs. Conversely, if the general interest rate drops to 0.5%, financing costs decrease by 75% to 0.8 €$_{2022}$/tCO_2, reducing the levelized transport costs by 17% and lowering the financing cost share to 7%.

Under RAB project finance, the base case levelized transport cost is 20 €$_{2022}$/tCO_2, with the financing cost comprising 46% of this. An increase in the general interest rate to 4.9%

raises the financing costs by 40% from 9.2 to 12.8 €$_{2022}$/tCO_2. This, in turn, increases the levelized transport costs by 18%, so that the financing cost share accounts for more than half of the total levelized transport costs. Conversely, if the general interest rate drops to 0.5%, the financing costs decrease by 55% to 4.1 €$_{2022}$/tCO_2, thereby reducing the levelized transport costs by 25% and the financing cost share to 28%.

The sensitivity of financing costs to changes in general interest rates is notably higher for public finance than for RAB project finance. Public finance is tied closely to government-backed securities whose returns move directly with the general interest rate. More technically, since the WACC in public finance directly corresponds to the risk-free rate, any alteration in the general interest rate leads to a corresponding and proportional adjustment in the WACC.

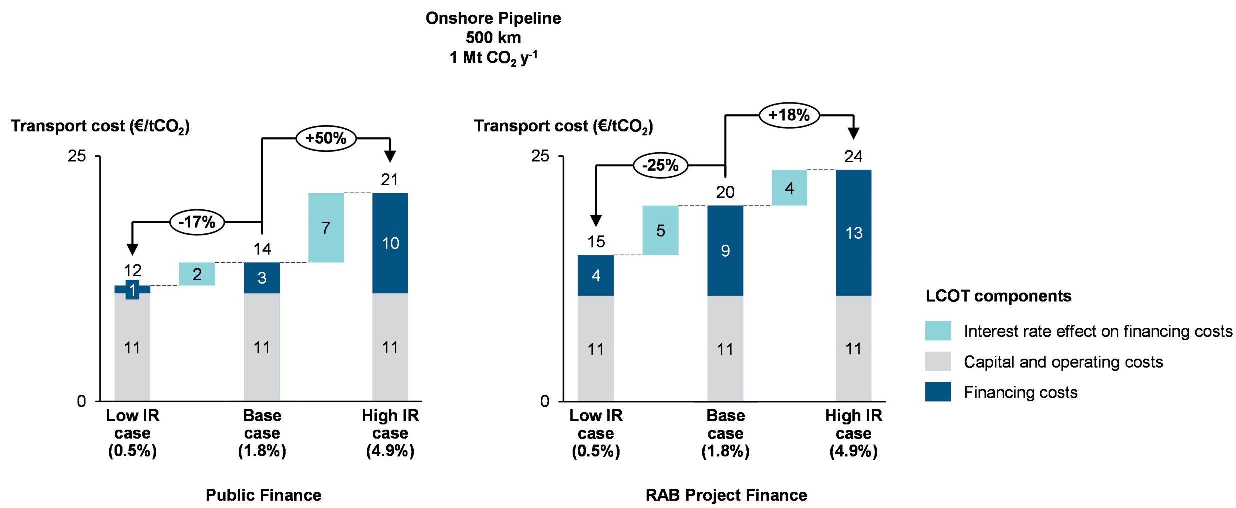

Figure 6: General interest rate level scenarios; levelized transport cost comparison for onshore pipelines at 500 km and 1 MtCO_2/year for public finance and RAB project finance; middle bars show the base case interest rate of 1.8%, reflecting the 10-year German government bond rate as of December 2023; left bars show a scenario with a decreased interest rate of 0.5%; right bars show an increased interest rate of 4.9%.

5 Discussion and conclusion

Overall, we find that the impact of financing structures on the cost of capital and thus the cost of CO_2 transport varies notably by transport mode but also by financing structure. Comparing onshore transport modes (pipelines, barges, ships; 500 km, 1 MtCO_2/year) under public finance, we find a cost difference of 48 €$_{2022}$/tCO_2, with pipeline transport at 31 €$_{2022}$/tCO_2 and train transport at 79 €$_{2022}$/tCO_2. Under RAB and private corporate finance, the cost difference is 41 €$_{2022}$/tCO_2, with pipeline transport at 37 €$_{2022}$/tCO_2 and train transport at 78 €$_{2022}$/tCO_2. Pipelines, which require high upfront capital investments, are highly sensitive to the financing structure chosen (reflected in transport costs of 31

€$_{2022}$/tCO_2 versus 38 €$_{2022}$/tCO_2 with different financing structures, ceteris paribus). With a cost of capital of 8.5% or above, financing costs could account for more than half the total transport costs for onshore pipelines (see Figure 6). In contrast, for the other CO_2 transport modes, including barges, trains and ships, we find a relatively small impact of different financing structures. Hence, our results highlight the importance of low financing costs for the feasibility of particularly capital-intensive pipelines.

Generally, our results suggest that public finance appears to be the most cost-effective financing structure for CO_2 transport infrastructure, if the government cost of capital sets the discount rate. However, it is highly sensitive to fluctuations in the general interest rate. Levelized transport costs for an onshore pipeline could be 50% higher if the general interest rate increases from 1.8% to 4.9%. In contrast, under RAB project finance—where the risk-free rate contributes only partially to both the cost of debt and equity—the increase in transport costs is lower at 18%. This sensitivity matters for newly built pipelines, and potentially also for existing infrastructure if the financing conditions are not locked in (but floating with interest levels). Public finance consistently offers the lowest financing costs because the benefits of a lower cost of capital under public finance, compared to RAB and private finance, outweigh the operational efficiency losses associated with it. However, these results are contingent upon our assumptions—we assume a 5% operational efficiency loss under public finance. The understanding of efficiency differences both between public and private financing structures, and among various types of public delivery remains very limited, highlighting the need for further empirical research.

Our findings are relevant for policymakers, as the cost of financing is an important factor in the choice of a financing structure for CO_2 transport infrastructure. However, there are also other important factors at play: On the one hand, the development of the CCS industry depends on a timely deployment of transport infrastructure, especially in light of the ambitious CO_2 injection targets of 50 Mt/year by 2030 in Europe (European Commission, 2023). Policymakers need to ensure efficient and rapid development of CO_2 transport infrastructure to avoid jeopardizing these targets. Here, private or regulated finance could be advantageous. On the other hand, specifically for pipelines, private finance could impact accessibility and usage rights if the financing entity retains full control over the pipeline's usage. The key characteristic here is exclusivity; the pipeline is typically designed to serve the owner's interests, which might include prioritizing its own transport needs over others.[6] Absent effective regulation of pipeline access and third-party usage, the owner can exercise

[6] In the United States, for example, existing CO_2 transport pipelines are privately owned and managed by oil and gas companies, directly linking CO_2 sources to oil fields for enhanced oil recovery (Parfomak, 2023).

market power by excluding other users (Hubert & Orlova, 2018). In contrast, pipelines built under public finance or regulated private finance can be designed with a broader public benefit in mind, including maximizing utility and accessibility. Beyond costs, these scenarios should be considered in broader network considerations to facilitate more efficient and widespread use of the infrastructure, allowing various emitters to transport CO_2.

For researchers, our findings suggest that assessing the economic viability of CCS (including transport) requires a detailed examination of the role of finance in levelized cost assessments. Currently, techno-economic studies omit the representation of financing sources and structures. Our results indicate that different financing structures lead to varying total transport costs, which are also influenced by changes in general interest rates. These findings are relevant not only for CO_2 transport but also for capital-intensive CO_2 capture and storage installations. If researchers fail to account for these dynamics, they might over- or underestimate the costs. This is critical as levelized cost assessments from techno-economic studies serve as inputs for integrated assessment models (IAM) that describe the role of CCS in decarbonization pathways (Dalla Longa et al., 2020; Schreyer et al., 2024; van Sluisveld et al., 2021).

Regarding the limitations of our analysis, first, it is important to note that our approach does not capture the variance in risks across different countries, which presents an opportunity for future research. For instance, differences in country risk can be relevant even in the same region, as in Europe between countries such as Germany and France (Polzin, Sanders, Steffen, et al., 2021). Future research should detail these variances to explore the extent to which the conclusions of this paper apply to other regions. Second, for the public finance options we do not differentiate the cost of capital between the different transport modes - this is in line with budgetary practices in many countries, but future model-based research could evaluate potential differences in investment risks from a public sector point of view. Third, our analysis focuses solely on greenfield investments, assuming that CO_2 transport assets will be newly constructed. The possibility of retrofitting existing natural gas pipelines for CO_2 transport, similarly to proposals made for hydrogen (ACER, 2021), could be an interesting avenue for future research. In such cases, stakeholders need to assess not only the technical feasibility of retrofitting an existing pipeline for CO_2 transport but also its financial viability within the prevailing economic and regulatory framework. While retrofitting could prove to be less capital-intensive than greenfield investments - thereby reducing the dependence on the cost of capital - the financial viability might also hinge on the debt and equity arrangements of the to-be-retrofitted existing pipeline.

In sum, our model-based analysis illustrates the effect of conceivable financing structures on CO_2 transport costs, emphasizing the potentially important role of public finance. Given the scarcity of actual data from the sector, the approach naturally depends on industry analogies and economic principles to a certain extent. With investment plans being realized in the coming decade, empirical studies should complement the ex-ante analysis to gain further evidence on actual differences in cost of capital and operational efficiency, and their impact on CO_2 transport costs and CCS deployment outcomes.

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Credit authorship contribution statement

Katrin Sievert: Conceptualization, methodology, data curation, formal analysis, visualization, validation, writing -– original draft, writing -– review & editing. **Alexandru Stefan Stefanescu:** Methodology, data curation, formal analysis. **Pauline Oeuvray:** Data curation, visualization, validation, writing -– review & editing. **Bjarne Steffen:** Conceptualization, methodology, funding acquisition, supervision, writing -– review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Online Appendix: The impact of financing structures on the cost of CO_2 transport in Europe

A Cost of capital input parameters and sources

Table A1: Weighted average cost of capital (WACC) based on Damodaran (2024) values for Western Europe for January 2024; Debt share, cost of debt, and cost of equity values are used in this study for private corporate financing of CO_2 transport modes.

Transport mode	**Industry Name**	**Firms**	**Beta**	**CoE**	**E/(D+E)**	**CoD**	**Tax Rate**	**After-tax CoD**	**D/(D+E)**	**CoC**
Pipeline	Utility (General)	16	0.89	9.10%	47.72%	5.46%	24.71%	4.11%	52.28%	6.50%
Train, Barge, Ship	Transportation	101	0.97	9.60%	79.48%	6.05%	24.71%	4.55%	20.52%	8.56%

For corporate finance WACC calculations, we use the cost of debt and cost of equity in Euro (converted from the 2023 USD cost of debt and cost of equity), taking inflation rates into consideration:

$$C_{\mathrm{d}}[€] = (1 + C_{\mathrm{d}}) \cdot \left(\frac{1 + \text{expected inflation rate } €}{1 + \text{expected inflation rate US } \$} \right) - 1 \tag{A.1}$$

$$C_{\mathrm{e}}[€] = (1 + C_{\mathrm{e}}) \cdot \left(\frac{1 + \text{expected inflation rate } €}{1 + \text{expected inflation rate US } \$} \right) - 1 \tag{A.2}$$

Equation A.1 and Equation A.2 adjust the nominal cost of debt and cost of equity from \$ to € by considering the expected inflation in both economies, here €:1.5% and \$:3% (Damodaran, 2024). The result is a nominal rate of return in Euro that would be equivalent to the nominal rate of return in US dollars, considering the differences in inflation.

Table A2: Long-term credit ratings of largest European utilities as of 2023

Utility	**Country**	**Rating**	**Outlook**	**Rating agency**	**Source**
Engie SA	France	BBB+	stable	S&P	(ENGIE, 2024)
E.ON AG	Germany	BBB+	stable	S&P	(E.ON, 2024)
EDF SA	France	BBB	stable	S&P	(EDF, 2024)
Enel S.p.A	Italy	BBB	stable	S&P	(ENEL, 2024)
Iberdrola SA	Spain	BBB+	stable	S&P	(Iberdrola, 2024)
RWE AG	Germany	BBB+	stable	Fitch	(RWE, 2024)
SSE PLC	UK	BBB+	positive	S&P	(SSE, 2024)
CEZ a.s.	Czech Republic	A-	stable	S&P	(CEZ Group, 2024)
Fortum OYJ	Finland	BBB+	stable	S&P	(Fortum, 2024)
Gas Natural SDG, SA	Spain	BBB	stable	Fitch	(Naturgy Energy Group, 2024)
EnBW AG	Germany	A-	stable	S&P	(EnBW, 2024)
EDP SA	Portugal	BBB	stable	S&P	(EDP, 2024)
National Grid PLC	UK	BBB	stable	S&P	(National Grid, 2024)
Centrica PLC	UK	BBB	stable	S&P	(Centrica, 2024)

Table A3: Synthetic rating estimation for large nonfinancial service firms, manufacturing companies, and utilities, where the average credit rating from Table A2 is used to determine a default spread; data are as of January 2024 (Damodaran, 2024)

Rating	**Spread**
Baa2/BBB	1.47%
A3/A-	1.21%
A2/A	1.07%
A1/A+	0.92%
Aa2/AA	0.70%
Aaa/AAA	0.59%

B CO_2 transport options and required conditioning units

The analysis focuses on pipelines, barges, and trains for inland CO_2 transport and pipelines and ships for offshore CO_2 transport.

For pipelines (onshore and offshore), CO_2 is transported at ambient temperature either as a gas or in the dense phase, depending on the operating pressure (Oeuvray et al., 2024). In this study, we model pipeline transport in the dense phase at ambient temperature and above the critical pressure of 74 bar.

For barges, trains and ships, our modeling focuses on dedicated transportation that utilizes tanks permanently integrated in and affixed to the transport vehicles. These tanks are designed to carry CO_2 in liquid form at either medium or low pressure (Oeuvray et al., 2024). For CO_2 shipping, our modeling focuses on low-pressure vessels (8 bar) since they are more cost-effective than medium-pressure vessels (16 bar) (Oeuvray et al., 2024; Roussanaly et al., 2021). Unlike container-based transport, CO_2 tanks are fixed and cannot be moved, requiring them to be either filled or emptied when transport modes are switched. This requirement for handling CO_2 necessitates intermediate storage to accommodate dedicated transport options (Oeuvray et al., 2024) (see Appendix C, C.7. CO_2 intermediate storage).

The transport conditions, loading conditions, and required conditioning units are listed in Table 2. The characteristics of the dedicated transport options and pipeline transport, such as the capacity, the loading and operating conditions, and the holding time, as well as the cost parameters, are described in Appendix C–D.

Table B1: Transport and loading conditions for inland and offshore transport modes

Terrain	Mode	Transport conditions	Loading conditions	Conditioning unit	Source
Inland	Train	Liquid	8 bar	Liquefaction	Roussanaly et al. (2017)
	Barge	Liquid	8 bar	Liquefaction	Interview with barging company
	Pipeline	Dense phase liquid	> 74 bar	Compression	Oeuvray et al. (2024)
Offshore	Ship	Liquid	8 bar	Liquefaction	Oeuvray et al. (2024) and Roussanaly et al. (2021)
	Pipeline	Dense phase liquid	> 74 bar	Compression	Oeuvray et al. (2024)

C Detailed cost calculations by transport mode

This section supplements the techno-economic assessment outlined in Section 3.2 of the main text by providing detailed capital expenditure (capex) and operational expenditure (opex) calculations for each transport mode. The equations employed here are derived from existing techno-economic studies on CO_2 transport. Specifically, for pipelines, the calculations are based on Knoope et al. (2014), Oeuvray et al. (2024), and van den Broek et al. (2010); for barges, the calculations are based on Oeuvray et al. (2024); for trains, the calculations are based on Roussanaly et al. (2017) and Oeuvray et al. (2024); and for ship transport, the calculations are based on Roussanaly et al. (2021) and UK Department for Energy Security and Net Zero (2018).

C.1 CO_2 transportation via pipeline

C.1.1 Capex pipeline

The capex for pipelines depends on the costs of materials, labor, and miscellaneous expenses, along with additional costs for pumping stations. For inland pipelines, it also includes right-of-way costs (Oeuvray et al., 2024), while for offshore pipelines, it factors in machinery premiums Knoope et al. (2014) and the costs associated with offshore platforms (van den Broek et al., 2010). While we use the equations provided by Oeuvray et al. (2024) (Table 3 and Appendix B), who build their work on Knoope et al. (2014), we do not apply an optimization algorithm but instead use fixed pipe sizes for certain flows.

The capex is calculated as follows:

$$\begin{aligned}
\text{capex}_{\text{pipeline inland}}[€] &= I_{\text{mat}}[€] + I_{\text{lab}}[€] + I_{\text{misc}}[€] + I_{\text{pump}}[€] + I_{\text{ROW}}[€] \\
\text{capex}_{\text{pipeline offshore}}[€] &= I_{\text{mat}}[€] + I_{\text{lab}}[€] + I_{\text{misc}}[€] + I_{\text{pump}}[€] + I_{\text{offshore misc}}[€]
\end{aligned} \tag{C.1.1}$$

where:

$I_{\text{mat}}[€]$ = material cost

$I_{\text{lab}}[€]$ = labor cost

$I_{\text{misc}}[€]$ = other cost

$I_{\text{pump}}[€]$ = pumping station cost

$I_{\text{ROW}}[€]$ = right-of-way cost; applicable only to inland pipelines

$I_{\text{offshore misc}}[€]$ = machinery premium + (pumping stations · offshore platform); only applicable to offshore pipelines with the investment material cost:

$$
\begin{aligned}
I_{\text{mat}}[€] &= V_{\text{pipe}} \cdot \rho_{\text{steel}} \cdot C_{\text{steel}} \cdot \xi_{\text{steel}} \\
&= \pi \cdot t[\text{m}] \cdot (\text{OD}_{\text{NPS}}[\text{m}] - t[\text{m}]) \cdot d[\text{m}] \cdot \rho_{\text{steel}} \left[\frac{\text{kg}}{\text{m}^3}\right] \cdot C_{\text{steel}} \left[\frac{€}{\text{kg}}\right] \cdot \xi_{\text{steel}}
\end{aligned} \tag{C.1.1.1}
$$

where:

$t[\text{m}]$ = thickness
$\text{OD}_{\text{NPS}}[\text{m}]$ = outside diameter
$d[\text{m}]$ = distance
$C_{\text{steel}} \left[\frac{€}{\text{kg}}\right]$ = steel cost
ξ_{steel} = steel factor = 1
$\rho_{\text{steel}} \left[\frac{\text{kg}}{\text{m}^3}\right] = 7900$

with the thickness of the pipeline adopted from Oeuvray et al. (2024) (Equation (B.6)):

$$
t[\text{m}] = \frac{\text{OD}_{\text{NPS}} \cdot (P_2[\text{Pa}] \cdot \text{PSF})}{2 \cdot F[\text{Pa}] \cdot S \cdot E} + \text{CA}[\text{m}] \cdot \text{OD}_{\text{NPS}}[\text{m}] \tag{C.1.1.1.1}
$$

where:

$P_2 \left[\frac{\text{Pa}}{\text{m}}\right] = P_{\text{inlet}}$ for onshore and P_{outlet} for offshore
PSF = pressure safety margin
$F[\text{Pa}]$ = corrosion factor
S = design factor
E = longitudinal factor
$\text{CA}[\text{m}]$ = corrosion allowance

with the investment labor cost adopted from Oeuvray et al. (2024) (Equation (B.27)):

$$
I_{\text{lab}}[€] = c_{\text{lab}} \left[\frac{€}{\text{m}^2}\right] \cdot \text{OD}_{\text{NPS}}[\text{m}] \cdot d[\text{km}] \cdot 1000 \tag{C.1.1.2}
$$

where:

$c_{\text{lab}} \left[\frac{€}{\text{m}^2}\right]$ = labor cost rate
$\text{OD}_{\text{NPS}}[\text{m}]$ = outside diameter

$d[\mathrm{n}] = \text{distance}$

with additional other investment costs adopted from Oeuvray et al. (2024) (Equation (B.29)):

$$I_{\text{misc}}[€] = \mu_{\text{misc}}[\%] \cdot (I_{\text{mat}}[€] + I_{\text{lab}}[€]) \tag{C.1.1.3}$$

where:

$\mu_{\text{misc}}[\%] = \text{other cost factor}$

The investment costs for all pumping stations are adopted from Oeuvray et al. (2024) (Equation (B.32)):

$$I_{\text{pump}}[€] = \sum_{p=1}^{N_{\text{pump}}} I_{1\ \text{pump,p}}[€] \tag{C.1.1.4}$$

with the investment costs for one pumping station adopted from Oeuvray et al. (2024) (Equation (B.31)):

$$\begin{aligned} I_{1\ \text{pump}}[€] &= 74.3 \cdot 10^3[€] \cdot \left(\frac{W_{1\ \text{pump}}[\text{MW}_\text{e}] \cdot 10^3[\text{kW}_\text{e}\text{MW}_\text{e}^{-1}]}{n}\right)^{0.58} \cdot n^{0.9} \\ &= 74.3 \cdot 10^3[€] \cdot (W_{1\ \text{pump}}[\text{MW}_\text{e}] \cdot 10^3[\text{kW}_\text{e}\text{MW}_\text{e}^{-1}])^{0.58} \cdot n^{0.32} \\ &= 74.3 \cdot 10^3[€] \cdot (W_{1\ \text{pump}}[\text{MW}_\text{e}] \cdot 10^3[\text{kW}_\text{e}\text{MW}_\text{e}^{-1}])^{0.58} \\ &\cdot \left(\frac{W_{1\ \text{pump}}[\text{MW}_\text{e}]}{2.0[\text{MW}_\text{e}]}\right)^{0.32} \end{aligned} \tag{C.1.1.4.1}$$

where:

$\frac{W_{1\text{pump}}}{2.0} = \text{no. of pumping stations in parallel}$

with the capacity of one pumping station adopted from Oeuvray et al. (2024) (Equation (B.19)):

$$W_{1\ \text{pump}}[\text{MW}_\text{e}] = E_{\text{pump}}\left[\frac{\text{MJ}}{\text{kg}}\right] \cdot m\left[\frac{\text{kg}}{\text{s}}\right] \tag{C.1.1.4.2}$$

where:

$m\left[\frac{\mathrm{kg}}{\mathrm{s}}\right]$ = mass flow

with the specific energy required for the pumping adopted from Oeuvray et al. (2024) (Equation (B.20)):

$$E_{\text{pump}}\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] = \frac{P_{\text{pump outlet}}[\mathrm{MPa}] - P_{\text{pump inlet}}[\mathrm{MPa}]}{\eta_{\text{pump}} \cdot \rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]} \tag{C.1.1.4.3}$$

where:

$P_{\text{pump outlet}}[\mathrm{MPa}]$ = inlet pressure of pipeline is outlet pressure of the pump
$P_{\text{pump inlet}}[\mathrm{MPa}]$ = outlet pressure of pipeline is outlet pressure of the pump
η_{pump} = pump efficiency
$\rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$ = density

The right-of-way fee (applicable only for inland pipelines) is adapted from Oeuvray et al. (2024) (Equation (B.28)):

$$I_{\text{ROW}}[€] = c_{\text{ROW}}\left[\frac{€}{\mathrm{m}}\right] \cdot d[\mathrm{m}] \tag{C.1.1.5}$$

where:

$c_{\text{ROW}}\left[\frac{€}{\mathrm{m}}\right]$ = right-of-way cost rate
$d[\mathrm{m}]$ = distance

Additional miscellaneous investment costs (applicable only for offshore pipelines) are:

$$I_{\text{offshore misc}} = I_{\text{machinery premium}}[€] + (n_{\text{pump}} \cdot I_{\text{offshore platform}}[€]) \tag{C.1.1.6}$$

where:

$I_{\text{machinery premium}}[€]$ = investment cost machinery premium
$I_{\text{offshore platform}}[€]$ = investment cost offshore platform

For offshore pipelines, the objective is to minimize the number of pumping stations required during transport. This is particularly crucial for offshore operations, as each required pumping station necessitates the construction of an offshore platform. In comparison to building onshore pipelines, constructing offshore pipelines involves additional equipment, incurring an additional machinery premium fixed cost (Knoope et al., 2014). Furthermore, when pumping stations are needed, the construction of each offshore platform incurs a fixed investment cost (van den Broek et al., 2010).

C.1.2 Opex pipeline

The opex for pipelines depends on the yearly maintenance costs of the pipeline itself, the energy costs for operating the pumps, and the maintenance costs associated with the pumping stations. The equations are adopted from Oeuvray et al. (2024) (Equations (B.33)–(B35) and (B.37)).

Therefore, the opex is calculated as follows:

$$\text{opex}_{\text{pipe}}\left[\frac{€}{\text{y}}\right] = \text{OM}_{\text{pipe}}\left[\frac{€}{\text{y}}\right] + \text{EC}_{\text{pump}}\left[\frac{€}{\text{y}}\right] + \text{OM}_{\text{pump}}\left[\frac{€}{\text{y}}\right] \tag{C.1.2}$$

with pipeline operation and maintenance costs:

$$\text{OM}_{\text{pipe}}\left[\frac{€}{\text{y}}\right] = \mu_{\text{pipe}}[\%] \cdot I_{\text{pipe}}[€] \tag{C.1.2.1}$$

where:

$\mu_{\text{pipe}}[\%]$ = O&M costs pipeline factor
$I_{\text{pipe}}[€]$ = capex pipeline

with the energy cost for pumping:

$$\text{EC}_{\text{pump}}\left[\frac{€}{\text{y}}\right] = \sum_{p=1}^{N_{\text{pump}}} W_{1\ \text{pump}}[\text{MW}_{\text{e}}] \cdot H\left[\frac{\text{h}}{\text{y}}\right] \cdot C_{\text{el}}\left[\frac{€}{\text{kWh}}\right] \tag{C.1.2.2}$$

where:

$W_{1\ \text{pump}}[\text{MW}_{\text{e}}]$ = pumping capacity
$H\left[\frac{\text{h}}{\text{y}}\right]$ = operating hours
$C_{\text{el}}\left[\frac{€}{\text{kWh}}\right]$ = electricity cost

with the operation and maintenance cost for pumping:

$$\text{OM}_{\text{pump}}\left[\frac{€}{\text{y}}\right] = \mu_{\text{pump}}[\%] \cdot I_{\text{pump}}[€] \tag{C.1.2.3}$$

where:

$\mu_{\text{pump}}[\%]$ = O&M costs pumping station factor
$I_{\text{pump}}[€]$ = Capex pumping station

C.2 CO_2 transportation via barge

C.2.1 Capex barge

The capex for barges depends on the annual capacity of CO_2 transported, the capacity of an individual barge, the average capacity utilization of the barges, and the cost per barge, factoring in the number of round trips a barge can make in a year. The capex for dedicated barges also includes costs for intermediate storage facilities. The capex is modeled as in Oeuvray et al. (2024) (see Table 1). We account for both loading and unloading costs.

Therefore, the capex is computed as follows:

$$\begin{aligned}\text{capex}_{\text{barge}}[€] &= n_{\text{barges}} \cdot C_{\text{barges}}[€] + m_i[\text{tCO}_2] \cdot C_{\text{loading}}\left[\frac{€}{\text{tCO}_2}\right] \cdot 2 \\ &\quad + \text{capex}_{\text{int storage}} \\ &= \frac{m_i\left[\frac{\text{tCO}_2}{\text{y}}\right]}{\frac{t_{\text{operating}}[\text{h}]}{t_{\text{trip}}[\text{h}]\cdot 2} \cdot m_{\text{barge}}\left[\frac{\text{tCO}_2}{\text{y}}\right] \cdot M_{\text{barge}_{\text{avg}}}[\%]} \cdot C_{\text{barge}}[€] \\ &\quad + 2 \cdot m_i[\text{tCO}_2] \cdot C_{\text{loading}}\left[\frac{€}{\text{tCO}_2}\right] + \text{capex}_{\text{int storage}}\end{aligned} \tag{C.2.1}$$

where:

$m_i\left[\frac{\text{tCO}_2}{\text{y}}\right]$ = capacity of CO_2 transported per year
$m_{\text{barge}}\left[\frac{\text{tCO}_2}{\text{y}}\right]$ = capacity of a barge
$M_{\text{barge}_{\text{avg}}}[\%]$ = average capacity of barge (in percentage)
$C_{\text{barge}}[€]$ = cost of a barge
$t_{\text{operating}}\left[\frac{\text{h}}{\text{y}}\right]$ = operating hours
$t_{\text{trip}}[\text{h}]$ = duration of trip
$C_{\text{loading}}\left[\frac{€}{\text{tCO}_2}\right]$ = cost of loading facility
$\text{capex}_{\text{int storage}}$ = investment cost intermediate storage

with the duration of the round trip as:

$$t_{\text{trip}}[\text{h}] = 2 \cdot \frac{d[\text{km}]}{v\left[\frac{\text{km}}{\text{h}}\right]} + 2 \cdot t_{\text{load/unload}}[\text{h}] \tag{C.2.1.1}$$

and the round trips per barge as:

$$\text{round trip}_{\text{barge}} = \frac{t_{\text{operating}}[\text{h}]}{t_{\text{trip}}[\text{h}]} \tag{C.2.1.2}$$

where:

$t_{\text{load/unload}}[\text{h}]$ = loading time

C.2.2 Opex barge

The opex for barges consists of a percentage of the capex as operation and maintenance fees and the fuel cost plus operational cost for intermediate storage. The opex is modeled as in Oeuvray et al. (2024).

Therefore, the opex is computed as follows:

$$\begin{aligned}\text{opex}_{\text{barge}}\left[\frac{€}{\text{y}}\right] = {} & \text{capex}_{\text{barge}}[€] \cdot c_{\text{opex}}[\%] + \frac{m_i\left[\frac{\text{tCO}_2}{\text{y}}\right] \cdot d[\text{km}] \cdot c_{\text{fuel}}\left[\frac{\left(\frac{\text{g}}{\text{tCO}_2}\right)}{\text{km}}\right]}{1000000} \\ & \cdot C_{\text{fuel}}\left[\frac{€}{t}\right] + C_{\text{harbor}}[€] + \text{opex}_{\text{int storage}}\end{aligned} \tag{C.2.2}$$

where:

$c_{\text{opex}}[\%]$ = percentage of operation and maintenance fees
$c_{\text{fuel}}\left[\frac{\left(\frac{\text{g}}{\text{tCO}_2}\right)}{\text{km}}\right]$ = fuel consumption
$d[\text{km}]$ = distance
$C_{\text{fuel}}\left[\frac{€}{t}\right]$ = fuel cost
$C_{\text{harbor}}[€]$ = harbor fees
$\text{opex}_{\text{int storage}}$ = operational expenditure intermediate storage

with the harbor fees as in Oeuvray et al. (2024):

$$C_{\text{harbor}}[€] = c_{\text{harbor}}\left[\frac{€}{\text{tCO}_2}\right] \cdot m_i\left[\frac{\text{tCO}_2}{\text{y}}\right] \tag{C.2.2.1}$$

where:

$c_{\text{harbor}}\left[\frac{€}{\text{tCO}_2}\right]$ = harbor fee cost per ton of CO_2 transported

C.3 CO_2 transportation via train

C.3.1 Capex train

The capex for trains depends on the number of wagons and their maximum CO_2 capacity, the cost per ton of CO_2 for each wagon, the number and cost of loading stations, and intermediate storage cost. We model the capex in the same way as (Oeuvray et al., 2024), except that we assume that wagons are purchased rather than rented.

Therefore, the capex is computed as follows:

$$\begin{aligned}\text{capex}_{\text{train}}[€] = n_{\text{wagon}} \cdot m_{\text{max wagon}}[\text{tCO}_2] \cdot C_{\text{wagon}}\left[\frac{€}{\text{tCO}_2}\right] \\ + (n_{\text{loading stations}} \cdot C_{\text{loading stations}}[€]) + \text{capex}_{\text{int storage}}\end{aligned} \tag{C.3.1}$$

where:

n_{wagon} = number of wagons
$m_{\text{max wagon}}[\text{tCO}_2]$ = max mass transported in one wagon
$C_{\text{wagon}}\left[\frac{€}{\text{tCO}_2}\right]$ = cost of wagons
$n_{\text{loading station}}$ = number of loading stations
$C_{\text{loading station}}[€]$ = cost of loading station
$\text{capex}_{\text{int storage}}$ = investment cost of intermediate storage

with the number of wagons computed as in Equation (3) in Oeuvray et al. (2024):

$$n_{\text{wagon}} = \frac{m_i\left[\frac{\text{tCO}_2}{\text{y}}\right]}{\frac{t_{\text{op}}[\text{h}]}{\text{round trip duration}[\text{h}][\text{tCO}_2]} \cdot m_{\text{max wagon}}[\text{tCO}_2]} \tag{C.3.1.1}$$

with the duration of a round trip computed as in Table A.4 in Oeuvray et al. (2024):

$$\text{round trip duration}[\text{h}] = \text{time}_{\text{load}}[\text{h}] + \text{time}_{\text{unload}}[\text{h}] + \left(\frac{d[\text{km}]}{v\left[\frac{\text{km}}{\text{h}}\right]} \cdot 2\right) \tag{C.3.1.2}$$

with number of loading stations computed as in Equation (5) in Oeuvray et al. (2024)

multiplied by 2 for loading and unloading:

$$n_{\text{loading station}} = 2 \cdot \frac{n_s t_{\text{wagon load}}[\text{h}]}{t_{\text{op}}\left[\frac{\text{h}}{\text{y}}\right]} \tag{C.3.1.3}$$

and the number of shipments n_s as in Equation (2) in Oeuvray et al. (2024):

$$n_s = \frac{m_i\left[\frac{\text{tCO}_2}{\text{y}}\right]}{m_{\text{max wagon}}\left[\frac{\text{tCO}_2}{\text{y}}\right]} \tag{C.3.1.4}$$

where:

$n_{\text{locomotive}}$ = number of locomotives
$C_{\text{locomotive}}[\text{tCO}_2]$ = cost of locomotive
$m_i\left[\frac{\text{tCO}_2}{\text{y}}\right]$ = actual capacity transported per year
$\text{time}_{\text{load}}[\text{h}]$ = loading time for train
$\text{time}_{\text{unload}}[\text{h}]$ = unloading time for train
$v\left[\frac{\text{km}}{\text{h}}\right]$ = train speed
$t_{\text{wagon load}}[\text{h}]$ = duration of loading for one wagon
$t_{\text{op}}[\text{h}]$ = yearly operating hours
$m_{\text{max wagon}}[\text{h}]$ = maximum mass transported in one wagon

C.3.2 Opex train

The opex for trains depends on the labor costs at each loading station, the number of shipments, the transport and service costs per rail tank car, and the operational cost for intermediate storage. The opex is modeled in the same way as in Oeuvray et al. (2024) (see Table 4), except the customs cost and the fact that the cost factor for wagons is already included in the capex as we assume that wagons are purchased rather than rented.

Therefore, the opex is computed as follows:

$$\begin{aligned}\text{opex}_{\text{train}} = n_{\text{lab}} \cdot n_{\text{loading station}} \cdot C_{\text{lab}}\left[\frac{€}{\text{y}}\right] + b_c \cdot f\left[\frac{1}{\text{y}}\right] \cdot C_{\text{c}}\left[\frac{€}{\text{shipment}}\right] \\ + n_s\left[\frac{\text{shipment}}{\text{y}}\right] \cdot C_t\left[\frac{€}{\text{shipment}}\right] + \text{opex}_{\text{int storage}}\end{aligned} \tag{C.3.2}$$

where:

$n_{\text{lab}} \left[\frac{\#}{\text{loading station}}\right]$ = number of labor force for loading station
$C_{\text{lab}} \left[\frac{€}{\text{y}}\right]$ = cost of labor for loading station
$n_s \left[\frac{\text{shipment}}{\text{y}}\right]$ = number of shipments
$C_t \left[\frac{€}{\text{shipment}}\right]$ = transport and service cost
$d_{\text{rail}}[\text{km}]$ = distance
$\text{opex}_{\text{int storage}}$ = operational expenditure intermediate storage

C.4 CO_2 transportation via ship

For CO_2 shipping, we consider low-pressure (8-bar) vessels due to their greater cost-effectiveness relative to medium-pressure (16-bar) vessels (Oeuvray et al., 2024; Roussanaly et al., 2021). For ships operating at low pressure, the capex is calculated for a vessel with a capacity of 50,000 tCO_2 at temperatures of -50°C. The capex includes the costs associated with constructing the loading and unloading facilities for liquified CO_2.

C.4.1 Capex ship

The capex for ships depends on the number of ships, the cost per ship, the annual CO_2 capacity transported, the cost for loading and unloading facilities, and the cost for intermediate storage facilities, as per Roussanaly et al. (2021).

Therefore, the capex is computed as follows:

$$\text{capex}_{\text{ship}} = n_{\text{ship}} \cdot C_{\text{ship}}[€] + m_i[\text{tCO}_2] \cdot C_{\text{loading}} \left[\frac{€}{\text{tCO}_2}\right] \cdot 2 + \text{capex}_{\text{int storage}} \tag{C.4.1}$$

where:

$C_{\text{ship}}[€]$ = construction cost per ship
$C_{\text{loading}} \left[\frac{€}{\text{tCO}_2}\right]$ = cost of loading facility
$\text{capex}_{\text{int storage}}$ = investment cost intermediate storage

with the number of ships as:

$$n_{\text{ship}} = \frac{m_i[\text{tCO}_2]}{\text{round trip}_{\text{ship}} \cdot m_{\text{ship}}[\text{tCO}_2]} \tag{C.4.1.1}$$

with the round trips per ship as:

$$\text{round trip}_{\text{ship}} = \frac{t_{\text{operating}}[\text{h}]}{t_{\text{trip}}[\text{h}]} \tag{C.4.1.2}$$

with the duration of the round trip as:

$$t_{\text{trip}}[\text{h}] = 2 \cdot \frac{d[\text{km}]}{\text{speed}\left[\frac{\text{km}}{\text{h}}\right]} + 2 \cdot t_{\text{load/unload}}[\text{h}] + 2 \cdot t_{\text{port}}[\text{h}] \tag{C.4.1.3}$$

where:

$t_{\text{operating}}[\text{h}]$ = operating hours
$t_{\text{loading/unloading}}[\text{h}]$ = loading time
$t_{\text{port}}[\text{h}]$ = port entry and exit time

C.4.2 Opex ship

The opex for ships depends on the distance traveled, the annual CO_2 transport capacity, the fuel consumption rate per ton of CO_2 per kilometer and the cost of fuel, plus miscellaneous costs incurred annually (including operational cost for loading stations) and operational costs for intermediate storage, as per Roussanaly et al. (2021).

$$\begin{aligned}\text{opex}_{\text{ship}}\left[\frac{€}{\text{y}}\right] = {} & d[\text{km}] \cdot m_i\left[\frac{\text{tCO}_2}{\text{y}}\right] \cdot c_{\text{fuel}}\left[\frac{\left(\frac{\text{g}}{\text{tCO}_2}\right)}{\text{km}}\right] \cdot C_{\text{fuel}}\left[\frac{€}{t}\right] \cdot C_{\text{misc}}\left[\frac{€}{\text{y}}\right] \\ & + \text{opex}_{\text{int storage}}\end{aligned} \tag{C.4.2}$$

where:

$c_{\text{fuel}}\left[\frac{\left(\frac{\text{g}}{\text{tCO}_2}\right)}{\text{km}}\right]$ = fuel consumption
$C_{\text{fuel}}\left[\frac{€}{t}\right]$ = fuel cost
$C_{\text{misc}}[\frac{€}{\text{y}}]$ = miscellaneous cost
$\text{opex}_{\text{int storage}}$ = operational expenditure intermediate storage

with the miscellaneous cost as:

$$C_{\text{misc}}[\frac{€}{\text{y}}] = (n_{\text{ship}} \cdot C_{\text{ship}}[€] \cdot \mu_{\text{misc}}[\%]) + (m_i[\text{tCO}_2] \cdot C_{\text{loading}}\left[\frac{€}{\text{tCO}_2}\right] \cdot \mu_{\text{loading}}[\%]) + C_{\text{harbor}}[€] \tag{C.4.2.1}$$

where:

$\mu_{\text{misc}}[\%]$ = operational cost factor
$\mu_{\text{loading}}[\%]$ = loading station cost factor
$C_{\text{harbor}}[€]$ = operational cost factor

C.5 CO_2 intermediate storage

C.5.1 Capex intermediate storage

The capex for intermediate storage depends on the reference capex of a storage unit and the ratio of the actual storage capacity to the reference storage capacity. The actual storage capacity is derived by multiplying the mass of CO_2 stored by the ratio of 5 days to a full year (365 days).

Therefore, the capex is computed as follows:

$$\text{capex}_{\text{int storage}}[€] = C^{\text{ref}}_{\text{storage}}[€] \cdot \left(\frac{S[\text{t}]}{S^{\text{ref}}[\text{t}]}\right)^{\text{R}_{\text{st}}} \tag{C.5.1}$$

with:

$$S[\text{t}] = m_i[\text{tCO}_2] \cdot \left(\frac{5[\text{d}]}{365[\text{d}]}\right) \tag{C.5.2}$$

where:

$C^{\text{ref}}_{\text{storage}}[€]$ = capex storage unit
$S[\text{tCO}_2]$ = capacity intermediate storage
$S^{\text{ref}}[\text{tCO}_2]$ = reference capacity intermediate storage
R_{st} = exponent factor

C.5.2 Opex intermediate storage

The opex for intermediate storage is defined as a constant percentage of the capex for intermediate storage, as in Equation (18) in Oeuvray et al. (2024).

Therefore, the opex for intermediate storage is calculated as follows:

$$\text{opex}_{\text{int storage}}\left[\frac{€}{\text{y}}\right] = \mu_{\text{int storage}}\left[\frac{\%}{\text{y}}\right] \cdot \text{capex}_{\text{int storage}}[€] \tag{C.5.3}$$

where:

$\mu_{\text{int storage}}[\%]$ = O&M cost factor intermediate storage

D Detailed cost calculations by conditioning units

The conditioning plant design is based on the studies of Deng et al. (2019) and Roussanaly et al. (2021) for liquefaction and Knoope et al. (2014) for compression. Conditioning is considered to occur only once before transport. Reconditioning is excluded from the analysis. The energy needed for conditioning CO_2 prior to transport depends on the transport conditions (liquid, dense phase liquid, or gaseous) and loading conditions (in bars) specific to each CO_2 transport mode (see Appendix B). The conditioning energy requirement mentioned here does not include the energy used by pumping stations along the pipelines, which is included within the transport category (see Table 2 in the manuscript).

D.1 CO_2 conditioning: Compression

D.1.1 Capex compression

The capex for compression depends on the compressor capacity. The capex is calculated by means of a power law relation to the compressor's capacity, with coefficients that adjust for the size and number of units. The CO_2 compression costs considered in this study are based on Knoope et al. (2014) and Oeuvray et al. (2024) (Equation (B.30)):

$$
\begin{aligned}
I_{\text{comp}} &= 21.9 \cdot 10^6 \cdot \left(\frac{W_{1\ \text{comp}}[\text{MW}_\text{e}]}{13[\text{MW}_\text{e}]}\right)^{0.67} \cdot n^{0.9} = I_{\text{comp}} \\
&= 21.9 \cdot 10^6 \cdot \left(\frac{W_{\text{comp}}[\text{MW}_\text{e}]}{n \cdot 13[\text{MW}_\text{e}]}\right)^{0.67} \cdot n^{0.9} = I_{\text{comp}} \\
&= 21.9 \cdot 10^6 \cdot \left(\frac{W_{\text{comp}}[\text{MW}_\text{e}]}{13[\text{MW}_\text{e}]}\right)^{0.67} \cdot \left(\frac{W_{\text{comp}}[\text{MW}_\text{e}]}{35[\text{MW}_\text{e}]}\right)^{0.32}
\end{aligned}
\tag{D.1.1}
$$

with the capacity of the compressor based on Oeuvray et al. (2024) (Equation (B.13)):

$$
W_{\text{comp}}[\text{MW}_\text{e}] = E_{\text{comp}}\left[\frac{\text{J}}{\text{kg}}\right] \cdot m\left[\frac{\text{kg}}{\text{s}}\right] \cdot 10^{-6}\left[\frac{\text{MW}_\text{e}}{\text{W}_\text{e}}\right] \tag{D.1.1.1}
$$

where:

$E_{\text{comp}}\left[\frac{\text{J}}{\text{kg}}\right]$ = specific energy required for the compression

D.1.2 Opex compression

The opex for compression depends on energy costs and operation and maintenance costs, which are based on Equations (B.35) and (B.36) in Oeuvray et al. (2024), respectively.

Therefore, the opex for compression is calculated as follows:

$$\text{opex}_{\text{comp}}\left[\frac{€}{\text{y}}\right] = \text{EC}_{\text{comp}}\left[\frac{€}{\text{y}}\right] + \text{OM}_{\text{comp}}\left[\frac{€}{\text{y}}\right] \tag{D.1.2}$$

with the energy costs for compression:

$$\text{EC}_{\text{comp}}\left[\frac{€}{\text{y}}\right] = W_{\text{comp}}[\text{MW}_\text{e}] \cdot 10^3 \cdot H\left[\frac{\text{h}}{\text{y}}\right] \cdot C_{\text{el}}\left[\frac{€}{\text{kWh}}\right] \tag{D.1.2.1}$$

and with the operation and maintenance cost for compression:

$$\text{OM}_{\text{comp}}\left[\frac{€}{\text{y}}\right] = \mu_{\text{pump, comp}}\left[\frac{\%}{\text{y}}\right] \cdot I_{\text{comp}}[€] \tag{D.1.2.2}$$

where:

$H\left[\frac{\text{h}}{\text{y}}\right] = 8760$
$C_{\text{el}}\left[\frac{€}{\text{kWh}}\right]$ = electricity cost as const. given
$\mu_{\text{pump, comp}}\left[\frac{\%}{\text{y}}\right]$ = O&M cost factor compression and pumping stations

D.2 CO_2 conditioning: Liquefaction

D.2.1 Capex liquefaction

The capex for CO_2 liquefaction depends on the actual capacity of CO_2 transported per year and the specific cost of conditioning. This specific cost is derived from the reference capacity, adjusted for actual throughput, and scaled according to the power law, multiplied by the reference cost of conditioning over the lifetime of the conditioning unit. The CO_2 liquefaction costs considered in this study are based on Deng et al. (2019) and Roussanaly et al. (2021).

Therefore, the capex is computed as follows:

$$\text{capex}_{\text{liq}}[€] = m_i\left[\frac{€}{\text{tCO}_2}\right] \cdot C_{\text{liq}}\left[\frac{€}{\text{tCO}_2}\right] \tag{D.2.1}$$

with the specific cost of conditioning calculated as in Roussanaly et al. (2021) (Equation (1)):

$$C_{\text{liq}}\left[\frac{€}{\text{tCO}_2}\right] = m_{\text{ref}}[\text{tCO}_2] \cdot C_{\text{liq,ref}}\left[\frac{€}{\text{tCO}_2}\right] \cdot t[\text{y}] \cdot \left(\frac{m_i[\text{tCO}_2]}{m_{\text{ref}}[\text{tCO}_2]}\right)^{0.85} \tag{D.2.1.1}$$

where:

$m_{\text{ref}}[\text{tCO}_2]$ = reference capacity transported per year
$m_i[\text{tCO}_2]$ = actual capacity transported per year
$C_{\text{liq,ref}}\left[\frac{€}{\text{tCO}_2}\right]$ = reference cost of conditioning
$t[\text{y}]$ = lifetime of conditioning unit

D.2.2 Opex liquefaction

The opex for CO_2 liquefaction is the sum of variable and annual fixed operation costs. The variable operating costs cover electricity and cooling water. The fixed operating costs are a fixed percentage of the investment cost.

Therefore, the opex is calculated as follows:

$$\begin{aligned}\text{opex}_{\text{liq}}\left[\frac{€}{\text{y}}\right] = &\left(m_i[\text{tCO}_2] \cdot \frac{c_{\text{elec}}\left[\frac{\text{kWh}}{\text{tCO}_2}\right]}{\eta_{\text{cond}}} \cdot C_{\text{elec}}\left[\frac{€}{\text{kWh}}\right]\right) \\ &+ \left(m_i[\text{tCO}_2] \cdot c_{\text{water}}\left[\frac{\text{kWh}}{\text{tCO}_2}\right]\right) + \left(\mu_{\text{liq}}\left[\frac{\%}{\text{y}}\right] \cdot \text{capex}_{\text{liq}}[€]\right)\end{aligned} \tag{D.2.2}$$

where:

$c_{\text{elec}}\left[\frac{\text{kWh}}{\text{tCO}_2}\right]$ = specific electricity consumption
η_{cond} = efficiency of conditioning
$C_{\text{elec}}\left[\frac{€}{\text{kWh}}\right]$ = cost of electricity
$c_{\text{water}}\left[\frac{\text{kWh}}{\text{tCO}_2}\right]$ = cost of cooling water
$\mu_{\text{liq}}[\%]$ = O&M cost factor liquefaction

E Transport and conditioning cost input data

Table E1: European Central Bank consumer price index (ECB CPI); cost inputs are taken from different sources, compiled from 2011 until 2021, and CPI-adjusted (ECB, 2023); for papers with values in GBP or CHF, values are converted to EUR (at conversion rate for the reference year) and then adjusted to €$_{2022}$ prices

Date	**Time period**	**Obs. value [%]**
2011-12-31	2011	3.1
2012-12-31	2012	2.6
2013-12-31	2013	1.5
2014-12-31	2014	0.6
2015-12-31	2015	0.1
2016-12-31	2016	0.2
2017-12-31	2017	1.7
2018-12-31	2018	1.9
2019-12-31	2019	1.5
2020-12-31	2020	0.7
2021-12-31	2021	2.9
2022-12-31	2022	9.2

Table E2: Electricity prices for non-household consumers (consumption from 2 000 MWh to 19 999 MWh) in €/kWh all taxes and levies included; biannual data from 2010 onward (Eurostat, 2024); average electricity price is used as input for cost calculations

Time	**Value** [€/kWh]
2010-S1	0.1275
2010-S2	0.1278
2011-S1	0.1366
2011-S2	0.1375
2012-S1	0.1418
2012-S2	0.1424
2013-S1	0.1481
2013-S2	0.1456
2014-S1	0.1507
2014-S2	0.1470
2015-S1	0.1457
2015-S2	0.1424
2016-S1	0.1408
2016-S2	0.1386
2017-S1	0.1412
2017-S2	0.1391
2018-S1	0.1405
2018-S2	0.1403
2019-S1	0.1504
2019-S2	0.1451
2020-S1	0.1534
2020-S2	0.1523
2021-S1	0.1567
2021-S2	0.1745
2022-S1	0.2220
2022-S2	0.2495
Average	**0.15**

Table E3: Input data for onshore pipeline levelized cost of CO_2 transport

Parameter	**Value**	**Unit**	**Source/Notes**
Inlet pressure onshore	12	MPa	Knoope et al. (2014)
Outlet pressure onshore	8	MPa	Knoope et al. (2014)
Temperature (onshore)	15	°C	Knoope et al. (2014)
CO_2 density onshore	868.4	kg/m^3	Oeuvray et al. (2024)
CO_2 density offshore	939.74	kg/m^3	Oeuvray et al. (2024)
Pressure safety margin	0.1	-	Knoope et al. (2014)
Corrosion allowance	0.001	m	Knoope et al. (2014)
Longitudinal factor	1	-	Oeuvray et al. (2024)
Steel cost (X120)	2.15	$€_{2022}/kg$	Knoope et al. (2014)
Yield stress (X120)	890	MPa	Knoope et al. (2014)
Steel cost (X80)	1.8	$€_{2022}/kg$	Knoope et al. (2014)
Yield stress (X80)	620	MPa	Knoope et al. (2014)
Outer diameter 100 kg/s	0.32	m	Knoope et al. (2014), Table 3
Outer diameter 250 kg/s	0.51	m	Knoope et al. (2014), Table 3
Labor costs	1,106	$€_{2022}/m^2$	Oeuvray et al. (2024)
Right-of-way fee	98,604	$€_{2022}/km$	Knoope et al. (2014)
Miscellaneous	0.25	-	Knoope et al. (2014)
Lifetime	50	years	Knoope et al. (2014)
Pressure drop	40	Pa/m	Knoope et al. (2014); fixed
Design factor	0.61	-	Oeuvray et al. (2024)
CO_2 velocity	0.47	m/s	-

Table E4: Input data for offshore pipeline levelized cost of CO_2 transport

Parameter	Value	Unit	Source/Notes
Design factor	0.5	-	Oeuvray et al. (2024)
Steel cost (X65)	1.64811	€$_{2022}$/kg	Knoope et al. (2014)
Yield stress (X65)	460	MPa	Knoope et al. (2014)
Thickness (offshore)	2.5	% of ODNPS	Knoope et al. (2014)
Outer diameter (OD) $\leq$ 100 kg/s flow	0.32	m	Knoope et al. (2014)
Outer diameter (OD) $>$100 $\leq$200 kg/s flow	0.41	m	Knoope et al. (2014)
Outer diameter (OD) $>$200 $\leq$250 kg/s flow	0.51	m	Knoope et al. (2014)
Outer diameter (OD) $>$250 $\leq$300 kg/s flow	0.61	m	Knoope et al. (2014)
Outer diameter (OD) $>$300 $\leq$500 kg/s flow	0.76	m	Knoope et al. (2014)
Outer diameter (OD) $\leq$500 kg/s flow	1.06	m	Knoope et al. (2014)
Pressure drop	20	Pa/m	Knoope et al. (2014); fixed
Labor costs	1,106	€$_{2022}$/m^2	Oeuvray et al. (2024)
Machinery premium	43,015,000	€$_{2022}$	Knoope et al. (2014), Table 4
Right-of-way fee offshore	0	€$_{2022}$/km	not applicable offshore
Miscellaneous	0.25	-	Knoope et al. (2014)
Lifetime	50	years	Knoope et al. (2014)
Opex pipeline	0.015	%	Knoope et al. (2014)
Steel density	7900	kg/m^3	Knoope et al. (2014)
Offshore platform	74,969,000	€$_{2022}$	van den Broek et al. (2010)
CO_2 velocity	0.45	m/s	-

Table E5: Input data for pipeline pumping stations used for onshore and offshore levelized cost of CO_2 transport

Parameter	Value	Unit	Source/Notes
Multiplication factor	74.3	-	Knoope et al. (2014) and Meerman et al. (2012)
Capacity	2000	kWe	Own assumption
Exponent factor	0.58	-	Knoope et al. (2014) and Meerman et al. (2012)
Pumps onshore	100	km/pump	Own assumption
Lifetime	25	years	Knoope et al. (2014)
Pump efficiency	75	%	Knoope et al. (2014)

Table E6: Input data for barge levelized cost of CO_2 transport; data validated in an interview with a European barge transport provider in 2022

Parameter	**Value**	**Unit**	**Source**
Capex 8x380	16,300,000	€$_{2022}$	Validated in interview (2022)
Barge design 8x380	3040	m^3	Validated in interview (2022)
Density	1050	kg/m^3	Validated in interview (2022)
Opex	7.4%	-	Validated in interview (2022)
Fuel consumed diesel	10.49	$g/tCO_2/km$	Validated in interview (2022)
Fuel cost	500	€$_{2022}$/t	Validated in interview (2022)
Harbor fees	0.26	€$_{2022}/tCO_2$	Validated in interview (2022)
Loading/unloading time	12	h	Validated in interview (2022)
Average sailing	11.9	km/h	Validated in interview (2022)
Average capacity	65%	%	Validated in interview (2022)
Operating hours	8400	h	Validated in interview (2022)
Lifetime	25	years	Validated in interview (2022)
Pressure	8	bar	Validated in interview (2022)
Temperature	-50 to -20	°C	Validated in interview (2022)
Loading facility cost	2.87	€$_{2022}/tCO_2$	Roussanaly et al. (2021); scaled linearly from ref case

Table E7: Input data for levelized cost of CO_2 transport via train

Parameter	**Value**	**Unit**	**Source**
Pressure	8	bar	Rounded from Roussanaly et al. (2017)
Temperature	-50	°C	Roussanaly et al. (2017)
Scaling factor	0.85	-	Roussanaly et al. (2017)
Locomotive cap.	1250	ton of freight	Roussanaly et al. (2017)
Locomotive cost	4,500,000	€$_{2022}$	Interview train transport provider
Wagon cost	4,520	€$_{2022}$/tCO_2	Roussanaly et al. (2017)
Train speed	18	km/h	(European Court of Auditors, 2016)
Time for load	6	h	Oeuvray et al. (2024)
Time for unload	12	h	Oeuvray et al. (2024)
Max wagons per train	20	#	Roussanaly et al. (2017)
Investment cost loading stations	120,000	€	Own assumption, Validated in interview, industry data for triangulation
Max mass transported in one wagon	50	t	Interview train transport provider
Operating hours within a year	8520	h/y	Own assumption
No. labor forces loading stations	1	#/loading station	Own assumption, Validated in interview, industry data for triangulation
Cost of labor, loading stations	65,000	€$_{2022}$/y/capita	Average yearly salary: Electronics technician or industrial mechanic in Germany
Transport & service cost fixed	650	€$_{2022}$/RTC	Validated in interview, industry data for triangulation
Transport & service cost variable	2.5	€$_{2022}$/km	Own assumption, Validated in interview, industry data for triangulation
Lifetime	25	years	Roussanaly et al. (2017)

Table E8: Input data for ship levelized cost of CO_2 transport

Parameter	**Value**	**Unit**	**Source, Notes**
Loading/unloading time	15	h	UK Department for Energy Security and Net Zero (2018)
Loading facility cost	2.87	€$_{2022}$/tCO_2	Roussanaly et al. (2021); scaled linearly from ref case
Opex loading cost estimate	2	%	Apeland et al. (2011) and Roussanaly et al. (2021)
Port entry/exit	2	h	Seo et al. (2016) and UK Department for Energy Security and Net Zero (2018)
Operating hours	8400	h	Roussanaly et al. (2021) and UK Department for Energy Security and Net Zero (2018)
Speed	15	nm/h	Seo et al. (2016) and UK Department for Energy Security and Net Zero (2018)
km to nm (nautical miles)	1.852	-	Conversion
Speed km	27.78	km/h	Seo et al. (2016) and UK Department for Energy Security and Net Zero (2018); 15 knots
Pressure	8	bar	UK Department for Energy Security and Net Zero (2018)
Temperature	-49	°C	UK Department for Energy Security and Net Zero (2018)
Density	1150	kg/m^3	UK Department for Energy Security and Net Zero (2018)
Capacity	50000	tCO_2	Roussanaly et al. (2021) and UK Department for Energy Security and Net Zero (2018), maximum ship capacity for low-pressure ships chosen
Capex ship	92,468,700	€$_{2022}$	Roussanaly et al. (2021), Table 4
Fuel consumed	5.19	g/tCO_2/km	Roussanaly et al. (2021), Table 4
Opex	5	%	Roussanaly et al. (2021)
Harbor fees	1.2	€$_{2022}$/tCO_2	Roussanaly et al. (2013, 2021)
Lifetime	25	years	Same assumption as for barges

Table E9: Input data for intermediate storage of CO_2 for train, barge, and ship transport

Parameter	**Value**	**Unit**	**Source**
Ref capacity intermediate storage	1000	t	Own assumption
Capex storage reference	2,000,000	$€_{2022}$	Own assumption
Exponent storage	0.9	-	Own assumption
Storage tank capacity	5	d	Oeuvray et al. (2024)
Lifetime	25	y	Own assumption
Fixed opex	6	%	Own assumption

Table E10: Input data for compression used for levelized cost of CO_2 conditioning

Parameter	**Value**	**Unit**	**Source**
Base case capacity	1,000,000	t/y	Roussanaly et al. (2017)
Base case capex	2.29	$€_{2022}/tCO_2$	Roussanaly et al. (2017)
Efficiency	0.8	-	Oeuvray et al. (2024)
Lifetime	25	y	OECD (2023)
Energy consumption comp. onshore	95	kWh/tCO_2	Oeuvray et al. (2024)
Energy consumption comp. offshore	106.2	kWh/tCO_2	Oeuvray et al. (2024)
Exponent factor	0.85	-	Deng et al. (2019) and Roussanaly et al. (2021)
Fixed OPEX	6	%	Roussanaly et al. (2021)

Table E11: Input data for liquefaction at 8 bar and -50°C used for levelized cost of CO_2 conditioning

Parameter	**Value**	**Unit**	**Source/Notes**
Base case capacity	1,000,000	t/y	Deng et al. (2019) and Roussanaly et al. (2021)
Capex	4.59	$€_{2022}/tCO_2$	Roussanaly et al. (2021), Table 3
Fixed opex	6	%	Roussanaly et al. (2021)
Lifetime	25	years	Deng et al. (2019)
Energy consumption	96.3	kWh/tCO_2	Roussanaly et al. (2017)
Exponent factor	0.85	-	Deng et al. (2019) and Roussanaly et al. (2021)
Cooling water	0.59	$€_{2022}/tCO_2$	Deng et al. (2019); Table B.1
Efficiency of conditioning	0.9	-	Own assumption

F Sensitivity analysis: Transport and conditioning costs

For a comprehensive comparative analysis of CO_2 transport and conditioning modes, we assess the levelized cost as a function of distance (km) and CO_2 transported per year ($MtCO_2$ per year) in Figure F1, assuming a uniform financing structure with public finance at a cost of capital of 1.8%. Transport modes include pipelines, barges, and trains for onshore transport and pipelines and ships for offshore transport.

For onshore and offshore pipelines, the CO_2 conditioning method is compression; for barges, trains and ships, it is liquefaction. We assume all conditioning units are located at the emitter site and owned by the emitter, financed under private corporate finance at a cost of capital of 7.1%. The conditioning costs for liquefaction are consistent across barges, trains, and ships, while the variance in compression costs for pipelines is negligible.

The grey dots in Figure F1 represent two cases: 500 km with 1 $MtCO_2$ per year for onshore transport and 1000 km with 3 $MtCO_2$ per year for offshore transport, as used in the main manuscript. These cases reflect the routes of the potential European CO_2 network illustrated in Figure 1 and align with the scope of currently announced projects.

For onshore transport and conditioning, pipelines are the most cost-effective, particularly for larger CO_2 volumes. With fixed wagon and vessel sizes, the costs for trains and barges do not vary with the mass transported, leaving no room for economies of scale. The transport and conditioning costs for trains range from 52–169 $€_{2022}/tCO_2$ and for barges from 37-98 $€_{2022}/tCO_2$. Therefore, barges are more favorable than trains for accessible inland waterways, in line with the findings of (Oeuvray et al., 2024).

For offshore transport and conditioning, pipelines are the most cost-effective at 1000 km and 3 $MtCO_2$ per year and more generally for distances below 1000 km. At higher distances and lower volumes transported, ships are cost-competitive with pipelines. Therefore, they remain an economically viable option, as previously discussed by Roussanaly et al. (2021) and Oeuvray et al. (2024). The cost patterns of onshore and offshore pipelines differ. For offshore pipelines, once the volume of CO_2 surpasses a threshold, a larger outer diameter for the pipeline becomes necessary, leading to a notable increase in capital expenditure because of higher material expenses. This change results in a distinctive bend in the cost curve.

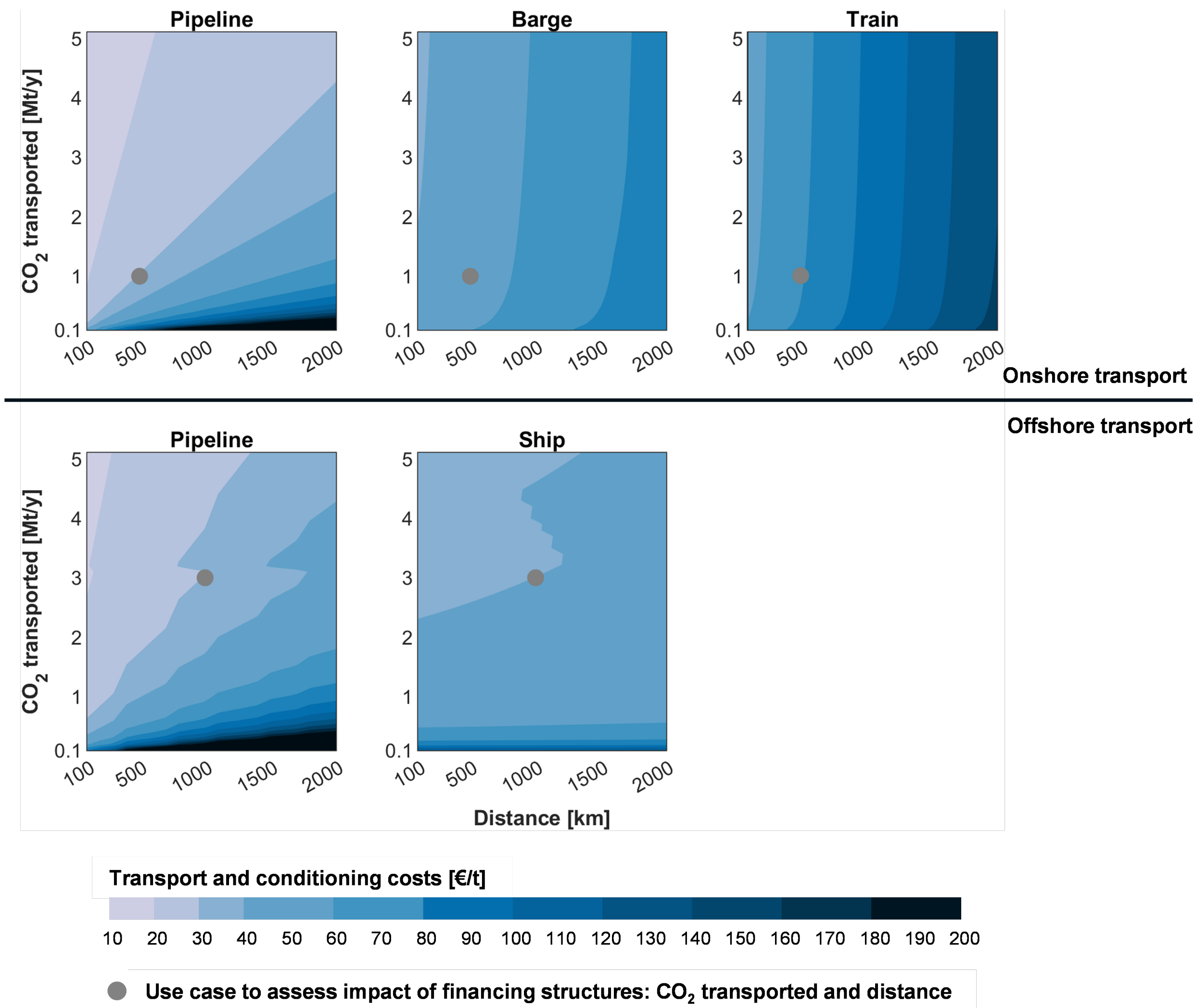

Figure F1: Levelized cost of CO_2 transport and conditioning (top row: onshore transport; bottom row: offshore transport); axes measure distance (km) against $MtCO_2$ per year; for transport assets, we adopt a uniform financing structure with public finance at a discount rate of 1.8%; for conditioning units, we uniformly assume private corporate finance at a discount rate of 7%; grey dots highlight cases (onshore: 500 km, 1 Mt; offshore: 1000 km, 3 Mt) used to assess the impact of financing structures on the cost of CO_2 transport and conditioning used in the main text.

G Sensitivity analysis: Impact of financing structures on transport costs

To assess whether pipelines maintain their cost-effectiveness with a shortened asset lifetime of 25 years, we adjust these parameters. Under public finance, the financing costs for onshore and offshore pipelines decrease by 2 percentage points. For RAB project and RAB corporate finance, financing costs decrease by 5 and 6 percentage points for onshore and offshore pipelines, respectively. Despite the reduction in total interest paid due to the shorter asset lifetime, under public finance, the overall transport and conditioning costs increase by 18% for onshore and offshore pipelines. Under RAB project and RAB corporate finance, these costs rise by 14% and 13% for onshore and by 13% and 12% for offshore pipelines. Consequently, the shorter asset lifetime of 25 years results in an increase in levelized costs despite the reductions in financing costs from the lower total interest payments over the years. Overall, the results highlight that onshore pipelines continue to be the most cost-effective option for onshore transport, while offshore pipeline cost become comparable to those of ships.

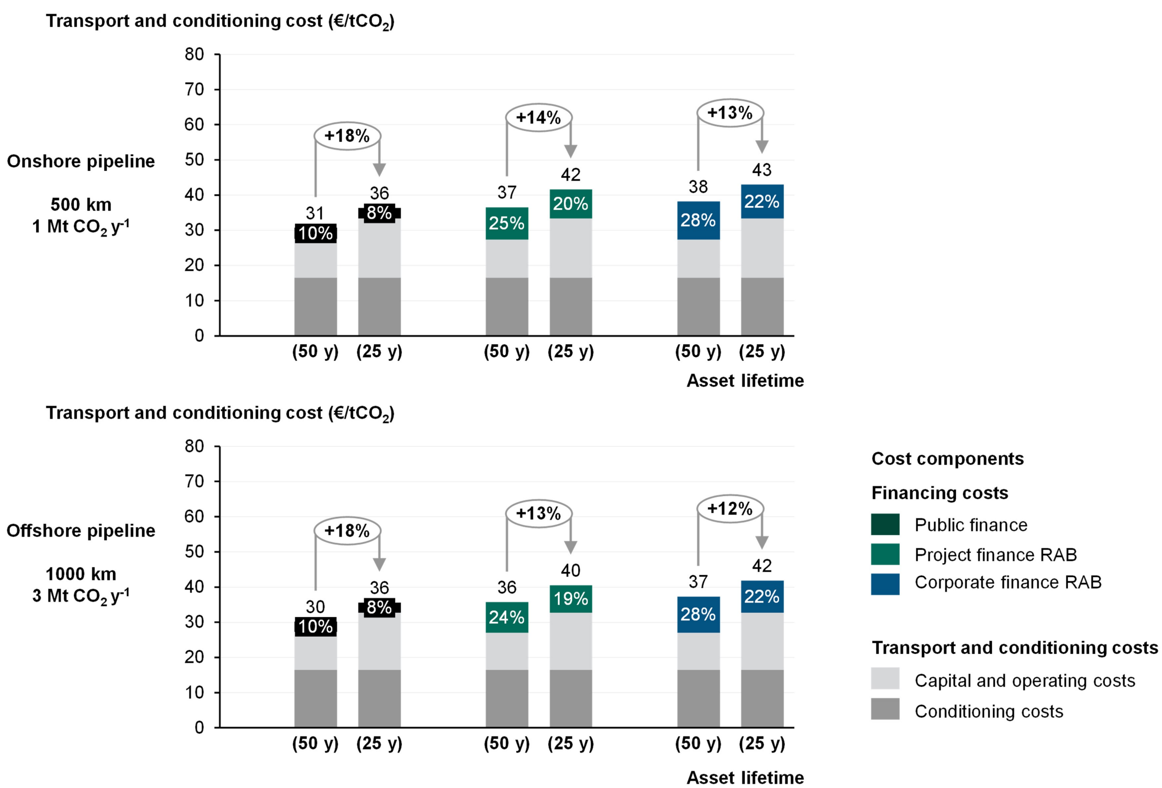

Figure G1: Comparative analysis of levelized cost of CO_2 transport and conditioning via pipeline under varying asset lifetimes in $€_{2022}/tCO_2$.

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