Modeling CO2 Pipeline Systems: An Analytical Lens for CCS Regulation

Adrien Nicolle, Diego Cebreros, Olivier Massol, Emma Jagu Schippers

Modeling CO_2 Pipeline Systems: An Analytical Lens for CCS Regulation

Adrien Nicolle,[a] Diego Cebreros,[a] Olivier Massol,[b,c,a,d] and Emma Jagu Schippers[b,c,d]*

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, this paper aims 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. This analysis will usefully inform the emerging regulatory policy debates on CCS by providing the first analytically determined cost function of a CO_2 pipeline.

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

https://doi.org/10.5547/2160-5890.12.2.anic

1. INTRODUCTION

The perception of Carbon Capture Storage (CCS) as a relevant technology to achieve global climate targets has fluctuated substantially 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 instance, 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 deployment targets. At present, CCS is again gaining momentum as new policies – e.g., the Inflation Re-

[a] Industrial Engineering Research Department, CentraleSupélec, Université Paris-Saclay, 9 ter rue Joliot-Curie, 92190 Gif-sur-Yvette, France.
[b] IFP Énergies nouvelles, 1-4 avenue de Bois Préau, 92852 Rueil-Malmaison, France.
[c] Center for Energy Economics and Management, IFP School, 228-232 av. Napoléon Bonaparte, 92852 Rueil-Malmaison, France.
[d] Department of Economics, City, University of London, Northampton Square, London EC1V 0HB, UK.
* Corresponding author. E-mail: adrien.nicolle@chaireeconomieduclimat.org.

Economics of Energy & Environmental Policy, Vol. 12, No.2.

duction Act (117th Congress 2022) and the Net Zero Industry Act (European Commission 2023) – ambition to accelerate its deployment by lowering administrative barriers and closing the financial gap with generous subsidies. Nevertheless, one can wonder whether they will be sufficient to unlock the emergence of CCS as recent reports call for new policy approaches to reduce the institutional uncertainties surrounding that technology (IPCC 2022; IEA 2021).

Choosing the right policy instrument is challenging because it must simultaneously address issues about 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 for transporting the captured emissions. As the pipeline operator will presumably be monopolistic, 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 to reduce the informational asymmetry between the regulated firm and itself. Bridging this informational gap will help the regulator identify the required pricing scheme to maximize 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 (Chenery 1949; Yépez 2008; Massol 2011; Perrotton and Massol 2018). 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 alleviate 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 envi-

ronmental objectives. Following these results, we discuss some assumptions of our model and suggest future avenues of research.

Our technological representation departs from the usual representations of CCS pipeline transportation in Integrated Assessment Models (IAMs) and the economic literature. In IAMs, these representations have been criticized for lacking transparency and 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 (Middleton and Bielicki 2009; Mendelevitch et al. 2010; Kemp and Sola Kasim 2010; Klokk et al. 2010; Morbee, Serpa, and Tzimas 2012; Oei, Herold, and Mendelevitch 2014; IEAGHG 2016; d'Amore and Bezzo 2017; Tutton 2018; Zhang et al. 2018; Holz et al. 2021; Waxman et al. 2021; Jagu Schippers and Massol 2022). The merits of these numerical studies are that they capture the network interactions among multiple sources and sinks. However, they rely on optimization models solved numerically and de facto embed a simplified (typically linear) cost function representation. In the present manuscript, we thus abstract from analyzing 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 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 and Rubin 2005; McCoy 2008; McCoy and Rubin 2008) 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. A portion of the economic literature seeks the causes behind the failure of large-scale deployment, but few papers provide substantial regulatory insights.

Our paper is organized as follows. Section 2 provides an overview of the regulatory approaches envisioned for CO_2 infrastructures. Section 3 presents the engineering-based production function and its properties. The implications are discussed in Section 4. The last section concludes. For concision, the appendices are presented in an online companion to this manuscript.

2. BACKGROUND AND MOTIVATION

2.1 CO_2 pipeline systems: an infrastructure sector in need of regulation

CCS is experiencing an upward momentum. In 2022, the annual capacity of the CCS projects under development attained 244 million tons of CO_2, which is 45% larger than the

2021 inventory (Global CCS Institute 2022). Most of these projects focus on the emissions from industrial plants (e.g., cement, iron and steel, gas treatment, petrochemical plants) and are located in the US, the UK, Norway, and the EU, in which public authorities recently unveiled ambitious development plans.[1]

These projects heavily rely on the installation of a CO_2 pipeline system connecting a carbon capture facility to a storage site. These transportation infrastructures are expected to grow organically to connect several emitters and form a network that could ultimately reach a continental scale.[2] However, deploying a CO_2 pipeline infrastructure critically depends on the institutional framework governing its provision.

Infrastructure sectors, such as CCS pipeline infrastructures, 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 operating 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.

2.2 The contemporary regulatory frameworks governing CO_2 pipeline systems

Table 1 summarizes the institutional approaches and practices retained in early-adopter regions: the US, the UK, Norway, and the EU.

From Table 1, these jurisdictions tend to advocate third-party access to these infrastructures. That said, we observe essential variations in the governance and pricing schemes imposed on CCS pipelines. We distinguish here three types.

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 subject 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 transport and store.[3] The state intervenes at several levels: it leads the Longship project via its state-owned enterprise

1. 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 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. For example, the European CO_2 pipeline system modeled in Oei and Mendelevitch (2016) runs 45,000 km by 2050. In the US, the full economy decarbonization scenario examined by Larson et al. (2020) requires the installing installation of 21,000 km of trunk lines and 85,000 km of spur lines by 2050.

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.

TABLE 1
Review of regulatory initiatives in early-adopter regions for CCS pipeline 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 in 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

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 TotalEnergies 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. In contrast, 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 unclear whether Northern Lights will be subject 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 echoes the non-exclusive powers of the Federal/EU jurisdictions concerning CO_2 pipelining and can accommodate the diversity of 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, the contours of the regulation imposed on CO_2 pipeline systems look poorly defined. Regulatory mandates are uncertain in most cases, suggesting that public authorities have not grasped the monopolistic nature of the pipeline operator and the consequences that

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.

this may have (as seems to be the case in the US and the EU). Where a mandate exists, as in the UK, the regulatory framework seems to be strongly inspired by the case of natural gas. This choice might be due to the lack of data on the cost function of CO_2 pipeline systems, forcing the regulator to draw on the natural gas case and apply the same policy instruments. In light of this observation, it is urgent to clarify (i) whether the CO_2 pipeline system verifies the conditions of a natural monopoly and, if so, (ii) to determine the associated cost function, thus reducing the information asymmetry with the regulated firm.

To our knowledge, the literature on CCS largely ignores these issues. Only a handful of papers mention the possibility that the pipeline operator is a natural monopoly (Roggenkamp and Haan-Kamminga 2010; Krahé et al. 2013; Massol, Tchung-Ming, and Banal-Estañol 2015) but do not provide evidence of this claim nor present a quantitative discussion of the associated social impacts. In the extensive gray literature, only a few policy briefs and reports mention the industry's lack of economic regulation (Global CCS Institute 2012; Elkerbout and Bryhn 2019; Whitmore 2021).

2.3 Possible regulatory approaches to model the economics of CO_2 pipelines

Recall that 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 must undertake, considering their capacities for actions and means. Given their bounded capacities, having analytical tools capable of mimicking a regulated firm's investment and operation decisions is necessary for designing effective regulatory frameworks. 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.

Regulatory economics apply three different methodological approaches 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). This nonparametric method determines 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. Regulation of natural gas pipelines in North America has widely applied this method (Ellig and Giberson 1993; Gordon, Gunsch, and Pawluk 2003; Oliver 2015). 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 (1949; 1952), Leontief and his associates (Leontief 1953), and Smith (1961; 1959). Studies have used this method to deal with regulatory issues of nat-

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

ural gas pipeline (Thompson, Proctor, and Hocking 1972; Callen 1978; Yépez 2008; Massol 2011; Perrotton and Massol 2018).

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, such as CO_2 pipelining. The industrial organization retained for the few existing CCS projects is also problematic: So far, these demonstration projects were vertically integrated supply chains 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.

3. AN ENGINEERING-BASED ANALYTICAL COST FUNCTION FOR CO_2 PIPELINING

3.1 Modeling a CO_2 pipeline cost function

Inspired by Chenery (1949) and Yépez (2008), we consider a CO_2 pipeline system consisting of a point-to-point pipeline and a pumping station. This system is the simplest possible CO_2 transportation infrastructure connecting one entry node (e.g., a cluster of industrial emitters with carbon capture capabilities) to one sink (e.g., a neighboring storage site as in emerging CCS projects: Northern Lights in Norway or Net Zero Teesside in the UK[7]). By nature, this basic system can also provide valuable knowledge on more complex infrastructures with a modular type. For example, a trunkline system can be decomposed into a collection of such basic infrastructures that are serially associated with enabling long-distance transportation. Similarly, the extensive network systems envisioned at the national or continental scale can also be decomposed into a collection of such elementary infrastructures.[8]

As explained in Appendix B, three engineering variables (the pumping power, the mass flow or output, and the inside diameter of the pipe) and a system of three engineering equations (a pumping equation, a flow equation, and a mechanical stability equation; see the details in Table B.2) govern the simple infrastructure at hand.

Remarking that the infrastructure uses two economic inputs – namely K the capital immobilized, and E the energy needed for powering the pumping equipment – and has a single

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 trunkline then transports the emissions to the offshore storage site.

8. Although the candidate topology of pipeline systems retained in network optimization studies allows 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.

output Q (i.e., the flow of CO_2 to be transported) and clarifying the relations between these economic variables and the engineering ones, we show in Appendix B that the system of engineering equations at hand defines the following Cobb-Douglas production function:

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

where the values of the technical coefficients $\beta = \frac{9}{11}$, and $= \frac{8}{11}$ are directly obtained from the engineering analysis presented in Appendix B. The production function (1) allows smooth substitutions between the two input variables.

Given the prevailing energy[9] and capital market prices (denoted by e and r, respectively), the least-cost combination of inputs required to transport a given flow Q is the solution to the long-run cost-minimization problem in Appendix B. Solving, one obtains the following long-run total cost function $C(Q)$:

$$C(Q) = \frac{r^{\alpha} e^{1-\alpha}}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}} Q^{\beta} \tag{2}$$

Observe that $\beta < 1$. 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.

3.2 Market outcomes

Using the cost function above, 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. We consider the market outcomes obtained under the three standard cases of a regulator with complete information (see the associated programs in Table C.1 - Appendix C): (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}).

We assume that the demand for pipeline transportation originates from a collection of large stationary emitters equipped with carbon capture capabilities that can connect 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: $P(Q) = A \cdot Q^{-\epsilon}$ where $1/\epsilon$ is the absolute price elasticity of demand and A the demand coefficient. We also retain the technical assumptions: $\epsilon < 1$ so that without any output, the monopolist's total revenue is zero, and $\epsilon > 1 - \beta$. Using these assumptions, we determine the closed-form expressions of the solutions to the three standard cases above (see Table C.2 - Appendix C).

To compare the market outcomes, we use the performance ratios detailed in Appendix C (see Table C.3). These ratios have closed-forms expressions and are determined by the technol-

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 from the installed capacity, the capacity factor, and the cost of electricity.

ogy parameters (i.e., α and β) and the demand elasticity. They are invariant with the relative input prices and the demand coefficient A. We opt for a numerical approach and 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 2.

TABLE 2
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					
$\frac{\Pi(Q^*)}{P(Q^*)Q^*}$	–0.222	–0.222	–0.222	–0.222	–0.222
$\frac{\Pi(Q^M)}{P(Q^*)Q^*}$	0.603	0.516	0.449	0.395	0.345
$\frac{\Pi(Q^{avg})}{P(Q^*)Q^*}$	0.000	0.000	0.000	0.000	0.000
Welfare ratio					
$\frac{W(Q\ )}{W(Q^*)}$	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 monopoly's profit in each scenario over its revenue in the marginal cost-pricing scenario.

Absent any form of regulation, a private monopoly transports less than 10% of Q^*, the socially desirable quantity of CO_2. This rationing is also apparent in the operator's investment

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).

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. Unsurprisingly, the monopolist obtains hefty profits $\Pi\left(Q^M\right)$ and that organization brings a considerable deadweight loss representing between 19% and 29% of the maximal net social welfare $W\left(Q^*\right)$. These results show 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 decision supports a classic microeconomic result indicating that pricing at marginal cost maximizes social welfare and is 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 $\Pi\left(Q^*\right)$ represents –22.2% of the total revenue $P(Q^*)Q^*$. Absent any subsidy, this 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 minimizing social welfare losses (i.e., it is the second-best solution). Compared with the socially desirable benchmark, this second-best organization achieves a high level of net social welfare $W\left(Q^{avg}\right)$ that represents at least 98% of the theoretical reference level $W\left(Q^*\right)$.

4. 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 advanced knowledge of the demand of emitters – could influence its approach and how our model could incorporate such aspects.

4.1 Providing a first analytical cost function to CCS pipeline transportation

In contrast to most earlier studies that rely on natural gas cost data to infer the economics of CO_2 pipelining (Knoope, Ramírez, and Faaij 2013), the present analysis accounts for the technical properties of the CO_2 fluid. 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 proved that the CO_2 pipeline system verifies the technological condition for a natural monopoly as the cost function is strictly subadditive.[11] This critical finding provides a scientific justification for an assumption repeatedly retained but so far unproven.

Aside from this analytical result, our model is a practical analytical tool for policymakers governing CCS transportation infrastructures. Indeed, our technological representation allows the regulator to determine the operator's long-run total costs and the substitution effects between the pipeline's dimensions and the pumps. From a practical point of view, the analysis in Appendix B improves the technological understanding of the CO_2 pipeline system as it clarifies the links between the diameter of the pipeline and the amount of capital immobilized.[12] As

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

12. As indicated in Appendix B, the capital is linked to the squared diameter D as $K = p_s w_s L\pi D^2\left(a + a^2\right)$, where p_s denotes the unit price of steel, w_s denotes the weight of steel per unit of volume and a a fraction of the pipeline diameter.

measuring a diameter is straightforward, that relation provides the regulator with observable data to assess and track whether the capital expenditures made by the pipeline operator are justified for efficient transportation. Consequently, this technological representation reduces the information asymmetry between the regulator and the pipeline operator. It can help prevent some regulatory distortions (e.g., the Averch-Johnson effect, which 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.

4.2 Insights for regulation

Using the previous technological representation, we test the impact of different pricing schemes for the CCS transportation network on generic benchmark strategies of economic regulation. We assume 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.[13] However, while this pricing scheme allows 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 2), 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 $P\left(Q^{avg}\right)$. 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.[14] We now argue that our study can be extended to account for specific environmental policies by modifying the elasticity of demand. Indeed, our study could be adapted to study the impact of CCS 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 specifying the link between the CO_2 emission price and elasticity is left to future research.[15]

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 (Garðarsdóttir et al. 2018; Johnsson, Normann, and Svensson 2020). Regions could adopt price discrimination depending on the nature of the heterogeneity to maximize the industry's social welfare. Indeed, economic theory

13. 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.

14. 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.

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

suggests that it is a suitable option if the regulated firm can identify different submarkets with various willingness-to-pay or different demand elasticities. From this perspective, Norway already seems to depart from the non-discriminatory tradition. It adapts its tariffication to the heterogeneous demand: although promoting non-discriminatory access, Northern Lights seems to 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.

5. CONCLUSION

There are both high hopes and concerns over the future deployment of CCS. CCS is gaining unprecedented momentum, and mitigation scenarios expect it to become a relevant technology to achieve global climate targets efficiently, 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 significantly from one region to another. Our study questions whether regulators have genuinely grasped the monopolistic character of these infrastructures and the risk that the exertion 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 to reduce 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 complete 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 be helpful 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 technical accuracy and economic interpretability. We examine the market outcomes and show that the deadweight loss can be substantial without regulation. Our findings indicate that average cost pricing performs well regarding social welfare but yields a critical environmental issue, as allocative efficiency is not achieved. Nevertheless, 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 categories 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 the monopoly charges over time. This representation could also inform emerging policy discussions, such as the need for optimally oversized transportation infrastructures (see, e.g., Nicolle and Massol (2023) for a preliminary discussion), the debates on the timing of future regulatory interventions, or whether regulation should be ex-ante or ex-post.

From a spatial point of view, our study essentially focuses on regulating a hypothetical pipeline project and thus omits spatial considerations regarding 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) is 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 a better knowledge to assist the emergence of this industry, foster its large-scale deployment, and reduce the social cost of achieving carbon neutrality.

ACKNOWLEDGMENTS

We are indebted to the editor and three anonymous referees for insightful comments and suggestions. This paper has greatly benefited from suggestions and discussions with Christian Hauenstein, Jean-Philippe Hiegel, Pao Yu Oei, Calvin Peck, Yannick Perez, and the participants of the PhD seminars at CentraleSupélec and the Climate Economics Chair. The remaining errors and omissions are our responsibility. Adrien Nicolle, Diego Cebreros, Emma Jagu, and Olivier Massol gratefully acknowledge research funding from the *Climate Economics Chair*, the Chair "*Hybrid Technologies and Electromobility Economy*" (a.k.a. the Armand Peugeot Chair), the Chair "*Carbon Management and Negative CO_2 Technologies: Towards a low carbon future (CarMa)*", and the Chair "*The Economics of Gas*" respectively. The views expressed herein are strictly those of the authors and should not be construed to reflect the opinions of their affiliations.

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.

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.

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. https://doi.org/10.2307/1882136.

Chenery, Hollis B. 1952. "Overcapacity and the Acceleration Principle." *Econometrica* 20: 1–28. https://doi.org/10.2307/1907804.

d'Amore, Federico, and Fabrizio Bezzo. 2017. "Economic Optimisation of European Supply Chains for CO2 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. https://doi.org/10.1007/BF01066315.

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-.

Färe, R., S. Grosskopf, and C. K. Lovell. 1985. *The Measurement of Efficiency of Production*. Vol. 6. Springer Science & Business Media. https://doi.org/10.1007/978-94-015-7721-2.

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. "Implmenting Incentive Regulation and Regulatory Alignment with Resource Bounded Regulators." *Competition and Regulation in Network Industries* 14 (3). http://rru.worldbank.org/Toolkits/InfrastructureRegulation/. https://doi.org/10.1177/178359171301400303.

Global CCS Institute. 2012. "Carbon Dioxide (CO2) 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.

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 CO2 Storage – Post-Demonstration CCS in the EU." Brussels. https://www.globalccsinstitute.com/archive/hub/publications/119816/costs-co2-storage-post-demonstration-ccs-eu.pdf.

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.

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. 2022. "Unlocking CO2 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 CO2 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 CO2 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. https://doi.org/10.1086/261392.

———. 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).

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. https://doi.org/10.1038/s41560-021-00937-z.

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 CO2 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 CO2 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 CO2 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. https://doi.org/10.2139/ssrn.1678398.

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.

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.

Nicolle, A., and O. Massol. 2023. "Build More and Regret Less: Oversizing H2 and CCS Pipeline Systems under Uncertainty." *Energy Policy* 179 (August): 113625. https://doi.org/10.1016/j.enpol.2023.113625.

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 CO2 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."

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

Sharkey, William W. 1982. *The Theory of Natural Monopoly.* Cambridge Books. https://doi.org/10.1017/CBO9780511571817.

Smith, V. L. 1959. "The Theory of Investment and Production. , ." *The Quarterly Journal of Economics* 73 (1): 61–87. https://doi.org/10.2307/1883826.

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). https://doi.org/10.1287/mnsc.18.10.B544.

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

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.

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. https://doi.org/10.2307/20075947.

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.