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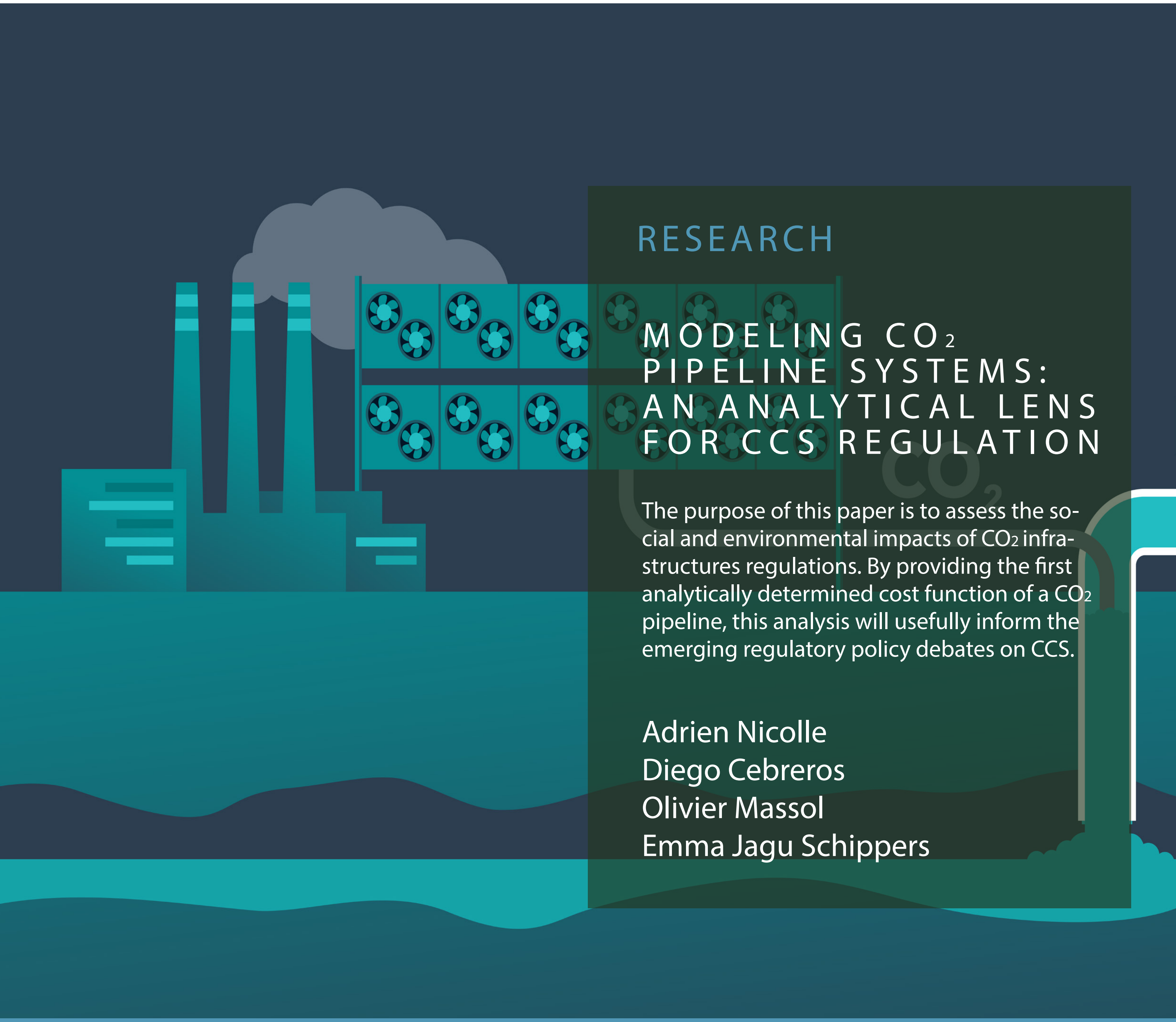

RESEARCH

MODELING CO$_2$ PIPELINE SYSTEMS: AN ANALYTICAL LENS FOR CCS REGULATION

The purpose of this paper is to assess the social and environmental impacts of CO$_2$ infrastructures regulations. By providing the first analytically determined cost function of a CO$_2$ pipeline, this analysis will usefully inform the emerging regulatory policy debates on CCS.

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Diego Cebreros
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Modeling CO_2 pipeline systems: An analytical lens for CCS regulation

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Executive Summary

Although Carbon Capture and Storage (CCS) is widely viewed as an essential technology to achieve carbon neutrality, the lack of clarity regarding regulatory procedures for CO_2 infrastructure installation is a significant barrier to its deployment. This paper explores the challenges of regulatory frameworks for CCS pipeline systems and their impact on the social cost of achieving climate targets.

Background and motivations

The deployment of CCS projects is increasing, with around 200 projects at various stages of development in 2022, representing a significant increase in capacity compared to previous years. However, the success of these projects relies heavily on the installation of CO_2 transportation infrastructure, which often takes the form of a pipeline system connecting a carbon capture facility to a storage site. The deployment of a CO_2 pipeline infrastructure depends critically on the institutional framework governing its provision. Regulatory frameworks for these infrastructures are currently being developed in the US, Norway, the UK, and the European Union. However, there is no consensus on the pricing mechanisms that can be used to ensure the socially optimal economic regulation of CO_2 pipelines. This paper discusses the social and environmental impact of the regulatory frameworks governing CO_2 pipeline systems.

Methodology and results

After a review of the different regulatory approaches envisioned for CO_2 infrastructures in the main jurisdictions, an analytical approach to explore the social and environmental impact of CO_2 pipeline regulation is proposed. The authors prove that the engineering equations governing CO_2 pipeline transportation implicitly define a Cobb-Douglas production function that verifies the technological condition of a natural monopoly. This technological representation reduces information asymmetry between the regulator and the pipeline operator and can help prevent regulatory distortions.

An initial analysis shows that economies of scale are present in CO_2 pipeline systems, which can lead to a substantial deadweight loss in the absence of regulation. Then, the authors assessed the impact of different pricing schemes for the transportation of CO_2 emissions in CCS systems. The study finds that imposing average cost pricing on a CO_2 pipeline operator allows the operator to break-even but may result in an efficiency gap, with only 69% to 75% of the desirable CO_2 emissions being captured and sequestered.

Conclusions and policy implications

Overall, the paper highlights the importance of regulatory frameworks for CCS pipeline systems and suggests a new representation of the system that can assist regulators, policymakers, and academics in their deployment. The numerical analysis supports the idea that economic regulation and environmental regulation are interrelated, and future research should account for the heterogeneity of emitters' demand for transportation to determine the optimal pricing scheme. The authors suggest that price discrimination may be a relevant option for regulators to maximize social welfare.

In future research, the technical representation of pipelines described in this work could be integrated into dynamic models to provide more detailed policy recommendations, such as the timing of regulatory interventions. Finally, the paper does not discuss social issues such as public acceptance or right-of-way, but the authors suggest that defining a clear regulatory framework and coordination among stakeholders are mandatory to reduce the social cost of achieving carbon neutrality.

Modeling CO_2 pipeline systems:

An analytical lens for CCS regulation ☆

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Abstract

Carbon Capture and Storage (CCS) is regularly depicted as a crucial technology to reduce the social cost of achieving carbon neutrality. However, its deployment critically depends on the installation of CO_2 infrastructures. As the regulatory procedures governing their provision are yet to be clarified, the purpose of this paper is to assess the social and environmental impacts of such regulations. We show how the engineering equations of a CO_2 pipeline implicitly define a Cobb-Douglas production function. We then infer that the resulting cost function exhibits economies of scale and verifies the technological condition for a natural monopoly. As the possible exertion of market power is a concern, we evaluate the social distortion of the unregulated monopoly and the average-cost pricing solution, which we compare to the outcomes of the welfare-maximizing solution. While the deadweight loss obtained under average-cost pricing remains lower than 5% compared to the first-best solution, our findings indicate that allocative efficiency is an issue, with more than a quarter of the CO_2 emissions not being transported. By providing the first analytically determined cost function of a CO_2 pipeline, this analysis will usefully inform the emerging regulatory policy debates on CCS.

Keywords: *Carbon Capture and Storage (CCS), CO_2 pipelines, Cobb-Douglas, Regulation*

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1. Introduction

The perception of Carbon Capture Storage (CCS) as a relevant technology to achieve global climate targets has substantially fluctuated over time, alternating between periods of high hopes and disillusionment. In the 2000s, mitigation scenarios envisioned a widespread and rapid deployment of CCS, a technology then presented as promising and cost-effective (IPCC 2005). For example, the International Energy Agency (IEA) emphasized that renouncing this technology might increase social mitigation costs by 70% (IEA 2009). However, in the 2010s, the meager progress observed in CCS implementation triggered a growing skepticism (Hirschhausen, Herold, and Oei 2012), questioning the feasibility of previous targets of CCS deployment. Nowadays, CCS is again gaining momentum in public policy debates. The Intergovernmental Panel for Climate Change (IPCC 2022) stresses its critical role either in the mitigation of the hard-to-abate emissions from a variety of industrial sectors (e.g., cement, iron and steel, fertilizer, hydrogen and chemical processing, pulp and paper) or in enabling negative emissions technologies by combining CCS with bioenergy (Jagu Schippers and Massol 2022) (i.e., the so-called BioEnergy with CCS – BECCS) or direct air capture (i.e., the so-called Direct Air Carbon Capture and Storage – DACCS concept). Against this background, governments have implemented a new series of policies – e.g., the Inflation Reduction Act (117th Congress 2022), the Net Zero Industry Act (European Commission 2023), and the European Innovation Fund (European Commission and Directorate-General for Climate Action 2022) – to accelerate the development of CCS projects by lowering administrative barriers and providing generous subsidies. Yet, one cannot help but wonder whether closing the financial gap is sufficient to unlock the emergence of CCS, as recent studies also highlight the importance of issues pertaining to the institutional framework chosen to govern the provision of CCS (Wang, Akimoto, and Nemet 2021). That opinion concurs with the recent reports by the IPCC and the IEA, which call for new policy instruments aimed at reducing the institutional uncertainties surrounding the implementation of CCS.

However, choosing the right policy instrument is complex because it must simultaneously address issues pertaining to the supply and demand of CCS. From the supply-side, attracting investors to develop CCS transportation infrastructures is challenging because of the high sunk costs and the need to gather a critical volume of captured CO_2 in the projected infrastructure. That volume has significant implications for the sizing of the infrastructure and its cost. Thus, investors need more certainty on the expected volume of CO_2 emissions to be transported (Cai et al. 2014). From the demand-side, emitting firms are cautious about investing in a capture unit, as they face uncertainties from a possible range of future carbon prices and options to mitigate their emissions (Heydari, Ovenden, and Siddiqui 2012). Moreover, both sides face uncertainty in the prices charged for the transportation of the captured emissions. As the pipeline operator will presumably be in a monopolistic position, its pricing behavior (i.e., pricing levels, tariff structure) may be prone to regulatory oversight. If the actions taken by the governmental agency that creates and enforces sectoral regulations are uncertain, so are both the consumer surplus obtained by the emitters that adopt carbon capture and the ability of the pipeline operator to recoup its cost. Hence, absent a clear regulatory signal, neither emitters nor pipeline operators will engage in CCS deployment.

The purpose of this paper is thus the following: How does the regulation of CCS pipeline transportation impact social welfare? Our study aims to provide insights into the impact of CCS transport regulation, with the broader goal of quantifying the social cost of decarbonization. From a policymaking perspective, we aim to provide the CCS pipeline infrastructure's regulator with the first analytical cost function so as to reduce the informational asymmetry between the regulated firm and itself. Bridging this informational gap will help the regulator to identify the required pricing scheme that maximizes the social welfare of CCS pipeline infrastructures.

From a methodological perspective, this paper adapts the theoretical lens of engineering economics applied to natural gas pipelines, which shows the substitution effects between capital and energy (Perrotton and Massol 2018; Massol 2011; Yépez 2008; Chenery 1949) Through this technical representation, we describe the microeconomic behavior of a CO_2 pipeline operator that transports the emissions through a single point-to-point pipeline system. By assuming a cost-minimizing operator, we quantify the impact of regulation on the level of capital investment analytically, the quantity of CO_2 that the pipeline operator agrees to transport – i.e., the supply for the transportation service – the pipeline operator's profit, and the social welfare.

Our analysis conveys a series of new findings. We show that the technology of a point-to-point CO_2 trunk pipeline system can be represented using a Cobb-Douglas production function with two inputs: capital and energy. We prove that this system exhibits pronounced economies of scale, that the long-run total cost function is subadditive, and that it thus verifies the theoretical condition for a natural monopoly. This finding has important policy implications, as it suggests that some form of regulatory intervention may be necessary to attenuate the adverse effects resulting from the exertion of monopolistic power. We show how this could create an underutilization of the CCS transportation system, thus undermining eventual environmental objectives. Following these results, we discuss some assumptions of our model and suggest future avenues of research.

Our technological representation departs from usual representations of CCS pipeline transportation in Integrated Assessment Models (IAMs) and in the economic literature. In IAMs, these representations have been criticized for their lack of transparency and their lack of precision (Luderer et al. 2022; Butnar et al. 2020). In the economic literature, the cost functions for CCS transportation do not account for the specificity of CO_2 (Knoope, Ramírez, and Faaij 2013), with most studies considering the physics of natural gas transportation instead. In this perspective, Viebahn and Chappin (2018) stress in their literature review that CCS is a complex technology that requires interdisciplinary approaches. This perspective has inspired the present technological representation, which brings together economic and engineering models that have so far developed independently. With few exceptions (e.g., Massol et al. 2015), economists use a simplified representation of the technology of a CO_2 pipeline, typically a total cost function with a linear (sometimes piecewise linear) specification. Hence, our approach substantially departs from the network optimization studies (Jagu Schippers and Massol 2022; Holz et al. 2021; Waxman et al. 2021; Perrotton and Massol 2018; Tutton 2018; Zhang et al. 2018; d'Amore and Bezzo 2017; IEAGHG 2016; Oei, Herold, and Mendelevitch 2014; Morbee, Serpa, and Tzimas 2012; Kemp and Sola Kasim 2010; Klokk et al. 2010; Mendelevitch et al. 2010; Middleton and Bielicki 2009). The merits of these numerical studies are that they capture the network interactions among multiples sources and sinks, but they are based on optimization models that are solved numerically and *de facto* embed a simplified (typically linear) representation of the cost function. In the present manuscript, we thus abstract from the analysis of the interactions among multiple sources and aim to concentrate on an analytical approach capable of revealing essential features of the technology of a simple point-to-point CO_2 pipeline infrastructure. These models are used extensively to guide policymaking but they consistently overlook the underlying engineering problems in developing pipeline systems. By contrast, the engineering literature focuses on the complex physics governing CO_2 pipeline transportation (McCoy 2008; McCoy and Rubin 2008; 2005) but does little to explore the economic implications.

This paper's first main contribution is its technical representation of the CO_2 pipeline technology, bridging the gap between engineering and economics. Second, this paper contributes to the growing literature that identifies and provides policy insights to overcome barriers faced by the large-scale deployment of CCS infrastructures. Through our novel technical representation of the CO_2 pipeline system, this paper is the first quantitative contribution to the economic regulation literature of CCS pipeline infrastructures. Indeed, the literature has focused very little on this topic, although it has identified that technical expertise is not the main barrier (Bui et al. 2018; Herzog 2011). A portion of the economic literature seeks the causes behind the failure of large-scale deployment, but few papers provide substantial economic regulatory insights.

Our paper is organized as follows. Section 2 gives a concise overview of the prospects for CCS deployment, the different regulatory approaches envisioned for CO_2 infrastructures, and the differences with other infrastructure sectors. Section 3 proves that the engineering equations governing CO_2 pipeline transportation implicitly define a Cobb-Douglas production function. We leverage that finding to explore its economic implications in section 4. In light of current regulation and of our model, section 5 discusses our assumptions and results. Section 6 presents the conclusions.

2. Background and motivation

This section briefly presents the contemporary prospects for CCS deployment and the different regulatory approaches retained for CO_2 infrastructures in the UK, the US, Norway, and the EU. It then provides a concise review of the economic regulatory issues surrounding the deployment of these infrastructures. Lastly, it explains why the regulatory practice of that sector – and more specifically, the approach retained to evaluate the cost function – must depart from the ones conventionally retained in other network industries.

2.1 The prospects for CCS deployment and the associated need for CO_2 transportation infrastructure

CCS is experiencing an upward momentum: in 2022, about 200 CCS projects were at various stages of development. They jointly represented a cumulative annual carbon capture capacity of 244 million tons of CO_2, which is 45% larger than the inventory from 2021 and four times the capacity of 2017 (Global CCS Institute 2022). Earlier failed attempts to develop CCS almost exclusively targeted emissions from power generation – a sector that has alternative decarbonization technologies (Hirschhausen, Herold, and Oei 2012) – and have mostly failed (Wang, Akimoto, and Nemet 2021). In contrast, recent projects consider the emissions captured from a broader group of industrial sectors (e.g., cement plants, iron and steel, gas treatment units, petrochemical plants). They are also promoted by large creditworthy industrial investors – such as international oil companies.[1] A large part of these

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[1] A non-exhaustive list includes projects in Texas (e.g., Calpine's power plant, Occidental's direct air capture project in the Permian Basin, Rio Grande LNG Terminal), Louisiana (e.g., Air Product's hydrogen project), Illinois (Illinois Clean Fuels

projects is in the US, the UK, Norway, and the EU, in which public authorities recently enacted ambitious policies to support CCS.[2]

These projects heavily rely on the installation of a CO_2 transportation infrastructure in the form of a pipeline system connecting a carbon capture facility to a storage site. By providing the anchor load needed to finance that infrastructure, the installation of a first CCS project is expected to subsequently unlock a broader adoption of carbon capture capabilities, first at neighboring industrial sites and then in the surrounding area – as in the case of natural gas networks, e.g., World Bank (2007). As the number of connected emitters rises, it is anticipated that the infrastructure will grow organically and could ultimately reach a continental scale. For example, under a scenario with an 80% reduction in greenhouse gas emission by 2050 compared to 1990, Oei and Mendelevitch (2016) obtain a European CO_2 pipeline system that runs 45,000 km and covers large parts of the continent. In the US, the CO_2 pipeline infrastructure required under the full economy decarbonization scenario examined by Larson et al. (2020) requires the installation of 21,000 km of trunk lines and 85,000 km of spur lines by 2050. That said, the deployment of a CO_2 pipeline infrastructure critically depends upon the institutional framework implemented to govern its provision.

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project that ambitions to produce synthetic fuels), Norway (the Northern Lights project), the UK (the biomass-fueled Drax power station, BP's H_2 Teesside), Denmark (TotalEnergies' Bifrost project, and the Greensand project), and the Netherlands (e.g., the Porthos and Aramis projects in the Rotterdam area).

[2] Namely: the US Inflation Reduction Act of 2022 (117th Congress 2022), the UK's CCUS Infrastructure Fund (BEIS 2022b), the Net Zero Industry Act (European Commission 2023), the EU Innovation Fund (European Commission and Directorate-General for Climate Action 2022), the State Support Agreements defining the participation of the Norwegian state in the Longship CCS project in Norway (Norwegian Ministry of Petroleum and Energy 2022), the Danish Carbon Capture scheme (Danish Energy Agency 2022), or the Dutch Sustainable Energy Transition Subsidy Scheme "SDE++" (Dutch Ministry of Economic Affairs and Climate Policy 2022).

2.2 The contemporary regulatory framework governing CO_2 pipeline systems

Table 1 provides a compact summary of the different institutional approaches and practices retained in early-adopter regions: the US, the UK, Norway, and the EU. We observe from that table essential variations in the governance imposed on CCS pipeline transportation infrastructures. We distinguish here three types.

Table 1: Review of regulatory initiatives in early-adopter regions for CCS pipeline transportation infrastructures

	UK	**U.S. Interstate**	**U.S. Intrastate**	**Norway**	**EU**
Regulatory agency for rates and access	Ofgem likely to be appointed (BEIS 2022a)	Unclear regulatory mandate for pipelines crossing some federal lands and for pipelines not crossing federal lands	No agency, except for common carriers in Texas and Colorado	No agency, but the state intervenes as a project leader and as a stakeholder of the transportation infrastructure (Gassnova SF 2022)	Silent legislation
Non-discriminatory access prices	Yes	Mandatory for common carriers	Generally mandatory for common carriers	Yes (informational discussion)	Yes
Pricing scheme	Rate-of-return regulation combined with performance incentives (BEIS 2022a)	Project-dependent (STB intervenes in case of a dispute, see discussion in Appendix A)	Project-dependent	Two-tariff structure: (i) a user-specific maritime component based on distance, and (ii) a non-discriminatory access charge to the Norwegian onshore receiving terminal, the offshore pipeline, and the storage site	Silent regulation

Note: We detail the case of the US in Appendix A

The first type is the explicit approach retained in the UK. It provides Ofgem – the independent regulatory agency in charge of natural gas and power infrastructures – with an enlarged mandate that makes it responsible for regulating CO_2 infrastructures. Accordingly, the CCS chain is subjected to a vertical unbundling, whereby a dedicated infrastructure operator must provide transportation under price control (BEIS 2022a). Consistent with Ofgem's conventional approach to the regulation of natural gas networks, the regulator sets and administers the allowed revenue by defining: (i) a regulated asset base comprising the allowed capital expenditures, (ii) an allowed rate of return, (iii) the operating expenditures that the operator can recoup, and (iv) a series of performance targets to be defined.

The second approach involves some degree of state participation, as in Norway's Longship project. Two Norwegian industrial sites (a cement plant and waste-to-energy facility) will capture their CO_2 emissions, which the Northern Lights consortium will then transport and store.[3] The state intervenes at several levels: it leads the Longship project via its state-owned enterprise Gassnova (Gassnova SF 2022), has signed separate agreements with firms participating in the CCS value chain (Norwegian Ministry of Petroleum and Energy 2022), and is an equal shareholder – together with Total and Shell – of the Northern Lights consortium through the state-owned company Equinor (Whitmore 2021). From informal discussions with stakeholders, we understand that the pipeline system operator is supposed to charge cost-reflective non-discriminatory prices, whereas no obligations are set on the price charged for maritime shipments, which can thus vary according to the emitter's willingness. So far, it is not clear whether Northern Lights will be subjected to some form of economic regulation after the first decade of operations.

The third type of approach depends on the federal setting of the governance regime, which is the case of the EU and the US. A fuzzy approach prevails, which somehow echoes the non-exclusive powers of the Federal/EU jurisdictions with respect to CO_2 pipelining and can accommodate the diversity of

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[3] Northern Lights has two activities: (i) it ships the CO_2 to an onshore reception terminal and, from there, (ii) transports the CO_2 by pipeline to a subsea storage.

approaches prevailing at the lower (i.e., state or national) level.[4,5] However, this approach has not boosted the emergence of significant changes in the governance regime of CCS, which remains unclear in most parts (see Appendix A for a concise presentation of the different approaches identified within the US).

Overall, we retain two critical features of regulatory initiatives for CCS pipeline transportation infrastructures: (i) despite having three governance regimes, jurisdictions tend to advocate third-party access to the transportation and storage infrastructure. (ii) However, pricing schemes greatly differ from jurisdiction to jurisdiction.

Assuming that some form of regulation might be necessary, we think that Table 1 raises questions regarding the regulation of CCS. First, should the regulatory tools and governance of gas pipelines be directly transposed to the CCS context? Or does CCS transport infrastructure require a specific type of consideration?

To the best of our knowledge, these issues are largely ignored in the literature on CCS. Wang, Akimoto, and Nemet (2021) identify the imbalance between risk and return for investors as a fundamental barrier to CCS deployment and highlight several quantitative policy recommendations related to public and private intervention. However, the authors focus on entire CCS projects and thus overlook the interaction between capture sites and the pipeline operator. Krahé et al. (2013) identify and propose solutions related to the market failures of the CCS industry. The study mentions the monopolistic character of the pipeline operator and proposes several remedies. However, these measures are described qualitatively and do not provide a quantitative understanding of the impact on the social

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[4] In Europe, the EU authorities stress the obligation to grant third-party access, but they remain silent on important issues such as: the nature of the vertical unbundling imposed on the CCS chain, the pricing provisions (i.e., to what extent can prices depart from purely uniform charges?), and the type of price controls imposed on the pipeline operator.

[5] In the US, while it is likely that some form of rate of return regulation will be implemented on an interstate level – an approach already applied to other infrastructure sectors (Viscusi, Vernon, and Harrington 2000) – the allowed rate of return and thus the allowed revenue obtained by the operator still needs to be clarified.

welfare of the industry. Similarly, Roggenkamp and Haan-Kamminga (2010) presume the natural monopoly characteristics of the pipeline operator but do not quantify the risk associated with the exercise of market power. Through qualitative arguments, they conclude that a regulated access system is not appropriate for CO_2 pipelines. In the extensive gray literature, only a few policy briefs and think-tank reports point out the industry's lack of economic regulation (Whitmore 2021; Elkerbout and Bryhn 2019; Global CCS Institute 2012). Lastly, the cooperative game-theoretic analysis in Massol et al. (2015) examines numerically how the benefits generated by a CCS chain are apportioned among a group of heterogeneous emitters and how the pipeline operator's obligation to use non-discriminatory prices affects the feasibility of the project. Nevertheless, that last analysis is not based on an analytical model and overlooks the regulatory issues pertaining to CO_2 pipelines. In contrast, the legal literature has identified some inconsistencies and uncertainties in the economic regulation of CCS infrastructures, but these studies focus exclusively on legal barriers in the US (Jacobs and Craig 2017; Mack and Endemann 2010; Marston and Moore 2008; Nordhaus and Pitlick 2009; Vann and Parfomak 2008). Overall, to the best of our knowledge, no study quantifies analytically the potential deadweight losses caused by the exertion of market power by the natural monopoly.

2.3 Insights from the broader literature on regulatory economics

Infrastructure sectors are commonly designated as "natural monopolies" as it is more cost-efficient when a single firm, the monopolist, supplies the market. Indeed, the cost functions of network infrastructures typically exhibit substantial economies of scale, declining average costs, and subadditivity. Furthermore, these sectors are capital-intensive, with high upfront sunk costs. However, even if there are efficiencies from having a monopoly to operate infrastructures, it also creates the risk of market power abuse. In this case, the monopoly would reduce social efficiency by increasing consumer prices, which calls for regulatory intervention.

Regulators must find a pricing scheme that maximizes social surplus under incomplete information (Laffont and Tirole 1994; 1986). The regulator faces many informational gaps, but the incomplete knowledge of the regulated firm's costs is the most relevant (Joskow 1999).[6] In other words, the economic regulator needs to make a preliminary assessment of the cost function of the regulated firm through auditing – requiring the regulated firm to produce reports – or benchmarking. Indeed, firms might seize this information gap to maximize their profits given the constraints imposed by the regulatory process (Wolak 1994). More recently (Glachant et al. (2013) explained how bounded regulatory commissions can select regulation tools according to the type of investments and decisions they have to undertake, taking into account their capacities for actions and means. Given their bounded capacities, having analytical tools capable of mimicking the investment and operation decisions of a regulated firm is of paramount importance for designing effective regulatory tools.

Over the years, practitioners have developed and used various regulatory tools to deal with informational asymmetries, such as cost-of-service regulation, price caps, cost-return, and yardstick competition (Shleifer 1985), among other mechanisms. All these practices aim at setting prices closer to a theoretical optimal, given the imperfect information that regulators have. Knowledge of the cost function and the technology at hand (i.e., the relations between the output of the infrastructure and the inputs) is particularly relevant in this context.

2.4 Research question and possible methodological approaches

Motivated by the literature on climate change policy, which has stressed the social costs of deferring investment in CCS technologies (IPCC 2022; IEA 2021; Rogelj et al. 2018; IPCC 2005), we focus on closing a gap for the economic regulation of CCS transportation network. Our objective is to address pricing mechanisms for CCS pipeline transportation, as the literature has overlooked these aspects. Hence, in the following sections, we propose a cost model for CCS pipeline transportation that accounts

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[6] Other sources of informational asymmetry concern budget constraints and governance weaknesses

for the specificity of CO_2. The resulting cost function might help regulators close the information asymmetries when designing the optimal economic regulation.

In regulatory economics, three different methodological approaches are applied to gain insights into the technology of an infrastructure sector. The first category gathers the studies based on frontier-based benchmarking techniques developed in the vein of Data Envelopment Analysis (DEA). DEA uses piecewise linear programming to calculate the efficient frontier of a sample (Färe, Grosskopf, and Lovell 1985). That nonparametric method makes it possible to determine the efficient performance frontier from best industry practices and represents a popular benchmarking tool in the electricity sector (Jamasb, Nillesen, and Pollitt 2004). The second category involves the econometric estimation of a flexible functional form – usually a translog specification – to obtain an approximate cost function. This method has already been widely applied in the context of natural gas pipelines in North America (Gordon, Gunsch, and Pawluk 2003; Oliver 2015; Ellig and Giberson 1993). The third category gathers the process models that derive analytical production and cost functions from technological information. That approach has its theoretical roots in the pioneering works of Chenery (1952; 1949), Leontief and his associates (Leontief 1953), and Smith (1961; 1959). It has already been applied to examine regulatory issues facing natural gas pipelines (Perrotton and Massol 2018; Massol 2011; Yépez 2008; Callen 1978; Thompson, Proctor, and Hocking 1972).

By nature, frontier-oriented benchmarking and econometric methods have an empirical nature and thus require a sample of observations. This feature is a concern when the infrastructure sector under scrutiny is emerging and only gathers a handful of projects, as in the case of CO_2 pipelining. Another difficulty is linked to the industrial organization retained for the few existing CCS projects. So far, these demonstration projects have been conceived as a vertically integrated supply chain with a firm possessing the capture plant and its transportation system (Global CCS Institute et al. 2021). To our knowledge, none of these projects publishes detailed accounting data, which makes it possible to decompose the cost of each component. This context contrasts sharply with other network infrastructures, whose regulation intervened for existing and well-known infrastructures. Interestingly, cost functions in the academic literature do not provide any help to regulators either, as reported by Knoope, Ramírez, and Faaij (2013): only a few models account for the costs of the pumping station, and most models rely on the empirical cost data of the natural gas industry instead of considering the impact of CO_2's physical properties on the cost function. Against this background, the present paper opts for the third approach and examines how the specification of a process model can provide regulators with valuable insights.

In the sequel, we concentrate on the simplest possible pipeline system connecting one entry node to one sink. This basic infrastructure has two essential components – a pipeline and a booster station – and can be used to directly connect an industrial cluster equipped with carbon capture capabilities to a neighboring storage site as in emerging CCS projects (e.g., Northern Lights in Norway or Net Zero Teesside in the UK).[7] Studying such a basic point-to-point infrastructure also provides valuable knowledge on more complex infrastructures that have a modular nature. For example, a trunkline system can be decomposed into a collection of such basic infrastructures that are serially associated to enable long-distance transportation. Similarly, the large network systems envisioned at the national or continental scale can also be decomposed into a collection of such elementary infrastructures.

By nature, our focus on elementary infrastructures departs from the top-down approach of network optimization models. According to that tradition, a central planner is capable of numerically determining the least-cost deployment of a large infrastructure, possibly with a continental scale (Jagu Schippers and Massol 2022; Holz et al. 2021; Waxman et al. 2021; Perrotton and Massol 2018; Tutton 2018; Zhang et

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[7] Northern Lights collects CO_2 emissions through shipping and stores the aggregated CO_2 emissions in an intermediate storage site before transporting them to the storage site through an offshore CO_2 pipeline. For Net Zero Teesside, CO_2 emissions are first collected through feeder pipelines. An offshore point-to-point trunk pipeline then transports the emissions to the offshore storage site.

al. 2018; IEAGHG 2016; Oei, Herold, and Mendelevitch 2014; Morbee, Serpa, and Tzimas 2012; Kemp and Sola Kasim 2010; Klokk et al. 2010; Mendelevitch et al. 2010; Middleton and Bielicki 2009).

As a side remark, although the candidate topology of pipeline systems retained in network optimization studies allow a potentially meshed structure, the structure of the resulting least-cost solutions exhibits a conventional star/tree network topologies with no mesh properties – see the solutions obtained for the cases of California (Middleton and Bielicki 2009), Europe (Morbee, Serpa, and Tzimas 2012), Spain (Massol, Tchung-Ming, and Banal-Estañol 2018), Norway (Klokk et al. 2010), the UK (Kemp and Sola Kasim 2010) or Sweden (Jagu Schippers and Massol 2022). Hence, such networks can be decomposed into elementary modules such as the one under scrutiny in this paper.

3. Modeling the cost function of a CCS pipeline system

In this section, we first examine the engineering equations governing the operation of a CO_2 pipeline system. We then show that the underlying economics is well captured by a Cobb-Douglas production function. Lastly, we derive the resulting cost function.

3.1 The engineering of CO_2 pipelines: A simplified view

We consider a simple CO_2 pipeline system that combines two components: (i) a point-to-point CO_2 trunk pipeline that runs a given distance L , and (ii) a pump-based booster station.[8] This CO_2 pipeline system transports a specified mass flow rate Q of fluid over a given distance L. We list all the technical assumptions in Table 2.

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[8] This is in sharp contrast to the case of natural gas, in which transportation is ensured by compressors, instead of pumps.

Table 2: Main assumptions

Description	Source
Assumption 1: CO_2 is transported in a dense state.	Wang et al. (2016)
Assumption 2: The conversion of CO_2 into a fluid with a dense state is out of our scope.	Knoope, Ramírez, and Faaij (2013)
Assumption 3: The pipeline has no bends.	
Assumption 4: The terrain along the pipeline has a constant elevation.	

Notes: (1) From Assumption 1, the pipeline system at hand uses pump-based booster stations and not compressors as in the case of natural gas. (2) From assumption 1, this model is not suitable for repurposed natural gas pipelines, as the pressure constraints for these pipelines require CO_2 to be transported in gaseous form (Brownsort, Scott, and Haszeldine 2016)*. (3) From Assumption 2, the initial compression converting the CO_2 from a gas at atmospheric pressure into a fluid with a dense state is performed at the capture stage by the emitters and is thus out of the scope of the present analysis. (4) Assumptions 3 and 4 can be relaxed without significantly affecting the validity of our results. Nevertheless, they simplified the analytical treatment. (5) The present paper's representation applies to both onshore and offshore pipelines.*

First, we want to identify the link between the system's output Q and the engineering input variables. Since our system contains two elements, a trunk pipeline and a pumping station, our goal is to express the output Q as a function of two engineering variables that characterize each of these elements: the diameter of the pipeline D and the power of the pump W_p. To this end, we combine their respective engineering equations, the pumping power equation and the flow equation (Table 3), by eliminating the pressure drop ΔP.

Table 3: Engineering equations

Engineering equations	Parameters	Source
Pumping power		
$W_p = \frac{Q \cdot \Delta P}{\rho \cdot \eta_p}$	η_p: efficiency of the pump	Mohitpour, Golshan, and Murray (2003)
	ρ: density of CO_2	Ikeh and Race J.M (2011)
Flow equation		
$D = \left(\frac{4^{\frac{10}{3}} n^2 Q^2 L \rho g}{\pi^2 \rho^2 \Delta P} \right)^{3/16}$	g: gravity constant	Vandeginste and Piessens (2008)
	n: Manning factor	
	π : the geometric constant	

Notes: (1) The literature provides a few alternative approaches to specifying the flow equation (see: Lu et al. 2020*), but most of them rely on numerical procedures to evaluate some of the parameters (e.g., the fanning friction factor, which is not in this flow equation) and do not have a closed form specification which makes them poorly adapted for the present analysis. (2) Because CO_2 is transported in a dense state and not as a gas, the engineering equations of natural gas do not apply here. In particular, the Weymouth equation, popular in natural gas transportation models* (Chenery 1949)*, is not appropriate here.*

We obtain the following engineering equation:

$$Q = A^{1/3} W_p^{1/3} D^{16/9} \tag{1}$$

Where *A* is a technical parameter, i.e., $A = \pi^2 \rho^2 \eta_p / (4^{\frac{10}{3}} g L n^2)$.

In this equation, the pumping power and pipe diameter needed to yield a given output level are not unique, indicating a substitution between these two engineering variables.

3.2 Toward an economic production function

In economics, it is preferable to think in terms of the capital and operating costs of the infrastructure, using standard inputs as decision variables. We therefore let K and E denote the capital and energy inputs, respectively.

The amount of capital required for the pumping equipment is negligible compared with that required for the pipeline. Thus, we assume that the capital stock K is directly proportional to the weight of the steel embedded in the pipeline. w_s denotes the weight of steel per unit of volume and p_s denotes the unit price of steel. One can thus readily evaluate the capital stock K from the volume of an open cylinder with inside diameter D and thickness τ:

$$K = p_s w_s \, L\pi \left[\left(\frac{D}{2} + \tau\right)^2 - \left(\frac{D}{2}\right)^2 \right] \tag{2}$$

The thickness τ is usually determined by mechanical stability concerns. Yet, we follow Callen (1978) and Ruan et al. (2009) and adopt a simplified view that assumes that the value of τ roughly equals a fraction a of the pipeline diameter, i.e., $\tau = a \cdot D$. So, the capital required for the infrastructure is:

$$K = p_s w_s L\pi \, D^2 (a + a^2) \tag{3}$$

Equation (3) indicates that the capital stock is proportional to the squared diameter.

Noting that the energy requirement of the infrastructure E is directly proportional to the pumping power W_p, we can use (3) to reformulate the engineering production function (1) to only use standard economic variables:

$$Q = BK^{8/9} \, E^{1/3} \tag{4}$$

where B is a constant parameter that plays no significant role in our analysis.' we normalize the output Q to eliminate it and obtain the standard Cobb-Douglas production function:

$$Q^{\beta} = K^{\alpha} E^{1-\alpha} \tag{5}$$

where $\beta = \frac{9}{11}, \alpha = \frac{8}{11}$.

3.3 The long-run total cost function

We let e and r denote the energy and capital market prices, respectively.[9] The long-run total cost $C(Q)$ to transport a given flow Q is the solution to the cost-minimizing programming problem:

$$\min_{K,E} C(Q) = rK + eE \tag{6}$$

$$s.t \quad Q^{\beta} = K^{\alpha} E^{1-\alpha}$$

Solving, we obtain a simple univariate specification for that cost function:

$$C(Q) = \frac{r^{\alpha} e^{1-\alpha}}{\alpha^{\alpha} (1-\alpha)^{1-\alpha}} Q^{\beta} \tag{7}$$

Because $\beta < 1$, the long-run cost function is strictly concave and thus strictly subadditive (Sharkey 1982). It is cheaper to transport CO_2 from point to point within an infrastructure operated by a single firm than by any collection of independent pipeline systems. Therefore, the CO_2 pipeline system verifies the technical definition of a natural monopoly (Joskow 2007). This result raises the question of allocative efficiency, which we discuss in the next section.

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[9] In the context of CO_2 pipeline systems, the pumping equipment is powered by electricity. Knoope, Ramírez, and Faaij (2013) summarize the energy costs of several studies. While one study considers this cost to be independent of the booster station's capacity (Piessens et al. 2008), other studies calculate the cost of energy e from the installed capacity, the capacity factor, and the cost of electricity.

4. Assessment of the economic regulation for CCS transportation network

Using the cost function developed in the last section, we adopt the regulator's perspective to address the following two issues: (i) the magnitude of the associated social cost from the lack of economic regulation, and (ii) the effect of a regulatory setting on the monopolist's decisions, and thus on social welfare. To gain insight into the social cost of this market failure, we compare the market outcomes obtained under the three standard cases of a regulator with full information in Table 4: (i) the marginal cost-pricing organization (superscripted *), (ii) the unregulated private monopoly (superscripted ^{M}), and (iii) the average cost-pricing solution, where the net social welfare is maximized while allowing the infrastructure operator to break even (superscripted ^{avg}).

Table 4: The three polar cases

Cases	Optimization problems
Marginal cost-pricing (*)	$\max_Q W(Q) = \int_0^Q P(q)dq - C(Q)$
Unregulated private monopoly (^{M})	$\max_Q \Pi(Q) = P(Q)Q - C(Q)$
Average cost-pricing solution (^{avg})	$\max_Q W(Q) = \int_0^Q P(q)dq - C(Q)$ $s.t\ \Pi \geq 0$

Notes: (1) Here, we let Π denote the profit of the pipeline operator and W(Q) the net social welfare. (2) For concision, the analytical results for the output, the capital invested by the pipeline operator, its costs and the net social welfare are in Appendix C.

We assume that the demand for pipeline transportation originates from a collection of large stationary emitters equipped with carbon capture capabilities that can be connected to the infrastructure. For concision, we overlook their decision problems and state that their aggregate demand for CO_2 transportation services can be modeled using a simple inverse demand function: $P(Q) = AQ^{-\epsilon}$ where

$1/\epsilon$ is the absolute price elasticity of demand. We also retain the technical assumptions: $\epsilon < 1$ so that without any output, the monopolist's total revenue is zero, and $\epsilon > 1 - \beta$.

Table 5 presents the performance ratios based on the results of the different scenarios. We choose the marginal cost-pricing scenario as a reference and calculate, for each of the two remaining cases (unregulated and regulated under average cost-pricing monopoly), the ratio of output, capital, and costs (Panel A). We also determine the welfare and profit for each scenario relative to the total revenue of a welfare-maximizing operator (Panel B). All these ratios are determined by the technology parameters (i.e., α and β) and the demand elasticity. They are thus invariant with the input prices and the demand coefficient A.

Table 5: Performance ratios

Panel A: The output, capital, and cost ratios

	Unregulated monopoly (^{M}) vs. marginal cost-pricing scenario (*)	Average cost pricing (^{avg}) vs. Marginal cost-pricing scenario (*)
Output ratio	$\frac{Q^M}{Q^*} = (1-\epsilon)^{\frac{1}{\gamma}} < 1$	$\frac{Q^{avg}}{Q^*} = \beta^{1/\gamma} < 1$
Capital ratio	$\frac{K^M}{K^*} = (1-\epsilon)^{\frac{\beta}{\gamma}} < 1$	$\frac{K^{avg}}{K^*} = \beta^{\beta/\gamma} < 1$

Panel B: Profit and net social welfare ratios

Profit ratio	$\frac{\Pi(Q)}{P(Q^*)Q^*} = \left(\frac{Q}{Q^*}\right)^{1-\epsilon} - \frac{1}{\beta}\left(\frac{Q}{Q^*}\right)^{\beta}$
Welfare ratio	$\frac{W(Q)}{P(Q^*)Q^*} = \frac{1}{1-\epsilon}\left(\frac{Q}{Q^*}\right)^{1-\epsilon} - \frac{1}{\beta}\left(\frac{Q}{Q^*}\right)^{\beta}$

Note: To simplify the notation, we follow Callen, Mathewson, and Mohring (1976) *and let* $\gamma := \beta + \epsilon - 1$.

We opt for a numerical approach to gain further understanding and therefore consider a realistic value for the price elasticity parameter. In the sequel, we take -1.25 for the price elasticity of demand and conduct a sensitivity analysis around that reference.[10] The results are presented in Table 6.

Absent any form of regulation, a private monopoly transports less than 10% of Q^*, the socially desirable quantity of CO_2. That rationing is also apparent in the operator's investment decisions K^M. With the price elasticity figures at hand, the monopolist installs less than 15% of the capital stock K^* installed by a benevolent social planner (the diameter of the monopolist's pipeline system indicated in (3) does not exceed 38% of the socially optimal value). Unsurprisingly, the monopolist obtains hefty profits $\Pi(Q^M)$ and that organization brings a considerable deadweight loss representing between 19% and 29% of the maximal net social welfare $W(Q^*)$. These figures illustrate the necessity of protecting consumers from the monopoly pricing behavior of a private pipeline operator.

To correct this market failure, one can suggest imposing the marginal cost-pricing solution by transporting Q^*, as it maximizes social welfare. This supports a classic microeconomic result indicating that pricing at marginal cost maximizes social welfare and is therefore the first-best solution. Similarly, microeconomic textbook results suggest that this socially desirable organization does not allow the monopolist to recover its costs. Indeed, the corresponding loss is substantial as $\Pi(Q^*)$ represents -22.2% of the total revenue $P(Q^*)Q^*$. Absent any subsidy, that solution does not allow the pipeline operator to break even.

The average cost pricing rule alleviates this issue by ensuring a non-negative profit for the pipeline operator and by minimizing social welfare losses (i.e., it is the second-best solution). Compared with

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[10] The -1.25 figure was obtained from the econometric estimation of a simple isoelastic inverse demand specification using data representing the volume and marginal willingness to pay for transportation services in Sweden. That willingness-to-pay was computed using the capture cost data in Johnsson, Normann, and Svensson (2020), a reference carbon price of 100€ per ton of CO_2 and the carbon storage cost data in IEAGHG and ZEP (2011).

the socially desirable benchmark, this second-best organization achieves a high level of net social welfare $W(Q^{avg})$ that represents at least 98% of the theoretical reference level $W(Q^{*})$.

Table 6: Numerical results of the performance ratios.

	$\frac{1}{\epsilon}$				
	1.13	1.19	1.25	1.31	1.38
Output ratio					
$\frac{Q^{M}}{Q^{*}}$	0.046	0.062	0.074	0.084	0.093
$\frac{Q^{avg}}{Q^{*}}$	0.752	0.737	0.723	0.708	0.691
Capital ratio					
$\frac{K^{M}}{K^{*}}$	0.081	0.102	0.119	0.132	0.143
$\frac{K^{avg}}{K^{*}}$	0.792	0.779	0.767	0.754	0.739
Profit ratio					
$\frac{\Pi(\mathrm{Q}^{*})}{P(Q^{*})Q^{*}}$	-0.222	-0.222	-0.222	-0.222	-0.222
$\frac{\Pi(\mathrm{Q}^{M})}{P(Q^{*})Q^{*}}$	0.603	0.516	0.449	0.395	0.345
$\frac{\Pi(\mathrm{Q}^{avg})}{P(Q^{*})Q^{*}}$	0.000	0.000	0.000	0.000	0.000
Welfare ratio					
$\frac{W(Q^{M})}{W(Q^{*})}$	0.804	0.772	0.748	0.729	0.711
$\frac{W(Q^{avg})}{W(Q^{*})}$	0.996	0.995	0.992	0.990	0.987

Note: For output, capital, and welfare, we compute the ratio of the unregulated monopoly and the average cost-pricing parameter over their respective marginal cost-pricing parameter. For the profit ratio, we compute the profit of the monopoly in each scenario over its revenue in the marginal cost-pricing scenario.

5. Discussion and policy implications

We organize our discussion in two parts. First, we discuss the advantages of considering the physical characteristics of CO_2 emissions. Then, we adopt the perspective of the economic regulator and analyze how other factors – environmental policy and a refined knowledge of the demand of emitters – could influence its approach, and how our model could incorporate such aspects.

5.1 Providing a first analytical cost function to CCS pipeline transportation

When modeling the cost function of the investment and operation of a CO_2 pipeline, we consider the technical characteristics of CO_2 emissions. Indeed, the latter relies heavily on cost data and the physics of natural gas to build its CO_2 cost functions (Knoope, Ramírez, and Faaij 2013). Calculating the marginal to average cost ratio, we find that it is less than one, which proves that there are substantial economies of scale in CO_2 pipelining. We also prove that it verifies the technological condition for a natural monopoly as the cost function is strictly subadditive.[11] This important finding provides a scientific justification to an assumption repeatedly retained, but so far unproven.

Aside from this analytical result, we believe that our model is a practical analytical tool for policymakers in charge of governing CCS transportation infrastructures. Indeed, our technological representation allows the regulator to determine the operator's long-run total costs, as well as the substitution effects between the pipeline's dimensions and the pumps. From a practical point of view, we provide a technological understanding of the CO_2 pipeline system that, through equation (3), links the pipeline's diameter to the installed capital. As measuring a diameter is straightforward, that relation provides the regulator with observable data that can be used to assess and track whether the capital expenditures made by the pipeline operator are justified for an efficient transportation. Consequently, this technological representation reduces the information asymmetry between the regulator and the

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[11] Here β =0.81, which is slightly greater than the 0.61 figure obtained in the empirical analysis conducted on natural gas pipelines by Massol (2011).

pipeline operator and can be useful for preventing some regulatory distortions (e.g., the Averch-Johnson effect that is the tendency of the regulated firm subjected to rate-of-return regulation to overcapitalize). Hence, it can usefully assist a regulator bounded in its allocation of resources.

5.2 *Insights for regulation*

Using the previous technological representation, we test the impact of different types of pricing schemes for the CCS transportation network to benchmark generic strategies of economic regulation. To this end, we assume that the regulator is fully informed of the firm's cost function. We find that imposing average cost pricing on a CO_2 pipeline operator yields only a slight deadweight loss while allowing the pipeline operator to break even.[12] However, while this pricing scheme allows for investors to break even, compared to marginal pricing, its pernicious consequences on the social cost of achieving environmental targets might be substantial. Indeed, under average cost pricing the network transports (and thus captures and sequesters) fewer CO_2 emissions: the volume Q^{avg} comprises between 69% and 75% of the socially desirable benchmark Q^* (see Table 6), which indicates that at least a quarter of the volume Q^* is not captured. The corresponding efficiency gap $(Q^* - Q^{avg})$ emanates from emitters with a marginal willingness-to-pay for a transportation service that is both: (i) greater than the marginal cost to provide the service $C'(Q^*)$, and (ii) smaller than the average cost price $P(Q^{avg})$. The monopolist also installs a capital stock comprised of between 74% and 79% of the theoretical reference K^*.

We see from the above that economic regulation is inseparable from environmental regulation.[13] We now argue that our study can be extended to account for specific environmental policies, via the modification of the elasticity of demand. Indeed, our study could be adapted to study the impact of CCS

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[12] The purpose of this paper is not to discuss the challenges faced in the implementation of that second-best solution, something that can be found elsewhere. We refer to Joskow (2007) for a comprehensive discussion of the challenging implementation of that pricing rule which requires a perfect knowledge of both the costs and the price elasticity of demand.

[13] Through a game-theoretic perspective, Jagu Schippers and Massol (2022) explore the impact of carbon removal accounting on the CO_2 infrastructure development for CCS and BECCS.

regulation in combination with other environmental policies. For example, if a state adopts a CO_2 emission price, this will affect the overall elasticity of transport demand. If the price is high enough, emitting sites will prefer to capture their emissions and their elasticity will be low (and $1/\epsilon$ will be close to 1). Our study allows us to quantify such effects (and in such cases the ratio of the monopolist's welfare over the first-best welfare is almost equal to 1), but precising the link between the CO_2 emission price and elasticity is left to future research.[14]

We assumed an aggregate demand from emitters without acknowledging their differences. However, the demand for transportation is heterogeneous because of the plurality of emitters' profiles: industrial emitters do not have the same emission profiles, whether in terms of volumes, seasonality, or substitutes to carbon capture (Johnsson, Normann, and Svensson 2020; Garðarsdóttir et al. 2018). Depending on the nature of the heterogeneity, regulators could adopt price discrimination to maximize the industry's social welfare. Indeed, economic theory suggests that it is a relevant option if the regulated firm can identify different submarkets with various willingness-to-pay or different demand elasticities. In this perspective, Norway already seems to depart from the non-discriminatory tradition and adapts its tariffication to the heterogeneous demand: although promoting non-discriminatory access, it seems that Northern Lights will have to arbitrate between future users due to the limited capacity of its infrastructure. Indeed, of the 1.5 $MtCO_2/y$ of planned capacity in the first phase, already 0.8 $MtCO_2/y$ is reserved for the first two users. In short, access to Northern Lights appears to be similar to third-degree price discrimination. Overall, our study suggests that a closer look at the demand for transportation could incentivize more specific forms of regulation, such as price discrimination. We leave these aspects to further research.

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[14] Similarly, the existence of an emission allowance market will necessarily impact demand, which can be partially reflected through the elasticity of demand.

6. Conclusion

There are both high hopes and concerns over the future deployment of CCS. CCS is supported by an unprecedented momentum and is expected to become a relevant technology to efficiently achieve global climate targets; especially within industries where CO_2 mitigation alternatives are limited or too expensive to implement. However, little attention is devoted to CCS pipeline infrastructures, although the deployment of the CCS industry is contingent upon these infrastructures. Thus, the fundamental policy issue addressed in this paper is to examine and quantify the economic effects that the regulatory framework imposed on a CCS pipeline system has on the social cost of achieving climate targets. The existing regulatory frameworks imposed on CO_2 pipelining remain unclear and vary greatly from one region to another. Our study questions whether regulators have truly grasped the monopolistic character of these infrastructures, and the risk that the exhibition of market power can represent. Since part of the difficulty in regulating lies in the information asymmetry between the pipeline operator and the regulator, our paper aims at reducing this gap by determining the cost function of the former.

We propose a new representation of CO_2 pipeline systems that captures their essential engineering features: a Cobb-Douglas production function that allows substitution between two inputs (capital and energy), which verifies the technological condition of a natural monopoly. Our representation analytically validates the widely accepted – but rarely demonstrated – hypothesis that the CO_2 pipeline system exhibits economies of scale. We believe that this representation provides an observable and simple analytical understanding of the CO_2 pipeline system for policymakers, thus reducing the informational asymmetry between the regulator and the regulated firm. In practice, regulators most likely do not have full information on the pipeline operator’s cost function as these infrastructures are still emerging. Our model thus provides a framework for analyzing their economics and should thus prove useful to academics, regulators, and policymakers interested in their deployment.

Our work could also enrich cost functions retained in partial equilibrium models of the CCS industry thanks to its technological accuracy and economic interpretability. We examine the market outcomes and show that the deadweight loss can be substantial in the absence of regulation. Our findings indicate that average cost pricing performs well in terms of social welfare, but yields an important environmental issue, as allocative efficiency is not achieved. Yet, the efficiency gap identified in this study critically relies on the posited use of a uniform, non-discriminatory price.

Future research could consider a more detailed analysis of the emitters' demand and explore alternative pricing forms. Adapting our model to accommodate different category of emitters based on their respective willingness-to-pay and price elasticity is a possible research avenue. From a temporal point of view, future research could also integrate our technical representation in a dynamic version, including the rates charged by the monopoly over time. This representation could provide specific policy recommendations, such as the timing of regulatory interventions or whether regulation should be ex-ante or ex-post. We think an interesting research avenue is to analyze the microeconomics of CCS with offset markets. Most probably, CCS will be one of several options that industrial emitters might have to achieve carbon neutrality, and the interaction of potential markets for offset reduction of CO_2 is vastly underexplored.

From a spatial point of view, our study essentially focuses on the regulation of a hypothetical pipeline project and thus omits spatial considerations pertaining to the regulation of transnational infrastructures. Likewise, our study does not discuss social issues such as public acceptance or right-of-way. Defining a clear regulatory framework and coordination among stakeholders (Jagu Schippers, Da Costa, and Massol 2022; Jagu Schippers and Massol 2020) are mandatory, and we believe that our CO_2 pipeline system representation can serve to quantify these purposes. Exploring these aspects would provide the CCS infrastructures' regulator with better knowledge to assist the emergence of this industry, foster its large-scale deployment, and reduce the social cost of achieving carbon neutrality.

References

117th Congress. 2022. *Public Law 117-169: Inflation Reduction Act of 2022*. U.S. Congress. https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

BEIS. 2022a. "Carbon Capture, Usage and Storage - An Update on the Business Model for Transport and Storage."

———. 2022b. "The Carbon Capture and Storage Infrastructure Fund: An Update on Its Design." December 16, 2022. https://www.gov.uk/government/publications/design-of-the-carbon-capture-and-storage-ccs-infrastructure-fund/the-carbon-capture-and-storage-infrastructure-fund-an-update-on-its-design-accessible-webpage#cif-allocation.

Brownsort, Peter A., Vivian Scott, and R. Stuart Haszeldine. 2016. "Reducing Costs of Carbon Capture and Storage by Shared Reuse of Existing Pipeline—Case Study of a CO_2 Capture Cluster for Industry and Power in Scotland." *International Journal of Greenhouse Gas Control* 52 (September): 130–38. https://doi.org/10.1016/j.ijggc.2016.06.004.

Bui, Mai, Claire S. Adjiman, André Bardow, Edward J. Anthony, Andy Boston, Solomon Brown, Paul S. Fennell, et al. 2018. "Carbon Capture and Storage (CCS): The Way Forward." *Energy and Environmental Science*. Royal Society of Chemistry. https://doi.org/10.1039/c7ee02342a.

Butnar, Isabela, Pei Hao Li, Neil Strachan, Joana Portugal Pereira, Ajay Gambhir, and Pete Smith. 2020. "A Deep Dive into the Modelling Assumptions for Biomass with Carbon Capture and Storage (BECCS): A Transparency Exercise." *Environmental Research Letters* 15 (8). https://doi.org/10.1088/1748-9326/ab5c3e.

Cai, W., D. I. Singham, E. M. Craparo, and J. A. White. 2014. "Pricing Contracts Under Uncertainty in a Carbon Capture and Storage Framework." *Energy Economics* 43: 56–62. https://doi.org/10.1016/j.eneco.2014.02.003.

Callen. 1978. "Production, Efficiency, and Welfare in the Natural Gas Transmission Industry." *The American Economic Review* 68 (3): 311–23.

Callen, G Frank Mathewson, and Herbert Mohring. 1976. "The Benefits and Costs of Rate of Return Regulation." *The American Economic Review* 66 (3): 290–97.

Chenery, Hollis B. 1949. "Engineering Production Functions." *The Quarterly Journal of Economics* 63 (4): 507–31. https://academic.oup.com/qje/article/63/4/507/1902302.

Chenery, Hollis B. 1952. "Overcapacity and the Acceleration Principle." *Econometrica* 20: 1–28.

d'Amore, Federico, and Fabrizio Bezzo. 2017. "Economic Optimisation of European Supply Chains for CO_2 Capture, Transport and Sequestration." *International Journal of Greenhouse Gas Control* 65: 99–116. https://doi.org/10.1016/j.ijggc.2017.08.015.

Danish Energy Agency. 2022. “Invitation to Second Market Dialogue - CCUS Fund.” https://ens.dk/sites/ens.dk/files/CCS/note_regarding_second_round_of_market_dialogue_-_07.03.2022.pdf.

Dutch Ministry of Economic Affairs and Climate Policy. 2022. “Stimulation of Sustainable Energy Production and Climate Transition (SDE++).” December 17, 2022. https://english.rvo.nl/subsidies-programmes/sde.

Elkerbout, Milan, and Julie Bryhn. 2019. “An Enabling Framework for Carbon Capture and Storage (CCS) in Europe: An Overview of Key Issues.” www.ceps.eu.

Ellig, Jerry, and Michael Giberson. 1993. “Scale, Scope, and Regulation in the Texas Gas Transmission Industry.” *Journal of Regulatory Economics*. Vol. 5.

European Commission. 2023. *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Establishing a Framework of Measures for Strengthening Europe’s Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act) (Text with EEA Relevance)*. Brussels. https://dealroom.co/uploaded/2022/04/Dealroom-Talis-.

European Commission, and Directorate-General for Climate Action. 2022. “Innovation Fund Progress Report : Report from the Commission to the European Parliament and the Council, August 2022.” https://doi.org/10.2834/58165.

Färe, R., S. Grosskopf, and C. K. Lovell. 1985. *The Measurement of Efficiency of Production*. Vol. 6. Springer Science & Business Media.

Garðarsdóttir, Stefanía Ósk, Fredrik Normann, Ragnhild Skagestad, and Filip Johnsson. 2018. “Investment Costs and CO2 Reduction Potential of Carbon Capture from Industrial Plants – A Swedish Case Study.” *International Journal of Greenhouse Gas Control* 76 (September): 111–24. https://doi.org/10.1016/j.ijggc.2018.06.022.

Gassnova SF. 2022. “Regulatory Lessons Learned from Longship.”

Glachant, Khalfallah, Perez, Rious, and Saguan. 2013. “Implementing Incentive Regulation and Regulatory Alignment with Resource Bounded Regulators.” *Competition and Regulation in Network Industries* 14 (3). http://rru.worldbank.org/Toolkits/InfrastructureRegulation/.

Global CCS Institute. 2012. “Carbon Dioxide (CO_2) Distribution Infrastructure - The Opportunities and Challenges Confronting CO2 Transport for the Purposes of Carbon Capture and Storage (CCS).” www.globalccsinstitute.com.

———. 2022. “Global Status of CCS 2022.”

Global CCS Institute, Christina Staib, Tony Zhang, Jamie Burrows, Angus Gillespie, Ian Havercroft, Dominic Rassool, et al. 2021. “Global Status of CCS 2021.”

Gordon, D. V., K. Gunsch, and C. V. Pawluk. 2003. “A Natural Monopoly in Natural Gas Transmission.” *Energy Economics* 25 (5): 473–85. https://doi.org/10.1016/S0140-9883(03)00057-4.

Herzog, Howard J. 2011. “Scaling up Carbon Dioxide Capture and Storage: From Megatons to Gigatons.” *Energy Economics* 33 (4): 597–604. https://doi.org/10.1016/j.eneco.2010.11.004.

Heydari, Somayeh, Nick Ovenden, and Afzal Siddiqui. 2012. “Real Options Analysis of Investment in Carbon Capture and Sequestration Technology.” *Computational Management Science* 9 (1): 109–38. https://doi.org/10.1007/s10287-010-0124-5.

Hirschhausen, Christian, Johannes Herold, and Pao Yu Oei. 2012. “How a ‘low Carbon’ Innovation Can Fail-Tales from a ‘Lost Decade’ for Carbon Capture, Transport, and Sequestration (CCTS).” *Economics of Energy & Environmental Policy* 1 (2): 115–23. https://doi.org/10.5547/2160-5890.1.2.8.

Holz, Franziska, Tim Scherwath, Pedro Crespo del Granado, Christian Skar, Luis Olmos, Quentin Ploussard, Andrés Ramos, and Andrea Herbst. 2021. “A 2050 Perspective on the Role for Carbon Capture and Storage in the European Power System and Industry Sector.” *Energy Economics* 104 (December). https://doi.org/10.1016/j.eneco.2021.105631.

IEA. 2009. “Technology Roadmap - Carbon Capture and Storage 2009.” Paris. https://www.iea.org/reports/technology-roadmap-carbon-capture-and-storage-2009.

———. 2021. “Net Zero by 2050 - A Roadmap for the Global Energy Sector.” Paris https://www.iea.org/reports/net-zero-by-2050. www.iea.org/t&c/.

IEAGHG. 2016. “European Scenarios of CO2 Infrastructure Investment.” In *Energy Journal*, 37:171–94. International Association for Energy Economics. https://doi.org/10.5547/01956574.37.SI3.poei.

IEAGHG, and ZEP. 2011. “The Costs of CO_2 Storage – Post-Demonstration CCS in the EU.” Brussels. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf.

Ikeh, L, and Race J.M. 2011. “Comparing the Effects of Pipe Diameter on Flow Capacity of CO_2 Pipeline.”

IPCC. 2005. “IPCC Special Report on Carbon Dioxide Capture and Storage.”

———. 2022. “Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.” Cambridge, Uk and New York, NY, USA. https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

Jacobs, Wendy B, and Michael Craig. 2017. “Legal Pathways to Widespread Carbon Capture and Sequestration.” Washington DC. http://www.eli.org,.

Jagu Schippers, Emma, Pascal Da Costa, and Olivier Massol. 2022. “Coordinating the Deployment of Bioenergy with Carbon Capture and Storage.” *Science and Technology for Energy Transition* 77: 19. https://doi.org/10.2516/stet/2022018.

Jagu Schippers, Emma, and Olivier Massol. 2020. “Building Infrastructures for Fossil-and Bio-Energy with Carbon Capture and Storage: Insights from a Cooperative Game-Theoretic Perspective.” London.

———. 2022. “Unlocking CO_2 Infrastructure Deployment: The Impact of Carbon Removal Accounting.” *Energy Policy* 171 (December): 113265. https://doi.org/10.1016/J.ENPOL.2022.113265.

Jamasb, Tooraj, Paul Nillesen, and Michael Pollitt. 2004. “Strategic Behaviour under Regulatory Benchmarking.” *Energy Economics* 26 (5): 825–43. https://doi.org/10.1016/J.ENECO.2004.04.029.

Johnsson, Filip, Fredrik Normann, and Elin Svensson. 2020. “Marginal Abatement Cost Curve of Industrial CO2 Capture and Storage – A Swedish Case Study.” *Frontiers in Energy Research* 8 (August). https://doi.org/10.3389/fenrg.2020.00175.

Joskow. 1999. “Regulatory Priorities for Infrastructure Sector Reform in Developing Countries.”

———. 2007. “Chapter 16 Regulation of Natural Monopoly.” *Handbook of Law and Economics*. https://doi.org/10.1016/S1574-0730(07)02016-6.

Kemp, Alexander G., and A. Sola Kasim. 2010. “A Futuristic Least-Cost Optimisation Model of CO_2 Transportation and Storage in the UK/UK Continental Shelf.” *Energy Policy* 38 (7): 3652–67. https://doi.org/10.1016/j.enpol.2010.02.042.

Klokk, P. F. Schreiner, A. Pagès-Bernaus, and A. Tomasgard. 2010. “Optimizing a CO_2 Value Chain for the Norwegian Continental Shelf.” *Energy Policy* 38 (11): 6604–14. https://doi.org/10.1016/j.enpol.2010.06.031.

Knoope, M. M.J., A. Ramírez, and A. P.C. Faaij. 2013. “A State-of-the-Art Review of Techno-Economic Models Predicting the Costs of CO2 Pipeline Transport.” *International Journal of Greenhouse Gas Control* 16 (August): 241–70. https://doi.org/10.1016/j.ijggc.2013.01.005.

Krahé, Max, Wolf Heidug, John Ward, and Robin Smale. 2013. “From Demonstration to Deployment: An Economic Analysis of Support Policies for Carbon Capture and Storage.” *Energy Policy* 60 (September): 753–63. https://doi.org/10.1016/j.enpol.2013.05.019.

Laffont, J. J., and J. Tirole. 1986. “Using Cost Observation to Regulate Firms.” *Journal of Political Economy* 94 (3): 614–41.

———. 1994. “Access Pricing and Competition.” *European Economic Review* 38 (9): 1673–1710.

Larson, Eric, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, et al. 2020. “Net-Zero America: Potential Pathways, Infrastructure, and Impacts.” Princeton, NJ.

Leontief, W. W. 1953. “Studies in the Structure of the American Economy.” *Oxford University Press* 1 (2).

Lu, Hongfang, Xin Ma, Kun Huang, Lingdi Fu, and Mohammadamin Azimi. 2020. “Carbon Dioxide Transport via Pipelines: A Systematic Review.” *Journal of Cleaner Production*. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.121994.

Luderer, G., S. Madeddu, L. Merfort, F., Ueckerdt, M., Pehl, and R. Pietzcker. 2022. “Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios.” *Nature Energy* 7 (1): 32–42.

Mack, Joel, and Buck Endemann. 2010. “Making Carbon Dioxide Sequestration Feasible: Toward Federal Regulation of CO2 Sequestration Pipelines.” *Energy Policy* 38 (2): 735–43. https://doi.org/10.1016/j.enpol.2009.10.018.

Marston, Philip M, and Patricia A Moore. 2008. “From EOR to CCS: The Evolving Legal and Regulatory Framework for Carbon Capture and Storage.” *Energy L.J.* 29: 421–90. http://www.marstonlaw.com/index.

Massol, Olivier. 2011. “A Cost Function for the Natural Gas Transmission Industry: Further Considerations.” *Engineering Economist* 56 (2): 95–122. https://doi.org/10.1080/0013791X.2011.573615.

Massol, Olivier, Stéphane Tchung-Ming, and Albert Banal-Estañol. 2015. “Joining the CCS Club! The Economics of CO2 Pipeline Projects.” *European Journal of Operational Research* 247 (1): 259–75. https://doi.org/10.1016/j.ejor.2015.05.034.

———. 2018. “Capturing Industrial CO2 Emissions in Spain: Infrastructures, Costs and Break-Even Prices.” *Energy Policy* 115 (April): 545–60. https://doi.org/10.1016/j.enpol.2018.01.015.

McCoy, Sean T. 2008. “The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs.” Pittsburgh PA: Carnegie Mellon University.

McCoy, Sean T, and Edward S Rubin. 2005. “Models of CO_2 Transport and Storage Costs and Their Importance in CCS Cost Estimates.” In *Fourth Annual Conference On Carbon Capture And Sequestration*, edited by DOE/NETL.

———. 2008. “An Engineering-Economic Model of Pipeline Transport of CO_2 with Application to Carbon Capture and Storage.” *International Journal of Greenhouse Gas Control* 2 (2): 219–29. https://doi.org/10.1016/S1750-5836(07)00119-3.

Mendelevitch, Roman, Johannes Herold, Pao-Yu Oei, and Andreas Tissen. 2010. “CO_2 Highways for Europe: Modelling a Carbon Capture, Transport and Storage Infrastructure for Europe.” Centre for European Policy Studies.

Middleton, Richard S., and Jeffrey M. Bielicki. 2009. “A Scalable Infrastructure Model for Carbon Capture and Storage: SimCCS.” *Energy Policy* 37 (3): 1052–60. https://doi.org/10.1016/j.enpol.2008.09.049.

Mohitpour, M., H. Golshan, and M. A. Murray. 2003. *Pipeline Design & Construction: A Practical Approach.* Amer Society of Mechanical.

Morbee, Joris, Joana Serpa, and Evangelos Tzimas. 2012. “Optimised Deployment of a European CO2 Transport Network.” *International Journal of Greenhouse Gas Control* 7 (March): 48–61. https://doi.org/10.1016/j.ijggc.2011.11.011.

NETL, and Great Plains Institute. 2017. “Siting and Regulating Carbon Capture, Utilization and Storage Infrastructure.”

Nordhaus, Robert R, and Emily Pitlick. 2009. “Carbon Dioxide Pipeline Regulation.” *Energy Law Journal* 30 (85). http://web.mit.edu/coal.

Norwegian Ministry of Petroleum and Energy. 2022. “Statsstøtteavtaler Til Langskip-Prosjektet.” December 7, 2022. https://www.regjeringen.no/no/tema/energi/co2-handtering/f/id2950113/.

Oei, Pao Yu, Johannes Herold, and Roman Mendelevitch. 2014. “Modeling a Carbon Capture, Transport, and Storage Infrastructure for Europe.” *Environmental Modeling and Assessment* 19 (6): 515–31. https://doi.org/10.1007/s10666-014-9409-3.

Oei, Pao Yu, and Roman Mendelevitch. 2016. “European Scenarios of CO_2 Infrastructure Investment.” In *Energy Journal*, 37:171–94. International Association for Energy Economics. https://doi.org/10.5547/01956574.37.SI3.poei.

Oliver, Matthew E. 2015. “Economies of Scale and Scope in Expansion of the U.S. Natural Gas Pipeline Network.” *Energy Economics* 52 (November): 265–76. https://doi.org/10.1016/J.ENECO.2015.11.004.

Perrotton, Florian, and Olivier Massol. 2018. “The Technology and Cost Structure of a Natural Gas Pipeline: Insights for Costs and Rate-of-Return Regulation.” *Utilities Policy* 53 (August): 32–37. https://doi.org/10.1016/j.jup.2018.05.004.

Piessens, K., B. Laenen, W. Nijs, and et al. 2008. “Policy Support System for Carbon Capture and Storage.”

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development.” *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways,in the context of strengthening the global response to the threat of climate change.

Roggenkamp, Martha M, and Avelien Haan-Kamminga. 2010. “CO_2 Transportation in the EU: Can the Regulation of CO2 Pipelines Benefit from the Experiences in the Energy Sector?” http://ssrn.com/abstract=1701126.

Ruan, Yingjun, Qingrong Liu, Weiguo Zhou, Bill Batty, Weijun Gao, Jianxin Ren, and Toshiyuki Watanabe. 2009. “A Procedure to Design the Mainline System in Natural Gas Networks.” *Applied Mathematical Modelling* 33 (7): 3040–51. https://doi.org/10.1016/J.APM.2008.10.008.

Sharkey, William W. 1982. *The Theory of Natural Monopoly.* Cambridge Books.

Shleifer, A. 1985. “A Theory of Yardstick Competition.” *The RAND Journal of Economics* 16 (3): 319–27.

Smith, V. L. 1959. “The Theory of Investment and Production. , .” *The Quarterly Journal of Economics* 73 (1): 61–87.

Smith, V.L. 1961. *Investment and Production. A Study in the Theory of the Capital-Using Enterprise. Harvard Economic Studies*. Vol. 117. Harvard University Press.

Thompson, R. G., M. S. Proctor, and R. R. Hocking. 1972. “Investment-Borrowing Decisions in Natural Gas Transmission.” *Management Science* 18 (10).

Tutton, Peter. 2018. “Carbon Capture and Storage Network Optimization Under Uncertainty.” The University of Texas at Austin.

US General Accounting Office. 1998. *Surface Transportation: Issues Associated With Pipeline Regulation by the Surface Transportation Board.* https://rosap.ntl.bts.gov/view/dot/13512.

Vandeginste, V., and K. Piessens. 2008. “Pipeline Design for a Least-Cost Router Application for CO2 Transport in the CO2 Sequestration Cycle.” *International Journal of Greenhouse Gas Control* 2 (4): 571–81. https://doi.org/10.1016/j.ijggc.2008.02.001.

Vann, Adam, and Paul W. Parfomak. 2008. *Regulation of Carbon Dioxide (CO2) Sequestration Pipelines: Jurisdictional Issues*. Congressional Research Service.

Viebahn, Peter, and Emile J.L. Chappin. 2018. “Scrutinising the Gap between the Expected and Actual Deployment of Carbon Capture and Storage - A Bibliometric Analysis.” *Energies* 11 (9). https://doi.org/10.3390/en11092319.

Viscusi, Vernon, and Harrington. 2000. *Economics of Regulation and Antitrust. Thrid Edition.* MIT Press.

Wang, Keigo Akimoto, and Gregory F. Nemet. 2021. “What Went Wrong? Learning from Three Decades of Carbon Capture, Utilization and Sequestration (CCUS) Pilot and Demonstration Projects.” *Energy Policy* 158 (November). https://doi.org/10.1016/j.enpol.2021.112546.

Wang, D., Y. D. Zhang, Emmanuel Adu, J. P. Yang, Q. W. Shen, Lei Tian, and Lijuan Wu. 2016. “Influence of Dense Phase CO_2 Pipeline Transportation Parameters.” *International Journal of Heat and Technology* 34 (3): 479–84. https://doi.org/10.18280/ijht.340318.

Waxman, Andrew R., Sean Corcoran, Andrew Robison, Benjamin D. Leibowicz, and Sheila Olmstead. 2021. “Leveraging Scale Economies and Policy Incentives: Carbon Capture, Utilization & Storage in Gulf Clusters.” *Energy Policy* 156 (September). https://doi.org/10.1016/j.enpol.2021.112452.

Whitmore, Adam. 2021. “Models for Transport and Storage of Captured CO2 - An Overview of Options.”

Wolak, F. A. 1994. “An Econometric Analysis of the Asymmetric Information, Regulator-Utility Interaction.” *Annales d’Economie et de Statistique*, 13–69.

World Bank. 2007. “Yemen: A Natural Gas Incentive Framework.” Washington, DC. https://openknowledge.worldbank.org/handle/10986/7616.

Yépez, Rigoberto Ariel. 2008. “A Cost Function for the Natural Gas Transmission Industry.” *The Engineering Economist* 53 (1): 68–83. https://doi.org/10.1080/00137910701854602.

Zhang, Shuai, Linlin Liu, Lei Zhang, Yu Zhuang, and Jian Du. 2018. “An Optimization Model for Carbon Capture Utilization and Storage Supply Chain: A Case Study in Northeastern China.” *Applied Energy* 231 (December): 194–206. https://doi.org/10.1016/j.apenergy.2018.09.129.

Appendix A – Specificities of the US economic regulatory framework

We detail here the particular case of the US. These details complement Table 1 and show the wide variety of approaches and the complexity of CO_2 pipeline regulation for CCS. This discussion is mainly based on the studies by Jacobs and Craig (2017), and Mack and Endemann (2010), and the report following the US Department of Energy (DOE) Workshop (2017). These works detail the legal barriers to large-scale CCS implementation in the US. Here, we essentially retain the main elements related to the rates and non-discriminatory access from these works in Table A.1.

Table A.1: CO_2 pipeline regulation in the US

	Intrastate	**Interstate**		
		Nonfederal lands (3)	**Federal lands**	
			Managed by Department of Interior (4)	**Other federal lands**
Regulatory oversight for rates	**Texas** (Texas Railroad Commission) for common carriers, and **Colorado** (Colorado public utilities commission) for common carriers (1)	**None** (neither FERC or STB) STB would intervene in case of a dispute	Bureau of Land Management (BLM)	unknown
Siting and right-of-way (ROW) through eminent domain	**Texas** (for common carriers), **New Mexico** (for any CO_2 pipeline), **Colorado** (any kind of pipeline), **Louisiana** (for sequestration purposes), **Illinois** (for any CO_2 pipeline), **Mississippi** (for EOR), **North Dakota** (for any CO_2 pipeline) (2)	**None** (neither FERC or STB) Thus, unlike natural gas, there is no federal eminent domain for operators to secure right-of-way	BLM chose the Mineral Leasing Act (MLA) for siting on federal lands under its jurisdiction – and not the Federal Land Policy and Management Act (FLMA)	Unknown
Non-discriminatory access rates	Likely for pipelines with eminent domain authority	**None**	If a ROW is granted under the MLA, the pipeline must operate as a **common carrier** (and thus impose non-discriminatory rates)	unknown

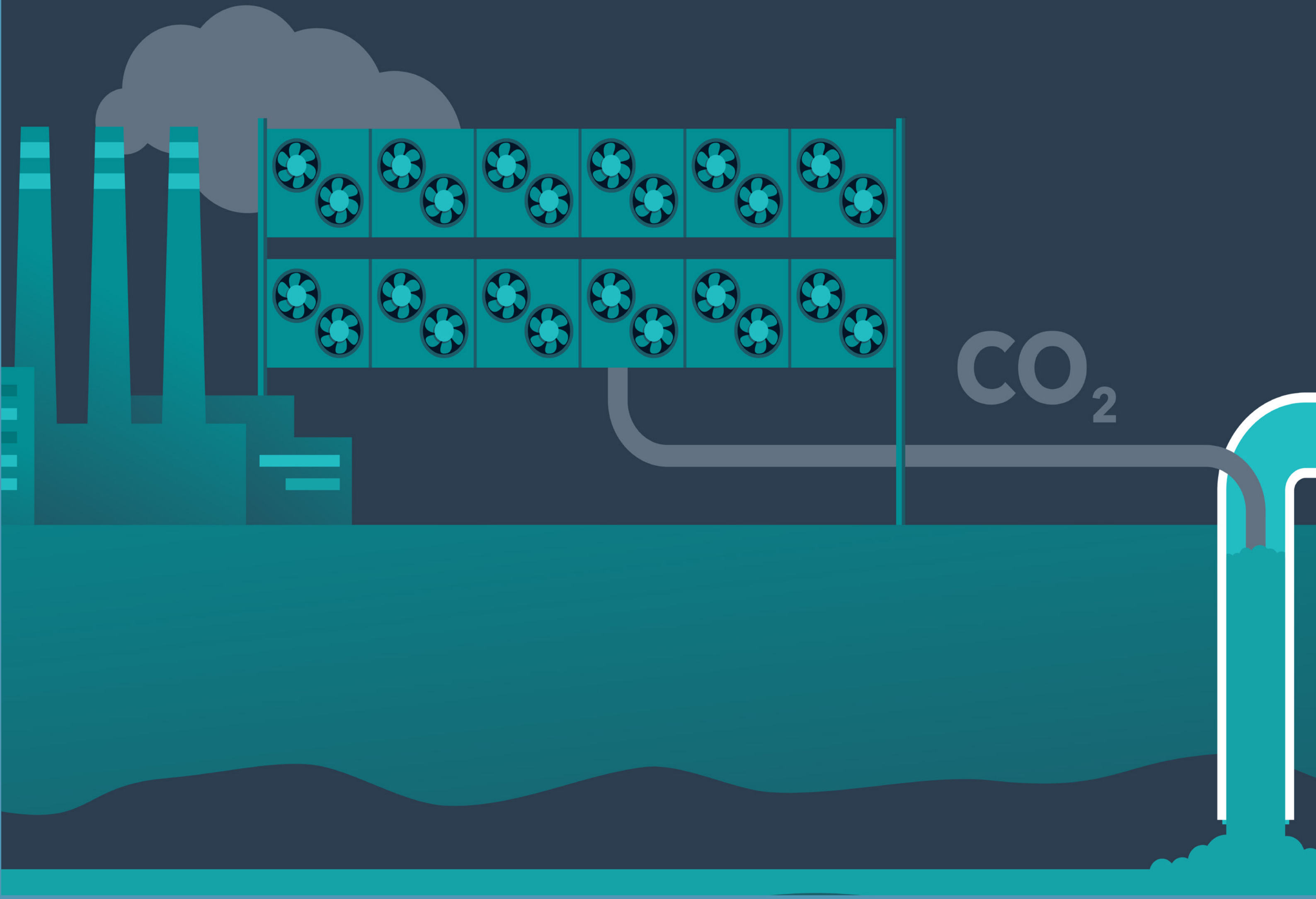
Notes: (1) To our knowledge, no other state has disclaimed regulatory oversight over rates of CO_2 pipelines. Interestingly, Wyoming set up a public authority to identify ROW corridors for EOR purposes only (NETL and Great Plains Institute 2017). *However, this public authority does not have any control over rates* (Mack and Endemann 2010) *(2) Some states with CO_2 pipelines have little regulatory authority for the siting or rate regulation. This is the case of Oklahoma, Utah, and Michigan* (Mack and Endemann 2010). *(3) FERC and STB, which possess statutory authority over the rates and terms of service of various pipelines, have both disclaimed jurisdiction over CO_2 pipelines* (Jacobs and Craig 2017). *The FERC is assigned jurisdiction over natural gas and oil pipelines, and has specifically disclaimed jurisdiction over CO_2 pipelines* (Nordhaus and Pitlick 2009). *Jurisdiction over economic regulation for "other" types of pipelines, such as CO_2 pipelines, should reside with the STB, as put in evidence by the report of the General Accounting Office* (US General Accounting Office 1998). *While the report stated that interstate CO_2 pipelines are subject to the STB's oversight authority, the latter stated in a personal communication to the Congressional Research Service, that it did not want to state an opinion as to the current extent of its jurisdiction over CO_2*

pipelines and that it would likely not act to resolve this conflict unless a CO_2 *pipeline dispute comes before it* (Vann and Parfomak 2008)*. Consequently, such pipelines are not subject to non-discriminatory access or rates. (3) The BLM asserts that* CO_2 *is a "natural gas", which entitles it to exercise its right-of-way authority under the MLA. This status was challenged by Exxon, which claimed that* CO_2 *is not a natural gas, and that the right-of-way should be granted under the FLMA. This decision has a strong impact on the regulation of the* CO_2 *pipeline, since the MLA imposes a common carrier status while the FLMA does not. Following a court decision, it was concluded that the interpretation of the BLM was appropriate* (Nordhaus and Pitlick 2009)

Appendix B – Analytical results

Table B.1: Optimal decisions of a profit-maximizing monopoly under different scenarios

	Unregulated monopoly $(^{M})$	**Marginal cost-pricing scenario** $(^{*})$	**Average-cost pricing scenario** $(^{avg})$
Output	$Q^{M}=\left[\frac{A(1-\epsilon)}{\beta}\cdot\left(\frac{\alpha}{r}\right)^{\alpha}\cdot\left(\frac{1-\alpha}{e}\right)^{1-\alpha}\right]^{1/\gamma}$	$Q^{*}=\left[\frac{A}{\beta}\cdot\left(\frac{\alpha}{r}\right)^{\alpha}\cdot\left(\frac{1-\alpha}{e}\right)^{1-\alpha}\right]^{1/\gamma}$	$Q^{avg}=\left[A\cdot\left(\frac{\alpha}{r}\right)^{\alpha}\cdot\left(\frac{1-\alpha}{e}\right)^{1-\alpha}\right]^{1/\gamma}$
Capital	$K^{M}=\left(\frac{e\alpha}{r(1-\alpha)}\right)^{1-\alpha}\cdot(Q^{M})^{\beta}$	$K^{*}=\left(\frac{e\alpha}{r(1-\alpha)}\right)^{1-\alpha}\cdot(Q^{*})^{\beta}$	$K^{avg}=\left(\frac{e\alpha}{r(1-\alpha)}\right)^{1-\alpha}\cdot(Q^{avg})^{\beta}$
Costs	$C(Q^{M})=\frac{r^{\alpha}\,e^{1-\alpha}}{\alpha^{\alpha}\,(1-\alpha)^{1-\alpha}}\cdot(Q^{M})^{\beta}$	$C(Q^{*})=\frac{r^{\alpha}\,e^{1-\alpha}}{\alpha^{\alpha}\,(1-\alpha)^{1-\alpha}}\cdot(Q^{*})^{\beta}$	$C(Q^{avg})=\frac{r^{\alpha}\,e^{1-\alpha}}{\alpha^{\alpha}\,(1-\alpha)^{1-\alpha}}\cdot(Q^{avg})^{\beta}$
Welfare	$W(Q^{M})$ $=\frac{A}{1-\epsilon}Q^{M^{1-\epsilon}}$ $-\left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{e}{1-\alpha}\right)^{1-\alpha}(Q^{M})^{\beta}$	$W^{*}(Q^{*})$ $=\frac{A}{1-\epsilon}Q^{*1-\epsilon}$ $-\left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{e}{1-\alpha}\right)^{1-\alpha}(Q^{*})^{\beta}$	$W^{avg}(Q^{avg})$ $=\frac{A}{1-\epsilon}(Q^{avg})^{1-\epsilon}$ $-\left(\frac{r}{\alpha}\right)^{\alpha}\left(\frac{e}{1-\alpha}\right)^{1-\alpha}(Q^{avg})^{\beta}$



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