School of Social Sciences
CITY UNIVERSITY LONDON

Department of Economics

Olivier Massol*
City University London
IFP Energies Nouvelles

Stephane Tchung-Ming
IFP Energies Nouvelles

Department of Economics
Discussion Paper Series
No. 12/10

[1] Department of Economics, City University London, Social Sciences Bldg, Northampton Square, London EC1V 0HB, UK ; email: olivier.massol@ifpen.fr

Joining the CCS Club! Insights from a Northwest European CO_2 Pipeline Project☆

Olivier MASSOL [a,b,c*] **Stéphane TCHUNG-MING** [a,d]

November 08, 2012

Abstract

The large-scale diffusion of Carbon Capture and Storage (CCS) imposes the construction of a sizeable CO_2 pipeline infrastructure. This paper analyzes the conditions for a widespread adoption of CCS by a group of emitters that can be connected to a common pipeline system. It details a quantitative framework capable of assessing how the tariff structure and the regulatory constraints imposed on the pipeline operator impact the overall cost of CO_2 abatement via CCS. This modeling 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.

JEL Classification: L43, L95, Q52, R48

☆ We are grateful to Albert Banal-Estañol, Benoît Chèze, Jeremy Eckhause, Steven Gabriel, Mathias Laffont and Jacques Percebois for insightful comments on earlier versions of this paper. In addition, we thank conference participants at the EEM12 (Florence, 2012), at the 25th EURO (Vilnius, 2012) and at INFORMS (Phoenix, 2012) for useful discussions. Of course, any remaining errors are ours. The views expressed herein are strictly those of the authors and are not to be construed as representing those of IFP Energies Nouvelles.

a IFP Energies Nouvelles, 1-4 av. de Bois Préau, F-92852 Rueil-Malmaison, France.

b Center for Economics and Management, IFP School, 228-232 av. Napoléon Bonaparte, F-92852 Rueil-Malmaison, France.

c Department of Economics, City University London, Northampton Square, London EC1V 0HB, UK.

d CREDEN, Université de Montpellier I, Avenue Raymond Dugrand, F-34960 Montpellier, France.

* Corresponding author. Tel.: +33 1 47 52 68 26; fax: +33 1 47 52 70 66.
E-mail address: olivier.massol@ifpen.fr

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 the trajectory of carbon dioxide (CO_2) emissions (IEA, 2011). Against this daunting background, Carbon Capture and Storage (CCS)[1] represents a technically conceivable option to isolate large volumes of CO_2 from the atmosphere (Pacala and Socolow, 2004). In principle, a widespread deployment of this decarbonizing 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 dangerous effects of global warming.

Previously, a large body of literature[2] emerged with the aim of providing insights for the decision makers concerned by CCS (policymakers, governments, and businesses). Yet, the spatial nature of CCS (i.e., the fact that sources can be remotely located from geologic sequestration sites imposing the construction of dedicated CO_2 transport systems) is surprisingly disregarded in most of these works. Several factors may explain this relative lack of consideration for carbon transportation issues, including the series of engineering-based cost estimates that typically emphasize the inexpensive nature of transportation compared to the other components of the CCS chain (IPCC, 2005; Al-Juaied and Whitmore, 2009); and the fact that, in the United States, some long-distance CO_2 pipelines are already in operation for Enhanced Oil Recovery (EOR) purposes (IPCC, 2005). Still, CCS experts repeatedly emphasize that the deployment of CCS remains contingent upon the installation of a sizeable CO_2 transportation infrastructure with a national and possibly continental scope (de Coninck et al., 2009; Herzog, 2011; Flannery, 2011).

The purpose of this paper is to contribute to the burgeoning analysis of the economic and regulatory issues connected to the *ex-nihilo* creation of a sizeable CO_2 pipeline system. In recent years, there has been an upsurge in interest in the application of operations research 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). While very much needed for indicative regional planning purposes (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, in reality, several stakeholders are likely to be involved in the creation of a CCS infrastructure (e.g., the emitters, the CO_2 pipeline operator). This fact can hardly be

[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 from fossil-fuel combustion, (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 (Gerlagh and van der Zwaan, 2006; Grimaud et al., 2011); (ii) the detailed bottom-up analyses on the future prospects for CCS (Kemp and Kasim, 2008; Golombek et al., 2011; Lohwasser and Madlener, 2012); (iii) the investment analyses applying the real-option approach to CCS projects (Yang et al., 2008; Eckhause, 2011; Eckhause and Herold, 2012)...

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.[3] In this paper, we explicitly focus on these coordination issues.

The theoretical basis of our approach stems from a club theory perspective (Buchanan, 1965). 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 of 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. More specifically, our aim is to test the condition for a large voluntary adoption of CCS as a function of the CO_2 transportation technology, the nature of the tariffs regulation imposed on the pipeline operator, the other CCS costs, and the economic incentives that set the price of CO_2 emissions (either through a tax or a cap-and-trade system).

The contributions of this paper are twofold. First, we provide an adapted modeling framework that analyzes the coordination issue at hand with the help of cooperative game theoretic considerations. Second, we consider an application of the proposed framework to the case of a realistic European CCS project[4]. This allows us to present a series of original empirical findings that clarify the interactions between the nature of the tariff structure used in the CO_2 pipeline industry and the minimum price of the CO_2 emission allowances required to construct that infrastructure. In particular, these findings confirm that spatial issues (the emitter's locations) significantly narrow the choice of a pipeline tariff structure: any kind of uniform postage stamp tariff impedes the adoption of CCS, whereas geographical discrimination is more effective. In the latter case, poorly defined tariffs significantly raise the minimum CO_2 price required to adopt the CCS. Moreover, our modeling framework can 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 less important for the adoption of CCS than the detailed decisions related to the tariff structure imposed to pipeline operators.

This paper also has a practical approach: it is intended to provide valuable guidance for professionals and scholars interested in the regulation of CO_2 pipeline systems and more generally for the public decision makers who have to calibrate on the economic incentives (either a tax or a cap-and-trade system) aimed at promoting the transition to a low-carbon economy. Therefore, a great

---

[3] *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.*

[4] *This project assumes the construction of a CO_2 trunkline aimed at collecting 19.7 millions of tons of CO_2 per year ($MtCO_2$/year) captured by 14 small to large-size industrial facilities located in both Le Havre (France) and Antwerp (Belgium), and transporting this CO_2 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.*

attention has been paid to address the practical issues faced in the implementation of the proposed methodology.

The paper is organized as follows: Section 2 provides a brief engineering-inspired overview of the CO_2 pipelines technology with the aim to detail the problem's background. Section 3 presents a cooperative game theoretic model of the adoption of pipeline transport of CO_2. Then, Section 4 details an application of this methodology to the case of a real European 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: background

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[5] and put that representation to work to determine the cost-minimizing design of a given CO_2 pipeline infrastructure (the pipeline diameter; the number and the size of the compression equipments installed along the pipeline).

From an engineering perspective, McCoy and Rubin (2008) underlined that their equations differ from those used in the natural gas industry as they pointed out the differences in the fluids' physical properties (natural gas is typically transported in a gaseous state whereas CO_2 is piped in supercritical state). Yet, from a conceptual perspective, their approach bears a strong analogy with those typically used in the natural gas industry. As far as natural gas pipelines are concerned, a prolific literature[6] stemmed from Chenery's (1949) seminal contribution has combined engineering and economics to guide both investment and operational decisions. Using that analogy, 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.

Regarding point-to-point CO_2 pipelines, the numerical simulations based on these engineering models consistently indicate that the technology at hand exhibits significant increasing returns to scale

[5] *A comprehensive presentation of these engineering considerations is beyond the scope of this paper, yet we can note that these studies typically includes: (i) a thermodynamic-derived flow equation that describes the frictional loss of energy through the pipe (i.e. the pressure drop) as a function of the fluid's physical properties (flow-rate, pressure, temperature...) and engineering parameters (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 compress the CO_2 from a given inlet pressure to a predefined outlet pressure.*

[6] *The list includes: (i) the analytical studies dedicated to the simple point-to-point infrastructure that uses a single compressor equipment (Chenery, 1949; Massol, 2011); (ii) those dedicated to long-distance trunkline systems that have a series of compressor stations installed along the pipeline (André and Bonnans, 2011); and (iii) the numerous applications of mathematical programming to model meshed transmission networks (e.g., André et al., 2009).*

over a large range of output in the long run (IPCC, 2005; McCoy and Rubin, 2008; McCoy, 2009) which is also coherent with the findings obtained using the natural gas analogue (Chenery, 1949; Massol, 2011). From an industrial organization perspective, this finding has important implications as these economies of scale represent an incentive for the construction of a sizeable pipeline infrastructure aimed at serving the needs of a large group of CCS adopters. *Ex ante*, an emitter located near the inlet of the CO_2 pipeline who voluntary adopts CCS could benefit from the wide participation of the other emitters located in the neighborhood. That's the reason why, we aim to study the creation of a private good club à la Sorenson et al. (1978).[7] Our goal is to explore the relations between the tariff policy adopted by the pipeline operator, and the voluntarily adhesion of the CO_2 emitters. As the CO_2 pipeline tariffs are likely to be subject to some kind of regulation, this exploration is of major importance to provide useful guidance to both regulators and policy makers.

3. A game-theoretic approach to infrastructure pricing

In this section, we present the analytical framework used in the sequel of the manuscript. To begin with, we clarify the notation. Then, we analyze the economics of a common CO_2 pipeline infrastructure successively using a cost-sharing and a benefit-sharing perspective. This analysis allows us to clarify the connections between both approaches. Lastly, we show how the tariff structure used by the pipeline operator influences the minimal price of the CO_2 emission allowance required to obtain an incentive-compatible allocation of the total benefit generated by the construction of that infrastructure.

3.1 Background and main notation

We consider the construction of a pipeline system aimed at transporting the CO_2 emitted by a finite set of existing industrial facilities. Let N denote the finite set of emitters that can be connected to the CO_2 pipeline system, indexed by subscript i. Let $|N|$ denote the cardinality of this set and S denote a subset of N. Each industrial facility has a series of specific features (e.g., location, flows of CO_2). Thus, it is convenient to associate each emitter with a specific transportation service. So, N is also the set of goods provided by the CO_2 pipeline industry.

In this paper, we abstract from the level of CO_2 captured at each industrial facility that may potentially adopt the CCS technology. Accordingly, we simply assume a binary decision that concerns whether or not the amount of CO_2 generated by each industrial facility is captured. Let Q_i denote the annual volume CO_2 emitted by i that can potentially be captured. Additionally, each emitter i is assumed to be endowed with Q_i emission allowances.[8] If the CCS technology is adopted, these

[7] *We also refer to Sandler and Tschirhart (1980) for a comprehensive definition of a club good.*
[8] *Thus, each emitter is endowed with an amount of emission allowances that is exactly equal to its annual emissions. This assumption is consistent with the "grandfathering" allocation of emission allowances (i.e. the distribution free of charge to polluting industries based on historical data on emissions or fuel use) observed during Phases I and II of the European Union Emissions Trading Scheme (EU ETS).One natural way to relax this assumption would consist of assuming that part of*

allowances will be sold. Emitters are assumed to be price takers on the market for allowances. Hereafter, the selling price of an emission allowance is an exogenous parameter that is simply denoted p_{CO_2}.

The costs related to both capture and storage operations are separable. Let χ_i denote the levelized unit cost of the site-specific, carbon capture operations conducted at industrial facility i; and σ denote the price of the storage service provided by an independent storage operator.[9] For each emitter, the capture and storage costs are only incurred if the CCS technology were to be adopted. Thus, $\left(p_{CO_2} - \chi_i - \sigma\right)Q_i$ represents the willingness to pay for CO_2 pipeline service of industrial facility i.

Entry is assumed to be free in the CO_2 pipeline industry. The discussion in the preceding section suggests that the technology used in CO_2 pipelines is not proprietary. Thus, we assume that all the pipeline firms potentially have access to the same technology and therefore have the same cost function. 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 of this paper, the $2^{|N|}$ values taken by the function C will correspond to the numerical outcomes of an engineering process model.[10] We assume that $C(\varnothing) = 0$ and $C(S) \geq 0$ for any non-empty S in N.

3.2 A cost-based analysis: are we facing a sustainable natural monopoly?

To begin with, we focus on the cost structure of the CO_2 pipeline industry and analyze whether or not a monopolistic organization can sustainably be implemented in that industry. Two items are successively discussed: the sub-additivity of the cost function and the sustainability of a natural monopoly.

Sub-additivity

To check whether the pipeline industry that serves these $|N|$ emitters is a natural monopoly or not, one has to verify the sub-additivity of the cost function.

A cost function C is sub-additive if $C(S \cup T) \leq C(S) + C(T)$ for any coalitions $S, T \subseteq N$, with $S \cap T = \varnothing$. In case of a sub-additive cost function, no combination of multiple firms can

---

the initial allowances should be bought on a primary market, before the surplus allowances may be sold on a secondary market. Apart from the issue of making coherent assumptions regarding the carbon prices on the two markets, accounting for this would add a fixed cost to the welfare of each emitter. This, in turn, would lower the threshold CO_2 price necessary to ensure each emitter joins the club.

[9] *σ may also be interpreted as a levelized unit cost of storage.*

[10] *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).*

collectively produce the industry output at lower cost than a monopolist (Berg and Tschirhart, 1988). Thus, a pipeline operator that serves these $|N|$ emitters with a sub-additive cost function is said to be a natural monopoly.[11]

Sustainability

Given that entry is supposed to be free in the CO_2 pipeline industry, one has to take into consideration the possible entry of a potential rival firm. Following Baumol et al. (1977), a monopolistic organization is reputed sustainable for that industry if there exists a revenue vector $r=\left(r_1,...,r_{|N|}\right)'$ so that: (i) a monopoly that serves the entire market and charges these revenues 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 for a sustainable monopoly are:

$$\sum_{i\in N} r_N \geq C(N) \tag{1}$$

$$\sum_{i\in S} r_S \leq C(S), \qquad \forall S \subseteq N \tag{2}$$

Thus, even in the absence of a regulatory profit constraint, these conditions jointly demand the sustainable monopoly to adopt a revenue vector r that exactly recovers the total cost (Sharkey, 1982):

$$\sum_{i\in N} r_N = C(N). \tag{3}$$

The conditions (2) and (3) are related to the conditions for subsidy-free revenues proposed by Faulhaber (1975) that insure 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 cost game (N,C), i.e., the set:

$$\Lambda := \left\{ r \in \mathbb{R}^{|N|} : \sum_{i\in N} r_i = C(N) \text{ and, } \forall S \subset N, \sum_{i\in S} r_i \leq C(S) \right\}. \tag{4}$$

Thus, a necessary and sufficient condition for a sustainable monopoly is a non-empty set Λ. From an empirical perspective, the conditions (4) can be checked using the following linear program:

---

[11] *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.*

LP1:

$$\underset{r,\varepsilon}{\text{Max}} \quad \varepsilon \tag{5}$$

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

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

$$\varepsilon \ge 0\,. \tag{8}$$

The gain derived from cooperation by any non-trivial coalitions $S \subset N \quad (S \ne \varnothing, N)$ with respect to a cost allocation r is measured by the excess: $\left[C(S) - \sum_{i\in S} r_i\right]$. In LP1, the non-negative variable ε can be interpreted as the maximum possible value of the lowest excess obtained by a non-trivial coalition. Obviously, a non-empty feasible set for the program LP1 is a necessary and sufficient condition for sustainability (i.e., it proves the existence of a non-empty core Λ).

3.3 Taking revenues into account: a benefit game

The cost-based perspective discussed in the previous subsection provides useful insights to the sustainability of a natural monopoly. Yet, this approach does not take into consideration the emitter's decisions to adopt CCS technology as a whole.

So, we now think of emitters as potential members of a club gathering the CO_2 pipeline users (i.e., the CCS adopters). We adopt a game theoretic specification based on Littlechild (1975) and Sharkey (1982) and assume that the emitters are interested in maximizing the difference between benefits and total costs of CCS (i.e., the net benefits which they receive). The game at hand is a transferable utility game. For each club with members S, the voluntary non-participation of some members may be needed to maximize the net benefits collectively attained by that club. Thus, the characteristic function for the game, denoted v, gives for each coalition of players S, the net benefits for the sub-coalition players in S which maximizes this difference:

$$v\left(S, p_{CO_2}\right) = \underset{R\subseteq S}{\text{Max}} \left\{\sum_{i\in R}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(R)\right\}, \qquad \forall S \subseteq N\,. \tag{9}$$

If no CO_2 is captured, then no costs are incurred which indicates that $v\left(S, p_{CO_2}\right) \ge 0$ for all S. By construction, v is monotonic since the condition $v\left(R, p_{CO_2}\right) \le v\left(S, p_{CO_2}\right)$ systematically holds for any pair of subsets R, S in N with $R \subset S$.

The definition (9) indicates that v is parameterized by the price of an emission allowance. Thus, this price conditions the voluntary adoption of CCS by all the emitters in the grand coalition N. The necessary and sufficient condition for all the emitters in N to adopt the CCS technology is that the total benefit of any club with members S must be at least as large as the incremental cost of transporting the CO_2 captured by the emitters in S (Sharkey, 1982):

$$\sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right] \geq C(N)-C(N\setminus S), \qquad \forall S\subset N. \tag{10}$$

Hence, for any club with members S, the condition (10) holds if and only if the price of an emission allowance is larger than the sum of the volume-weighted average unit capture costs, the unit incremental cost to connect the club members to a pipeline system serving the other emitters, and the unit storage cost. Gathering all these conditions indicates that any carbon price p_{CO_2} lower than the threshold level:

$$\underline{p_{CO_2}} = \underset{S\subset N}{\mathrm{Min}}\left\{\frac{\sum_{i\in S}\chi_i Q_i + C(N)-C(N\setminus S)}{\sum_{i\in S} Q_i}\right\}+\sigma, \tag{11}$$

cannot be compatible with the voluntary sequestration of the total volume of CO_2 emitted by the grand coalition. As a consequence, the promoters of a CO_2 pipeline project should not consider connecting all these emitters if that minimum price is not attained.

Hereafter, we assume that $p_{CO_2} \geq \underline{p_{CO_2}}$ so that all the emitters are willing to be connected to the CO_2 pipeline system. We now analyze the repartition of the total benefit obtained by the grand coalition – i.e., $v\left(N, p_{CO_2}\right)=\sum_{i\in N}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(N)$ – among the players. Let the vector $y=\left(y_1,\ldots,y_{|N|}\right)'$ with $\sum_{i\in N} y_i = v\left(N, p_{CO_2}\right)$ denote an allocation of the total benefit, and the set $\Gamma\left(p_{CO_2}\right)$ denote the core of the net benefit game $\left(N, v_{p_{CO_2}}\right)$, i.e.,

$$\Gamma\left(p_{CO_2}\right):=\left\{y\in\mathbb{R}^{|N|}:\sum_{i\in N} y_i = v\left(N, p_{CO_2}\right) \text{ and, } \forall S\subset N, \sum_{i\in S} y_i \geq v\left(S, p_{CO_2}\right)\right\}. \tag{12}$$

By definition, choosing an allocation y in the core insures that the cooperation within the largest possible club N is unanimously preferred to any other smaller club S. Thus, any y in $\Gamma\left(p_{CO_2}\right)$ is an incentive-compatible allocation for the club N.

3.4 Reconciling the cost-based and the benefit-based approaches

We shall now reconcile the two previous perspectives in a common direction. For any individual emitter i, there exists a one-to-one correspondence between its allocated share y_i of the total net benefit and the amount r_i charged by the pipeline operator:

$$y_i = \left(p_{CO_2} - \chi_i - \sigma \right) Q_i - r_i , \qquad \forall i \in N . \tag{13}$$

We use this relation parameterized by the price of an emission allowance to define the function $F_{i,p_{CO_2}}$ that verifies $y_i = F_{i,p_{CO_2}}\left(r_i\right)$ and $r_i = F^{-1}_{i,p_{CO_2}}\left(y_i\right)$. For the sake of brevity, we simply use $F_{p_{CO_2}}\left(r\right)$ (respectively $F^{-1}_{p_{CO_2}}\left(y\right)$) as a vector notation for $\left(F^{-1}_{i,p_{CO_2}}\left(y_i\right)\right)_{i=1,\ldots,|N|}$ (respectively $\left(F^{-1}_{i,p_{CO_2}}\left(y_i\right)\right)_{i=1,\ldots,|N|}$).

As clarified by Sharkey (1982), the conditions for sustainable prices and those for an incentive-compatible allocation of the total net benefit obtained by the grand coalition are closely related:

Proposition 1 (Sharkey, 1982): If $y \in \Gamma\left(p_{CO_2}\right)$ *and* $p_{CO_2} \geq \underline{p_{CO_2}}$*, then* $F^{-1}_{p_{CO_2}}\left(y\right) \in \Lambda$.

The result stated in Proposition 1 clearly indicates that it may not be sufficient for the pipeline operator to pick any revenue vector r in Λ the core of the cost game. Indeed, any revenue vector $r \in \Lambda$ is necessary and sufficient to avoid cross-subsidies and to impede the entry of potential rivals. Yet, such a vector does not necessarily provide an impetus for the voluntary adoption of the CCS technology by all the emitters in the grand coalition. To overcome this problem, the pipeline operator must also take into consideration the conditions for an incentive-compatible allocation of the net benefits generated by the transportation infrastructure: i.e., pick a revenue vector r that verifies $F_{p_{CO_2}}\left(r\right) \in \Gamma\left(p_{CO_2}\right)$.

Is the core of the net benefit game non-empty? From a practitioner's perspective, this is a chief preoccupation. Unfortunately, a linear programming approach similar to the one detailed in LP1 is likely to be cursed by the dimension of the problem at hand. Indeed, the value function v as defined in (9) raises some computational issues as, for each of the $2^{|N|} - 2$ non-trivial coalitions S that can be formed in N, this definition requires to determine a maximum over a discrete set that has $2^{|S|}$ elements. Even at moderate values of $|N|$, plugging all these $\sum_{j=1}^{|N|} \binom{|N|}{j} 2^j$ conditions within a single linear program generates a very large problem... To overcome this difficulty, we now present a couple of analytical contributions that simplify the problem at hand.

Lemma 1: *The core of the net benefit game* $\Gamma\left(p_{CO_2}\right)$ *is equal to the set* $\Upsilon\left(p_{CO_2}\right)$ *where:*

$$\Upsilon\left(p_{CO_2}\right) := \left\{ y \in \mathbb{R}_+^{|N|} : \sum_{i=1}^{|N|} y_i = v\left(N, p_{CO_2}\right) \text{ and, } \forall S \subset N, \sum_{i \in S} y_i \geq \sum_{i \in S} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(S) \right\}.$$

This result considerably reduces the number of conditions to be verified[12] to check whether a given allocation of the net benefit generated by the CO_2 pipeline infrastructure is or not an incentive-compatible one. Besides, Proposition 2 can be used to formulate another interesting result:

Proposition 2: *If* $p_{CO_2} \geq \underline{p_{CO_2}}$*, then choosing a sustainable revenue vector* r *– i.e.,* $r \in \Lambda$ *– that allocates a non-negative net benefit to any individual emitters in the grand coalition – i.e.,* $r \in \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}$ *so that the emitters' individual participation constraints are verified – is a necessary and sufficient condition for implementing an incentive-compatible allocation of the total net benefit generated by the infrastructure. In short, for any* p_{CO_2} *with* $p_{CO_2} \geq \underline{p_{CO_2}}$*, we have* $F_{p_{CO_2}}\left(\Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\} \right) = \Gamma\left(p_{CO_2}\right)$.

In Section 3.2, we discussed the existence of sustainable revenue vectors and proposed an empirical approach to test for the non-empty nature of the set Λ. Now we assume that this test concluded that $\Lambda \neq \varnothing$ [13] and consider the following linear programming problem:

<u>LP2:</u>

$$\min_{r, p_{CO_2}} \quad p_{CO_2} \tag{14}$$

$$\text{s.t.} \quad r \in \Lambda, \tag{15}$$

$$\left(r, p_{CO_2}\right) \in \left\{ r \in \mathbb{R}^{|N|}, p_{CO_2} \in \mathbb{R}_+ : F_{p_{CO_2}}(r) \geq 0 \right\}. \tag{16}$$

---

[12] *Indeed, the right-hand side of the* $2^{|N|} - 1$ *inequalities used in the definition of* $\Upsilon\left(p_{CO_2}\right)$ *are all known and easy to evaluate whereas those used in the definition of* $\Gamma\left(p_{CO_2}\right)$ *impose either to precompute all the values of* $v\left(S, p_{CO_2}\right)$ *using the definition (9) or to use a "brute force" approach that consists in remarking that for any* S *in* N*, we have the logical equivalence* $\left[\sum_{i \in S} y_i \geq v\left(S, p_{CO_2}\right) \right] \Leftrightarrow \left[\sum_{i \in S} y_i \geq \sum_{i \in R} \left[\left(p_{CO_2} - \chi_i - \sigma \right) Q_i \right] - C(R),\ \forall R \subseteq S \right]$ *and thus replace the first inequality by the logically equivalent* $2^{|S|} - 1$ *conditions.*

[13] *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.*

In that linear program, the constraints (15) compel the pipeline operator to charge a sustainable revenue vector and the condition (16) represents the emitters' individual participation constraints.

The following proposition insures that a solution exists and that this solution is compatible with the condition for the voluntary adoption of CCS by all the emitters in the grand coalition N .

> <u>*Proposition 3:*</u> *If $\Lambda \neq \varnothing$, then there exists a solution to the problem LP2 that is denoted $\left(r^*, p_{CO_2}^*\right)$. Additionally, we have $p_{CO_2}^* \geq \underline{p_{CO_2}}$.*

By definition, any allowance price that is strictly lower than $p_{CO_2}^*$ cannot be compatible with the existence of an incentive-compatible repartition of the net benefits generated by the adoption of the CCS technology by the grand coalition (in other words, the existence of a non-empty core $\Gamma\left(p_{CO_2}\right)$). Interestingly, Proposition 3 indicates that $p_{CO_2}^* \geq \underline{p_{CO_2}}$. So, the condition for a non-empty core for the net benefit game is more restrictive than the condition (10) required to have $v\left(N, p_{CO_2}\right) = \sum_{i \in N}\left[\left(p_{CO_2} - \chi_i - \sigma\right)Q_i\right] - C(N)$.

As a result, $p_{CO_2}^*$ represents the minimum level of allowance price that has to be imperatively attained to convince both the pipeline operator and the emitters to capture all the volumes of CO_2 emitted by the grand coalition.

3.5 On the relation between pipeline tariffs and the price of an emission allowance

In the linear program LP2, we implicitly allowed the pipeline operator to discriminate the tariffs charged to emitters. Such a perfect discrimination hardly looks realistic. For example, in Europe the tariff structure used by infrastructure operators is usually subject to approval by a regulator that typically imposes a non-discriminatory tariff policy. A series of crucial questions emerge. First, is the proposed tariff structure compatible with the conditions for an incentive-compatible allocation of the total net benefit generated by the CO_2 pipeline system? Second, in case of a positive answer to the previous question, does this tariff structure impose a minimum allowance price greater than the level $p_{CO_2}^*$?

Our framework can be put to work to analyze how a given tariff structure interacts with the emitters' decision to adopt the CCS technology. Formally, compelling the operator to implement a certain tariff structure amounts to adding some further constraints and some further decision variables in the LP2 linear program. In the sequel of this section, two types of tariffs structure are discussed: a linear tariff and a menu of linear tariffs.

a – A non-discriminatory, multipart, linear tariff structure

The first type of pricing scheme corresponds to a possibly multipart, non-discriminatory, linear tariff whereby the pipeline operator considers a series of k, with $k \le |N|$, emitter-specific quantitative features (e.g., the annual volume of CO_2 emissions, the peak emission flow). 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 $t = \left(t_1, ..., t_k\right)'$ denote the associated tariffs charged by the pipeline operator. For simplicity, we also denote Φ the $\left(|N| \times k\right)$ matrix where the row i is $\left(\phi^i\right)'$. Thus, the revenue vector r charged by the pipeline operator is given by $r = \Phi t$.

To analyze whether this tariff structure verifies the conditions for an incentive-compatible allocation of the total benefit generated by the CO_2 pipeline system, we use a modified version of the preceding linear program. From the structure of LP2, we introduce the vector t of k additional decision variables and the additional restrictions imposed by the tariff structure to obtain the linear program LP3:

LP3:

$$\underset{r,t,p_{CO_2}}{\text{Min}} \quad p_{CO_2} \tag{17}$$

$$\text{s.t.} \quad r \in \Lambda, \tag{18}$$

$$\left(r, p_{CO_2}\right) \in \left\{ r \in \mathbb{R}^{|N|}, p_{CO_2} \in \mathbb{R}_+ : F_{p_{CO_2}}\left(r\right) \ge 0 \right\}, \tag{19}$$

$$\left(r, t\right) \in \left\{ r \in \mathbb{R}^{|N|}, t \in \mathbb{R}^k : r = \Phi t \right\}. \tag{20}$$

Any attempt to solve this problem results in one of the three following outcomes:

- Case #1: there is no solutions to LP3, which means that the feasible set associated with LP3 is empty. Recall that there is no maximum bound on the carbon price in LP3. So, a sufficiently large value of p_{CO_2} can conceivably insure that none of the emitters' individual participation constraints in (19) is binding. Thus, the empty nature of the feasible set has to deal with both the condition (18) for a subsidy-free revenue vector and the condition (20) related to the tariff structure. In other words, it means that the pipeline tariff structure at hand imposes some cross-subsidizations among customers. If entry were set free in the CO_2 pipeline industry, imposing such a tariff structure would impede the construction of a CCS pipeline system serving the grand coalition of emitters (because it creates the conditions for a profitable entry for a competitor serving a subset of emitters).

- Case #2: a solution is found and corresponds to a minimum allowance price $p^{**}_{CO_2}$ that verifies $p^{**}_{CO_2} = p^{*}_{CO_2}$. Obviously, such a result indicates that the tariffs structure imposed to the pipeline operator amounts to choosing an incentive-compatible distribution of the total benefit generated by that infrastructure. The tariff policy has no impact on the feasibility of the CCS project.

- Case #3: 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 tariffs structure imposed on the pipeline operator impedes the creation of the largest CCS infrastructure when the climate policy results in an allowance price that is in the interval $\left[p^{*}_{CO_2}, p^{**}_{CO_2}\right)$.

b – A menu of multi-part affine tariff structure

The second type of tariffs corresponds to a so-called second degree price discrimination scheme. The pipeline operator is allowed to design a menu of m multipart (i.e., at least two-part) affine 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 considers the emitter-specific vector $\phi^i = \left(\phi^i_1,...,\phi^i_k\right)'$ of quantitative features and determines a total of $k+1$ parameters: the vector $t^l = \left(t^l_1,...,t^l_k\right)'$ of k unit prices plus the fixed charge f^l. To avoid indeterminacy we impose the following restriction: $m(k+1) \le |N|$. For simplicity, we use t as a short notation for the collection of these m price vectors and f for the associated fixed charges.

In that case, each emitter i 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 (Bard, 1998) where the upper level problem is analogue to LP3 (determining the minimum price of CO_2 that is compatible with an incentive-compatible menu of tariffs), and the lower-level problem corresponds to the emitters' individual decisions.

Regarding the lower-level, the maximum revenue charged by the pipeline operator to each emitter is clearly equal to the emitter's minimum CO_2 transportation cost. Formally, each emitter's choice can be modeled using the following linear program:

$\underline{\mathrm{LP4}_i(f,t):}$

$$\underset{r_i}{\mathrm{Max}} \quad r_i \tag{21}$$

$$\text{s.t.} \qquad r_i \leq f^l + \phi^{i'} t^l, \qquad \forall l \in \{1,...,m\}. \tag{22}$$

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.

BLP5

$$\underset{r,f,t,p_{CO_2}}{\text{Min}} \qquad p_{CO_2} \tag{23}$$

$$\text{s.t.} \qquad r \in \Lambda, \tag{24}$$

$$\left(r, p_{CO_2}\right) \in \left\{ r \in \mathbb{R}^{|N|}, p_{CO_2} \in \mathbb{R}_+ : F_{p_{CO_2}}\left(r\right) \geq 0 \right\}, \tag{25}$$

$$\left(r, f, t\right) \in \left\{ r \in \mathbb{R}^{|N|}, f \in \mathbb{R}^m, t \in \mathbb{R}^{m \times k} : \ \forall i \in N, \ r_i \in \text{ArgMax}\left(\text{LP4}_i\left(f, t\right)\right) \right\}. \tag{26}$$

From a computational perspective, a reformulation is needed to solve this two-level optimization problem. To begin with, we focus on the lower-level problem faced by a given emitter i. Denoting $\alpha^i = \left(\alpha_1^i, ..., \alpha_m^i\right)'$ the vector of dual variables associated with the constraints (22), the KKT conditions for optimality correspond to the following linear complementarity constraints:

$$1 - \sum_{l=1}^{m} \alpha_l^i = 0 \tag{27}$$

$$r_i - \left(f^l + \phi^{i'} t^l\right) \leq 0, \quad \alpha_l^i \geq 0, \quad \alpha_l^i \left(r_i - \left(f^l + \phi^{i'} t^l\right)\right) = 0, \qquad \forall l \in \{1,...,m\}. \tag{28}$$

We can replace the complementarity conditions (28) by integer restrictions in the form of disjunctive constraints (Fortuny-Amat and McCarl, 1981). 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 $\left(f^l, t^l\right)$ 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.[14] Using these variables, the complementarity constraints (28) becomes:

$$-M\left(1 - \delta_l^i\right) \leq r_i - \left(f^l + \phi^{i'} t^l\right) \leq 0, \qquad \forall l \in \{1,...,m\}, \tag{29}$$

$$M \delta_l^i \geq \alpha_l^i \geq 0, \qquad \forall l \in \{1,...,m\}. \tag{30}$$

---

[14] *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* $M = 2 \times C\left(N\right)$ *looks like a possible candidate.*

Replacing the condition (26) by the constraints (27), (29) and (30) transforms the two-level optimization program BLP5 into an easy-to-solve mixed-integer linear program MILP6:

MILP6:

$$\underset{r,f,t,p_{CO_2},\alpha,\delta}{\text{Min}} \quad p_{CO_2} \tag{31}$$

$$\text{s.t.} \quad r \in \Lambda, \tag{32}$$

$$\left(r, p_{CO_2}\right) \in \left\{ r \in \mathbb{R}^{|N|}, p_{CO_2} \in \mathbb{R}_+ : F_{p_{CO_2}}(r) \geq 0 \right\}, \tag{33}$$

$$\left(r, f, t, \alpha, \delta\right) \in \Omega, \tag{34}$$

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

$$\Omega := \left\{ \begin{array}{c} r \in \mathbb{R}^{|N|}, f \in \mathbb{R}^m, t \in \mathbb{R}^{m \times k}, \alpha \in \mathbb{R}^{|N| \times m}, \delta \in \{0,1\}^{|N| \times m} : \\ \forall i \in N, \left[r_i - \sum_{l=1}^{m} \alpha_l^i = 0, \text{and}, \forall l \in \{1,...,m\}, \right. \\ \left. \left[\left(-M\left(1-\delta_l^i\right) \leq r_i - \left(f^l + \phi^{i'} t^l\right) \leq 0, \text{ and } M\delta_l^i \geq \alpha_l^i \geq 0 \right) \right] \right] \end{array} \right\}. \tag{35}$$

As in the case of LP3, any attempt to solve the mixed-integer linear program MILP6 results in one of the three following outcomes:

- Case #1: there is no solution to MILP6 which indicates that the feasible set is empty. Again, it means that the constraints (34) related to the tariffs structure imposed on the pipeline operator are not compatible with the conditions (32) for a cross-subsidy-free revenue.
- Case #2: a solution is found and corresponds to a minimum allowance price $p_{CO_2}^{**}$ that verifies $p_{CO_2}^{**} = p_{CO_2}^{*}$. Obviously, such a result indicates the tariff policy has no impact on the feasibility of the CCS project.
- Case #3: a solution is found and corresponds to a minimum allowance price $p_{CO_2}^{**}$ that verifies $p_{CO_2}^{**} > p_{CO_2}^{*}$. Again, the regulation imposed on the pipeline operator impedes the creation of the largest CCS infrastructure when the climate policy results in an allowance price that is in the interval $\left[p_{CO_2}^{*}, p_{CO_2}^{**}\right)$.

4. Case study

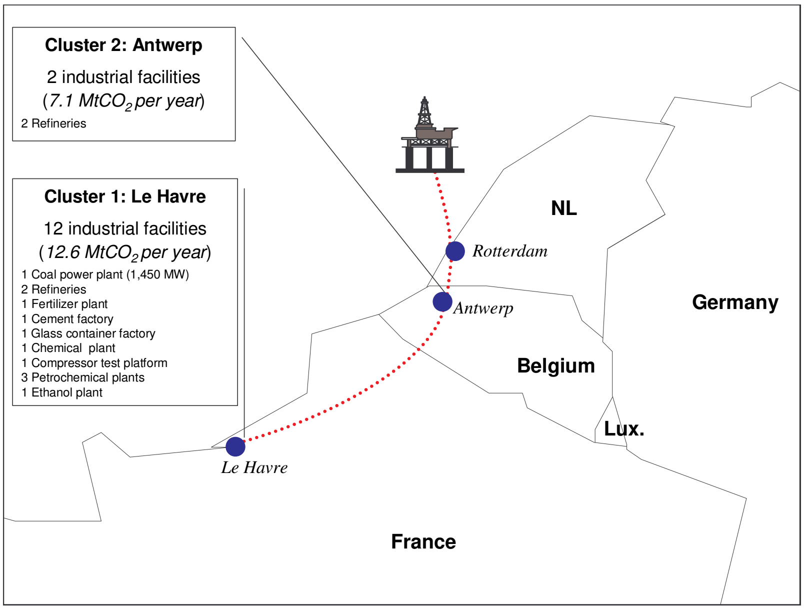
In this section, we detail an application of the proposed framework to analyze the economics of a given CO_2 pipeline system and examine the conditions for the deployment of that CCS chain.

4.1 A Northwestern European CO_2 pipeline project

a - Background

In this article, we consider a realistic case study inspired by the context of the EU-funded COCATE project:[15] the construction of a 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 offshore in depleted oil fields.[16]

Figure 1. A picture of the North-Western European CO_2 pipeline project



Using both the French and Belgian National Allocation Plans for CO_2-emission allowances, a total of 14 large to small industrial facilities (coal power plant, refineries, petrochemical plants...) have been identified as possible CCS adopters in these two clusters (cf. Figure 1 for an illustration). These 14 plants jointly emit 19.7 $MtCO_2$/year and together constitute the largest coalition that is denoted N_{All}.

---

[15] *The COCATE project was funded by the European Commission (DG Research) under the reference: 7th Framework Program, Energy.2009.5.2.2: Towards an infrastructure for CO2 transport and storage. Collaborative Project – GA No. 241381 (cf. http://projet.ifpen.fr/Projet/jcms/c_7832 for a presentation).*

[16] *These large volumes of CO_2 could also be used for Enhanced Oil Recovery (EOR) operations as there exists some plans for large scale CO_2-based EOR operations in the North Sea (Tzimas et al., 2005).*

We now review three important features that differentiate the CO_2 transportation service potentially demanded by each industrial facility. First, location obviously matters. To simplify, the subset of Belgian (respectively French) emitters is denoted B (respectively F).

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

Facility		Annual Emissions	Quarterly emissions (as a % of the annual emissions)				Annual unit cost for CO_2 Capture and Collection
Label	Type of industry	(tCO_2/year)	Q1	Q2	Q3	Q4	(€/tCO_2 per year)
Le Havre #1	Coal power plant	3 733 346	39.8%	12.7%	12.7%	34.8%	38.9
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	Oil 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	Oil 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 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 are in 2010 euros. They are based on proprietary engineering studies available at IFP Énergies Nouvelles. These figures correspond to a cost evaluation based on an "nth of a kind" assumption (i.e., cost engineers have assumed a widespread diffusion of the capture technologies allowing for substantial learning and thus significant cost reductions).

Second, there are significant differences in the annual volume of CO_2 emitted by each source. 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 the total emissions generated by the grand coalition N_{All} 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.[17] 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. In case of a “partial coverage” scheme, the two smallest emitters are eliminated from the list of potential CCS adopters and denote $N_{\geq 25ktCO_2}$ the coalition of emitters with an annual emission level greater than the threshold. In this case study, we are going to systematically contrast the results obtained with the two possible extent of coverage in an ETS, i.e., the two possible definitions of the grand coalition N, either N_{All} or $N_{\geq 25ktCO_2}$.

Third, 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 hourly CO_2 flow rates. The quarterly emission figures detailed Table 1 confirm that there are marked differences in the within-year patterns of emissions as 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). Hereafter, we denote $\overline{q}_i$ the within-year peak hourly flow emitted by the industrial facility i.

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} (cf. Appendix A). The CO_2 trunkline at hand can be decomposed into two subsystems (cf. Figure 1): 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 report the total annual costs of the components of an adapted CCS infrastructure for some attention-grabbing coalitions of emitters. According to this engineering process model, the annual total cost to install and operate an adapted pipeline system capable of transporting the CO_2

[17] *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.*

emitted by the largest set of emitters N_{All} is €123.8 million which represents 10.5% of the total annual cost of the whole CCS chain. For that grand coalition N_{All}, the average annual total cost of the whole CCS chain is 59.9 €/(tCO_2 per year), of which solely 6.29 €/(tCO_2 per year) are related to the CO_2 pipeline system. Because of its location, the coalition B that gathers the two Belgian emitters provides the lowest average total cost figure: 55.9 €/(tCO_2 per year), of which 2.47 €/(tCO_2 per year) are related to the CO_2 pipeline system.

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

Coalition	Annual Emissions (MtCO_2/year)	Annual Total Cost of Capture and Gathering lines (M€/year)	Annual Total Cost of an adapted pipeline (M€/year)		Annual Total Storage Cost (M€/year)
			$C_{F\to B}$	$C_{B\to NL}$	
B	7.081	321.85	0.00	17.50	56.65
F	12.613	575.55	74.85	33.81	100.90
$F \cap N_{\geq 25ktCO_2}$	12.603	575.07	74.80	33.79	100.82
$N_{\geq 25ktCO_2}$	19.684	896.93	74.78	48.96	157.47
N_{All}	19.694	897.40	74.85	48.98	157.55

Note: All cost figures are in 2010 euros.

4.2 Preliminary insights

a - The cost structure of the CO2 pipeline project

To begin with, we discuss the cost structure of the CO_2 pipeline project at hand. An exhaustive series of verifications confirms that the engineering-based cost function C at hand is sub-additive, which confirms the natural monopolistic nature of that infrastructure.[18]

Now, we focus on the sustainable nature of that natural monopoly. The conditions for sustainability have been tested using the linear program LP1 and several alternative definitions of the grand coalition N including: the case of a "blanket coverage" based on the largest coalition (i.e., $N = N_{All}$), those of a "partial coverage" using the restricted coalition (i.e., $N = N_{\geq 25ktCO_2}$), and those of a stand-alone policy including solely the Belgian emitters. In Table 3, we report the optimal value of the objective function ε^* obtained while solving LP1 with these different definitions of N.

In each case, ε^* has a strictly positive value which indicates that the core of the associated cost-sharing game is a non-empty set. Hence, each of these possible grand coalitions N represents a stable club because, in each case, there exists at least one core cost allocation that guarantees that no emitter

[18] *As a side remark, our numerical investigations also indicate that the cost-sharing 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).*

or subgroup of emitters has an incentive to drop out and go for a stand-alone infrastructure. We are thus dealing with a sustainable natural monopoly.

Table 3. The solution of LP1 for various definition of the grand coalition N

Grand Coalition N	ε^* (10^3 € per year)
B	910
F	605
$F \cap N_{\geq 25ktCO_2}$	804
$N_{\geq 25ktCO_2}$	708
N_{All}	572

As a side comment, we can mention that the optimal values attained by the objective function of the linear program LP1 suggest that the cores of these cost games are not large. For example, the creation of a unique infrastructure capable of serving the largest coalition N_{All} can provide the least well-off subgroup of emitters with a transmission cost economy that may attain €572 thousand per year compared to a stand-alone policy. Arguably, that least well-off subgroup contains at least one small emitter since the value of ε^* raises to 708 k€/yr when considering the case of a "partial coverage" (i.e., the restricted cost game $\left(N_{\geq 25ktCO_2}, C\right)$).

b - A benefit-based approach

We now proceed analyzing the associated benefit-sharing game. Again, we consider the preceding list of possible clubs of emitters (i.e., definitions of the grand coalition N). For each of them, we determine: (i) the minimum selling price of an emission allowance $\underline{p_{CO_2}}$ required to obtain the voluntary adoption of the CCS technology by all the members in N (cf. the definition in (11)), and (ii) the minimum selling price of an emission allowance $p^*_{CO_2}$ required for the existence of an incentive-compatible allocation of the total net benefit generated by the CO_2 trunkline system.

These results are reported in Table 4. In all these clubs, the condition (10) for a voluntary adoption of the CCS technology by all club members requires a carbon price level $\underline{p_{CO_2}}$ that is significantly larger than the average total cost of the CCS chain. This finding has important policy implications for the deployment of CCS technologies. Indeed, most of the engineering-based studies seek to evaluate the average total cost of plausible CCS chains and implicitly assume that it gives the minimum selling price of an emission allowance required for the abatement of these volumes of CO_2. Yet, our finding indicates that this engineering 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.

Table 4. The minimum prices of CO_2 required to organize a club of certain size

Grand Coalition N	Average cost of the entire CCS chain €/(tCO_2 per year)	Condition 1: voluntary adoption of CCS by all members $\underline{p_{CO_2}}$ €/(tCO_2 per year)	Condition 2: existence of an incentive compatible allocation of the total net benefit $p^*_{CO_2}$ €/(tCO_2 per year)
B	55.923	58.390	58.390
F	62.249	66.810	66.810
$F \cap N_{\geq 25ktCO_2}$	62.247	66.810	66.810
$N_{\geq 25ktCO_2}$	59.853	66.792	66.792
N_{All}	59.856	66.801	66.801

Note: All figures are in 2010 euros.

Interestingly, in all these clubs, the condition for the existence of an incentive-compatible allocation of the total net benefit generated by the pipeline system imposes a minimum allowance price $p^*_{CO_2}$ that is identical to $\underline{p_{CO_2}}$. In each of these cases, the core of the cost-sharing game at hand is large enough to allow the pipeline operator to pick a cost allocation that charges each emitter i a revenue r_i that 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 at a carbon price equal to $\underline{p_{CO_2}}$. Hence, these figures suggest that imposing the pipeline operator to use cross-subsidy free prices does not impact the adoption of the CSS technology.

Last but not least, a few words can be added on the absolute levels of these 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.[19]

4.3 An analysis of some conceivable tariffs structures

In the sequel of this paper, we analyze a series of plausible tariffs structure that could be imposed on the CO_2 pipeline operator. 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). In the European natural gas industry, the implementation of such

[19] *A much more voluntarist scenario – 450ppm – from IEA (2011) yields much higher carbon values in 2035, at 120 USD2010 per ton.*

pricing systems is usually motivated by their simplicity and their perceived fairness.[20] 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.

In this subsection, we first detail these two series of conceivable tariffs before discussing the results.

a – 'Postage stamp' pricing systems

We introduce three types of 'postage stamp' tariffs (simple linear tariffs, unique multi-part tariffs, and a menu of multipart tariffs) and detail for each type some possible implementations. For the sake of brevity, all these tariffs are summarized in Table 5.

Simple linear tariffs

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 a supplementary real decision variable: t_Q which is the transportation price per unit volume of CO_2 transported. In the second one (Tariff #PS2), we assume that 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.

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 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.

[20] Regarding the case of natural gas pipelines, we refer to David and Percebois (2004) for a presentation of the 'postage stamp' pricing system implemented in Denmark, Spain, Finland, and Sweden.

Table 5. 'Postage stamp' pricing systems

			Pricing scheme	Comment
Simple linear tariffs	Tariff #PS1	Price variables:	t_Q	a price per unit of volume
		Revenue charged:	$r_i = Q_i t_Q, \quad \forall i \in N. \quad (36)$	
	Tariff #PS2	Price variables:	$t_{\bar{q}}$	a price per unit of capacity
		Revenue charged:	$r_i = \bar{q}_i t_{\bar{q}}, \quad \forall i \in N. \quad (37)$	
Unique multipart linear tariffs	Tariff #PS3	Price variables:	f and t_Q	a fixed charge and a price per unit of volume
		Revenue charged:	$r_i = f + Q_i t_Q, \quad \forall i \in N. \quad (38)$	
	Tariff #PS4	Price variables:	f and $t_{\bar{q}}$	a fixed charge and a price per unit of capacity
		Revenue charged:	$r_i = f + \bar{q}_i t_{\bar{q}}, \quad \forall i \in N. \quad (39)$	
	Tariff #PS5	Price variables:	$t_{\bar{q}}$ and t_Q	a capacity charge and price per unit of volume
		Revenue charged:	$r_i = \bar{q}_i t_{\bar{q}} + Q_i t_Q, \quad \forall i \in N. \quad (40)$	
A menu of multipart tariffs	Tariff #PS6	Price variables:	f^l and $t_Q^l, \quad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a fixed charge and a price per unit of volume
		Revenue charged:	$r_i = \text{Min}_{l\in\{1,2\}} \left\{ f^l + Q_i t_Q^l \right\}, \quad \forall i \in N. \quad (41)$	
	Tariff #PS7	Price variables:	f^l and $t_{\bar{q}}^l, \quad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a fixed charge and price per unit of capacity
		Revenue charged:	$r_i = \text{Min}_{l\in\{1,2\}} \left\{ f^l + \bar{q}_i t_{\bar{q}}^l \right\}, \quad \forall i \in N. \quad (42)$	
	Tariff #PS8	Price variables:	$t_{\bar{q}}^l$ and $t_Q^l, \quad \forall l \in \{1,2\}$	a menu of two two-parts tariffs based on a price per unit of volume, and a price per unit of capacity
		Revenue charged:	$r_i = \text{Min}_{l\in\{1,2\}} \left\{ \bar{q}_i t_{\bar{q}}^l + Q_i t_Q^l \right\}, \quad \forall i \in N. \quad (43)$	

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 contribute to the creation of a large club of CCS users? 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 6). For the sake of clarity, the location-dependent tariff parameters are superscripted with B (respectively F) for Belgian (respectively French) emitters.

Table 6. Location-specific pricing systems

		Pricing scheme	Comment
Simple linear tariffs	Tariff #LS1	Price variables: $\left(t_Q^B, t_Q^F\right)$ Revenue charged: $r_i = Q_i t_Q^B, \quad \forall i \in B, \quad (44)$ $r_i = Q_i t_Q^F, \quad \forall i \in F. \quad (45)$	a price per unit of volume
	Tariff #LS2	Price variables: $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$ Revenue charged: $r_i = \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B, \quad (46)$ $r_i = \bar{q}_i t_{\bar{q}}^F, \quad \forall i \in F. \quad (47)$	a price per unit of capacity
Unique multipart linear tariffs	Tariff #LS3	Price variables: $\left(f^B, f^F\right)$ and $\left(t_Q^B, t_Q^F\right)$ Revenue charged: $r_i = f^B + Q_i t_Q^B, \quad \forall i \in B, \quad (48)$ $r_i = f^F + Q_i t_Q^F, \quad \forall i \in F. \quad (49)$	a fixed charge and a price per unit of volume
	Tariff #LS4	Price variables: $\left(f^B, f^F\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$ Revenue charged: $r_i = f^B + \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B, \quad (50)$ $r_i = f^B + \bar{q}_i t_{\bar{q}}^F, \quad \forall i \in F. \quad (51)$	a fixed charge and a price per unit of capacity
	Tariff #LS5	Price variables: $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$ and $\left(t_Q^B, t_Q^F\right)$ Revenue charged: $r_i = \bar{q}_i t_{\bar{q}}^B + Q_i t_Q^B, \quad \forall i \in B, \quad (52)$ $r_i = \bar{q}_i t_{\bar{q}}^F + Q_i t_Q^B, \quad \forall i \in F. \quad (53)$	a capacity charge and price per unit of volume
A menu of multipart tariffs	Tariff #LS6	Price variables: $\left(f^B, f^{F,1}, f^{F,2}\right)$ and $\left(t_Q^B, t_Q^{F,1}, t_Q^{F,2}\right)$ Revenue charged: $r_i = f^B + Q_i t_Q^B, \quad \forall i \in B,^* \quad (54)$ $r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ f^{F,l} + Q_i t_Q^{F,l} \right\}, \quad \forall i \in F. \quad (55)$	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*	Price variables: $\left(f^B, f^{F,1}, f^{F,2}\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^{F,1}, t_{\bar{q}}^{F,2}\right)$ Revenue charged: $r_i = f^B + \bar{q}_i t_{\bar{q}}^B, \quad \forall i \in B,^* \quad (56)$ $r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ f^{F,l} + \bar{q}_i t_{\bar{q}}^{F,l} \right\}, \quad \forall i \in F. \quad (57)$	a single two-parts tariff for Belgian emitters and a menu of two two-parts tariffs based on a fixed charge and price per unit of capacity for French emitters
	Tariff #LS8*	Price variables: $\left(t_{\bar{q}}^B, t_{\bar{q}}^{F,1}, t_{\bar{q}}^{F,2}\right)$ and $\left(t_Q^B, t_Q^{F,1}, t_Q^{F,2}\right)$ Revenue charged: $r_i = \bar{q}_i t_{\bar{q}}^B + Q_i t_Q^B, \quad \forall i \in B,^* \quad (58)$ $r_i = \mathrm{Min}_{l \in \{1,2\}} \left\{ \bar{q}_i t_{\bar{q}}^l + Q_i t_Q^l \right\}, \quad \forall i \in F, \quad (59)$	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 implemented these tariffs structures within the programs LP3 or MILP6. In Table 7 (respectively Table 8), we report the results obtained when solving these programs for the grand coalition of emitters N_{All} (respectively $N_{\geq 25ktCO_2}$). Several observations can be made from these results.

Table 7. The computed threshold CO_2 prices for the grand coalition N_{All}

	'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)
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	∅

Note: The results reported in the rows (a) were obtained using the linear program LP3. Those reported in the rows (b) have been generated using the mixed integer linear program MILP6. In this table, ∅ indicates that the solution set is empty. 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 adoption of a common 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. That's why, in the sequel of this paper, we focus solely on location-specific pricing systems and no longer refer to the 'postage stamp' pricing systems.

Second, the obligation to use a non-discriminatory pricing scheme for the pipeline component is non-neutral on the minimum incentive-compatible value of the carbon price. No matter what definition is adopted for the grand coalition (either N_{All} or $N_{\geq 25ktCO_2}$), the minimum carbon price values $p^{**}_{CO_2}$ reported in Tables 7 and 8 are systematically larger than the corresponding value $p^{*}_{CO_2}$ obtained with discriminatory pipeline tariffs (cf. the values reported in Table 4). 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 design 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.

Third, designing a non-discriminatory pipeline tariff compatible with the widest possible adoption of CCS technologies is a difficult task! According to the results detailed in Table 7, 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 LP3 or MILP6. 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, Table 8 indicates 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 LP3 or MILP6). Given the limited environmental impact of the two smallest emitters, this finding questions the relevance of a “blanket coverage” target for the CCS infrastructure.

Table 8. The computed threshold CO_2 prices for the grand coalition $N_{\geq 25ktCO_2}$

	'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)
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: The results reported in the rows (a) were obtained using the linear program LP3. Those reported in the rows (b) have been generated using the mixed integer linear program MILP6. In this table, ∅ indicates that the solution set is empty. All figures are in 2010 euros.

Lastly, it is interesting to compare the minimum carbon price $p^{**}_{CO_2}$ 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, or Tariff #LS5 vs. Tariff #LS8). No matter what definition is adopted for the grand coalition N, the obtained prices $p^{**}_{CO_2}$ 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 MILP6 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...

4.4 National vs. supranational regulation for the CO_2 pipeline industry

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, we can check whether or not the implementation of national regulatory constraints has an influence on the minimum price of the CO_2 emission allowance $p_{CO_2}^{**}$.

In the preceding subsection, we implicitly disregarded these national aspects. 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. To simplify, we assume that: (i) there is one regulator in charge of the pipeline subsystem connecting Le Havre to Antwerp, and another one in charge of those connecting Antwerp to Rotterdam; (ii) the pipeline operator is required to maintain a distinct accounting system for each territory; (iii) each regulator demands that the revenues obtained in its jurisdiction recover exactly the total cost incurred on that territory; and (iv) these revenues are cross-subsidy-free.

The modeling framework above (cf. the linear program LP3) can easily be modified to address that case. This gives us the linear program LP7:

LP7:

$$\underset{r_{F\to B},r_{B\to NL},t_{F\to B},t_{B\to NL},p_{CO_2}}{\text{Min}} \quad p_{CO_2} \tag{60}$$

$$\text{s.t.} \quad r_{F\to B} \in \Lambda_{F\to B}, \tag{61}$$

$$r_{B\to NL} \in \Lambda_{B\to NL}, \tag{62}$$

$$\left(r_{F\to B}, r_{B\to NL}, p_{CO_2}\right) \in \left\{\left(r_{F\to B}, r_{B\to NL}\right) \in \mathbb{R}^{|F|}\times\mathbb{R}^{|N|}, p_{CO_2} \in \mathbb{R}_+ : F_{p_{CO_2}}\left(r\right) \geq 0\right\}, \tag{63}$$

$$\left(r_{F\to B}, t_{F\to B}\right) \in \Omega_{F\to B}, \tag{64}$$

$$\left(r_{B\to NL}, t_{B\to NL}\right) \in \Omega_{B\to NL}, \tag{65}$$

where: $r_{F\to B}$ (respectively $r_{B\to NL}$) denotes the revenue vector charged by the pipeline operator to the French emitters for using the pipeline subsystem connecting Le Havre to Antwerp (respectively Antwerp to Rotterdam); the set $\Lambda_{F\to B}$ (respectively $\Lambda_{B\to NL}$) denotes the core of the cost game

$\left(F, C_{F\to B}\right)$ (respectively $\left(N, C_{B\to NL}\right)$); $F_{p_{CO_2}}\left(r\right)$ is the vector where the i^{th} component is the individual benefit of emitter i − i.e., $F_{i,p_{CO_2}}\left(\left(r_{F\to B} + r_{B\to NL}\right)_i\right)$ if $i \in F$ and $F_{i,p_{CO_2}}\left(\left(r_{B\to NL}\right)_i\right)$ if $i \in B$ − and the set $\Omega_{F\to B}$ (respectively $\Omega_{B\to NL}$) describes the tariff structure implemented for the pipeline subsystem connecting Le Havre to Antwerp (respectively Antwerp to Rotterdam). The conditions (61) and (62) compels the pipeline operator to adopt, for each jurisdiction, a cross-subsidy-free pricing policy that recovers exactly the exact total cost incurred on that territory. The conditions (63) represents the emitters' individual participation constraints and the conditions (64) (respectively (65)) describes the pricing scheme imposed by the French (respectively Belgian) regulator.

In Table 9, we report $p_{CO_2}^{**}$ the minimum price of CO_2 obtained while solving the linear program LP7 with a feasible multipart linear tariff similar to #LS4 for each of the two possible definitions of the grand coalition (either N_{All} or $N_{\geq 25ktCO_2}$). With this first tariff structure, both regulators compel the use of a two-part tariff based on a fixed term and a capacity component.

Table 9. The tariff-specific threshold CO_2 prices in case of national-based regulation

Pricing scheme		N_{All} $p_{CO_2}^{**}$ (€/(tCO2 per year)	$N_{\geq 25ktCO_2}$ $p_{CO_2}^{**}$ (€/(tCO2 per year)
Price variables:	$\left(f^B, f^F\right)$ and $\left(t_{\bar{q}}^B, t_{\bar{q}}^F\right)$	78.86	67.57
Revenue charged:	$r_i = f^B + \bar{q}_i t_{\bar{q}}^B,\ \forall i \in B,$ (66) $r_i = \left(f^B + \bar{q}_i t_{\bar{q}}^B\right) + \left(f^F + \bar{q}_i t_{\bar{q}}^F\right),\ \forall i \in F.$ (67)		

Note: These results were obtained using the linear program LP7. All carbon price figures are in 2010 euros.

The comparison of the results reported in Table 9 with those in Table 7 and Table 8 (cf. Tariff LS#4) indicates that a collection of national regulations systematically imposes a net increase in the minimum CO_2 price required for the adoption of the CCS technology (compared to a regulation organized at the EU-level). Though, that net increase remains modest (+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 the institutional scope (national vs. European) of the tariff regulation imposed on the pipeline operators may not play a major role compared to the detailed design of a CO_2 pipeline pricing scheme.

5. 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.

The challenge of this paper is to specify 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 club: the heterogeneity of the likely club members (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 decision makers involved in the institutional design of the CO_2 pipeline industry.

A case study focusing on a Northwestern European CO_2 pipeline project provided us with an opportunity to obtain a series of original findings. First, a preliminary cost-based analysis has confirmed that a CO_2 pipeline system constitutes a sustainable natural monopoly. Accordingly, one can rightly expect the pipeline operator to adopt a pricing policy that insures that none of the possible subcoalitions of emitters has an incentive to drop out the grand coalition and build an alternative infrastructure. Second, a benefit-based perspective confirms that the minimum selling price of an allowance required to obtain the voluntary adoption of the CCS technology by all the emitters (i.e., the price related to Sharkey's participation condition) is significantly larger than the average cost of the entire CCS chain. Third, 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 minimum price of an emission allowance capable of justifying the construction of the pipeline system, or even impede the construction of that infrastructure. Lastly, 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. 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 grandfathering allocation of emission rights. Recent proposals for the Phase III of the European Union Emission Trading Scheme call for a substantial modification of the grandfathering allocation of emission rights. Such a change can modify the emitter's individual incentive to adopt the CCS technology and constitutes an attractive agenda for future research.

References

Al-Juaied, M., & Whitmore, A. (2009). *Realistic Costs of Carbon Capture*. Discussion Paper 2009-08, Energy Technology Innovation Research Group, Belfer Center for Science and International Affairs, Harvard Kennedy School, Cambridge, MA.

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.

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.

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

Chapon, M. (1990). *Conception et Construction des réseaux de transport de gaz, Manuel pour le transport et la distribution du gaz, Livre IX.* Paris: Association Technique de l'Industrie du Gaz en France.

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

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 Coninck, H., Flach, T., Curnow, P., Richardson, P., Anderson, J., Shackley, S., et al. (2009). The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 1. Scientific, technical and economic dimensions. *International Journal of Greenhouse Gas Control*, 3(3), 333–343.

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. (2012). *Using Real Options to Evaluate Optimal Funding Strategies for Carbon Capture, Transport and Storage Projects in the European Union*. Personal Communication.

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

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

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 CO2 emissions: carbon capture or renewables, taxes or subsidies? *The Energy Journal*, 27(3), 25–48.

Golombek, R., Greaker, M., Kittelsen, S.A.C., Røgeberg, O., & Aune, F.R. (2011). Carbon Capture and Storage Technologies in the European Power Market. *The Energy Journal*, 32(3), 209–237.

Grimaud, A., Lafforgue, G., & Magné, B. (2011). Climate change mitigation options and directed technical change: A decentralized equilibrium analysis. *Resource and Energy Economics*, 33(4), 938–962.

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.

Kemp, A.G., & Kasim, A.S. (2008). A Least-Cost Optimisation Model of CO2 Capture Applied to Major UK Power Plants Within the EU-ETS Framework. *The 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). IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge: Cambridge University Press.

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.

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 Thesis. Department of Engineering and Public Policy. Carnegie Mellon University, Pittsburgh, PA.

McCoy, S.T., & Rubin, E.S. (2008). An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage. *International Journal of Greenhouse Gas Control*, 2(2), 219–229.

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.

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.

Sorenson, J.R., Tschirhart, J.T., & Whinston, A.B. (1978). Private Good Clubs and the Core. *Journal of Public Economics*, 10(1), 77–95.

Tzimas, E., Georgakaki, A., Garcia Cortes, C., & Peteves, S.D. (2005). *Enhanced oil recovery using carbon dioxide in the European energy system*. Technical Report EUR 21895 EN, DG JRC, Institute for Energy, Petten, The Netherlands.

Yang, M., Blyth, W., Bradley, R., Bunn, D.W., Clarke, C., & Wilson, T. (2008). Evaluating the power investment options with uncertainty in climate policy. *Energy Economics*, 30(4), 1933–1950.

Appendix A

Proof of Proposition 1 (Sharkey 1982)

If $y \in \Gamma\left(p_{CO_2}\right)$, *then (13) indicates that, for any* $S \subset N$, *we have* $\sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i - F_{i,p_{CO_2}}^{-1}\left(y_i\right)\right] \geq v\left(S, p_{CO_2}\right)$. *Using (9) and rearranging, we obtain that* $\sum_{i\in S} F_{i,p_{CO_2}}^{-1}\left(y_i\right) \leq C\left(S\right)$ *for any* $S \subset N$. *Besides, if* $p_{CO_2} \geq \underline{p_{CO_2}}$ *we have* $v\left(N, p_{CO_2}\right) = \sum_{i\in N}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right] - C\left(N\right)$. *Hence, any* $y \in \Gamma\left(p_{CO_2}\right)$ *implies that* $\sum_{i\in N} F_{i,p_{CO_2}}^{-1}\left(y_i\right) = C\left(N\right)$ *and thus* $F_{p_{CO_2}}^{-1}\left(y\right) \in \Lambda$. *Q.E.D.*

Proof of Lemma 1

The proof requires two independent steps.

<u>STEP #1:</u> Assume a given $y \in \Gamma\left(p_{CO_2}\right)$. *By definition,* y *verifies both:*

$$\sum_{i\in N} y_i = v\left(N, p_{CO_2}\right), \tag{A.1}$$

$$\sum_{i\in S} y_i \geq v\left(S, p_{CO_2}\right), \qquad \forall S \subset N. \tag{A.2}$$

Because of the definition (9), we clearly have $v\left(S, p_{CO_2}\right) \geq \sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right] - C\left(S\right)$ *for each* $S \subset N$. *Besides, we know that* $v\left(S, p_{CO_2}\right) \geq 0$ *for any* $S \subset N$ *which confirms that* $y \in \mathbb{R}_+^{|N|}$. *Hence, we have verified that* $y \in \Upsilon\left(p_{CO_2}\right)$ *and thus* $\Gamma\left(p_{CO_2}\right) \subseteq \Upsilon\left(p_{CO_2}\right)$.

<u>STEP #2:</u> Now, assume a given $y \in \Upsilon\left(p_{CO_2}\right)$. *By definition,* y *verifies both (A.1) and:*

$$\sum_{i\in S} y_i \geq \sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right] - C\left(S\right), \qquad \forall S \subset N. \tag{A.3}$$

For each $S \subset N$ *and any* $R \subset S \setminus \{\varnothing, N\}$, *we have:* $|R| < |S|$ *and thus* $\sum_{i\in S} y_i \geq \sum_{i\in R} y_i$ *because* $y \in \mathbb{R}_+^{|N|}$. *As* $y \in \Upsilon\left(p_{CO_2}\right)$, *the condition (A.3) holds for each coalition* $R \subset S \setminus \{\varnothing, N\}$ *and thus:* $\sum_{i\in R} y_i \geq \sum_{i\in R}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right] - C\left(R\right)$. *Hence, we have for any coalition* $S \subset N$ *:*

$$\sum_{i\in S} y_i \geq \sum_{i\in R}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(R), \qquad \forall R\subset S\setminus\{\varnothing,N\}. \qquad (A.4)$$

The inequalities (A.3) and (A.4) jointly indicate that:

$$\sum_{i\in S} y_i \geq \underset{R\subseteq S}{\mathrm{Max}} \left\{\sum_{i\in R}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(R)\right\}, \qquad \forall S\subseteq N. \qquad (A.5)$$

As a result, we have $y\in\Gamma\left(p_{CO_2}\right)$ *which proves that* $\Upsilon\left(p_{CO_2}\right)\subseteq\Gamma\left(p_{CO_2}\right)$. *To conclude, we have proven that* $\Upsilon\left(p_{CO_2}\right)=\Gamma\left(p_{CO_2}\right)$.

Q.E.D.

Proof of Proposition 2

Again, the proof requires two independent steps.

STEP #1: *Assume a given cost allocation* $r\in\Lambda\cap\left\{r\in\mathbb{R}^{|N|}:F_{p_{CO_2}}(r)\geq 0\right\}$. *By definition,* r *verifies* $F_{p_{CO_2}}(r)\geq 0$.

By construction, r *verifies the condition (3) and thus* $\sum_{i\in N}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i-r_i\right]=\sum_{i\in N}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(N)$. *As* $p_{CO_2}\geq \underline{p_{CO_2}}$, *we have:* $\sum_{i\in N}F_{p_{CO_2}}(r_i)=v\left(N,p_{CO_2}\right)$.

By construction, r *also verifies the condition (2) which indicates that, for any* $S\subset N$, *the inequality* $\sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i-r_i\right]\geq\sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(S)$ *holds and thus:* $\sum_{i\in S}F_{p_{CO_2}}(r_i)\geq\sum_{i\in S}\left[\left(p_{CO_2}-\chi_i-\sigma\right)Q_i\right]-C(S)$.

Hence, we have verified all the conditions for $F_{p_{CO_2}}(r)\in\Upsilon\left(p_{CO_2}\right)$. *Applying the result stated in Lemma 1 and using a set-based notation allows us to write:*

$$F_{p_{CO_2}}\left(\Lambda\cap\left\{r\in\mathbb{R}^{|N|}:F_{p_{CO_2}}(r)\geq 0\right\}\right) \subseteq \Gamma\left(p_{CO_2}\right). \qquad (A.6)$$

STEP #2: *Now, assume a given incentive-compatible allocation* $y\in\Gamma\left(p_{CO_2}\right)$. *Then, Lemma 1 indicates that* $y\in\Upsilon\left(p_{CO_2}\right)$. *Now, consider the cost allocation* $F^{-1}_{p_{CO_2}}(y)$.

As $y \in \mathbb{R}_+^{|N|}$, *the allocation verifies* $F_{p_{CO_2}}^{-1}(y) \in \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}$. *Besides, we assumed that* $p_{CO_2} \geq \underline{p_{CO_2}}$ *so using Proposition 1,* $F_{p_{CO_2}}^{-1}(y) \in \Lambda$. *Thus,* $F_{p_{CO_2}}^{-1}(y) \in \Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}$.

By construction, $F_{p_{CO_2}}\left(F_{p_{CO_2}}^{-1}(y)\right) \in F_{p_{CO_2}}\left(\Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}\right)$ *which proves that:*

$$F_{p_{CO_2}}\left(F_{p_{CO_2}}^{-1}\left(\Gamma\left(p_{CO_2}\right)\right)\right) \subseteq F_{p_{CO_2}}\left(\Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}\right). \qquad (A.7)$$

As $F_{p_{CO_2}} \circ F_{p_{CO_2}}^{-1}$ *is equal to the identity function, (A.7) can be rewritten as* $\Gamma\left(p_{CO_2}\right) \subseteq F_{p_{CO_2}}\left(\Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}\right)$ *which complete the second step.*

To conclude, we have proven that: $\Gamma\left(p_{CO_2}\right) = F_{p_{CO_2}}\left(\Lambda \cap \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}}(r) \geq 0 \right\}\right)$. *Q.E.D.*

Proof of Proposition 3

To begin with, we have to show that there exists a solution to LP2. For any $r \in \Lambda$, *the condition* (2) *imposes some bounds on the individual revenues. Thus, the individual benefits verify:* $F_{i,p_{CO_2}}(r_i) \geq \left(p_{CO_2} - \chi_i - \sigma\right)Q_i - C(\{i\})$ *for any* i. *As a result, any price* p_{CO_2} *with* $p_{CO_2} \geq \mathrm{Max}_{i\in N}\left\{\chi_i + C(\{i\})/Q_i\right\} + \sigma$ *verifies the conditions for* $F_{p_{CO_2}}(r) \geq 0$ *and thus the conditions for a non-empty feasible set for the program LP2.*

Now, we consider a solution $\left(p_{CO_2}^*, r^*\right)$ *of LP2. By construction,* $p_{CO_2}^*$ *is unique and* $r^* \in \left\{ r \in \mathbb{R}^{|N|} : F_{p_{CO_2}^*}(r) \geq 0 \right\}$. *Thus, for any coalition of players* $S \subset N$, *we have:*

$$\sum_{i\in S}\left[\left(p_{CO_2}^* - \chi_i - \sigma\right)Q_i\right] \geq \sum_{i\in S} r_i^* . \qquad (A.8)$$

Using the fact that $\sum_{i\in S} r_i^* = \sum_{i\in N} r_i^* - \sum_{i\in N\setminus S} r_i^*$ *and remarking that* $r^* \in \Lambda$, *we can write:*

$$\sum_{i\in S} r_i^* \geq C(N) - C(N\setminus S). \qquad (A.9)$$

Combining (A.8) and (A.9) and rearranging is sufficient to conclude that $p_{CO_2}^* \geq \underline{p_{CO_2}}$.

Q.E.D.

Appendix B - The long-run total cost function, an engineering model

In this Appendix, we clarify the methodology used to evaluate the long-run total cost of a CO_2 trunkline system (e.g., from Le Havre to Antwerp and from Antwerp to Rotterdam).

From a technological perspective, the CO_2 trunkline at hand can be decomposed into two subsystems: a first pipeline system connects Le Havre to Antwerp (distance 427 kilometers) and a second pipeline system connects Antwerp to the Rotterdam area (distance 164 kilometers). Each of these two subsystems can have a specific design (pipeline diameter; operating pressures...).

For each subsystem, our cost estimates are based on the following hypotheses:

- there are negligible differences in elevation along the projected routes;
- the pipeline's lifetime is 30 years;
- the real interest rate used in the analyses is 8.00%;[21]
- the exchange rate used in the analysis is 1.30 USD = 1.00 Euro;
- the future hourly flow rates of CO_2 that will be transported during the plant's lifetime are known ex ante;
- a one-year periodicity is assumed for these hourly flow rates so that the design of the infrastructure can be chosen so as to minimize the annual equivalent cost to transport the flows of CO_2 observed during a typical year;
- the terminal pressure at the delivery point is equal to those measured at the inlet of the system;
- several compression stations can possibly be installed along the pipe. In that case, we follow the rule of thumb detailed in Chapon (1990) and implicitly used in McCoy (2009, chapter 2)[22] and assume: (i) that there is a unique pipe-diameter for each subsystem; (ii) that these compression stations are regularly spaced along the pipeline; and (iii) that all these compression stations are operated at the same regime so that a unique compression ratio is used for all the compressors installed along the pipeline.[23]
- the size of the compressor equipments is imposed by the peak hourly flow rate, but on a given hour, their rate of use (and thus, the variable cost of the energy required to power these equipments during that hour) is imposed by that hour's output. The amount of energy required

[21] *To our knowledge, there is no foolproof way of choosing this rate. This figure is coherent with those typically used in Northwestern Europe for natural gas pipelines.*

[22] *A pipeline expert might argue that some of these hypotheses could be relaxed to obtain a slightly lower cost (e.g., the assumption of equally spaced stations as in André and Bonnans, 2011). Nevertheless, we proceed assuming that this engineering-based model conveys a sufficient level of sophistication to capture the essential features of the technology of a CO_2 trunkline system.*

[23] *Thus, the whole subsystem can be described as a sequence of identical elementary modules (each module includes a compressor station and a pipeline segment) that are serially connected one to the other.*

for compression purposes is obtained using the engineering relations detailed in McCoy (2009, subsection 2.1.3 and Appendix A).

These hypotheses together with the engineering process model detailed in McCoy (2009) allows us to compute, for any vector of future hourly flow rates of CO_2, the long-run cost-minimizing design of a point-to-point CO_2 pipeline infrastructure (i.e., the optimal value of the pipeline diameter, the number and the size of the compressor stations, the amount of energy used for compression purposes).