Joining the CCS Club!

The economics of CO_2 pipeline projects☆

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Abstract

The large-scale diffusion of Carbon Capture, transport and Storage (CCS) imposes the construction of a sizeable CO_2 pipeline infrastructure. This paper examines the economics of a CO_2 pipeline project and analyzes the conditions for a widespread adoption of CCS by a group of emitters that can be connected to that infrastructure. It details a modeling framework aimed at assessing the break-even value for joint CCS adoption, that is the critical value in the charge for CO_2 emissions that is required for each of the emitters to decide to implement capture capabilities. This model can be used to analyze how the tariff structure and the regulatory constraints imposed on the CO_2 pipeline operator modify the overall cost of CO_2 abatement via CCS. This framework is applied to the case of a real European CO_2 pipeline project. We find that the obligation to use cross-subsidy-free pipeline tariffs has a minor impact on the minimum CO_2 price required to adopt the CCS. In contrast, the obligation to charge non-discriminatory prices can either impede the adoption of CCS or significantly raises that price. Besides, we compared two alternative regulatory frameworks for CCS pipelines: a common European organization as opposed to a collection of national regulations. The results indicate that the institutional scope of that regulation has a limited impact on the adoption of CCS compared to the detailed design of the tariff structure imposed to pipeline operators.

Keywords: OR in Environment and Climate Change; Carbon Capture and Storage; CO_2 pipeline; Club theory; Regulation; Cross-subsidy-free tariffs.

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1. Introduction

The current dominance of hydrocarbon fuels in the global primary energy mix is likely to persist in the foreseeable future, suggesting that there will be no sharp decline in carbon dioxide (CO_2) emissions (IEA, 2011). Against this daunting background, geologic Carbon Capture transport and Storage (CCS)[1] represents a technically conceivable option to isolate large volumes of CO_2 from the atmosphere. A widespread deployment of this abatement technology to large industrial CO_2 point sources could reconcile the current world's dependence upon hydrocarbons with the large and rapid reduction of anthropogenic CO_2 emissions required to prevent the effects of global warming (Pacala and Socolow, 2004). However, the large scale deployment of CCS faces an enduring economic challenge: as CCS scales up from local, small-scale demonstration projects, it becomes contingent upon the construction of a costly CO_2 pipeline infrastructure with national or continental scope (Herzog, 2011).

The purpose of this paper is to contribute to the burgeoning analysis of the economics and regulatory issues of CO_2 pipeline projects. We consider the case of the *ex-nihilo* creation of a sizeable CO_2 pipeline system, aimed at gathering the emission streams produced by a given collection of independent industrial plants and transporting them to a storage site. We address two related questions. First, how far would the price of CO_2 emissions have to rise for the CCS technology to be adopted by that collection of emitters? Second, to what extent do the tariff and/or the regulatory structure imposed on the CO_2 pipeline operator modify this *break-even value* for joint CCS adoption?

Over the past decade, a large body of literature has emerged on CCS.[2] Despite the amount of literature, however, little research has considered the spatial nature of this abatement technology (i.e., the fact that sources can be remotely located from geologic sequestration sites imposing the construction of dedicated CO_2 transport systems). This relative lack of consideration can probably be explained by the engineering cost studies that typically highlight the inexpensive nature of CO_2 transportation relative to the other components of the CCS chain (i.e., capture and storage). Nevertheless, CCS experts repeatedly emphasize the importance of carbon transportation issues (Flannery, 2011). According to Herzog (2011), at least two barriers hamper the construction of a sizeable transportation infrastructure. The first is the "chicken and egg problem" faced by CO_2 pipeline project developers: on the one hand, it is not worth building a pipeline system without a critical mass of capture plants to feed CO_2 into it, but on the other hand, emitters are unlikely to invest into a costly capture equipment without being certain that a CO_2 pipeline will be constructed. The second is the lack of clarity in the regulatory regimes (and the tariff policies) governing CO_2 pipelines.

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[1] *CCS is a generic name for the combination of technologies applied in three successive stages: (1) the capture which consists of a separation of CO_2 from the emissions stream generated by the use of fossil fuels at industrial plants, (2) the transportation of the captured CO_2 via a dedicated infrastructure to a storage location, and (3) the long-term storage of the CO_2 within a suitable geological formation in a manner that ensures its long-term isolation from the atmosphere (IPCC, 2005).*

[2] *A tentative and non-exhaustive clustering of these contributions includes: (i) the applications of top-down dynamic models to contrast the relative performances of policy instruments and to check their influence on the adoption of CCS (e.g., Gerlagh and van der Zwaan, 2006); (ii) the detailed bottom-up analyses on the future prospects for CCS (e.g., Kemp and Kasim, 2008; Lohwasser and Madlener, 2012); (iii) the investment analyses applying the real-option approach to value CCS projects (e.g., Heydari et al., 2012); (iv) the contributions aimed at determining an optimal R&D policy for the CCS technology (Baker and Solak, 2011; Eckhause and Herold, 2014).*

The contributions of this paper are twofold. First, we provide a modeling framework that analyzes the coordination issue at hand with the help of cooperative game-theory techniques. The theoretical basis of our approach stems from a club theory perspective (Buchanan, 1965) and follows the early works of Littlechild (1975) and Sharkey (1982). Accordingly, the CO_2 emitter's decision to install or to not install capture equipment can be viewed as the outcome of a voluntary application to a "CCS club" aimed at aggregating the emissions captured in a given industrial cluster to generate economies of scale in the construction and subsequent operation of a joint CO_2 transportation infrastructure. Our aim is to derive conditions for large voluntary adoption of CCS, as a function of: (i) the price of CO_2 emissions (set through a tax or a cap-and-trade system), (ii) the CO_2 transportation technology, and (ii) the nature of the tariffs regulation imposed on the pipeline operator.

Second, we consider an application of the proposed framework to the case of the construction of a trunkline system collecting the CO_2 captured by 14 industrial facilities located in northwest France and Belgium, and transporting it to the Netherlands.[3] Our findings confirm that spatial pricing issues significantly narrow the possibility of constructing a pipeline tariff structure: any kind of uniform postage stamp tariff impedes the adoption of CCS, whereas geographical price discrimination is more effective. Our findings reveal that CCS adoption is easier to achieve in case of a smaller project that solely considers the 12 largest emitters. Our modeling framework can also be used to compare two alternative organizations for the regulation of CO_2 pipelines: a regulation designed at the EU-level and a collection of national-based regulations. Our findings indicate that an integrated European regulation is preferable to ease the deployment of that carbon removal technology. Yet, the choice of the institutional scope of the pipeline regulation (national vs. European) seems quantitatively less important for the adoption of CCS than the detailed decisions related to the tariff structure imposed to pipeline operators.

Our framework should prove useful in evaluating the cost effectiveness of CO_2 abatement via CCS. A series of widely quoted studies have attempted to estimate the cost effectiveness of carbon abatement by means of CCS technologies (IPCC, 2005; McKinsey, 2008; MIT, 2007). Apart from the accounting controversies pointed in İşlegen and Reichelstein (2011), all these studies typically make reference to average cost concepts. However, accounting-only approaches neglect the coordination issues associated with the joint adoption of CCS by a group of heterogeneous emitters. Because of this omission, average cost figures can underestimate the real break-even value. The empirical results reported in this paper document the magnitude of this underestimation and indicate that the difference can be substantial and varying with the emitters' heterogeneity and the tariff system used.

The paper is organized as follows: Section 2 justifies our approach. Section 3 presents a cooperative game theoretic model of the adoption of pipeline transport of CO_2. In Section 4, this framework is used to derive a numerical methodology evaluating the break-even value for joint CCS adoption. Then, Section 5 details an application of this methodology to the case of a real European

[3] To be precise, this project assumes the construction of a trunkline system aimed at collecting the CO_2 captured by 14 small to large-size industrial facilities located in both Le Havre (France) and Antwerp (Belgium), and transporting it to the Rotterdam area (Netherlands), where it can be stored in depleted oil fields in the North Sea. This sizeable project could represent one of the first attempts to build a transnational CO_2 pipeline system in Continental Europe.

project. Finally, the last section offers a summary and some concluding remarks. For the sake of clarity, all the mathematical proofs are presented in Appendix A.

2. CO_2 pipeline systems as a club good

In this section, we justify our approach by detailing the main economic features of a pipeline-based CO_2 transportation service. In a first subsection, we highlight the presence of very marked economies of scale. A second subsection reviews the recent models proposed to determine the deployment of a CO_2 pipeline system and argues that the decision to construct a CCS infrastructure resembles the decision to create a "club". Lastly, a third subsection introduces the tools needed to analyze club goods and the organizational structures to be analyzed.

2.1 Economies of scale in CO_2 pipeline systems

Recently, a series of engineering analyses have been conducted to model the economics of simple point-to-point pipeline systems capable of transporting a given steady flow rate of CO_2 across a given distance (e.g., McCoy and Rubin, 2008; McCoy, 2009). These studies detail an exhaustive, engineering-based, representation of the CO_2 pipeline technology[4] and put that representation to work to determine the cost-minimizing design of a given CO_2 pipeline infrastructure (the pipeline diameter; the size of the compression equipment installed along the pipeline).

From a conceptual perspective, these studies bear a strong analogy with the engineering economic methodology used in the natural gas industry. As far as natural gas pipelines are concerned, a prolific literature, stemmed from Chenery's (1949) seminal contribution, has combined engineering and economics to guide both investment and operational decisions.[5] Using that analogy,[6] one may describe the CO_2 pipeline technology as an engineering production function that has two inputs: (i) energy (to power the pumping equipment) and (ii) capital (to install a pipeline and the pumping equipment), which can be combined in varying proportions to transport a given future flow of CO_2. In the long-run, the CO_2 planner's problem amounts to finding the cost-minimizing combination of inputs compatible with this engineering production function.

Using these engineering models, a number of studies have examined how the cost of a simple point-to-point CO_2 pipeline varies with the output level. These cost simulations consistently indicate that the technology at hand exhibits very marked increasing returns to scale over a large range of output in the long run (IPCC, 2005; McCoy and Rubin, 2008; McCoy, 2009). The presence of decreasing

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[4] *A comprehensive presentation of these engineering considerations is beyond the scope of this paper. These studies typically includes: (i) a flow equation that describes the frictional loss of energy through the pipe (i.e. the pressure drop) as a function of the fluid's properties (e.g., flow-rate, pressure, temperature) and engineering parameters (e.g., the pipeline length, its diameter, an empirically determined friction coefficient); (ii) the mechanical constraints related to the pipeline's maximum operating pressure; and (ii) the equation governing the power required to pump the CO_2.*

[5] *For example: (i) the analytical studies conducted on simple point-to-point natural gas infrastructures (André and Bonnans, 2011; Massol, 2011), and (ii) the numerous applications of mathematical programming to model meshed networks (e.g., De Wolf and Smeers, 1996; André et al., 2009).*

[6] *There exists some technological differences between natural gas and CO_2 pipelines systems as methane is typically piped in a gaseous state whereas CO_2 is piped in supercritical state (McCoy and Rubin, 2008). Nevertheless, these differences are not sufficient to denounce the validity of this analogy.*

marginal costs has important implications for the industrial organization of the CO_2 transportation industry. In principle, each of the potential users of a given CO_2 pipeline system could independently build an infrastructure for itself, but the cumulated cost of these individual infrastructures would be prohibitive compared to those of a common pipeline system. Hence, economies of scale represent an incentive for the aggregation of the emitters' transportation demands and the construction of a unique pipeline infrastructure.

2.2 The need for a club theoretic approach

In recent years, there has been an upsurge in interest in the application of optimization techniques to determine the cost-minimizing design of an integrated CCS infrastructure network (Bakken and von Streng Velken, 2008; Middleton and Bielicki, 2009; Kemp and Kasim, 2010; Klokk et al., 2010; Mendelevitch et al., 2010; Kuby et al., 2011; Spiecker et al., 2014).[7] While very much needed for indicative regional planning purposes (e.g. to organize the source-to-sink allocation), these optimization models implicitly posit an idealized industrial organization: a unique decision maker is supposed to have total control of the whole CCS chain. However, the validity of such a central planning approach is controversial because, in reality, several independent stakeholders are likely to be involved in the creation of a CCS infrastructure (e.g., the emitters, the CO_2 pipeline operator).[8] This fact can hardly be overlooked: according to the policy discussion in Herzog (2011, p.600), an inappropriate coordination of these individual decisions can impede the massive deployment of CCS.[9] In this paper, we investigate these coordination issues.

Coordination is especially important in the pipeline industry because timing considerations matter. On a given CO_2 pipeline project, there is an incentive to organize the aggregation of the emitters' demands *ex ante*, i.e. during the planning phase. The size of a pipeline system is mainly determined by the diameter of the pipe, a parameter that cannot be modified *ex post* (i.e., once the infrastructure is installed). Because of this irreversibility, any *ex post* expansion in the demand for transportation requires the addition of extra pumping equipment, a move that would either be blocked by technological considerations (e.g. the allowable maximum stress of the pipe) or result in an excessive cost (compared to those of an optimally designed pipeline with an adapted capacity). Hence, the CO_2 transportation service is a good characterized *ex post* by rivalry and excludability of benefits.[10]

The conjunction of this feature together with the presence of marked economies of scale indicate that the CO_2 transportation service resembles a "club good" (Sandler and Tschirhart, 1980). Thus, the

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[7] These contributions are directly related to the operations research literature on the optimal design of a pipeline network, a well-known problem with numerous applications in the energy industries (e.g., Rothfarb et al., 1970; Bhaskaran and Salzborn, 1979; Brimberg et al., 2003; Babonneau et al., 2012; André et al., 2013).

[8] This statement is also shared by Mendelevitch (2014) who recently examined CCS deployment using a large-scale market equilibrium model formulated as a mixed-complementarity problem. However, in contrast to ours, this analysis assumes the presence of constant return to scale in the CO_2 pipeline industry (and thus neglects the role of decreasing marginal cost).

[9] Herzog (2011, p. 600) attributes the lack of deployment of CO_2 pipeline systems to what he casually depicts as a "chicken and egg" problem: on the one hand, a transportation infrastructure is required to foster the deployment of carbon capture equipments in a given area but, on the other hand, a critical flow of captured CO_2 is needed to justify the construction of the infrastructure.

[10] We refer to Sandler and Tschirhart (1980) for a comprehensive presentation of these notions.

construction of a CCS infrastructure amounts to the creation of a club of CCS adopters (Buchanan, 1965). The very marked returns to scale call for an optimum club size that consists of all the potential adopters. However, the creation of such club is not granted: it will result from the voluntarily adhesion of the CO_2 emitters. A poorly defined institutional structure can create an incentive for a subset of emitters to prefer either to disband or to create a smaller club.

2.3 Club goods and cooperative game theory techniques

Club goods are usually analyzed making use of cooperative game techniques (Sandler and Tschirhart, 1980). As opposed to non-cooperative, cooperative game theory does not build negotiation and enforcement procedures explicitly into the model, and describes only the outcomes that result when the players come together in different combinations. Non-cooperative results depend very strongly on the precise form of the procedures, on the order of making offers and counter-offers and so on. This may be appropriate in voting situations in which precise rules of parliamentary order prevail. But problems of negotiation are in many cases, and also in our setup, less clear; it is difficult to pin down just what the procedures are. More fundamentally, the procedures may not be really all that relevant; it is the possibilities for coalition forming, promising and threatening that are decisive, rather than whose turn it is to speak (Aumann, 1989).

A cooperative game consists of the following two elements: (i) a set of players, and (ii) a "characteristic function" specifying the value created by different subsets of the players in the game.[11] A group of players who commit themselves to come together is called a "coalition." What the members of the coalition get, after all the bribes, side payments, and quid pro quo have cleared, is called an "allocation". The main solution concept of a cooperative game is the core. The core of a cooperative game consists of all undominated allocations. In other words, the core consists of all allocations with the property that no subgroup within a coalition can do better by deserting that coalition.

In the sequel, we shall consider and compare two types of cooperative games and therefore two types of allocations. In the first, we analyze the decisions of a heterogeneous group of emitters that can own and share a common pipeline system, and thus form a "vertically integrated" club. The club is assumed to gather the individual net benefits of the infrastructure and redistribute them among its members. In the second, we examine the decisions of the emitters in the case that an independent pipeline operator can sell CO_2 transportation services. Before deciding its construction, the pipeline operator has to design and sign an enforceable long-term contract with each emitter that specifies the amount that will be charged to that emitter for the transportation service. In the theoretical literature, the resulting game is considered as a "cost-sharing game" (Young, 1985).

[11] By contrast, non-cooperative games must specify the following four elements: the players of the game, the information and actions available to each player at each decision point, and the payoffs for each outcome.

3. A cooperative game-theory approach to CO_2 infrastructure pricing

In this section, we present our framework and our main analytical results. In the first subsection, we present the assumptions and clarify the notation. In the second, we detail the conditions required for CCS adoption in the case of a group of emitters that own and share a common pipeline system, and thus form a "vertically integrated" club. Third, we examine CCS adoption in the case of an infrastructure owned by an independent pipeline operator. In a final subsection, we show that the conditions required for the creation of a vertically integrated club of emitters are equivalent to those required for the deployment of CO_2 pipeline infrastructure owned by an independent operator.

3.1 Assumptions and notation

To begin with, we detail the assumptions and clarify the notation.

a – Main setup

This paper examines the economics of a CO_2 pipeline project aimed at transporting the CO_2 captured at a number of industrial facilities and transporting it to a storage site. We let N denote the finite set of emitters that could potentially be connected to that CO_2 pipeline system (still, N is a subset of the total set of emitters in the economy in question). The objective of the paper consists in determining the minimum set of conditions that ensure that a pipeline infrastructure connecting all these emitters is constructed. Hereafter, the emitters in this set are indexed by subscript i and we let $|N|$ denote the cardinality of this set and S denote a subset of N.

The project is located in a large economy where an environmental regulation is aimed at reducing CO_2 emissions by putting a price on these emissions (either a carbon tax or a cap-and-trade system). We let p_{CO_2} denote the prevailing price for the emission of one ton of CO_2. We assume that, though important in volume, the emissions of the emitters in N represent only tiny shares of the economy's emissions so that the impact of the emitters' decisions on the carbon price p_{CO_2} can be neglected.[12]

Each emitter faces a binary decision that concerns whether or not it adopts the CCS technology. We let σ denote the price of the storage service provided by an independent storage operator.[13] For each emitter i, we let Q_i denote the annual quantity of CO_2 that can potentially be captured, and χ_i denote the levelized unit cost of the site-specific carbon capture unit. As a result, the amount $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i$ represents the willingness to pay for a CO_2 pipeline service for each emitter i.

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[12] This assumption is satisfied even in the case of the large scale European CCS project examined in Section 4. In this project, the emitters that can potentially be connected to the pipeline system together control less than 0.9% of the total amount of CO_2 emission allowances in the EU cap-and-trade system. As a result, their decisions to adopt CCS are unlikely to greatly modify the prevailing carbon price. Conceivably, the interactions between the emitters' decisions and the prevailing supply and demand conditions on the CO_2 market could become significant in case of a very large CCS project. To model these interactions, further developments would be needed (e.g. to introduce a complete market equilibrium model for the CO_2 market). Such developments are clearly beyond the scope of the present paper. Nevertheless, we believe that this approach is general enough to examine a very large number of proposed CCS projects.

[13] The parameter σ may also be interpreted as a levelized unit cost of storage.

b – The pipeline technology

Let C be a finite real-valued function on the subsets of N. Here, $C(S)$ denotes the stand-alone, long-run cost of a pipeline system gauged to transport the CO_2 emitted by the subset S. In the empirical section, the $2^{|N|}$ values taken by the function C will correspond to the numerical outcomes of an engineering process model.[14] We assume that $C(\varnothing)=0$ and $C(S)\geq 0$ for any non-empty S in N. Following the discussion in Section 2.1, we assume that the cost function C is sub-additive: i.e., $C(S\cup T)\leq C(S)+C(T)$ for any coalitions $S,T\subseteq N$, with $S\cap T=\varnothing$.[15] This assumption suggests that, for a given set of emitters, the construction of a common CO_2 pipeline system lowers the transportation cost compared to a situation where the transportation service is provided by several pipeline systems.

3.2 The case of a vertically integrated club

In this subsection, we think of emitters as potential members of a club aimed at constructing and operating a common pipeline infrastructure, i.e. a vertically integrated club. The club is assumed to gather the individual net benefits and redistribute them among its members. We proceed as follows. We first define the total net benefits that could be obtained, collectively, by any group of emitters S creating their "restricted" club. Then, we explore the conditions required for a club gathering all the emitters in N to build the largest possible infrastructure, i.e. a pipeline infrastructure connecting all the $|N|$ emitters. Lastly, we examine the conditions for incentive-compatible sharing of the benefits generated by that largest infrastructure, i.e. those that ensure that no subgroup within the grand coalition can do better by deserting the coalition.

a – The collective net benefits of any club: a definition

Consider any given group of emitters S, with $S\subseteq N$ and $S\neq\varnothing$. We assume that they can form a restricted club aimed at operating a shared CCS infrastructure. The club's objective is to install and operate the infrastructure that maximizes the difference between the total benefits obtained by the members and the cost of the infrastructure. Conceivably, the non-adoption of CCS by some emitters in that group S may be needed to obtain the maximum net benefits that collection can provide to that group S. Side payments among the club members may be necessary to reach an agreement.

Formally, a pipeline project aimed at serving the emitters in any subgroup R, with $R\subseteq S$, would generate a net benefit equal to the difference between: $\sum_{i\in R}\left(p_{CO_2}-\chi_i-\sigma\right)Q_i$, the willingness to pay for

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[14] As there is no global information available about the shape of that cost function beyond these $2^{|N|}$ local evaluations, it should be clear that we cannot use the arsenal of useful results obtained in the analytical literature dedicated to continuous multiproduct cost functions (e.g., Baumol, 1977; Sharkey, 1982).

[15] Testing the global sub-additivity of that cost function is computationally demanding as a total of $\sum_{j=1}^{|N|}\binom{|N|}{j}\left(2^j-2\right)$ conditions, where $\binom{|N|}{j}$ is the number of j-combinations from a given set N, have to be considered. From an empirical perspective, checking the sub-additive nature of a discrete cost function can be challenging (e.g., with a moderate size of $|N|$ =20 facilities, nearly 3.5 billion conditions must be verified). Yet, for small enough problems such as the one considered in the next section, an exhaustive enumeration of all these conditions remains computationally feasible.

a CO_2 pipeline service of the connected emitters, and $C(R)$, the pipeline cost. Hence, the maximum net benefits which can be received by the emitters in the club S, denoted by v, is obtained by considering all the possible configurations of CCS infrastructures that can be formed with these emitters (i.e., all the possible subgroups R with $R \subseteq S$):

$$v\left(S, p_{CO_2}\right) \;=\; \underset{R \subseteq S}{\mathrm{Max}} \left\{ \sum_{i \in R} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(R) \right\}, \qquad \forall S \subseteq N \,. \tag{1}$$

Of course it can be that the maximum takes place at $R = S$, and therefore $v\left(S, p_{CO_2}\right) = \sum_{i \in S} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(S)$.

We assume that if no CO_2 is captured then no costs are incurred, which means that $v\left(S, p_{CO_2}\right) \geq 0$ for all S. By construction, v is monotonic since the condition $v\left(S_1, p_{CO_2}\right) \leq v\left(S_2, p_{CO_2}\right)$ systematically holds for any pair of subsets S_1, S_2 in N with $S_1 \subset S_2$.

b – The construction of the largest possible infrastructure

We now explore the condition required by the largest possible club N to construct the largest possible infrastructure, i.e. a pipeline system aimed at transporting the emissions captured by all the emitters.

For that largest infrastructure project to be rationally selected by the club N, it has to provide the members with a total net benefit that is larger than that obtained with any of the alternative infrastructure configurations that connects a subset of emitters. Formally, it means that the total net benefit $\sum_{i \in R} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(R)$ must be maximized when R is equal to N, or equivalently, that the equality $v\left(N, p_{CO_2}\right) = \sum_{i \in N} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(N)$ holds. Following Sharkey (1982, p. 62), this condition is equivalent to:

$$\sum_{i \in S} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] \;\geq\; C(N) - C(N \setminus S), \qquad \forall S \subset N \,. \tag{2}$$

This condition states that the total benefit of any subgroup of club members S must be at least as large as the incremental cost of serving these emitters.

Rewriting, condition (2) holds if and only if, the prevailing carbon price p_{CO_2} verifies $p_{CO_2} \geq \underline{p_{CO_2}}$ where $\underline{p_{CO_2}}$ is the following threshold level:

$$\underline{p_{CO_2}} \;:=\; \underset{S \subset N}{\mathrm{Max}} \left\{ \frac{\sum_{i \in S} \chi_i Q_i + C(N) - C(N \setminus S)}{\sum_{i \in S} Q_i} \right\} + \sigma \,. \tag{3}$$

So, any carbon price p_{CO_2} lower than this threshold level impedes the construction of the largest possible infrastructure. In the rest of this subsection, we assume that the prevailing carbon price verifies the condition $p_{CO_2} \geq \underline{p_{CO_2}}$.

c – Club adoption: the emitter's decisions

So far, we have focused on the total net benefit the grand coalition can provide. But we have not yet investigated whether the creation of such a largest club is a rational decision by each of the potential members. So, this section focuses on the emitter's individual decisions to join the largest club N .

We examine the repartition of the total benefit $v\left(N, p_{CO_2}\right)$ among the emitters. We let the vector $y = \left(y_1, ..., y_{|N|}\right)'$ denote the payoffs allocated to each of the emitters. By construction, this vector is expected to allocate the club's total net benefit to its members, i.e.:

$$\sum_{i \in N} y_i = v\left(N, p_{CO_2}\right). \tag{4}$$

For the sake of stability, this payoff should prevent each possible subgroup of emitters to prefer the creation of a restricted club (and thus secede from the grand coalition). Hence, this vector must provide each subgroup of emitters with a total payoff that is at least greater than the total benefit that would be obtained with a stand-alone attitude. So, this payoff vector has to verify the following condition:

$$\sum_{i \in S} y_i \geq v\left(S, p_{CO_2}\right), \qquad \forall S \subset N . \tag{5}$$

A payoff vector that verifies this condition is said to be coalitionally rational. Remark that, if that condition is verified, the emitters' individual payoffs are non-negative.

In the game theoretic jargon, a payoff vector that verifies both conditions (4) and (5) is said to be in the core of the cooperative game (N, v), where N is the set of players and v is the characteristic function, i.e. the set:

$$\Gamma_{p_{CO_2}} := \left\{ y \in \mathbf{R}^{|N|} : \sum_{i \in N} y_i = v\left(N, p_{CO_2}\right) \text{ and, } \forall S \subset N, \sum_{i \in S} y_i \geq v\left(S, p_{CO_2}\right) \right\}. \tag{6}$$

A non-empty core $\Gamma_{p_{CO_2}}$ indicates that it is possible to share the club's total net benefit in a manner that insures the voluntary participation of the $|N|$ emitters because none of them would have an incentive to opt out or prefer an alternative organization. Recall that, because the carbon price verifies $p_{CO_2} \geq \underline{p_{CO_2}}$, the club's net benefit to be apportioned is maximized when all the emitters are connected to a common pipeline infrastructure. Thus, any payoff vector in the core would insure the spontaneous adoption of CCS by all the emitters in N.[16] This suggests a definition for the club's feasible set:

<u>Definition 1:</u> *The vertically integrated club's feasible set is defined by all the payoff vectors of net benefits y that ensure the voluntary participation of all the individual emitters in the grand coalition. Formally, the vertical integrated club's feasible set is given by $\Gamma_{p_{CO_2}}$.*

3.3 The case of an independent pipeline operator

We now focus on an alternative organization where the pipeline infrastructure is owned by an independent firm that sells a CO_2 transportation service to the emitters. Pipeline operators can construct and operate pipeline infrastructures aimed at serving emitters. Before deciding its construction, a pipeline operator has to design and sign an enforceable long-term contract with each emitter that specifies the amount that will be charged to that emitter for the transportation service. In this subsection, we examine the conditions required for that construction to be decided.

<u>a – The conditions imposed by free entry in the pipeline industry</u>

The technology used in CO_2 pipelines is reputed to be not proprietary. So, there are potentially several pipeline firms that may have access to the same technology and thus the same sub-additive cost function C defined in the preceding section. These rivals can potentially serve any subgroup of emitters. As a result, we assume entry to be free in the pipeline industry.

Following the theoretical literature on contestable markets, in case of an industry where entry is set free, a firm has to take into consideration the possible entry of a potential rival when deciding its pricing policy. The sustainability of an industrial structure based on a unique operator serving all the emitters is achieved if and only if this operator charges a revenue vector $r = \left(r_1, ..., r_{|N|}\right)'$, where r_i is the amount charged to emitter i, that insures that: (i) this operator is financially viable, and (ii) a potential entrant cannot find any financially viable opportunity to serve any market S with $S \subseteq N$. Formally, these conditions are:

$$\sum_{i \in N} r_i \geq C(N), \tag{7}$$

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[16] As a side remark, we can note that, from a practitioner's perspective, checking whether a proposed payoff vector is in the core $\Gamma_{p_{CO_2}}$ is computationally cumbersome. Two alternative computational tactics can be employed. The first one requires to: (i) to pre-compute the values of the function v for each of the possible subcoalitions $S \subset N$ (which is computationally demanding as the pre-computations requires, for each possible subcoalition $S \subset N$, to determine a maximum over a discrete set that has $2^{|S|}$ elements), and (ii) using these values to verify whether the allocation equation (4) and the $2^{|N|} - 2$ linear inequality constraints (5) are jointly verified. The second strategy uses an equivalent definition of the constraints (5). Using definition (1), these constraints can be replaced by the following equivalent: $\sum_{i \in S} y_i \geq \sum_{i \in R} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(R)$, $\forall S \subset N$, $\forall R \subset S$. With this second approach, there is no need to pre-compute the values of v but the number of linear inequality constraints becomes very large (since the $2^{|N|} - 2$ constraints (5) are replaced by these $\sum_{j=1}^{|N|} \binom{|N|}{j} 2^j$ linear inequality constraints).

$$\sum_{i\in S} r_i \le C(S), \qquad \forall S \subseteq N. \tag{8}$$

These two conditions jointly indicate that:

$$\sum_{i\in N} r_i = C(N). \tag{9}$$

Thus, even in the absence of a regulatory profit constraint imposed on the pipeline operator, these conditions jointly demand the pipeline operator to adopt a revenue vector r that exactly recovers the total cost (Sharkey, 1982). Note that the conditions (8) and (9) are the conditions for subsidy-free revenues proposed by Faulhaber (1975) that ensure that no set of customers pays more for service than their stand-alone cost (i.e., the cost to exclusively serve that group of customers).

In the game-theoretic jargon, any revenue vector r that verifies these constraints is a cost allocation that belongs to the core of the cooperative cost game (N,C), i.e., the set:

$$\Lambda := \left\{ r \in \mathbf{R}^{|N|} : \sum_{i\in N} r_i = C(N) \text{ and, } \forall S \subset N, \sum_{i\in S} r_i \le C(S) \right\}. \tag{10}$$

Therefore, sustainability issues impose the pipeline operator to propose a cross-subsidy free revenue vector. Thus, a non-empty set Λ is an important condition for the feasibility of such a pipeline project. Hereafter, we assume that the condition $\Lambda \neq \emptyset$ is verified. From an empirical perspective, the non-emptiness of this set can be checked using the linear program LP-B detailed in Appendix B.

b – The conditions required for CCS adoption

We now examine the emitters' decision to adopt the proposed CCS project. Recall that for any emitter i, the amount $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i$ represents its willingness to pay for a CO_2 pipeline service and, thus, the amount $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i$ is its individual net benefit. Because of individual rationality, the pipeline operator must provide a non-negative net benefit to each individual emitter, i.e.:

$$\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i \ge 0, \qquad \forall i \in N. \tag{11}$$

As entry is free in the CO_2 pipeline industry, a rival could potentially propose an alternative project aimed at solely connecting the emitters in a given subcoalition $S \subset N$. This rival would charge a revenue vector $\tilde{r}^S$ and incur a cost $C(S)$. Hence, for the largest infrastructure project to be preferred, it has to provide each possible subcoalition with a net benefit larger than the one obtained with the rival's project:[17]

$$\sum_{i\in S} \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i \ge \sum_{i\in S} \left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - \tilde{r}_i^S\right], \qquad \forall S \subset N. \tag{12}$$

[17] *Otherwise, the rival would potentially be able to charge a revenue vector $\tilde{r}^S$ capable to provide each emitter $i \in S$ with a larger net benefit and thus to convince all the emitters in that subgroup to opt for the alternative project.*

As the rival must be financially viable, its revenue vector must verify $\sum_{i\in S}\tilde{r}_i^S \geq C(S)$. As entry is free in the pipeline industry, the rival also has to charge a revenue vector that does not provide any financially viable opportunity to another potential entrant: $\sum_{i\in S}\tilde{r}_i^S \leq C(S)$. Thus, for any subcoalition $S \subset N$, the rival's revenue vector has to verify $\sum_{i\in S}\tilde{r}_i^S = C(S)$. Using this remark, the condition (12) can be rewritten as:

$$\sum_{i\in S}\left(p_{CO_2}-\chi_i-\sigma\right)Q_i - r_i \geq \sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(S), \qquad \forall S\subset N. \tag{13}$$

c – The construction of the largest possible infrastructure

To summarize, the construction of the grand infrastructure is subject to two types of conditions. First, according to the theory of contestable markets, the promoter of the pipeline project has to charge a sustainable revenue vector: i.e, $r\in\Lambda$ (cf. the conditions (8) and (9)). Second, the pipeline operator must charge a revenue vector r such that the emitters' individual benefits provides them with an incentive to accept the operator's proposition (cf. the conditions (11) and (13)). At first sight, these two types of conditions jointly impose numerous constraints on the selection of a revenue vector.[18] However, the conditions (8) and (13) are redundant which suggests the following parsimonious definition of the pipeline operator's feasible set:

Definition 2: *The pipeline operator's feasible set is defined by all the revenue vectors r that are both sustainable and provide a non-negative net benefit to any individual emitters in the grand coalition. Formally, we let $y_{p_{CO_2}}: r \mapsto \left(\left(p_{CO_2}-\chi_i-\sigma\right)Q_i - r_i\right)_{i=1,\ldots,|N|}$ so that $y_{p_{CO_2}}(r)$ is the vector of the emitter's individual net benefits associated with the revenue vector r charged by the pipeline operator. The pipeline operator's feasible set is $\Lambda\cap IP_{p_{CO_2}}$ where $IP_{p_{CO_2}} := \left\{r\in\mathbf{R}^{|N|} : y_{p_{CO_2}}(r)\geq 0\right\}$ is the set of revenue vectors that verify condition (11).*

As the prevailing carbon price intervenes in the evaluation of the individual net benefits, one may wonder whether the proposed pipeline project can be accepted for any carbon price level. The following proposition addresses this issue.

Proposition 1: *For any carbon price level such that $p_{CO_2} < \underline{p_{CO_2}}$, where $\underline{p_{CO_2}}$ is the threshold level defined in (3), a financially viable pipeline operator cannot decide the construction of the pipeline infrastructure aimed at serving all the $|N|$ emitters. For such carbon price levels, the feasible set $\Lambda\cap IP_{p_{CO_2}}$ is systematically empty.*

[18] *The set Λ is defined by one equation and $2^{|N|}-2$ linear inequality constraints. The conditions (11) and (13) jointly impose a total of $|N|+2^{|N|}-2$ linear inequality constraints.*

According to this proposition, a carbon price level that verifies $p_{CO_2} \geq \underline{p_{CO_2}}$ is necessary (but possibly not sufficient) for the pipeline project to be decided. Note that the threshold price level $\underline{p_{CO_2}}$ that was derived in the benchmark case of a vertically integrated club also affects feasibility when the pipeline infrastructure is owned by an independent pipeline operator.

3.4 Equivalence between the two cases

In the preceding subsections, we detailed the conditions required for the construction of the largest infrastructure in the case of a vertically integrated club of CCS emitters and in those of an independent pipeline operator. We now clarify the relation that exists between the benefit-sharing problem of a vertically integrated club and the tariff setting problem of an independent CO_2 pipeline operator.

Recall that, in the case of an independent pipeline operator, $y_{p_{CO_2}}(r)$ denotes the vector of the emitter's individual net benefits associated with the revenue vector r charged by the pipeline operator. Similarly, in case of a vertically integrated club, it is possible to associate any payoff vector y allocated by the club with an associated pipeline revenue vector $r_{p_{CO_2}}(y)$ where $r_{p_{CO_2}}: y \mapsto \left(\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - y_i\right)_{i=1,\dots,|N|}$. There is a relation between the conditions imposed on a pipeline operator that wishes to charge a sustainable revenue vector and those required for the creation of a stable vertically integrated club of CCS emitters:

<u>Proposition 2 (Sharkey, 1982):</u> *If the prevailing carbon price verifies* $p_{CO_2} \geq \underline{p_{CO_2}}$ *, then for any allocation* y *in the club's feasible set, the associated revenue vector* $r_{p_{CO_2}}(y)$ *is sustainable. Formally, if* $y \in \Gamma_{p_{CO_2}}$ *and* $p_{CO_2} \geq \underline{p_{CO_2}}$*, then* $r_{p_{CO_2}}(y) \in \Lambda$.

Proposition 2 indicates that selecting a cross-subsidy free tariff (i.e., a revenue vector r in Λ the core of the cost game) is a necessary condition to obtain a vector of individual benefits y capable to trigger the formation of a vertically integrated CCS club. However, that condition is not a sufficient one. So, we now propose a complementary condition to achieve a necessary and sufficient condition.

<u>Proposition 3:</u> *If the prevailing carbon price verifies* $p_{CO_2} \geq \underline{p_{CO_2}}$ *, then:*

(i) *If the allocation* y *is in the vertically integrated club's feasible set,* $y \in \Gamma_{p_{CO_2}}$ *, then the associated revenue vector* $r_{p_{CO_2}}(y)$ *is in the pipeline operator's feasible set,* $\Lambda \cap IP_{p_{CO_2}}$

(ii) *If a pipeline operator charges a revenue vector* r *in the feasible set,* $\Lambda \cap IP_{p_{CO_2}}$ *, then the associated allocation* $y_{p_{CO_2}}(r)$ *is in the vertically integrated club's feasible set,* $y \in \Gamma_{p_{CO_2}}$.

This proposition indicates that there is a one-to-one correspondence between the tariff setting problem faced by the promoter of an independent CO_2 pipeline project and the benefit-sharing problem faced by a vertically integrated club. It proves that the revenue vector charged by the pipeline operator must provide emitters with a share of the net benefits that verifies all the conditions required for the creation of a stable club of CCS emitters.

From a computational perspective, this one-to-one correspondence also provides a useful simplification. Recall that in case of a vertically integrated club, checking whether a proposed payoff vector y is in the core $\Gamma_{p_{CO_2}}$ can be computationally demanding (cf. Footnote 16). However, using Proposition 3, it is necessary and sufficient to consider the associated revenue vector $r_{p_{CO_2}}(y)$ and check whether it verifies the following conditions: (i) the linear equation (9), (ii) the $2^{|N|}-2$ linear inequality constraints (8), and (ii) the $|N|$ linear inequality constraints (11). Hence, this proposition offers a sharp reduction in the number of conditions to be verified. In the sequel, we make use of these simplifications to examine the role played by the prevailing carbon price on CCS adoption.

In the sequel, our analysis proceeds focusing solely on the case of an independent pipeline operator. Nevertheless, it is important to keep in mind that, using the one-to-one mapping function $y_{p_{CO_2}}(r)$, the tariff setting problem faced by a pipeline operator can systematically be reformulated and re-interpreted as a club formation problem.

4. Evaluating the break-even value for joint CCS adoption

In this section, we address an important question: what is the critical value in the charge for CO_2 emissions that would allow the adoption of CCS technologies? To answer it, we define the break-even value for joint CCS adoption and propose a linear programming approach aimed at evaluating this critical value. We then consider two extensions of this model. The first extension focuses on the case of a pipeline operator that is compelled to use an exogenously predetermined, non-discriminatory, tariff structure. The second one examines the case of a transnational pipeline infrastructure that is supervised by a collection of national regulators.

4.1 The break-even value for joint CCS adoption: definition and evaluation

In the preceding section, we have shown that the deployment of the largest infrastructure connecting all the emitters is systematically impeded if the prevailing carbon price is strictly lower than the threshold level $\underline{p_{CO_2}}$. However, it is possible to obtain that deployment with any carbon price larger than this threshold?

To answer this question, we can observe that the prevailing carbon price does not intervene in the definition of a sustainable revenue vector (i.e., in the definition of Λ the core of the cooperative cost game). In contrast, for any sustainable revenue vector r, the associated emitters' individual net benefits $\left(p_{CO_2}-\chi_i-\sigma\right)Q_i-y_i$ are monotonically increasing in the prevailing carbon price. These two remarks together suggest that: if the pipeline operator's feasible set $\Lambda\cap IP_{p_{CO_2}}$ is reputed to be non-empty for a given carbon price, so is the case with any carbon price level larger than this value. For the pipeline operator, it is thus crucial to determine the lowest value in the charge for CO_2 emissions that allows the pipeline operator to charge a revenue vector that is sustainable and such that every emitters obtains a non-negative net benefit.

<u>Definition 3:</u> *We let* $p^*_{CO_2}$ *be the break-even value for joint CCS adoption, that is the minimum value of the prevailing carbon price that is compatible with the construction of the projected infrastructure, i.e.,* $p^*_{CO_2} := \underset{p_{CO_2}}{\text{Min}} \left\{ p_{CO_2} \in \mathbf{R} : \Lambda \cap IP_{p_{CO_2}} \neq \varnothing \right\}$.

From a computational perspective, this break-even value for joint CCS adoption $p^*_{CO_2}$ can be evaluated using the following linear programming problem:

<u>LP1:</u>

$$\underset{r, p_{CO_2}}{\text{Min}} \quad p_{CO_2} \tag{14}$$

$$\text{s.t.} \quad \sum_{i \in N} r_i = C(N), \tag{15}$$

$$\sum_{i \in S} r_i \leq C(S), \qquad \forall S \subset N \setminus \{\varnothing, N\}, \tag{16}$$

$$\left(p_{CO_2} - \chi_i - \sigma\right) Q_i - r_i \geq 0, \qquad \forall i \in N. \tag{17}$$

In that linear program, the constraints (15) and (16) compel the pipeline operator to charge a sustainable revenue vector and the condition (17) represents the emitters' individual participation constraints. The following proposition insures that a solution to LP1 exists.

<u>Proposition 4:</u> *There is at least one solution to LP1 if and only if* $\Lambda \neq \varnothing$. *Moreover, if* $\Lambda \neq \varnothing$, *the optimal value of the objective function is unique and equal to* $p^*_{CO_2}$ *the break-even value for joint CCS adoption. In addition, if* $\Lambda \neq \varnothing$, *the break-even value for joint CCS adoption verifies* $p^*_{CO_2} \geq \underline{p_{CO_2}}$.

This proposition confirms that a carbon price level p_{CO_2}, with $p_{CO_2} \geq \underline{p_{CO_2}}$, is necessary but may not be sufficient to obtain the deployment of a pipeline infrastructure connecting all the $|N|$ emitters as a carbon price level larger than the break-even value for joint CCS adoption is required for that infrastructure to be decided. So, to summarize from an empirical perspective, any attempt to solve LP1 results in one of the three following outcomes:

- <u>Case #1:</u> a solution is found and $p^*_{CO_2}$, the obtained break-even value for joint CCS adoption, verifies $p^*_{CO_2} = \underline{p_{CO_2}}$.
- <u>Case #2:</u> a solution is found and $p^*_{CO_2}$, the obtained break-even value for joint CCS adoption, verifies $p^*_{CO_2} > \underline{p_{CO_2}}$. In that case, the threshold price level $\underline{p_{CO_2}}$ is not sufficient to trigger the construction of the largest CCS infrastructure.

- Case #3: there is no solution to LP1. Thus, $\Lambda = \varnothing$ which means that the pipeline operator cannot recover its costs without generating cross-subsidizations à la Faulhaber (1975) among customers.

4.2 Non-discriminatory pipeline tariffs: do they modify the break-even value?

So far, we have supposed that the pipeline operator is let free to charge any revenue vector in its feasible set. This analysis implicitly assumes that the pipeline operator can charge discriminatory tariffs. However, such a perfect discrimination hardly looks realistic. For example, the pricing scheme used by European infrastructure firms is usually subject to approval by a regulator that does not directly select the individual prices but typically instructs the operator to use a non-discriminatory tariff policy. Therefore, we now consider the situation where the pipeline firm is compelled to use non-discriminatory tariff structures and examine whether the existence of this exogenous regulatory constraint modifies the break-even value for joint CCS adoption.

In this subsection, we successively examine two types of non-discriminatory tariff structures: (i) the case of a multipart linear tariff; and (ii) the case where the pipeline operator is compelled to offer a menu of tariffs using the so-called second degree price discrimination principles. In each case, we address the following questions. First, is the proposed tariff structure compatible with the conditions for the deployment of the largest CO_2 pipeline infrastructure? Second, in case of a positive answer to the previous question, does this tariff structure modify the break-even value for joint CCS adoption?

a – The case of a multipart linear tariff structure

We analyze the case of a possibly multipart, non-discriminatory, linear tariff whereby the pipeline operator is allowed to use a series of k, with $k \leq |N|$, observable emitter-specific features (e.g., the volume of CO_2 emissions Q_i, the peak flow of emissions). Let the vector $\phi^i = \left(\phi_1^i, ..., \phi_k^i\right)'$ denote the value of these parameters for emitter i; and the vector of decision variables $t = \left(t_1, ..., t_k\right)'$ denote the tariffs charged by the pipeline operator. According to this tariff structure, the amount charged by the pipeline operator to emitter i is $\sum_{j=1}^{k} \phi_j^i t_j$. For example, a simple linear pricing would correspond to $k = 1$, $\phi_1^i = Q_i$, and $t_1 = p$ the price per unit.

We now detail a modified version of the linear program LP1 to examine how the proposed tariff structure modifies the break-even value for joint CCS adoption:

LP2:
$$\min_{t, p_{CO_2}} \quad p_{CO_2} \tag{18}$$

$$\text{s.t.} \quad \sum_{i \in N} \left(\sum_{j=1}^{k} \phi_j^i t_j \right) = C(N), \tag{19}$$

$$\sum_{i \in S} \left(\sum_{j=1}^{k} \phi_j^i t_j \right) \leq C(S), \qquad \forall S \subset N \setminus \{\varnothing, N\}, \tag{20}$$

$$\left(p_{CO_2} - \chi_i - \sigma \right) Q_i - \sum_{j=1}^{k} \phi_j^i t_j \geq 0, \qquad \forall i \in N. \tag{21}$$

In the linear program LP2, the constraints (19) and (20) jointly impose the sustainability of the revenue vector charged by the pipeline operator. The emitters' individual participation constraints are modeled using the condition (21). Compared to LP1, the decision variables $r=\left(r_1,...,r_{|N|}\right)'$ are simply replaced by the prices variables $t=\left(t_1,...,t_k\right)'$ together with the tariff structure.

From an empirical perspective, any attempt to solve this problem results in one of the three following outcomes. In Case #1, a solution is found and corresponds to a minimum allowance price $p_{CO_2}^{**}$ that verifies $p_{CO_2}^{**}=p_{CO_2}^{*}$. In that case, the use of this tariff structure has no impact on the feasibility of the CCS project as its break-even value is not modified. In Case #2, a solution is found and corresponds to a minimum allowance price $p_{CO_2}^{**}$ that verifies $p_{CO_2}^{**}>p_{CO_2}^{*}$. In that case, the tariff structure imposed on the pipeline operator impedes the creation of the largest CCS infrastructure when the prevailing carbon price is in the interval $\left[p_{CO_2}^{*},p_{CO_2}^{**}\right)$. Lastly, in Case #3, there is no solutions to LP2, which means that the feasible set associated with LP2 is empty. As there is no maximum bound on the carbon price in LP2, a sufficiently large value of p_{CO_2} can insure that none of the emitters' individual participation constraints in (21) is binding. Thus, the empty nature of the feasible set indicates the impossibility to jointly verify the conditions (19) and (20) which means that the pipeline operator cannot implement this tariff structure and recover its costs without generating cross-subsidizations among customers.[19]

b – The case of a menu of multi-part linear tariffs

We now consider a second type of tariffs that corresponds to a so-called second degree price discrimination scheme. The pipeline operator is compelled to design a menu of m different multipart linear tariffs. Knowing that menu, emitters are then assumed to choose the tariff that minimizes their CO_2 transportation cost given their emission features.

Formally, for each tariff l with $l\in\{1,...,m\}$, the pipeline operator is allowed to use an emitter-specific vector $\phi^i=\left(\phi_1^i,...,\phi_k^i\right)'$ of quantitative features and determines a total of k parameters: the vector $t^l=\left(t_1^l,...,t_k^l\right)'$ of unit prices. For example, if the operator is allowed to propose a menu of two-part tariffs that are based on a fixed charge plus a variable price, then, $k=2$, $t_1^l=f_l$ are the fixed price components, $t_2^l=p_l$ are the variable price components, and the emitters' features are $\phi^i=\left(1,Q_i\right)'$. To avoid indeterminacy, we impose the following restriction: $mk\leq|N|$. For simplicity, we use t as a short notation for the collection of these m price vectors.

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[19] *As entry is assumed to be free in the CO_2 pipeline industry, imposing the use of this pricing scheme would create the conditions for a profitable entry for a pipeline competitor serving a subset of emitters, and thus artificially generate a suboptimal organization of the CO_2 pipeline industry (i.e. an organization where several firms coexists whereas a single-firm organization would have been less costly).*

In that case, each emitter is assumed to rationally select the tariff that minimizes its CO_2 transportation cost. This choice in turn determines the revenue charged by the pipeline operator. Thus, we are dealing with a bilevel optimization problem (Bracken and McGill, 1973; Bard, 1998; Colson et al., 2007) where the upper level problem is analogue to LP2 (determining the tariff levels and the minimum value of the prevailing carbon price that are compatible with the conditions required for the deployment and adoption of the proposed infrastructure), and the lower-level problem corresponds to the emitters' individual decisions.

Regarding the lower-level, every emitter takes the proposed menu of tariffs t as given and rationally selects the tariff that minimizes its CO_2 transportation cost. From the pipeline operator's perspective, it means that the maximum amount of revenue r_i that can be obtained from an emitter i is equal to $\mathrm{Min}_{l\in\{1,\dots,m\}}\left\{\sum_{j=1}^{k}\phi_j^i t_j^l\right\}$ and is thus lower than the collection of amounts $\left\{\sum_{j=1}^{k}\phi_j^i t_j^l\right\}_{l\in\{1,\dots,m\}}$ invoiced with the various proposed tariffs. Formally, that emitter's choice can be modeled using the following linear program:

$$\underline{\mathrm{LP3}_i(t)}:\quad \mathop{\mathrm{Max}}_{r_i}\quad r_i \tag{22}$$

$$\text{s.t.}\quad r_i \le \sum_{j=1}^{k}\phi_j^i t_j^l\,,\qquad \forall l\in\{1,\dots,m\}\,. \tag{23}$$

Regarding the upper-level, we are looking for the minimum selling price of an emission allowance and the associated tariff design that insures an incentive-compatible allocation of the total net benefit.

$$\underline{\mathrm{BLP4}}:\quad \mathop{\mathrm{Min}}_{t,\,p_{CO_2}}\quad p_{CO_2} \tag{24}$$

$$\text{s.t.}\quad \sum_{i\in N} r_i = C(N)\,, \tag{25}$$

$$\sum_{i\in S} r_i \le C(S)\,,\qquad \forall S\subset N\setminus\{\varnothing,N\}\,, \tag{26}$$

$$\left(p_{CO_2}-\chi_i-\sigma\right)Q_i - r_i \ge 0\,,\qquad \forall i\in N\,, \tag{27}$$

$$\begin{pmatrix} \mathop{\mathrm{Max}}_{r_i} & r_i & \\ \text{s.t.} & r_i \le \sum_{j=1}^{k}\phi_j^i t_j^l, & \forall l\in\{1,\dots,m\}, \end{pmatrix}\qquad \forall i\in N\,. \tag{28}$$

In this bilevel optimization problem, the objective is to determine the critical value in the charge for CO_2 emissions that is required for: (i) allowing the pipeline operator to charge a sustainable revenue vector (cf. the conditions (25) and (26)), (ii) insuring the participation of all the emitters (cf. the conditions (27)), and (iii) taking into consideration the emitters' choice with respect to the proposed menu of tariffs (cf. the lower level problems (28)).

From a computational perspective, a reformulation is needed to solve this two-level optimization problem. In Appendix C, we apply the reformulation proposed in Fortuny-Amat and McCarl (1981) to construct the equivalent problem MILP-C which is a mixed-integer linear programming problem.

As in the case of LP2, any attempt to solve this bilevel optimization problem results in one of the three following outcomes. In Case #1, a solution is found and verifies $p_{CO_2}^{**} = p_{CO_2}^{*}$ which indicates that the pricing scheme has no impact on the feasibility of the CCS project. In Case #2, a solution is found and verifies $p_{CO_2}^{**} > p_{CO_2}^{*}$ which means that the tariffs structure imposed on the pipeline operator impedes the creation of the largest CCS infrastructure when the prevailing carbon price is in the interval $\left[p_{CO_2}^{*}, p_{CO_2}^{**}\right)$. Lastly in Case #3, there is no solution which indicates that the tariffs structure imposed on the pipeline operator is not compatible with the conditions required for the construction of the infrastructure (i.e., charging a cross-subsidy-free revenue vector and providing every emitter with a non-negative individual net benefit).

4.3 The case of transnational CO_2 pipelines

In Europe, a number of the projected CO_2 pipeline infrastructures will have a transnational nature (e.g., Mendelevitch, 2014). So, there is a possibility for these infrastructures to be supervised by a collection of national regulatory authorities. One may wonder whether a state-based regulatory organization could have an impact on the break-even value for joint CCS adoption?

To address this question, we consider the case of a transnational pipeline infrastructure installed across two states labeled A and B. The set of emitters connected to that pipeline can be decomposed as follows: $N := N_A \cup N_B$ where N_A (respectively N_B) is the subset of emitters in country A (respectively B) and $N_A \cap N_B = \varnothing$ because each emitter is associated with a unique country. To simplify, we assume that the CO_2 emissions captured in A are piped to B where the infrastructure transports all the emissions captured in both countries. Using the notation $C_A(.)$ and $C_B(.)$ denote the pipeline total cost function in country A (respectively B). The total cost incurred in country A (respectively B) is $C_A(N_A)$ (respectively $C_B(N)$).

We assume that there are two national regulators and that each of them has an exclusive competence to regulate the pricing structure used by the pipeline operator in its jurisdiction. Each regulator: (i) imposes the pipeline operator to maintain a distinct accounting system on its jurisdiction; (ii) demands that the revenues obtained in its jurisdiction recover exactly the total cost incurred on that territory; and (iii) imposes the pipeline operator to charge cross-subsidy-free revenues à la Faulhaber (1975). Thus, in each jurisdiction, the pipeline operator is let free to charge possibly discriminatory prices provided that the amount charged to any subgroup of emitters does not exceed the stand alone cost to serve solely that group of customers. We let r^A denote the revenue vector charged by the pipeline operator to the emitters that are using the infrastructure located in country A; and r^B denote the revenue vector charged to those that are using the infrastructure located in country B. Thus, the total amount that is charged to an emitter i is equal: to $r_i^A + r_i^B$ if $i \in N_A$, and to r_i^B if $i \in N_B$.

Using these assumptions, we propose a modified version of the linear program LP1 to examine how the existence of a state-based regulatory organization modifies the break-even value for joint CCS adoption:

$$\underline{\text{LP5:}} \qquad \min_{r^A, r^B, p_{CO_2}} \; p_{CO_2} \tag{29}$$

$$\text{s.t.} \quad \sum_{i \in N_A} r_i^A = C_A\left(N_A\right), \tag{30}$$

$$\sum_{i \in S} r_i^A \leq C_A\left(S\right), \qquad \forall S \subset N_A \setminus \left\{\varnothing, N_A\right\}, \tag{31}$$

$$\sum_{i \in N_A \cup N_B} r_i^B = C_B\left(N\right), \tag{32}$$

$$\sum_{i \in S} r_i^B \leq C_B\left(S\right), \qquad \forall S \subset N \setminus \left\{\varnothing, N\right\}, \tag{33}$$

$$\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - \left(r_i^A + r_i^B\right) \geq 0, \qquad \forall i \in N_A, \tag{34}$$

$$\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i^B \geq 0, \qquad \forall i \in N_B. \tag{35}$$

In LP5, the conditions (30) and (31) compel the pipeline operator to charge a revenue vector r^A that belongs to the core of the cooperative cost game $\left(N_A, C_A\right)$. These two conditions model the restrictions imposed by the first regulator that instructs the pipeline operator to charge a cross-subsidy-free revenue vector that recovers the total cost incurred in country A. Similarly, the conditions (32) and (33) jointly insure that the revenue vector r^B is in the core of the cooperative cost game $\left(N, C_B\right)$. These conditions impose the pipeline operator to charge a cross-subsidy-free revenue vector in country B. The condition (34) represents the individual participation constraints of the emitters in country A: it insures that, for each of these emitters, the sum of the amounts charged by the pipeline operator in each jurisdiction does not exceed that emitter's willingness to pay for a CO_2 pipeline service. The condition (35) represents the individual participation constraints of the emitters in country B.

We let $p_{CO_2}^{*,\text{National}}$ denote the solution of the linear program LP5 which is the break-even value for joint CCS adoption in case of an institutional organization based on two independent regulators that let the pipeline operator determines a cross-subsidy free tariff structure. From a regulatory policy perspective, it is interesting to compare this value $p_{CO_2}^{*,\text{National}}$, with $p_{CO_2}^{*}$ the break-even value for joint CCS adoption obtained in case of a transnational regulator. Recall that $p_{CO_2}^{*}$ can be computed using LP1 with the definition $C(S) := C_A(S \cap N_A) + C_B(S)$. As any solution to LP5 can be associated with a vector in the feasible set of LP1,[20] the following relation holds: $p_{CO_2}^{*,\text{National}} \geq p_{CO_2}^{*}$.

So, any attempt to solve LP5 results in one of the three following outcomes. In Case #1, a solution is found and verifies $p_{CO_2}^{*,\text{National}} = p_{CO_2}^{*}$ which indicates that the use of a state-based regulatory organization has no impact on the feasibility of the CCS project. In Case #2, a solution is found and verifies $p_{CO_2}^{*,\text{National}} > p_{CO_2}^{*}$ which means that the use of a state-based regulatory organization impedes the creation of the largest CCS infrastructure when the prevailing carbon price is in the interval $\left[p_{CO_2}^{*}, p_{CO_2}^{*,\text{National}}\right)$. Lastly in Case #3, there is no solution which indicates that the tariffs structure imposed on the pipeline operator is not compatible with the conditions required for the construction of the infrastructure (i.e., charging a cross-subsidy-free revenue vector and providing every emitter with a non-negative individual net benefit).

The program LP5 can also be used in a series of extensions. In LP5, the pipeline operator can charge possibly discriminatory prices. As in the preceding subsection, this program can also be adapted to deal with the case where the pipeline operator is compelled to use a predetermined pricing structure in each jurisdiction. This extension can be useful to examine the compatibility of two given national tariff structures. This extension is based on a modified version of the linear program LP5 where the decision variables r^A and r^B are replaced by the proposed price variables together with the associated tariff structure. For the sake of brevity, we shall not detail further these modifications which are analogous to the ones used in the construction of LP2 from LP1.

5. Case study

In this section, we detail an application of our framework to analyze the economics of a European project that involves the construction of a transnational CO_2 pipeline system.

5.1 A Northwestern European CO_2 pipeline project

<u>a - Background</u>

We consider the construction of a potential high-pressure CO_2 trunkline system aimed at gathering the CO_2 emissions originating from two large industrial clusters – Le Havre (France) and Antwerp (Belgium) – and transporting them to the Rotterdam area (Netherlands) where the CO_2 could be stored

[20] *A brief proof of this statement is follows. If the feasible set associated with LP5 is non-empty and* $\left(\hat{r}^A, \hat{r}^B, \hat{p}_{CO_2}\right)$ *verifies the conditions (30)-(35), then the vector* $\left(\hat{r}, \hat{p}_{CO_2}\right)$*, where* $\hat{r}$ *is the revenue vector such that* $\hat{r}_i = \hat{r}_i^A + \hat{r}_i^B$ *if* $i \in A$*, and* $\hat{r}_i = \hat{r}_i^B$ *otherwise, verifies the conditions (15)-(17).*

offshore in depleted oil fields.[21] We assume that this pipeline infrastructure will be constructed and operated by an independent operator. In Europe, entry is reputed to be free in the CO_2 pipeline industry.

Using both the French and Belgian National Allocation Plans for CO_2-emission allowances, a total of 14 large to small industrial facilities (e.g., coal power plant, refineries, petrochemical plants) have been identified as possible CCS adopters in these two clusters. These industrial emitters are listed in Table 1. For the sake of simplicity, the subset of all the Belgian (respectively French) emitters is denoted B (respectively F).

These 14 plants jointly emit 19.7 $MtCO_2$/year. According to the figures in Table 1, there is an uneven distribution of the annual emission volumes as the five largest emitters (Antwerp #1, Le Havre #1, #11, #2 and Antwerp #2) jointly generate 88% of these total emissions whereas the share of the two smallest emitters (Le Havre #8, and #12) looks negligible. The case of these very small emitters deserves a discussion. Recently, some concerns have emerged regarding the efficiency of an Emission Trading Scheme (ETS) based on a "blanket coverage" that includes all the industrial emitters of greenhouse gases in an economy.[22] As a result, the EU Commission has taken some steps toward a "partial coverage" scheme whereby emitters that do not attain a threshold level of 25,000 tCO_2 per year are exempted from the ETS. Formally, we let N_{All} denote the set that gathers all the 14 emitters. In case of a "partial coverage" scheme, the two smallest emitters are eliminated from the list of potential CCS adopters and we let $N_{\geq 25ktCO_2} := \{i \in N_{All} : Q_i \geq 25000\}$ denote this subcoalition of emitters with an annual emission level greater than the threshold level. In this case study, we are going to systematically contrast the results obtained with the two possible definitions of the grand coalition N, either the whole group $N := N_{All}$ or the subset $N := N_{\geq 25ktCO_2} \subset N_{All}$.

The quarterly emission figures detailed Table 1 indicate that there are marked differences in the within-year patterns of emissions. Some facilities emit a steady flow of CO_2 during the whole year (e.g., Antwerp #1 & #2) whereas others have significant within-year variations (e.g., Le Havre #1). These within-year variations in CO_2 emissions are of importance as the emission load factor influences the gauging of a pipeline system. Because of data availability issues, the analysis concentrates on the between-quarter variability in the daily CO_2 flow rates. Hereafter, we denote $\bar{q}_i$ the within-year peak daily flow emitted by the industrial facility i.

Table 1. The annual volumes of CO_2 emitted by the industrial facilities

Facility		Annual Emissions Q_i	Quarterly emissions (as a % of the annual emissions)				Annual unit cost for CO_2 Capture χ_i
Label	Type of industry	(tCO_2/year)	Quarter 1	Quarter 2	Quarter 3	Quarter 4	(€/tCO_2 per year)
Le Havre #1	Coal power plant	3 733 346	39.8%	12.7%	12.7%	34.8%	38.9

[21] *The context of this case study has been inspired by the COCATE project funded by the European Commission DG Research (reference: 7th Framework Program, Energy.2009.5.2.2: Towards an infrastructure for CO_2 transport and storage. Collaborative Project – GA No. 241381, cf. http://cordis.europa.eu/project/rcn/93104_en.html for a presentation).*

[22] *For example, the benefit–cost analysis conducted by Betz et al. (2010) indicated that a "partial coverage" solely focused on the largest emitters could generate substantial social cost savings.*

Le Havre #2	Oil refinery	3 020 379	24.7%	24.9%	25.2%	25.2%	48.7
Le Havre #3	Ammonia & Urea plant	147 664	24.7%	24.9%	25.2%	25.2%	31.3
Le Havre #4	Petrochemical plant	1 147 694	24.8%	24.9%	25.1%	25.2%	51.9
Le Havre #5	Cement factory	832 822	19.2%	28.3%	28.6%	24.0%	51.4
Le Havre #6	Glassworks	73 863	24.7%	24.9%	25.2%	25.2%	39.3
Le Havre #7	Ethanol Plant	70 364	24.7%	24.9%	25.2%	25.2%	50.1
Le Havre #8	Compressor test platform	2 076	49.5%	0.0%	0.0%	50.5%	53.6
Le Havre #9	Petrochemical plant	38 317	24.7%	24.9%	25.2%	25.2%	48.4
Le Havre #10	Petrochemical plant	34 555	24.7%	24.9%	25.2%	25.2%	50.6
Le Havre #11	Refinery & Petrochemicals	3 503 728	24.7%	24.9%	25.2%	25.2%	47.3
Le Havre #12	Specialty Chemicals	7 734	24.7%	24.9%	25.2%	25.2%	47.0
Antwerp #1	Refinery & Petrochemicals	5 261 052	24.7%	24.9%	25.2%	25.2%	44.5
Antwerp #2	Oil refinery	1 820 291	24.7%	24.9%	25.2%	25.2%	48.2

Note: The use of generic labels has been imposed by legal confidentiality provisions. The annual emissions data are based on the 2010 figures listed in the Belgian and French National Allocation Plans for CO_2-emission allowances. The quarterly shares have been obtained from industry-specific engineering studies. The annual unit costs for capture and collection are in 2010 euros.

b – Cost data

In this paper, we use the data detailed in Table 1 for the site-specific, annual unit cost of the capture equipments and the gathering lines connecting the industrial facilities to the CO_2 trunkline system (collection). The annual unit cost for offshore CO_2 storage in the North Sea is assumed to be equal to 8 €/tCO_2 per year. This figure is based on the estimates reported in IPCC (2005).

Regarding CO_2 pipeline transportation, a detailed engineering economic model based on McCoy (2009) has been put to work to determine the optimal combination of parameters (pipeline diameter, operating pressures, etc.) that minimizes the annual total cost to install and operate an adapted pipeline system for each possible coalition of emitters in the largest coalition N_{All}.[23] The CO_2 trunkline at hand can be decomposed into two subsystems: a first pipeline system connects Le Havre to Antwerp and a second pipeline system connects Antwerp to the Rotterdam area. Thus, for any coalition of CCS adopters S with $S \subset N_{All}$, the annual long-run total cost $C(S)$ to build and operate an adapted pipeline infrastructure is: $C(S) = C_{F\to B}(S \cap F) + C_{B\to NL}(S)$, where $C_{F\to B}(S \cap F)$ is the cost to transport the volume $\sum_{i\in S\cap F} Q_i$ of CO_2 from Le Havre to Antwerp and $C_{B\to NL}(S)$ is the cost to transport the volumes $\sum_{i\in S} Q_i$ from Antwerp to Rotterdam.

In Table 2, we consider a series of attention-grabbing coalitions of emitters and report, for each of them, the total annual costs of the components of an adapted CCS infrastructure and the associated average cost. According to this engineering process model, the annual total cost to install and operate an adapted pipeline system capable of transporting the CO_2 emitted by the largest set of emitters N_{All} is

[23] *The assumptions used in this engineering model are summarized in an online companion to this manuscript.*

€123.8 million which represents 10.5% of the total annual cost of the entire CCS chain (capture, transport and storage). Because of its location, the coalition B that gathers the two Belgian emitters provides the lowest average total cost figure: 55.92 €/(tCO_2 per year), of which 2.47 €/(tCO_2 per year) are related to the CO_2 pipeline system. For the largest coalition N_{All}, the average annual total cost of the whole CCS chain is 59.86 €/(tCO_2 per year), of which solely 6.29 €/(tCO_2 per year) are related to the CO_2 pipeline system. We can remark that the pipeline cost incurred when serving the grand coalition N_{All} is very close to the one obtained when serving the restricted coalition $N_{\geq 25ktCO_2} \subset N_{All}$ which suggests that the incremental cost associated with the connection of the two smallest emitters to a pipeline infrastructure aimed at serving $N_{\geq 25ktCO_2}$ remains limited.

Table 2. The stand-alone cost of the CCS infrastructure for some remarkable coalitions

Coalition	Annual Emissions ($MtCO_2$/year)	Annual Total Cost (M€/year)				Average Cost of the entire CCS chain €/(tCO_2 per year)
		Capture plants	Adapted pipeline system		Geological Storage	
			$C_{F\rightarrow B}$	$C_{B\rightarrow NL}$		
B	7.081	321.85	0.00	17.50	56.65	55.923
F	12.613	575.55	74.85	33.81	100.90	62.249
$F \cap N_{\geq 25ktCO_2}$	12.603	575.07	74.80	33.79	100.82	62.247
$N_{\geq 25ktCO_2}$	19.684	896.93	74.78	48.96	157.47	59.853
N_{All}	19.694	897.40	74.85	48.98	157.55	59.856

Note: All cost figures are in 2010 euros.

c - The cost structure of the CO2 pipeline project

We have verified the sub-additive nature of the engineering-based pipeline cost function C by numerically comparing, for any pair of coalitions in the grand coalition N_{All}, the cost to jointly serve these two coalitions with the cost to serve them separately. These exhaustive verifications confirm the presence of sub-additivity.[24] Thus, according to the literature on contestable markets, this CO_2 pipeline infrastructure is a natural monopoly (Baumol, 1977; Sharkey, 1982).

Using the linear program LP-B detailed in Appendix B, we have checked the non-emptiness of Λ the core of the cooperative cost-sharing game (N, C). We have successively considered the two alternative definitions of the grand coalition N: the case of a "blanket coverage" based on the largest coalition (i.e., $N := N_{All}$), and those of a "partial coverage" using the restricted coalition that only

[24] *As a side remark, our numerical investigations also indicate that the cost-sharing cooperative game at hand is not convex. Recall that a convex cost game is characterized by the property:* $C(S \cup \{i\}) - C(S) \geq C(T \cup \{i\}) - C(T)$ *for all* S, $T \subset N_{All}$ *and all* $i \in N_{All}$ *with* $S \subset T \subseteq N_{All} \setminus \{i\}$ *(Shapley, 1971).*

includes the largest emitters (i.e., $N := N_{\geq 25ktCO_2} \subset N_{All}$). In each case, we found that $\Lambda \neq \varnothing$.[25,26] Hence, for both N_{All} and $N_{\geq 25ktCO_2}$, there exists at least one sustainable revenue vector.

5.2 The break-even price for joint CCS adoption

Using the approach detailed in Section 4.1, we now proceed analyzing the conditions required for the construction of that infrastructure by an independent pipeline operator that is let free to decide its pricing policy. We successively consider two possible definitions for the grand coalition N: either the largest group of 14 industrial facilities N_{All}, or the restricted coalition that only includes the 12 largest emitters $N_{\geq 25ktCO_2}$. For each of these definitions, we first evaluate the threshold price $\underline{p_{CO_2}}$ defined in (3) which is the minimum value of the prevailing carbon price required for the maximum amount of total net benefits to be attained when all the emitters in the grand coalition N are connected to the CCS infrastructure. Then, we solved the linear program LP1 to obtain the break-even value for joint CCS adoption $p^*_{CO_2}$, the critical value in the charge for CO_2 emissions that is required for the adoption of CCS capabilities by all the emitters in N.

These results are reported in Table 3. In either definition of the grand coalition, we can notice that the break-even value for joint CCS adoption $p^*_{CO_2}$ is identical to the threshold price $\underline{p_{CO_2}}$. Hence, in either case, the core of the cooperative cost-sharing game Λ is large enough to allow the pipeline operator to find at least one revenue vector r such that the amount r_i charged to each emitter i does not exceed $\left(\underline{p_{CO_2}} - \chi_i - \sigma\right)Q_i$ i.e., its willingness to pay for CO_2 pipeline service when the prevailing carbon price is equal to $\underline{p_{CO_2}}$.

Table 3. The critical values in the charge for CO_2 emissions

Grand Coalition N	Condition 1: voluntary adoption of CCS by all members [(a)] $\underline{p_{CO_2}}$ €/(tCO_2 per year)	Condition 2: break-even value for joint CCS adoption [(b)] $p^*_{CO_2}$ €/(tCO_2 per year)
$N_{\geq 25ktCO_2}$	66.792	66.792
N_{All}	66.801	66.801

Note: All figures are in 2010 euros. (a) These results were obtained using the definition (3). (b) These results were obtained using the linear program LP1.

A comparison of these values with the average total cost of the CCS chain reported in Table 2 reveals important policy implications for the deployment of CCS technologies. Indeed, most of the accounting-based studies seek to evaluate the average total cost of plausible CCS chains and implicitly

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[25] *The optimal value of the objective function ε^* for the grand coalition N_{All} (respectively $N_{\geq 25ktCO_2}$) is 572 (respectively 708) in 10^3 €.*

[26] *Obviously, if the conclusion of that preliminary test were $\Lambda = \varnothing$, there is no need to pursue the analysis as the creation of a unique infrastructure aimed at serving all the emitters in the grand coalition cannot constitute a sustainable solution. Hence, there cannot exist any rationale for the creation of a club gathering all these emitters.*

assume that it gives the break-even price required to trigger investment in CCS capabilities. Yet, our finding indicates that this approach can significantly underestimate the price at which CCS will be adopted by the grand coalition at stake. For example, below a CO_2 price of 66.8 €/t, there is no way to obtain the adhesion of all emitters in N_{All} to the infrastructure project. The difference between that price level and the average total cost of the whole CCS chain is larger than 6.9 €/(tCO_2 per year) and clearly matters as it represents 110% of the average total cost of the CO_2 pipeline system.

Last but not least, a few words can be added on the absolute levels of these break-even prices. These absolute thresholds, although relatively high compared to values of the carbon prices nowadays, do not seem unattainable in the mid-run. For example, the IEA carbon price assumptions used in IEA (2011), range from \$45 to \$120 (USD 2010) per ton by 2035.[27]

5.3 Conceivable non-discriminatory pipeline tariffs structures

We now apply the framework detailed in Section 4.2 to analyze a series of plausible tariffs structures that could be imposed on the CO_2 pipeline operator. In this subsection, we first present two series of conceivable tariffs before discussing their impacts on the break-even value for joint CCS adoption.

Inspired by the natural gas analogue, the discussion focuses on two main classes of tariffs structures. First, we present the so-called 'postage stamp' pricing systems that consists of determining a uniform toll structure that is levied on all the injection points to the pipeline system (Hewicker and Kesting, 2009).[28] Yet, it compels charging the same rate irrespective of the location of the CO_2 emitters and thus neglects spatial issues. So, we also consider a second class of pricing systems that reflects a third-degree price discrimination based on location.

<u>a – 'Postage stamp' pricing systems</u>

We introduce three types of 'postage stamp' tariffs: (i) simple linear tariff, (ii) unique multi-part tariffs, and (iii) a menu of multipart tariffs. The first two of them can be examined using the concepts detailed in subsection 4.2.a. The third one is based on a second-degree price discrimination scheme and is thus examined using the approach detailed in subsection 4.2.b. For the sake of brevity, all these tariffs are summarized in Table 4.

A unique simple linear tariff

To begin with, we focus on the simplest case: a single-part unit price. We analyze two possible pricing schemes. In the first one (Tariff #PS1), the revenue charged to each emitter is obtained using the transportation price per unit volume of CO_2 transported t_Q. In the second one (Tariff #PS2), emitters are required to pay for the maximum capacity (i.e., the peak flow rate of their emissions) given a unit price $t_{\bar{q}}$ per unit of capacity.

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[27] *The 450ppm voluntarist scenario in IEA (2011) yields much higher carbon values in 2035, at 120 USD2010 per ton.*

[28] *In the European natural gas industry, the implementation of 'postage stamp' pipeline pricing systems is usually motivated by their simplicity and their perceived fairness (cf. David and Percebois (2004) for a presentation of the 'postage stamp' pricing system implemented in Denmark, Spain, Finland, and Sweden).*

A unique multipart linear tariff

As the ‘postage stamp’ tariff structures used for natural gas pipelines typically combine several elements, we also consider three two-parts tariffs. In Tariff #PS3, the revenue charged to each emitter includes a fixed charge t_f and a volume-related term based on the unit price t_Q. Tariff #PS4 is similar except that the volume-related component is replaced by a capacity-related one using the unit capacity price $t_{\bar{q}}$. Tariff #PS5 corresponds to another variation where there are no fixed charges but the pipeline operator is let free to charge a price per unit of volume transported and a price per unit of capacity.

A menu of multipart tariffs

As it is conceivable to combine a ‘postage stamp’ tariff structure with a second-degree price discrimination scheme, we also analyze the case where the pipeline operator is allowed to create a menu of two two-part tariffs. Such a menu could take into consideration the fact that there are marked differences in the transportation services required by the different users.

Table 4. 'Postage stamp' pricing systems

		Pricing scheme		Comment
Simple linear tariffs	**Tariff #PS1**	Price variables:	t_Q	a price per unit of volume
		Revenue charged:	$r_i = Q_i t_Q, \qquad \forall i \in N$.	
	Tariff #PS2	Price variables:	$t_{\bar{q}}$	a price per unit of capacity
		Revenue charged:	$r_i = \bar{q}_i t_{\bar{q}}, \qquad \forall i \in N$.	
Unique multipart linear tariffs	**Tariff #PS3**	Price variables:	t_f and t_Q	a fixed charge and a price per unit of volume
		Revenue charged:	$r_i = t_f + Q_i t_Q, \qquad \forall i \in N$.	
	Tariff #PS4	Price variables:	t_f and $t_{\bar{q}}$	a fixed charge and a price per unit of capacity
		Revenue charged:	$r_i = t_f + \bar{q}_i t_{\bar{q}}, \qquad \forall i \in N$.	
	Tariff #PS5	Price variables:	$t_{\bar{q}}$ and t_Q	a price per unit of capacity and price per unit of volume
		Revenue charged:	$r_i = \bar{q}_i t_{\bar{q}} + Q_i t_Q, \qquad \forall i \in N$.	
A menu of multipart tariffs	**Tariff #PS6**	Price variables:	t_f^l and $t_Q^l, \qquad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a fixed charge and a price per unit of volume
		Revenue charged:	$r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ t_f^l + Q_i t_Q^l \right\}, \quad \forall i \in N$.	
	Tariff #PS7	Price variables:	t_f^l and $t_{\bar{q}}^l, \qquad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a fixed charge and a price per unit of capacity
		Revenue charged:	$r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ t_f^l + \bar{q}_i t_{\bar{q}}^l \right\}, \quad \forall i \in N$.	
	Tariff #PS8	Price variables:	$t_{\bar{q}}^l$ and $t_Q^l, \qquad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a price per unit of volume, and a price per unit of capacity
		Revenue charged:	$r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ \bar{q}_i t_{\bar{q}}^l + Q_i t_Q^l \right\}, \quad \forall i \in N$.	

b – Location-specific pricing systems

Location can be used as an objective attribute to implement a third-degree price discrimination. So, we now assume that the pipeline operator is allowed to charge possibly different tariffs depending on the location of each emitters.

Compared to the non-discriminatory cases above, one can expect that a third degree price discrimination provides the pipeline operator with an enlarged feasible set for its pricing policy. To what extent can this relaxation facilitate CCS adoption? To gain insight on that issue, one may compare the solutions obtained with each of the 'postage stamp' tariff structures above and those obtained with their location-specific analogue denoted Tariff #LS1 to Tariff #LS8 (cf. Table 5). For the sake of clarity, the location-dependent tariff parameters are superscripted with B (respectively F) for Belgian (respectively French) emitters.

Table 5. Location-specific pricing systems

		Pricing scheme: Price variables	Pricing scheme: Revenue charged	Comment
Simple linear tariffs	**Tariff #LS1**	$\left(t_Q^B, t_Q^F\right)$	$r_i = Q_i t_Q^B, \quad \forall i \in B,$ $r_i = Q_i t_Q^F, \quad \forall i \in F.$	a price per unit of volume
	Tariff #LS2	$\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$	$r_i = \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B,$ $r_i = \bar{q}_i t_{\bar{q}}^F, \quad \forall i \in F.$	a price per unit of capacity
Unique multipart linear tariffs	**Tariff #LS3**	$\left(t_f^B, t_f^F\right)$ and $\left(t_Q^B, t_Q^F\right)$	$r_i = t_f^B + Q_i t_Q^B, \quad \forall i \in B,$ $r_i = t_f^F + Q_i t_Q^F, \quad \forall i \in F.$	a fixed charge and a price per unit of volume
	Tariff #LS4	$\left(t_f^B, t_f^F\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$	$r_i = t_f^B + \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B,$ $r_i = t_f^F + \bar{q}_i t_{\bar{q}}^F, \quad \forall i \in F.$	a fixed charge and a price per unit of capacity
	Tariff #LS5	$\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$ and $\left(t_Q^B, t_Q^F\right)$	$r_i = \bar{q}_i t_{\bar{q}}^B + Q_i t_Q^B, \quad \forall i \in B,$ $r_i = \bar{q}_i t_{\bar{q}}^F + Q_i t_Q^F, \quad \forall i \in F.$	a price per unit of capacity and price per unit of volume
A menu of multipart tariffs	**Tariff #LS6**	$\left(t_f^B, t_f^{F,1}, t_f^{F,2}\right)$ and $\left(t_Q^B, t_Q^{F,1}, t_Q^{F,2}\right)$	$r_i = t_f^B + Q_i t_Q^B, \quad \forall i \in B,^*$ $r_i = \mathrm{Min}_{l\in\{1,2\}} \left\{t_f^{F,l} + Q_i t_Q^{F,l}\right\}, \quad \forall i \in F.$	a single two-parts tariff for Belgian emitters and a menu of two two-parts tariffs based on a fixed charge and a price per unit of volume for French emitters
	Tariff #LS7*	$\left(t_f^B, t_f^{F,1}, t_f^{F,2}\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^{F,1}, t_{\bar{q}}^{F,2}\right)$	$r_i = t_f^B + \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B,^*$ $r_i = \mathrm{Min}_{l\in\{1,2\}} \left\{t_f^{F,l} + \bar{q}_i t_{\bar{q}}^{F,l}\right\}, \quad \forall i \in F.$	a single two-parts tariff for Belgian emitters and a menu of two two-parts tariffs based on a fixed charge and a price per unit of capacity for French emitters
	Tariff #LS8*	$\left(t_{\bar{q}}^B, t_{\bar{q}}^{F,1}, t_{\bar{q}}^{F,2}\right)$ and $\left(t_Q^B, t_Q^{F,1}, t_Q^{F,2}\right)$	$r_i = \bar{q}_i t_{\bar{q}}^B + Q_i t_Q^B, \quad \forall i \in B,^*$ $r_i = \mathrm{Min}_{l\in\{1,2\}} \left\{\bar{q}_i t_{\bar{q}}^l + Q_i t_Q^l\right\}, \quad \forall i \in F.$	a single two-parts tariff for Belgian emitters and a menu of two two-parts tariffs based on a price per unit of volume, and a price per unit of capacity for French emitters

Note: * As (i) there are only two emitters located in Belgium and (ii) there are no seasonal variations in their emission patterns, it is not possible to determine a unique menu of two two-part tariffs for Belgian emitters. Thus, we assumed that a unique tariff is implemented in Belgium.

c – Results

We have successively tested these tariffs structures using the programs LP2 or MILP-C. In Table 6, we report the break-even value for joint CCS adoption obtained when solving these programs for the grand coalition of emitters N_{All} (case I) and for the restricted coalition $N_{\geq 25ktCO_2}$ that solely includes the largest emitters (case II). Several observations can be made from these results.

Table 6. The break-even value for joint CCS adoption for two definitions of the grand coalition

		'Postage stamp' pricing systems		Location-specific pricing systems	
		Pricing scheme	$p^{**}_{CO_2}$ (€/(tCO_2 per year)	Pricing scheme	$p^{**}_{CO_2}$ (€/(tCO_2 per year)
Case I the grand coalition N_{All}	Simple linear tariffs (a)	Tariff #PS1	∅	Tariff #LS1	∅
		Tariff #PS2	∅	Tariff #LS2	∅
	Unique multipart linear tariffs (a)	Tariff #PS3	∅	Tariff #LS3	∅
		Tariff #PS4	∅	Tariff #LS4	78.042
		Tariff #PS5	∅	Tariff #LS5	∅
	A menu of multipart tariffs (b)	Tariff #PS6	∅	Tariff #LS6	∅
		Tariff #PS7	∅	Tariff #LS7	78.042
		Tariff #PS8	∅	Tariff #LS8	∅
Case II the restricted coalition $N_{\geq 25ktCO_2}$	Simple linear tariffs (a)	Tariff #PS1	∅	Tariff #LS1	∅
		Tariff #PS2	∅	Tariff #LS2	67.436
	Unique multipart linear tariffs (a)	Tariff #PS3	∅	Tariff #LS3	∅
		Tariff #PS4	∅	Tariff #LS4	67.436
		Tariff #PS5	∅	Tariff #LS5	67.436
	A menu of multipart tariffs (b)	Tariff #PS6	∅	Tariff #LS6	∅
		Tariff #PS7	∅	Tariff #LS7	67.436
		Tariff #PS8	∅	Tariff #LS8	67.436

Note: (a) These results were obtained using the linear program LP2. (b) These results were obtained using the mixed integer linear program MILP-C detailed in Appendix C. ∅ is used to indicate an empty solution set. All figures are in 2010 euros.

First, spatial issues matter! Indeed, the implementation of a 'postage stamp' pricing system that neglects the emitters' difference in locations systematically impedes the construction of the proposed CO_2 transportation infrastructure. Our investigations confirm that such a tariff system would clearly penalize the Belgian emitters because they would be charged an amount larger than the stand-alone cost to construct a dedicated pipeline system gauged for these two emitters.

Second, designing a non-discriminatory pipeline tariff compatible with the widest possible adoption of CCS technologies is a difficult task! According to the results obtained for the grand coalition N_{All} (Case I), very few tariffs (only the multipart tariffs #LS4 and #LS7 based on a fixed charge and a capacity-based component) verify the conditions for a non-empty feasible set for the programs LP2 or MILP-C. This finding suggests that imposing a poorly-defined, non-discriminatory, pricing scheme (e.g., a volume-based tariff) is likely to hamper the construction of a CCS chain capable to capture the emissions of all these 14 plants. In contrast, the results obtained with the coalition

$N_{\geq 25ktCO_2}$ (Case II) indicate that achieving a "partial coverage" is less restrictive (as six tariffs out of eight are compatible with a non-empty feasible set for the programs LP2 or MILP-C). Given the limited environmental impact of the two smallest emitters, this finding questions the relevance of a "blanket coverage" target for the promoters of that CO_2 pipeline project.

Third, the obligation to use a non-discriminatory pricing scheme for the pipeline component is non-neutral on the break-even value for joint CCS adoption. No matter what definition is adopted for the grand coalition (either N_{All} or $N_{\geq 25ktCO_2}$), the break-even value for joint CCS adoption $p^{**}_{CO_2}$ reported in Table 6 are systematically larger than the corresponding value $p^{*}_{CO_2}$ obtained when the pipeline operator is allowed to charge discriminatory tariffs (cf. the values reported in Table 3). The difference $\left(p^{**}_{CO_2} - p^{*}_{CO_2}\right)$ is directly attributable to the use of a given non-discriminatory tariff and can be used to provide guidance in the selection of a pricing scheme. In the worst case (the multipart capacity-based tariff #LS4 with the largest possible coalition N_{All}), that difference attains 11.24 €/(tCO_2 per year), that is 1.8 times the average cost of the pipeline system in that configuration.

Lastly, it is interesting to compare the break-even value for joint CCS adoption $p^{**}_{CO_2}$ obtained when using a menu of two-part tariffs to those obtained when a unique two-part tariff is implemented (e.g., Tariff #LS4 vs. Tariff #LS7). No matter what definition is adopted for the grand coalition N, the obtained break-even values $p^{**}_{CO_2}$ are systematically identical. This indicates that imposing such a second-degree price discrimination schemes does not at all ease the adoption of the CCS technology. We are going to argue that this seemingly surprising result is not that surprising! Indeed, the analysis of the solutions of the mathematical programs MILP-C confirms that the two optimum tariffs are identical. Intuitively, this outcome suggests that the pipeline operator cannot offer some volume or capacity related rebates to "large" users without charging extra revenue to the "small" users (recall that the pipeline operator has to recover its costs). Interestingly, these "small" users are typically those with the lowest willingness to pay per (either volume or capacity) unit of CO_2 pipeline service and are thus the ones with a binding participation constraint.

5.4 National vs. supranational regulation for this CO_2 pipeline infrastructure

The infrastructure at hand has a transnational nature, which raises a policy issue: "Should the regulation of that infrastructure be organized at the national level or at the EU-level?"

To address this question, we follow the analysis detailed in subsection 4.3 and check whether or not the extra-requirements imposed by national regulators have an influence on the break-even value for joint CCS adoption. So, we now suppose that there exists two local (i.e., national) regulators and that each of them has an exclusive competence to regulate the pricing structure used by the pipeline operator in its jurisdiction. In the first row of Table 7, we report the break-even values $p^{*,\text{National}}_{CO_2}$ obtained when solving the linear program LP5 with each of the two alternative definitions of the grand coalition N_{All} and $N_{\geq 25ktCO_2}$.

We have also considered the case of a pipeline operator that is compelled to use a predetermined tariff structure in each jurisdiction. In the second row of Table 7, we report $p_{CO_2}^{**,\text{National}}$ the break-even values for joint CCS adoption assuming that the two regulators instruct the pipeline operator to use a multipart linear tariff similar to #LS4 (i.e. a two-part tariff based on a fixed term and a capacity component).[29]

Table 7. The break-even value for joint CCS adoption measured in €/(tCO_2 per year) when two national regulatory agencies are monitoring the pipeline pricing schemes

Pricing scheme	Grand Coalition N	
	N_{All}	$N_{\geq 25ktCO_2}$
Break-even value for joint CCS adoption in case of discriminatory prices: $p_{CO_2}^{*,\text{National}}$ (a)	76.051	66.792
Break-even value for joint CCS adoption in case of multipart tariffs: $p_{CO_2}^{**,\text{National}}$ (b) Price variables: $\left(f^B, f^F\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$ Revenue charged: $r_i = f^B + \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B,$ $r_i = \left(f^B + \bar{q}_i t_{\bar{q}}^B\right) + \left(f^F + \bar{q}_i t_{\bar{q}}^F\right), \ \forall i \in F.$	78.863	67.572

Note: (a) These results were obtained using the linear program LP5. (b) These results were obtained using a modified version of the linear program LP5 where the pipeline operator uses the described two-part tariff. All carbon price figures are in 2010 euros.

From these results, several facts stand out. First, we focus on $p_{CO_2}^{*,\text{National}}$ the break-even value for joint CCS adoption obtained when the pipeline operator can freely charge discriminatory tariffs. The difference between $p_{CO_2}^{*,\text{National}}$ and $p_{CO_2}^{*}$ the break-even value for joint CCS adoption obtained in case of a unique transnational regulator provides a direct assessment of the impact of a national-based regulatory organization on the adoption of CCS. Compared to the values $p_{CO_2}^{*}$ reported in Table 3, these results indicate that the geographical scope of the regulation has zero impact on CCS adoption for a pipeline project aimed at gathering the emissions from the restricted coalition $N := N_{\geq 25ktCO_2}$. In contrast, the break-even value of a pipeline project tailored to capture the emissions from the largest coalition $N := N_{All}$ is substantially increased in case of two national regulators. For a CCS project developer, this finding suggests that CCS adoption is harder to achieve in a project aimed at connecting all the possible emitters to a common infrastructure than in an alternative project solely focused on the largest emitters.

Second, we focus on the situation where the two regulators impose the use of non-discriminatory tariffs and examine the break-even values $p_{CO_2}^{**,\text{National}}$. A comparison of the results reported in Table 7 with those in Table 6 (cf. Tariff LS#4) indicates that a collection of national regulations systematically imposes a net increase in the break-even value for joint CCS adoption compared to a regulation

[29] *Remark that the distinction between 'postage stamp' tariffs and location-specific ones is pointless here because this national-based institutional organization allows prices to differ in each country. Thus, the pipeline operator is implicitly allowed to charge location-specific prices.*

organized at the EU-level. Though, that net increase remains modest ($p^{**,\text{National}}_{CO_2} - p^{**}_{CO_2}$ =0.82 €/tCO$_2$ in case of a “blanket coverage”, and 0.14 €/tCO$_2$ in case of a partial one). These modest increases suggest that, for a feasible location-specific pricing structure, implementing a national-based regulation may not play a major role compared to the choice of the grand coalition of emitters. [30]

Third, a comparison of these results with those obtained in the preceding subsection confirms that, *ceteris paribus*, the break-even values for joint CCS adoption computed for the pipeline project serving the partial coalition $N_{\geq 25ktCO_2}$ are systematically lower than those obtained in case of a project aimed at serving all the emitters N_{All}. The magnitude of the extra economies of scale provided by the inclusion of the two smallest emitters that are in N_{All} but not in $N_{\geq 25ktCO_2}$ are not sufficient to compensate the benefit-sharing issues generated by the inclusion of the two smallest emitters. Though modest in case of a transnational regulator that does not impose the use of a particular pricing structure (the difference in $p^{*}_{CO_2}$ is less than +0.01 €/tCO$_2$ in Table 3), the difference in break-even values can become substantial under certain regulatory arrangements (e.g. the difference in $p^{**,\text{National}}_{CO_2}$ reported in Table 7 is close to 11.3 €/tCO$_2$ a magnitude larger than the average total cost of the CO$_2$ pipeline). This finding has important implications for the deployment of the CCS technology. Given the existing regulatory and tariffs uncertainties observed in the CO$_2$ pipeline industry (Herzog, 2011), a pipeline project developer that cannot precisely anticipate the level of the future carbon prices may rationally prefer to design its infrastructure so as to solely serve the largest emitters (i.e. those in the smaller CCS club $N_{\geq 25ktCO_2}$) because the associated break-even value would be more robust to unexpected changes in the regulatory organization.

6. Concluding remarks

The question of how to design an appropriate regulatory framework for CO$_2$ pipeline systems is one of the key design issues that regulators and policy makers across the world will have to address to clarify the conditions for the deployment of a large-scale CCS industry. In this paper, we analyze the role played by pipeline-related regulations on the emitter’s decision to adopt the CCS technology and thus share the common CO$_2$ pipeline cost.

This paper specifies an adapted modeling framework that has its roots in the cooperative game theoretic treatment of clubs. Our approach explicitly takes into consideration the main features of the CCS industry: the heterogeneity of the likely club members (caused by differences in the emitter-specific capture costs, in their location, in the size of their annual emissions and in their infra-annual patterns of emissions) and an engineering-based model of the long-run cost to build and operate a CO$_2$ pipeline. We believe that this model-based approach is able to provide valuable guidance for the

[30] *Following a remark raised by a referee, we can notice that an institutional design based on two national regulators allows the pipeline operator to charge different prices in the two countries. Hence, the pipeline operator is ‘de facto’ allowed to charge location-specific prices in the two countries. That’s why, the comparisons conducted in this subsection are restricted to the location-specific tariffs discussed in Subsection 5.3.*

professionals and scholars interested in the institutional design of the regulation that will be applied to the CO_2 pipeline industry. As this paper has a practical ambition, a great attention has been paid to address the practical issues faced in the implementation of the proposed methodology.

This club-theoretic perspective allows to clarify the conditions required for CCS adoption. In the paper, two cases are successively examined: (i) the case of a group of emitters that can own and share a common pipeline system, and thus form a "vertically integrated" club; and (ii) the case of an infrastructure owned by an independent pipeline operator. As the conditions obtained in these two cases are equivalent, the problem faced by the promoter of a CO_2 pipeline project amounts to the creation of a stable club of emitters.

Using these conditions, the paper provides a formal definition of the break-even value for joint CCS adoption which is the threshold carbon price required to obtain the creation of a club gathering all the emitters. From an applied economics perspective, we show that this value can be computed using a linear programming problem and that this approach can be adapted to take into consideration a variety of regulatory constraints that may be imposed on an independent pipeline operator. For example, we consider the case of a pipeline operator compelled to use an exogenously-predetermined, non-discriminatory tariff structure and model the interactions between the proposed tariff structure and the break-even value for joint CCS adoption. In another example, we consider the case of a transnational pipeline infrastructure supervised by two national regulators and adapt our framework to verify whether this institutional organization modifies the break-even value for joint CCS adoption.

We then consider an application to the case of a Northwestern European CO_2 pipeline project. The main findings can be summarized as follows. First, the break-even value for joint CCS adoption is significantly larger than the average cost of the entire CCS chain, a cost concept that is often misleadingly interpreted as the CO_2 abatement cost of the CCS technology. Second, we have analyzed a series of non-discriminatory pricing schemes that may conceivably be imposed on the pipeline operator. Interestingly, our findings confirm that the design of these pipeline access charges is non-neutral on the adoption of the CCS technology. For example, the results reveal that the emitter's location must be taken into consideration in the design of a pricing scheme and that a poorly designed pricing scheme can either: significantly raise the break-even value for joint CCS adoption, or even impede the construction of a single pipeline infrastructure. Third, we have compared the outcomes obtained in case of a pricing regulation organized at the EU-level to those obtained with a collection of national regulations. Our findings indicate that the scope of the regulation does not significantly impact the adoption of the CCS technology. Lastly, these results reveal that CCS adoption is always easier to achieve when considering a restricted club of CCS adopters that does not include the two smallest emitters.

Although our discussion is centered on this specific project, it should be clear that the methodology detailed hereafter could apply to other CO_2 pipeline projects as well. As in any modeling effort, we made some simplifying assumptions. The main one is related to the static nature of the approach used to treat the coordination problem of joining a common pipeline network. The design of a dynamic framework where emitters would be allowed to join/exit the agreement depending on the evolution of variable like the carbon price constitutes an attractive agenda for future research.

References

André, J., Auray, S., Brac, J., De Wolf, D., Maisonnier, G., Ould-Sidi, M.-M., Simonnet, A., (2013). Design and Dimensioning of Hydrogen Transmission Pipeline Networks. *European Journal of Operational Research*, 229(1), 239–251.

André, J., Bonnans J.F., (2011). Optimal structure of gas transmission trunklines. *Optimization and Engineering*, 12(1-2), 175–198.

André, J., Bonnans, J.F., Cornibert, L., (2009). Optimization of Capacity Expansion Planning for Gas Transportation Networks. *European Journal of Operational Research*, 197(3), 1019–1027.

Aumann, R., (1989). Game Theory. In Eatwell, J., Milgate, M., and P. Newman (Eds), *The New Palgrave*, New York: Norton, pp. 8-9.

Hewicker, C., Kesting, S., (2009). The New Entry-exit Model in the EU and Its Consequences for Gas. Supply Companies. In Bausch, A., and B. Schwenker (Eds), *Handbook Utility Management*. Berlin: Springer.

Babonneau, F., Nesterov, Y., Vial, J.-Ph., (2012). Design and Operations of Gas Transmission Networks. *Operations Research*, 60, 34–47.

Baker, E., Solak, S., (2011). Climate Change and Optimal Energy Technology R&D Policy. *European Journal of Operational Research*, 213(2), 442–454.

Bakken, B.H., von Streng Velken, I., (2008). Linear Models for Optimization of Infrastructure for CO_2 Capture and Storage. *IEEE Transactions on Energy Conversion*, 23(3), 824–833.

Bard, J.F., (1998). *Practical bilevel optimization. Nonconvex optimization and its applications (Vol. 30)*. Dordrecht: Kluwer Academic.

Baumol, W.J., (1977). On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry. *The American Economic Review*, 67(5), 809–822.

Baumol, W.J., Bailey, E.E., Willig, R.D., (1977). Weak Invisible Hand Theorems on the Sustainability of Multiproduct Natural Monopoly. *The American Economic Review*, 67(3), 350–365.

Berg, S., Tschirhart, J., (1988). *Natural Monopoly Regulation: Principles and Practices*. Cambridge University Press.

Betz, R., Sanderson, T., Ancev, T., (2010). In or out: efficient inclusion of installations in an emissions trading scheme? *Journal of Regulatory Economics*, 37(2), 162–179.

Bhaskaran, S., Salzborn, F., (1979). Optimal design of gas pipeline networks. *The Journal of the Operational Research Society*, 30(12), 1047–1060.

Bracken, J, McGill, J.T., (1973). Mathematical Programs with Optimization Problems in the Constraints. *Operations Research*, 21(1), 37–44.

Brimberg, J., Hansen, P., Lin, K.-W., Mladenovic, N., Breton, M., (2003). An Oil Pipeline Design Problem. *Operations Research*, 51(2), 228–239.

Buchanan, J.M., (1965). An Economic Theory of Clubs. *Economica*, 32(125), 1–14.

Chenery, H.B., (1949). Engineering production functions. *The Quarterly Journal of Economics*, 63(4), 507–531.

Colson, B., Marcotte, P., Savard, G., (2007) An overview of bilevel optimization. *Annals of Operations Research*, 153(1), 235–256.

David, L., Percebois, J., (2004). Access Pricing on Gas Networks and Capacity Release Markets: Lessons from North American and European Experiences. *Energy Studies Review*, 12(2), 125–142.

De Wolf, D., Smeers, Y., (1996) Optimal dimensioning of pipe networks with application to gas transmission network. *Operations Research*, 44(4), 596–608.

Eckhause, J.M., (2011). *Methods for Employing Real Options Models to Mitigate Risk In R&D Funding Decisions.* PhD Dissertation. College Park (MD):University of Maryland.

Eckhause, J.M., Herold, J., (2014). Using real options to determine optimal funding strategies for CO2 capture, transport and storage projects in the European Union. *Energy Policy*, 66, 115–134.

Faulhaber, G.R., (1975). Cross-Subsidization: Pricing in Public Enterprises. *The American Economic Review*, 65(5), 966–977.

Flannery, B.P., (2011). Comment. *Energy Economics*, 33(4), 605–607.

Fortuny-Amat, J., McCarl, B., (1981). A representation and economic interpretation of a two-level programming problem. *The Journal of the Operational Research Society*, 32(9), 783–792.

Gerlagh, R., van der Zwaan, B.C.C., (2006). Options and instruments for a deep cut in CO_2 emissions: carbon capture or renewables, taxes or subsidies? *The Energy Journal*, 27(3), 25–48.

Herzog, H.J., (2011). Scaling up carbon dioxide capture and storage: From megatons to gigatons. *Energy Economics*, 33(4), 597–604.

Hewicker, C., Kesting, S., (2009). The New Entry-exit Model in the EU and Its Consequences for Gas. Supply Companies. In Bausch, A., and B. Schwenker (Eds), *Handbook Utility Management*. Berlin: Springer.

Heydari, S., Ovenden, N., Siddiqui, A. (2012). Real Options Analysis of Investment in Carbon Capture and Sequestration Technology. *Computational Management Science*, 9(1), 109–138.

Kemp, A.G., Kasim, A.S., (2008). A Least-Cost Optimisation Model of CO_2 Capture Applied to Major UK Power Plants Within the EU-ETS Framework. *Energy Journal*, 29(Special Issue 1), 99–134.

Kemp, A.G., Kasim, A.S., (2010). A Futuristic Least-cost Optimisation Model of CO_2 Transportation and Storage in the UK/UK Continental Shelf. *Energy Policy*, 38(7), 3652–3667,

Klokk, Ø., Schreiner, P.F., Pagès-Bernaus, A., Tomasgard, A., (2010). Optimizing a CO_2 value chain for the Norwegian Continental Shelf. *Energy Policy*, 38(11), 6604–6614.

Kuby, M.J., Bielicki, J.M., Middleton, R.S., (2011). Optimal Spatial Deployment of CO_2 Capture and Storage Given a Price on Carbon. *International Regional Science Review*, 34(3), 285–305.

International Energy Agency (IEA). (2011). World Energy Outlook. Paris: OECD/IEA.

Intergovernmental Panel on Climate Change (IPCC). (2005). Carbon Dioxide Capture and Storage. IPCC Special Report. Geneva: IPCC.

İşlegen, Ö, Reichelstein, S., (2011). Carbon Capture by Fossil Fuel Power Plants: An Economic Analysis. *Management Science*, 57(1), 21–39.

Littlechild, S.C., (1975). Common Costs, Fixed Charges, Clubs and Games. *The Review of Economic Studies*, 42(1), 117–124.

Lohwasser, R., Madlener, R., (2012). Economics of CCS for coal plants: Impact of investment costs and efficiency on market diffusion in Europe. *Energy Economics*, 34(3), 850-863.

Massachusetts Institute of Technology (MIT). (2007). The future of coal. Accessed May 13, 2014, http://web.mit.edu/coal.

Massol, O., (2011). A Cost Function for the Natural Gas Transmission Industry: Further Considerations. *The Engineering Economist*, 56(2), 95–122.

McCoy, S.T., (2009). *The Economics of CO_2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs*. PhD Dissertation. Pittsburgh (PA): Carnegie Mellon University.

McCoy, S.T., Rubin, E.S., (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), 219–229.

McKinsey (2008). Carbon capture and storage: Assessing the economics. McKinsey Climate Change Initiative. September 22, 2008.

Mendelevitch, R., (2014). The role of CO2-EOR for the development of a CCTS infrastructure in the North Sea Region: A techno-economic model and applications. *International Journal of Greenhouse Gas Control*, 20, 132–159.

Mendelevitch, R., Herold, J., Oei, P-Y., Tissen, A., (2010). *CO_2 Highways for Europe: Modelling a Carbon Capture, Transport and Storage Infrastructure for Europe*. CEPS Working Document No. 340. Centre for European Policy Studies, Brussels, Belgium.

Middleton, R.S., Bielicki, J.M., (2009). A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy*, 37(3), 1052–1060.

Pacala, S., Socolow, R., (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, 305(5686), 1095–9203.

Rothfarb, B., Frank, H., Rosenbaum, D.M., Steiglitz, K., Kleitman, D.J. (1970). Optimal design of offshore natural-gas pipeline systems. *Operations Research*, 18(6), 992–1020.

Sandler, T., Tschirhart, J.T., (1980). The Economic Theory of Clubs: An Evaluative Survey. *Journal of Economic Literature*, 18(4), 1481–1521.

Shapley, L.S., (1971). Cores of Convex Games. *International Journal of Game Theory*, 1, 11–26.

Sharkey, W.W., (1982). Suggestions for a Game-Theoretic Approach to Public Utility Pricing and Cost Allocation. *The Bell Journal of Economics*, 13(1), 57–68.

Spiecker, S., Eickholt, V., Weber, C., (2014). The impact of carbon capture and storage on a decarbonized German power market. *Energy Economics*, 43, 166–177.

Young, H.P., (1985). Cost Allocation: Methods, Principles, Application. Amsterdam: North-Holland.

Appendix A

Proof of Proposition 1

Assume that there exists: (i) a carbon price level p_{CO_2} *with* $p_{CO_2} < \underline{p_{CO_2}}$*, and (ii) a revenue vector* r *such that* $r \in \Lambda \cap IP_{p_{CO_2}}$*. For any emitter* i*, we let* y_i *denote the emitter's individual net benefit, i.e.* $y_i := \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i$.

As $r \in \Lambda$*, it verifies:* $\sum_{i \in S} r_i \le C(S)$ *for any* $S \subset N$ *and thus the inequality* $\sum_{i \in S} y_i \ge \sum_{i \in S}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(S)$ *holds for any* $S \subset N$*. As* $r \in IP_{p_{CO_2}}$*, we have* $y_i \ge 0$ *for any emitter* i *and thus* $\sum_{i \in N} y_i \ge \sum_{i \in S} y_i$ *for any* $S \subset N$*. As* $r \in \Lambda$*, the equality* $\sum_{i \in N} r_i = C(N)$ *is verified. Hence, the sum of the emitters' individual net benefits is:* $\sum_{i \in N} y_i = \sum_{i \in N}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(N)$*. So, the following condition must hold:*

$$\sum_{i \in N}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(N) \ge \sum_{i \in S}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(S), \qquad \forall S \subset N, \tag{A.1}$$

Following the discussion in Section 3.2., a carbon price level p_{CO_2} *with* $p_{CO_2} \ge \underline{p_{CO_2}}$ *is a necessary and sufficient condition for that condition. Hence, in case of a carbon price* p_{CO_2} *with* $p_{CO_2} < \underline{p_{CO_2}}$*, the set* $\Lambda \cap IP_{p_{CO_2}}$ *is empty.* *Q.E.D.*

Proof of Proposition 2 (Sharkey 1982)

For any allocation $y \in \Gamma_{p_{CO_2}}$, *we evaluate the associated revenue vector* $r_{p_{CO_2}}(y)$ *and let* $r_i := \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - y_i$ *be its* i^{th} *component. If* $y \in \Gamma_{p_{CO_2}}$, *then* $\sum_{i \in S}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i\right] \geq v\left(S, p_{CO_2}\right)$ *for any* $S \subset N$. *Using* (1) *and rearranging, we obtain* $\sum_{i \in S} r_i \leq C(S)$ *for any* $S \subset N$. *Besides, as* $p_{CO_2} \geq \underline{p_{CO_2}}$, *the value of the largest coalition verifies* $v\left(N, p_{CO_2}\right) = \sum_{i \in N}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(N)$. *Hence, for any* $y \in \Gamma_{p_{CO_2}}$, *we have both* $\sum_{i \in N} r_i = C(N)$ *and* $\sum_{i \in S} r_i \leq C(S)$ *for any* $S \subset N$. *So,* $r_{p_{CO_2}}(y) \in \Lambda$. *Q.E.D.*

Proof of Proposition 3

The proof requires two independent steps.

<u>STEP #1:</u> Assume a given $y \in \Gamma_{p_{CO_2}}$. *The associated revenue vector is* $r_{p_{CO_2}}(y)$. *By construction, if a pipeline operator charges* $r(y)$, *every emitter* i *obtains a net benefit equal to* y_i. *As* $y \in \Gamma_{p_{CO_2}}$, *we have* $y_i \geq v\left(\{i\}, p_{CO_2}\right)$ *for every emitter* i. *Since* $v\left(S, p_{CO_2}\right) \geq 0$ *for all* S, *we obtain* $y_i \geq 0$ *which proves that* $r_{p_{CO_2}}(y) \in IP_{p_{CO_2}}$. *Using Proposition 2, we know also that* $r_{p_{CO_2}}(y) \in \Lambda$ *and thus* $r_{p_{CO_2}}(y) \in \Lambda \cap IP_{p_{CO_2}}$.

<u>STEP #2:</u> Assume a given $r \in \Lambda \cap IP_{p_{CO_2}}$. *The vector of the emitters' individual net benefits associated with* r *is* $y_{p_{CO_2}}(r)$ *where the* i^{th} *component is* $y_i := \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - r_i$. *As* $r \in \Lambda$, *it verifies* $\sum_{i \in N} r_i = C(N)$. *So, the sum of the components of* $y_{p_{CO_2}}(r)$ *is:* $\sum_{i \in N} y_i = \sum_{i \in N}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(N)$. *As the prevailing carbon price* p_{CO_2} *is assumed to verify the condition* $p_{CO_2} \geq \underline{p_{CO_2}}$, *we have* $\sum_{i \in N} y_i = v\left(N, p_{CO_2}\right)$.

As $r \in IP_{p_{CO_2}}$, *the associated individual net benefits are non-negative and thus the inequality* $\sum_{i \in S} y_i \geq \sum_{i \in R} y_i$ *holds for any coalition* $S \subset N$ *and any subcoalition* $R \subseteq S$. *As* $r \in \Lambda$, *it verifies* $\sum_{i \in R} r_i \leq C(R)$ *for any subcoalition* $R \subset N$ *Hence,* $\sum_{i \in R} y_i \geq \sum_{i \in R}\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - C(R)$ *for any subcoalition* $R \subset N$. *As a result, the condition* $\sum_{i \in S} y_i \geq \sum_{i \in R}\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - C(R)$ *is verified for any coalition* $S \subset N$ *and any subcoalition* $R \subseteq S$. *So, the condition* $\sum_{i \in S} y_i \geq v\left(S, p_{CO_2}\right)$, *where* $v\left(S, p_{CO_2}\right)$ *is defined as in (1), is verified for any coalition* $S \subset N$. *To summarize, the vector* $y_{p_{CO_2}}(r)$ *verifies both (4) and (5). So,* $y_{p_{CO_2}}(r) \in \Gamma_{p_{CO_2}}$. *Q.E.D.*

Proof of Proposition 4

To begin with, assume that $\left(r^*, p^*_{CO_2}\right)$ *is a solution to LP1. As* r^* *jointly verifies the constraints (15) and (16), we have* $r^* \in \Lambda$ *which proves that* $\Lambda \neq \varnothing$.

Now, we assume that $\Lambda \neq \varnothing$ *and have to show that the feasible set of LP1 is non-empty. As* $\Lambda \neq \varnothing$*, there exists at least one revenue vector* $\hat{r}$ *such that* $\hat{r} \in \Lambda$. *By definition, this vector verifies the constraints (15) and (16). As* $\hat{r} \in \Lambda$*, the condition (8) is verified. So, the inequalities* $\hat{r}_i \leq C(\{i\})$ *hold for all the emitters* $i \in N$. *These inequalities can be used to construct the following lower bounds on the emitters' individual net benefits:* $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - \hat{r}_i \geq \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - C(\{i\})$ *for any* i. *We now consider* p_{CO_2} *the carbon price level defined by* $p_{CO_2} := \mathrm{Max}_{i \in N}\left\{\chi_i + C(\{i\})/Q_i\right\} + \sigma$. *The vector* $\left(p_{CO_2}, \hat{r}\right)$ *is such that* $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i - \hat{r}_i \geq 0$ *for any* $i \in N$. *So, the vector* $\left(p_{CO_2}, \hat{r}\right)$ *verifies the conditions (15), (16) and (17) which proves that there is a non-empty feasible set for the program LP1.*

Now, we consider a vector $\left(p_{CO_2}, \tilde{r}\right)$ *in LP1's feasible set. As it verifies (17), the following condition holds:*

$$\sum_{i \in S}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] \geq \sum_{i \in S}\tilde{r}_i, \qquad \forall S \subset N. \tag{A.2}$$

Remark that, using (15), the following equality holds: $\sum_{i \in S}\tilde{r}_i = \sum_{i \in N}\tilde{r}_i - \sum_{i \in N \setminus S}\tilde{r}_i$. *Using (16), the following condition holds:*

$$\sum_{i \in S}\tilde{r}_i \geq C(N) - C(N \setminus S), \qquad \forall S \subset N. \tag{A.3}$$

As the conditions (A.2) and (A.3) are jointly verified, the condition (2) holds which suggests (cf. subsection 3.2) that the carbon price p_{CO_2} *verifies* $p_{CO_2} \geq \underline{p_{CO_2}}$ *where* $\underline{p_{CO_2}}$ *is the threshold defined in (3). Remark that this inequality does not depend on the feasible vector* $\left(p_{CO_2}, \tilde{r}\right)$. *Hence, the objective function (14) is bounded from below. This finding together with the non-emptiness of the feasible set indicates that there exists at least one optimal solution* $\left(r^*, p^*_{CO_2}\right)$ *to the program LP1 (cf., the Fundamental Theorem of Linear Programming). By definition,* $p^*_{CO_2}$ *is the optimal value of the objective function of linear program and is thus unique. Moreover, we have shown that the optimal value* $p^*_{CO_2}$ *is bounded from below and verifies:* $p^*_{CO_2} \geq \underline{p_{CO_2}}$. *Q.E.D.*

Appendix B

This appendix illustrates how a linear programming approach can be used to examine whether the conditions for a non-empty core Λ of the cooperative cost game are verified.

LP-B: $\quad \mathrm{Max}_{r,\varepsilon} \quad \varepsilon$ (B.1)

s.t. $\quad \sum_{i \in N} r_i = C(N),$ (B.2)

$$\sum_{i\in S} r_i + \varepsilon \le C(S), \qquad \forall S \subset N \setminus \{\varnothing, N\},$$

(B.3)

$$\varepsilon \ge 0. \tag{B.4}$$

The gain derived from cooperation by any non-trivial coalitions $S \subset N \ (S \ne \varnothing, N)$ with respect to a cost allocation r is measured by the excess: $\left[C(S) - \sum_{i\in S} r_i\right]$. In LP-B, the non-negative variable ε can be interpreted as the maximum possible value of the lowest excess obtained by a non-trivial coalition. A non-empty feasible set for the program LP-B is a necessary and sufficient condition for the existence of a non-empty core Λ.

Appendix C

In this appendix, we detail a computationally tractable reformulation of the two-level optimization problem BLP4. To begin with, we focus on the lower-level problem $\text{LP3}_i(t)$ for a given emitter i. Denoting $\alpha^i = \left(\alpha_1^i, ..., \alpha_m^i\right)'$ the vector of dual variables associated with the constraints (23), the KKT conditions for optimality correspond to the following linear complementarity constraints:

$$1 - \sum_{l=1}^{m} \alpha_l^i = 0 \tag{C.1}$$

$$r_i - \sum_{j=1}^{k} \phi_j^i t_j^l \le 0, \qquad \alpha_l^i \ge 0, \qquad \alpha_l^i \left(r_i - \sum_{j=1}^{k} \phi_j^i t_j^l \right) = 0, \qquad \forall l \in \{1, ..., m\}. \tag{C.2}$$

Following Fortuny-Amat and McCarl (1981), the complementarity conditions (C.2) can be replaced by integer restrictions in the form of disjunctive constraints. We introduce: $\delta^i = \left(\delta_1^i, ..., \delta_m^i\right)'$ a vector of binary variables such that a value $\delta_l^i = 1$ indicates that the particular tariff l (i.e. the price vector t^l) minimizes the CO_2 transportation cost of emitter i; and M a constant with a value that is large enough for the problem at hand.[31] Using these variables, the complementarity constraints (C.2) becomes:

$$-M\left(1 - \delta_l^i\right) \le r_i - \sum_{j=1}^{k} \phi_j^i t_j^l \le 0, \qquad \forall l \in \{1, ..., m\}, \tag{C.3}$$

$$M \delta_l^i \ge \alpha_l^i \ge 0, \qquad \forall l \in \{1, ..., m\}. \tag{C.4}$$

Replacing the condition (28) by the constraints (C.1), (C.3) and (C.4) transforms the two-level optimization program BLP4 into the mixed-integer linear program MILP-C:

[31] *For example, in the present case, one can rationally presume that the difference between the amount paid by an emitter for its CO_2 transportation service (and thus the revenue charged to him) and the amount that he would have paid if that emitter had chosen the worst tariffs offered by the pipeline operator will be smaller than, let say, two times the overall cost of the entire pipeline. Hence, the value* $M = 2 \times C(N)$ *looks like a possible candidate.*

$$\text{MILP-C:} \quad \min_{r,t,p_{CO_2},\alpha,\delta} \quad p_{CO_2} \tag{C.5}$$

$$\text{s.t.} \quad \sum_{i \in N} r_i = C(N), \tag{C.6}$$

$$\sum_{i \in S} r_i \leq C(S), \qquad \forall S \subset N \setminus \{\varnothing, N\}, \tag{C.7}$$

$$\left(p_{CO_2} - \chi_i - \sigma\right) Q_i - r_i \geq 0, \qquad \forall i \in N, \tag{C.9}$$

$$\sum_{l=1}^{m} \alpha_l^i = 1, \qquad \forall i \in N, \tag{C.10}$$

$$-M\left(1 - \delta_l^i\right) \leq r_i - \sum_{j=1}^{k} \phi_j^i t_j^l \leq 0, \qquad \forall i \in N, \ \forall l \in \{1, \ldots, m\}, \tag{C.11}$$

$$M \delta_l^i \geq \alpha_l^i \geq 0, \qquad \forall i \in N, \ \forall l \in \{1, \ldots, m\}. \tag{C.12}$$

where, α is the collection of $|N|$ vectors of dual variables, and δ is the collection of $|N|$ vectors of binary variables.