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# Kickstarting CCS Adoption: Tailoring Subsidies to Emitters' Needs

Adrien Nicolle\*      David Lowing\*      Diego Cebreros\*

## Abstract

Despite being an essential technology in industrial decarbonization scenarios, Carbon Capture and Storage (CCS) struggles to achieve large-scale deployment. Indeed, emitters face a coordination problem, which prevents them from forming the critical mass the transportation operator needs to develop a network that leverages economies of scale. In response, many public entities have multiplied financing mechanisms to support CCS adoption. However, current subsidy mechanisms overlook the network infrastructure and do not acknowledge the heterogeneity of emitters. This paper introduces a methodology for distributing subsidies among industrial emitters based on their capture costs and network cost contribution while accounting for potential budgetary constraints. Firstly, we evaluate each emitter's contribution to the network cost through the Shapley value. Secondly, we define each emitter's subsidy claim by combining results from the first step with their capture cost. We then distribute the subsidies according to the Proportional bankruptcy solution (i.e., proportionally to each emitter's claim). We justify this solution based on properties (axioms) we desire our subsidy distribution to verify. A key feature of our methodology is its flexibility. Indeed, each step can be adapted to suit the normative framework that a future study or policy-maker wishes to posit. We apply our methodology to CCS deployment in France and compare our results to the conservative case where subsidies are distributed without considering the network. Our case study shows that our methodology leads to a more favorable subsidy distribution to upstream emitters (i.e., whose emissions pass through many pipelines), which are the most influential in CCS adoption.

**Keywords:** CCS, Cooperative Games, Bankruptcy, Subsidy.

**JEL code:** C61, C71, H23

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# 1 Introduction

Carbon capture and storage (CCS) is gaining strong momentum, with more than 200 projects announced in the past year (IEA, 2024). This recent enthusiasm contrasts with a roll-out that has so far been doomed, with less than a quarter of the announced large projects entering operation (Wang et al., 2021). Furthermore, even if all these projects were to proceed, the cumulative capture capacity would only reach 400 million tons of CO<sub>2</sub> per year (MtCO<sub>2</sub>/y), far from the expected 1.6 GtCO<sub>2</sub>/y by 2030 (IEA, 2021) or 3 GtCO<sub>2</sub>/y by 2050 in the industrial sector only (IPCC, 2018).

Reaching the above figures requires building a costly CCS network infrastructure connecting emitters to storage sites. As in other networks, CCS pipeline transportation exhibits strong economies of scale and is the most cost-efficient transportation option in the long run (Ouvray et al., 2024). To harness these economies of scale, it is therefore necessary to create industrial clusters in which emitters share the transportation and storage (T&S) infrastructure (Brownsort et al., 2016). Forming CCS clusters can be challenging as an industrial emitter waits for the T&S infrastructure before investing into carbon capture and, conversely, the T&S operator builds a T&S network only if a critical mass of emitters is willing to connect to it. Thus, CCS deployment faces a chicken-and-egg dilemma (European Commission et al., 2023; Herzog, 2011). As an illustration of this challenge, current projects mainly operate as vertically integrated systems (Fattouh et al., 2024) - thus overlooking potential economies of scale of a shared T&S infrastructure.

We identify two main underlying problems to the CCS chicken-and-egg dilemma. The first issue is the lack of a clear regulatory framework for T&S tariffs. Because poorly designed future regulations could prevent the T&S operator from recovering its costs, it prefers not to invest in the T&S network. Similarly, an emitter could be exposed to monopoly tariffs without regulation, making its investment in capture more costly than emitting CO<sub>2</sub> directly into the atmosphere. Thus, without a clear regulatory framework, neither party commits to CCS. In this perspective, the CCS community perceived the lack of a clear regulatory framework as the main obstacle to reaching commercial-scale deployment (Davies et al., 2013). A decade later, regulation of T&S tariffs is still fuzzy and unclear in practice (Nicolle et al., 2023). However, studies by Massol et al. (2015, 2018) have addressed this issue by considering the impact of regulated T&S tariffs on carbon capture adoption by industrial emitters.

The second issue is the coordination of heterogeneous emitters to attain a critical mass. Indeed, due to the various industrial processes (Leeson et al., 2017; Roussanaly

et al., 2021) and purity of the flows (Naims, 2016), emitters face different capture costs. Moreover, some industries have a lack of alternatives to reduce their emissions while others have various options (Gerres et al., 2019). Consequently, under a similar economic incentive (such as the EU-ETS allowance price), emitters do not have the same willingness to join the CCS infrastructure. Thus, emitters face a coordination problem as described in Sákovic and Steiner (2012). According to the authors, public intervention in the form of appropriately distributed subsidies can overcome the coordination problem and avoid additional costs. In the case of CCS, appropriate subsidies could encourage enough emitters to invest in carbon capture simultaneously, thereby forming the critical mass needed for a T&S operator to invest in a network leveraging economies of scale.

In the literature, the coordination of heterogeneous emitters through subsidies has yet to receive attention. The study by Comello and Reichelstein (2014) identifies the subsidy path required by natural gas power plants to adopt carbon capture and meet an emissions' standard. While their study identifies the minimal subsidy budget to overcome the coordination problem, they consider homogeneous agents and overlook the T&S network in the distribution of subsidies. A second body of literature based on cooperative game theory (Massol et al., 2015, 2018) and mixed complementarity problems (Mendelevitch, 2014) addresses the investment and operational decisions of heterogeneous industrial emitters. These studies include T&S aspects in the emitters' investment decisions. However, both studies incentivize CCS through a unique CO<sub>2</sub> price, thus ignoring dedicated subsidies to overcome the emitters' coordination problem. In contrast, a last strand of literature relying on real options detail the investment decision of a single emitter by considering subsidies (see the literature review by Agaton (2021)). However, these studies adopt a project-by-project approach (i.e., a single emitter), thus overlooking potential synergies between projects.

In practice, public entities have multiplied financing mechanisms to support CCS in the past years to encourage investment, but they seem to follow the same flaws as the literature. Indeed, subsidies are generally provided project-by-project, do not unveil the rationale behind the subsidy distribution, and do not acknowledge the heterogeneity of industrial emitters (see Fattouh et al. (2024) and GCCSI (2023) for a description of current funding mechanisms). Moreover, most subsidy mechanisms target only one stage of the CCS infrastructure. As a result, for a CCS project to be subsidized and thus viable, emitters must turn to one subsidy fund, while the T&S operator must turn to another. In the worst case, the CCS project can be abandoned because one of the agents did not receive the hoped-for subsidy.

Overall, the literature has not dealt with the emitters' coordination problem un-

derlying the CCS chicken-and-egg dilemma and has not provided a general framework for distributing subsidies to industrial emitters. Thus, our research question is: How should CCS subsidies be distributed among emitters to kickstart CCS adoption?

To address this question, we develop a two-step methodology. In the first step, based on emitters' capture cost and a T&S network plan, our methodology assesses each emitter's funding need, hereafter referred to as each emitter's claim. Since T&S tariffs are unclear in the general case, we define an emitter's claim as the sum of its annual capture costs and network cost contribution - i.e., not the sum of its capture cost and the T&S tariff charged by a T&S operator. Because this first stage primarily consists of allocating the network cost among emitters, it relies on elements of game theory such as the Shapley value (Shapley, 1953). Before proceeding with the second step, we assume that the sum of the claims exceeds the budget allocated to the public entity in charge of kickstarting CCS. Thus, we define a simple claims problem as detailed by O'Neill (1982). This seminal paper has given rise to a literature that identifies distribution rules (so-called bankruptcy solutions) for solving claims problems (Thomson, 2003, 2015). A particular strength of bankruptcy solutions is that they can be disaggregated into axioms (see Thomson (2015) for a survey on axiomatic characterizations of popular bankruptcy solutions). In this context, selecting one bankruptcy solution over another implies selecting the axioms that the user desires the resulting allocation to respect. Consequently, in the second step of our methodology, we start by selecting axioms relevant to the CCS context. These axioms define the Proportional solution, which distributes subsidies proportionally to emitters' claims. This solution is generally considered as the definition of fairness (Thomson, 2003). In the Appendix, we suggest other relevant desirable axioms - and thus bankruptcy solutions.

We apply our methodology to the case of France, whose government wishes to support CCS deployment through subsidies over the next decade (Comité national de l'industrie, 2023). We compare our results to the case where the emitters' claims are solely defined based on capture costs, similar to existing support mechanisms in Denmark (Danish Energy Agency, 2023; European Commission, 2023) and the Netherlands (Ministry of Economic Affairs and Climate Policy, 2023). Although the T&S network represents a small share of the CCS costs (less than 15% in our case), including it in the emitters' claims disrupts the distribution of subsidies, thus implying that policymakers should not overlook it when designing the subsidy distribution. In particular, we find that an emitter whose emissions pass through a large part of the network receives 40% more subsidies than in cases where claims are based solely on capture. Indeed, these upstream emitters reduce the transportation cost of other emitters.

The contributions of our paper are two-fold. First, we highlight the emitters’ coordination problem and the need for public intervention through dedicated subsidies, which have yet to receive attention from policymakers and the CCS literature. From a policymaking perspective, we provide a subsidy distribution that acknowledges emitters’ heterogeneity, avoids strategic behavior, and incorporates all the components of a CCS infrastructure. Secondly, we present a methodology that formalizes the design of CCS subsidy mechanisms. Indeed, our methodology provides a flexible framework in which future studies can adapt the approach of each step: in the first step, future studies could replace the Shapley value with prevailing regulated T&S tariffs; in the second step, due to the axiomatic characterization of bankruptcy solutions, future studies could select axioms different from those retained in this study, thus obtaining a new distribution rule. Therefore, our methodology is part of a flexible normative framework that can be adjusted case-by-case.

The paper is organized as follows: in Section 2 we introduce the theoretical background, in Section 3, we present the methodology for the cooperative game and the bankruptcy approaches. In Section 4 we illustrate our methodology with the case of CCS deployment in France. We discuss our results in Section 5. Lastly, we conclude our paper in section 6.

## 2 Theoretical background

In this section, we introduce key concepts for our methodology. First, in Subsection 2.1, we provide some preliminaries on cooperative game theory, a research field well-known for addressing economic allocation problems where agents can benefit from coordinating with each other. Next, Subsection 2.2 discusses bankruptcy theory, another research field within game theory that studies resource allocation under budget constraints. Finally, Subsection 2.3 introduces the formalism of graph theory.

In the rest of the paper, we let  $N \subset \mathbb{N}$  be a finite and countable set of objects. The cardinality of  $N$ , i.e., the number of elements of  $N$  is denoted by  $|N|$ . For each real-valued vector  $x \in \mathbb{R}^{|N|}$ , the sum of the coordinates of  $x$  is denoted by the norm  $\|x\| = \sum_{i \in N} x_i$ .

### 2.1 Cooperative game theory

Consider a non-empty and finite set  $N \subset \mathbb{N}$  of economic agents referred to as **players**. Any subset  $E \in 2^N$  is called a **coalition**, representing a group of cooperating players. The grand coalition  $N$  represents the scenario where all players cooperate, while

the empty coalition  $\emptyset$  depicts a situation with no cooperation. A transferable utility game, abbreviated as a **TU-game**, is defined as a pair  $(N, v)$  consisting of a finite player set  $N \subset \mathbb{N}$  and a **characteristic function**  $v : 2^N \rightarrow \mathbb{R}$ , with  $v(\emptyset) = 0$ . The real number  $v(E)$  can be interpreted as the cost generated by the players in coalition  $E$  when they collaborate. The class of TU-games with a finite set of players is denoted by  $\mathbb{G}$ . A TU-game  $(N, v) \in \mathbb{G}$  is **submodular** if  $v(E) + v(T) \geq v(E \cup T) + v(E \cap T)$  for any two  $E, T \in 2^N$ . A submodular game is a game in which it is highly beneficial for players to cooperate with each others.<sup>1</sup>

A fundamental concern in TU-game theory revolves around the distribution of the grand coalition's cost  $v(N)$  among the players. This concern is addressed by **single-valued solutions** for TU-games. In a TU-game  $(N, v) \in \mathbb{G}$ , each player  $i \in N$  may obtain a payoff. A payoff vector  $x \in \mathbb{R}^{|N|}$  is a  $|N|$ -dimensional vector assigning a payoff  $x_i \in \mathbb{R}$  to each player  $i \in N$ . A single-valued solution, or a value, is a mapping  $f : \mathbb{G} \rightarrow \mathbb{R}$  that assigns a unique payoff vector  $f(N, v)$  to each  $(N, v) \in \mathbb{G}$ .

The **Shapley value**, introduced by Shapley (1953), stands out as arguably the most prominent single-valued solution for TU-games. Its definition unfolds as follows. Imagine the grand coalition forming step by step, starting from the empty coalition  $\emptyset$ . At each step, a player joins the coalition, and this formation process follows a linear order  $\theta \in \Theta_N$  defined over the player set  $N$ , where  $\Theta_N$  represents the set of all possible linear orders over  $N$ . The step  $\theta(i)$  denotes the step when player  $i \in N$  enters. Upon a player's entry, there is a positive or negative impact on the coalition's cost. This impact is termed the **marginal contribution** of a player  $i \in N$  to a coalition  $E \in 2^{N \setminus \{i\}}$  within a game  $(N, v) \in \mathbb{G}$  and is expressed as  $v(E \cup \{i\}) - v(E)$ . The Shapley value assigns to each player its average contribution to coalitions, assuming that the linear orders in  $\Theta_N$  occur with equal probability.

**Definition 1 (Shapley value).** *The Shapley value is the value  $Sh$  on  $\mathbb{G}$  defined, for each  $(N, v) \in \mathbb{G}$ , as*

$$\forall i \in N, \quad Sh_i(N, v) = \frac{1}{|\Theta_N|} \sum_{\theta \in \Theta_N} [v(E^{\theta, i} \cup \{i\}) - v(E^{\theta, i})].$$

where  $E^{\theta, i} = \{j \in N : \theta(j) < \theta(i)\}$  is the set of predecessors of  $i \in N$  with respect to  $\theta$ .

The Shapley value always prescribes **efficient** payoff vectors, meaning that, for each  $(N, v) \in \mathbb{G}$ , it holds that  $\|Sh_i(N, v)\| = v(N)$ . The value is known to satisfy a number

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<sup>1</sup>Note that submodularity is considered a desirable property in our context, particularly when coalitions incur costs. In other contexts where coalitions generate positive utilities, submodularity may be less desirable, and one might prefer the property of supermodularity, which is the converse of submodularity.

of other interesting properties with economic interpretations (see Winter (2002) and Algaba et al. (2019)) that emphasize its appeal. Among these properties, it is well-known that the Shapley value prescribes **coalition rational** payoff vectors on submodular TU-games. A payoff vector  $x \in \mathbb{R}^{|N|}$  is coalition rational if no coalition of players has an interest to split off from cooperation, i.e.,  $\sum_{i \in E} x_i \geq v(E)$  for each  $E \in 2^N$ .

The set of efficient and coalition rational payoff vectors associated with a game is known as its **Core**. The Core of a game can be interpreted as the set of stable payoff vectors, meaning that payoff vectors within this set incentivize players to participate in cooperation.

**Definition 2 (Core).** *For each  $(N, v) \in \mathbb{G}$ , the Core  $C(N, v)$  of  $(N, v)$  is defined as the set of efficient and coalition rational payoff vectors.*

Obviously, if a TU-game is submodular, then the Shapley prescribes a payoff vector in the Core. Consequently, on submodular games, the Shapley value always prescribes payoffs that incentivize players to cooperate.<sup>2</sup>

## 2.2 Bankruptcy theory

An endowment  $\mathcal{E} \in \mathbb{R}_+$  has to be divided among a set  $N$  of agents with claims adding up to more than  $\mathcal{E}$ . For each  $i \in N$ , let  $c_i \in \mathbb{R}_+$  denote agent  $i$ 's claim, and  $c = (c_i)_{i \in N}$  vector of claims. Altogether, a bankruptcy problem is a tuple  $(N, c, \mathcal{E})$  such that  $\sum_{i \in N} c_i \geq \mathcal{E}$ . Let  $\mathbb{B}$  denote the class of all bankruptcy problems. A solution for bankruptcy problems is a function that associates, to each  $(N, c, \mathcal{E}) \in \mathbb{B}$ , an award vector  $f(N, c, \mathcal{E}) \in \mathbb{R}^{|N|}$  whose coordinates add up to  $\mathcal{E}$  and satisfy the inequality  $0 \leq f_i(N, c, \mathcal{E}) \leq c_i$  for each  $i \in N$ . In this paper, we consider the Proportional solution to conduct our study. Alternative solutions are discussed in Appendix D. The Proportional solution assigns an award to each claimant proportional to their (relative) personal claim.

**Definition 3.** *Consider any  $(N, c, \mathcal{E}) \in \mathbb{B}$ . The **Proportional** solution  $P$  is defined as*

$$\forall i \in N, \quad P_i(N, c, \mathcal{E}) = \frac{c_i}{\sum_{j \in N} c_j} \mathcal{E}.$$

On the full domain of bankruptcy problems  $\mathbb{B}$ , the Proportional solution can be characterized by a combination of desirable properties, called axioms. This result is due to

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<sup>2</sup>This result is also formulated in terms of supermodularity, a concept opposite to submodularity, in contexts where coalitions generate positive utilities.

Moreno-Ternerero (2006) and it invokes two axioms. We provide the formal expression of these axioms along with their (general) economic interpretations.

1. **Claim monotonicity:** for each  $(N, c, \mathcal{E}) \in \mathbb{B}$ , each  $\lambda \in \mathbb{R}_{++}$  and each  $i \in N$ ,  $f_i(N, \mathcal{E}, c + \lambda e_i) \geq f_i(N, c, \mathcal{E})$ .
2. **Non-manipulability:** for each  $(N, c, \mathcal{E}), (N', c', \mathcal{E}) \in \mathcal{B}$  with  $N' \subset N$ , if there is a  $i \in N'$  such that  $c'_i = c_i + \sum_{j \in N \setminus N'} c_j$  and  $(c'_j)_{j \in M \setminus i} = (c_j)_{j \in M \setminus i}$ , then

$$f_i(N', c', \mathcal{E}) = f_i(N, c, \mathcal{E}) + \sum_{j \in N \setminus N'} f_j(N, c, \mathcal{E}).$$

Claim monotonicity states that if an agent's claim increases, ceteris paribus, then they should receive at least as much as they did initially. Non-manipulability prevents strategic behavior. It states that if there is no incentive for a group of claimants to merge their claims into a single one or for a single agent to represent their claim as a collection of several claims.

**Theorem 1 (Moreno-Ternerero (2006)).** *A solution  $f$  on  $\mathbb{B}$  is the  $P$  solution if and only if it satisfies Claim monotonicity and Non-manipulability.*

## 2.3 Graph theory

Let  $M \subset \mathbb{N}$  be a finite set of objects. A **directed graph** on  $M$  is a pair  $(M, P)$  where elements of  $M$  are the nodes and  $P : M \rightarrow 2^M$  is a map describing the links between the nodes. We assume that  $i \notin P(i)$  for any  $i \in M$ . In the following, we denote a directed graph  $(M, P)$  just by  $P$ . For each  $i \in M$ , the nodes in  $P(i)$  are called the successors of  $i$ . The nodes in  $P^{-1}(i) = \{i' \in M : i \in P(i')\}$  are called the predecessors of  $i$ . A **directed path** from  $i \in M$  to  $i' \in M$  is a sequence of nodes  $i = h_1, h_2, \dots, h_k = i'$  such that  $h_k \in P(h_{k-1}), \dots, h_2 \in P(h_1)$ . The transitive closure of a directed graph  $P$  is a directed graph  $\hat{P}$ , such that, for each  $i \in M$ ,  $i' \in \hat{P}(i)$  if and only if there exists a path from  $i \in M$  to  $i' \in M$ . The nodes in  $\hat{P}(i)$  are called the subordinates of  $i$  in  $P$ , and the nodes in  $\hat{P}^{-1}(i)$  are called the superiors of  $i$  in  $P$ . Similarly, the set  $\hat{P}(E)$  represents the subordinates of the nodes in  $E \subseteq M$  and the set  $\hat{P}^{-1}(E)$  represents the superiors of the nodes in  $E \subseteq M$ .

**Definition 4.** *A directed graph is a **tree graph** if and only if there is a unique sink  $i_0 \in M$  such that (i) the sink has no successor, i.e.,  $P(i_0) = \emptyset$ , (ii) the superiors of the sink are all the other nodes, i.e.,  $\hat{P}^{-1}(i_0) = M \setminus \{i_0\}$ , and (iii), each node aside from the sink has exactly one successor, i.e.,  $|P(i)| = 1$  for each  $i \in M \setminus \{i_0\}$ .*

## 3 Methodology

In this section, we present our methodology for distributing a subsidy among industrial CO<sub>2</sub> emitters. First, Subsection 3.1 formalizes our research question by introducing all the inputs and by defining the scope of our problem. It then provides a brief overview of the two steps of our methodology. Subsection 3.2 and Subsection 3.3 delve deeper into the explanation of our methodology, expanding upon the theoretical background covered in the previous section.

### 3.1 Problem formulation

**Inputs:** Let  $\mathcal{E} \in \mathbb{R}_+$  be the **subsidy budget** a public entity can afford to distribute. Let  $N = \{a, b, \dots, n\}$  be a finite set of industrial **emitters**. Each emitter  $i \in N$  is endowed with a real  $x_i \in \mathbb{R}_+$  corresponding to its **capture cost**. The vector  $x \in \mathbb{R}_+^n$  collects all capture costs. Let  $i_0$  denote the storage. Constructing and managing a transportation network to link the emitters to storage is costly. To maximize economies of scale, it is necessary for emitters to cooperate in order to build an optimal network that minimizes transportation costs. In this paper, we use a Mixed Integer Linear Program (MILP) to determine such a **cost-optimal network**. Consequently, we obtain a tree graph  $(N \cup \{i_0\}, P)$ , or  $P$  for short, representing the (cost-optimal) transportation network. In this graph, nodes correspond to emitters, links represent pipelines, and the storage node serves as the sink. In addition, each pipeline is endowed with a real number  $y_{ij} \in \mathbb{R}_+$ , where  $i, j \in N \cup \{i_0\}$  such that  $P(i) = j$ . This  $y_{ij}$  corresponds to the **transportation cost** generated by the pipeline linking emitters  $i$  and  $j$ . The vector of all transportation costs is given by  $y \in \mathbb{R}_+^n$ . For the rest of this paper,  $\mathcal{E}$ ,  $N$ ,  $x$ ,  $P$  and  $y$  are treated as inputs.

**Problematic:** We consider a public entity that wishes to kickstart the adoption of CCS by subsidizing industrial emitters. However, the subsidy budget the entity can afford to distribute does not cover the total costs faced by the emitters, i.e.,  $\mathcal{E} \leq \|x\| + \|y\|$ . In fact, the subsidy budget does not even cover capture costs, i.e.,  $\mathcal{E} \leq \|x\|$ . The problem addressed in this paper is to determine a fair and relevant methodology to distribute  $\mathcal{E}$  among the emitters according to their capture costs and their location on the network. We denote this type of problems by a tuple  $(\mathcal{E}, N, x, P, y)$ , and their domain by  $\mathbb{E}$ .

**Methodology:** We propose a two-step methodology as illustrated by Figure 1. In the **first step**, we evaluate the contribution to the network cost  $\|y\|$  of each emitter. This step is grounded in cooperative game theory and is based on the Shapley value. Doing

so, we obtain for each emitter  $i \in N$  a contribution to network cost  $Sh_i$ . This step has two advantages: (i) due to the specific structure of our problem, the Shapley value can be computed in polynomial time (see Algorithm 1); (ii) it appears that the Shapley value satisfies a form of Core-stability in our context, meaning that no emitter has an incentive to leave the coalition. Combining the capture cost  $x_i$  of emitter  $i$  with its contribution to the network cost  $Sh_i$ , we obtain the claim  $c_i$  of  $i$ , which corresponds to the theoretical cost this emitter faces in the coordination problem. In the **second step** of the methodology, we operate the actual subsidy distribution. As the public budget  $\mathcal{E}$  is insufficient to cover all emitters' claims, i.e.  $\|c\|$ , we use the Proportional solution from bankruptcy theory. The two axioms characterizing the solution, i.e., Non-manipulability and Claim monotonicity, have meaningful interpretations in our context. This second step results in a subsidy distribution that partially covers each emitter's subsidy claim. Thus, we assume that an emitter receiving partial subsidies closes the remaining financing gap through its own finances.<sup>3</sup>

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<sup>3</sup>In Appendix D, we discuss alternatives solution for bankruptcy problems that satisfy some claims entirely.

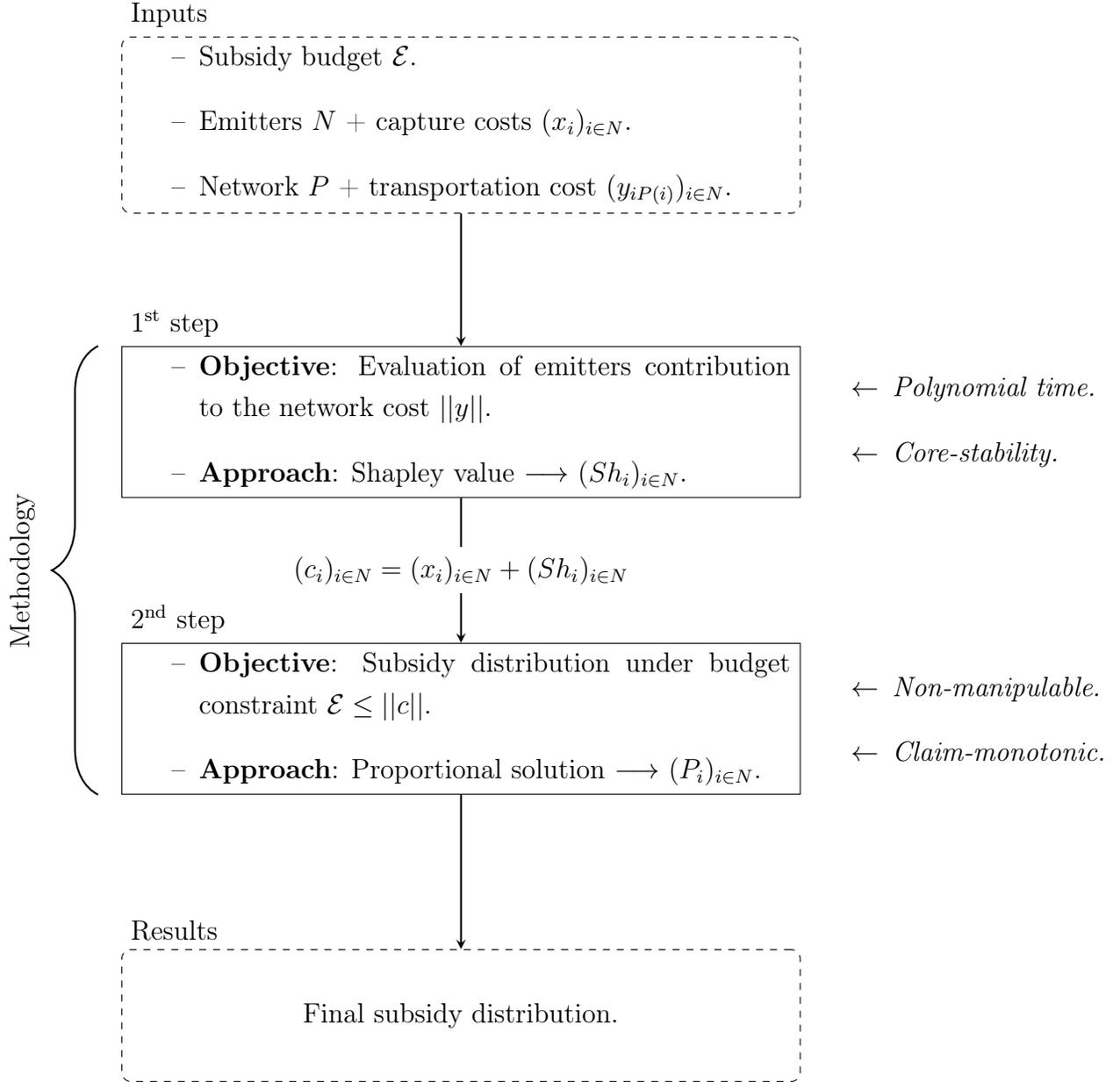


Figure 1: Two-steps methodology

### 3.2 First step: dividing network cost

In this step, we divide network cost among the emitters so that an emitter's share reflects its contribution to the total cost of the network. In economic literature, numerous studies have addressed the problem of dividing costs among a set of agents situated on a fixed tree graph (see, for instance, Littlechild and Owen (1973), Ni and Wang (2007), Dong et al.

(2012), van den Brink et al. (2018), and Oishi et al. (2023)). In these studies, the authors often apply the Shapley value to a specific TU-game that incorporates information about the costs and the tree graph. This approach allows for a fair division of costs among agents. We follow their approach and define TU-games that capture the economic characteristics of a transportation network. We call them **network games** and provide the following definition.

**Definition 5.** *Pick any problem  $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$ . The corresponding network game is the couple  $(N, v^P)$ , where  $v^P : 2^N \rightarrow \mathbb{R}$  is defined as*

$$\forall E \in 2^N, \quad v^P(E) = \sum_{i \in \hat{P}(E) \cup E} y_{iP(i)}.$$

The network game associates, to each coalition of emitters  $E$ , the cost of a hypothetical sub-network sufficient to connect these emitters to the sink. Obviously, it holds that  $v^P(N) = \|y\|$  and  $v^P(\emptyset) = 0$ . The class of all network games obtainable from problems in  $\mathbb{E}$  is denoted by  $\mathbb{G}(\mathbb{E})$ . Dividing network cost among emitters is equivalent to dividing the cost of the grand coalition  $v^P(N)$ .

We evaluate the emitters' contributions to the network cost by applying the Shapley value to network games. On  $\mathbb{G}(\mathbb{E})$ , the computation of the Shapley value differs from its original expression for general TU-games (see Definition 1). The value becomes easier to compute and can be interpreted differently.

**Proposition 1.** *The Shapley value can be expressed, for each  $(N, v^P) \in \mathbb{G}(\mathbb{E})$ , as*

$$\forall i \in N, \quad Sh_i(N, v^P) = \sum_{j \in \hat{P}(i) \cup \{i\}} \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}$$

*Proof.* See Appendix A.

On network games, the Shapley value assigns a fair portion of the costs incurred by the network pipelines connecting each emitter to the sink. More precisely, it distributes the cost of each pipeline equally among the emitters located upstream of it. In addition, it is clear that the typically computationally challenging Shapley value can be computed in polynomial time on network games according to the algorithm below.

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**Algorithm 1:** First step of the methodology

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**Data:** Emitters  $N$ , graph  $P$ , pipelines costs  $y$ .

$Sh \leftarrow (0, \dots, 0)$

**for**  $j \in N$  **do**

**for**  $i \in N$  **do**

**if**  $i \in \hat{P}^{-1}(j) \cup \{j\}$  **then**

$Sh_i \leftarrow Sh_i + \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}$

**else**

$Sh_i \leftarrow \varphi_i$

**end**

**end**

**end**

**Result:**  $Sh$

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Finally, it is important to note that network games are always submodular. As a result, the Shapley value of a network game always belongs to its Core, making it a stable cost division method. This implies that the first step of our methodology ensures that each emitter's network cost contribution is smaller than the cost of connecting itself directly to the storage.

**Proposition 2.** *For each  $(N, v^P) \in \mathbb{G}(\mathbb{E})$ ,  $Sh(N, v^P) \in C(N, v^P)$ .*

This concludes the first step of our methodology. We have obtained an efficient way to evaluate the contribution to the network cost of each emitter. Next, we will combine these contributions with capture costs to devise fair subsidy distributions.

### 3.3 Second step: subsidy distribution

To fairly distribute a subsidy among emitters, a public entity must assess the subsidy claim of each emitter. In this paper, we compute the claim  $c_i$  of an emitter  $i \in N$  as the sum of its capture cost and its contribution to network cost, i.e.,  $c_i = x_i + Sh_i(N, v^P)$ . By efficiency of the Shapley value and by definition of a network game, it holds that  $\|Sh_i(N, v^P)\| = \|y\|$ . Consequently, there is not enough subsidy to cover the claims of the emitters, i.e.,  $\mathcal{E} \leq \|c\|$ . Therefore, to distribute the subsidy, we turn to bankruptcy theory.

For each  $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$ , we can define an associated bankruptcy problem  $(N, \mathcal{E}, c)$ . In our framework, the endowment to be shared is the subsidy  $\mathcal{E}$ . The agents and their claims correspond to our emitters and their claims. The sum of the claims sur-

passes the subsidy. Finally, an award vector corresponds to a possible subsidy distribution. From here, one can apply any solution concept from bankruptcy theory. We decide to focus on the Proportional ( $P$ ) solution.<sup>4</sup>

Indeed, by applying the Proportional solution ( $P$ ), the subsidy distribution is immune to strategic behavior since the distribution is independent of the underlying merging or splitting of the emitters (Non-manipulability). This means that emitters cannot form alliances or split their activity in order to gain more subsidy. In addition, the Proportional solution ( $P$ ) guarantees that the distributed amount is increasing with respect to one’s claim (Claim monotonicity). This means that the subsidy allocated to an emitter will increase with respect to both its capture cost and its distance to the storage site.

## 4 Case study

In this section, we apply our methodology to the case of CCS deployment in France. Subsection 4.1 describes the context of CCS in France, presents our data, and displays the cost-minimizing pipeline network connecting industrial emitters to liquefaction terminals (i.e., storage sites). Subsection 4.2 applies our methodology. We discuss these results and highlight noteworthy observations.

### 4.1 Data

#### 4.1.1 CCS context in France

In June 2023, the French government launched a public consultation on policies to support CCS deployment (Comité national de l’industrie, 2023). This consultation also sets out a phased strategy for CCS deployment in industry up to 2050. Indeed, the report envisions the capture of between 4 and 8.5 MtCO<sub>2</sub>/year by 2030 and between 15 and 20 MtCO<sub>2</sub>/year by 2050 in six major industrial clusters. Because CO<sub>2</sub> storage capacities and locations are still theoretical, the consultation calls for a survey of storage potential in sedimentary basins, and expects initial injection tests to start in 2025. To remedy eventual lack of storage capacity, the report also identifies liquefaction terminals for exporting CO<sub>2</sub> to storage sites abroad. In our study, we will assume that these liquefaction terminals are the only exit points for CO<sub>2</sub>. We exclude subsequent shipping and storage from our study. The report estimates that the carbon capture and transportation infrastructure will cost

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<sup>4</sup>Additional solutions are discussed in Appendix D.

between 11 and 18 billion euros (b€). From exchanges with stakeholders, we know that the French government will provide around 5b€ through subsidies to emitters through an auction mechanism. Thus, the government will entail a part of the total costs, but not its entirety.

### 4.1.2 Capture data

For our case study, we rely on data of the Climate Trace database, which provides the location and annual emissions of all industrial emitters. We retain large emitters of industrial sectors for which carbon capture is the main lever for decarbonization.<sup>5</sup> We use emitters' 2022 emissions as a benchmark for their annual emissions. We map liquefaction terminals accordingly to France's CCUS consultation report (Figure 2). In total, we have 42 emitters and 6 CO<sub>2</sub> terminals.

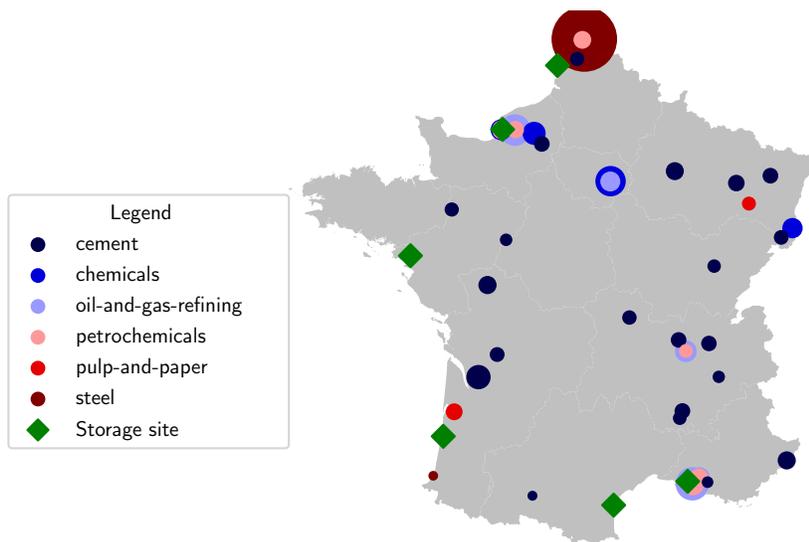


Figure 2: Map of emitters and CO<sub>2</sub> terminals.  
Size of dots are proportional to annual emissions.

For each industrial sector, we define its capture cost in euros per ton of CO<sub>2</sub> avoided [ $\text{€}/\text{tCO}_{2,\text{avoided}}$ ] and its capture rate, as shown in Table 1. These parameters greatly depend on the industrial site and the capture technology under consideration. We justify our choice for our carbon capture avoidance cost in the Appendix B.

<sup>5</sup>We consider an emitter as "large" if it emits more than 10,000 tons of CO<sub>2</sub> annually.

Industrial sector	Carbon avoided cost [€/tCO <sub>2,avoided</sub> ]	Capture rate [-]
Ammonia	20	0.8
Cement	50	0.9
Steel	60	0.9
Pulp & paper	60	0.9
Refineries and petrochemicals	100	0.7

Table 1: Carbon capture assumptions by sector (see Appendix B).

### 4.1.3 Transport data

Secondly, we identify potential pipelines that could link the emitting sites to the storage sites.<sup>6</sup> For sake of simplicity, we assume that pipelines can connect two emitters to each other or connect an emitter to a storage site. With 48 nodes - 42 nodes emitters and 6 liquefaction terminals- considering all possible connections would be computationally challenging. Following Morbee et al. (2012), we apply Delaunay (1934) triangulation, which reduces the number of potential pipelines that can be built. Excluding pipelines crossing countries other than France, we obtain the potential transport routes shown in Figure 3.

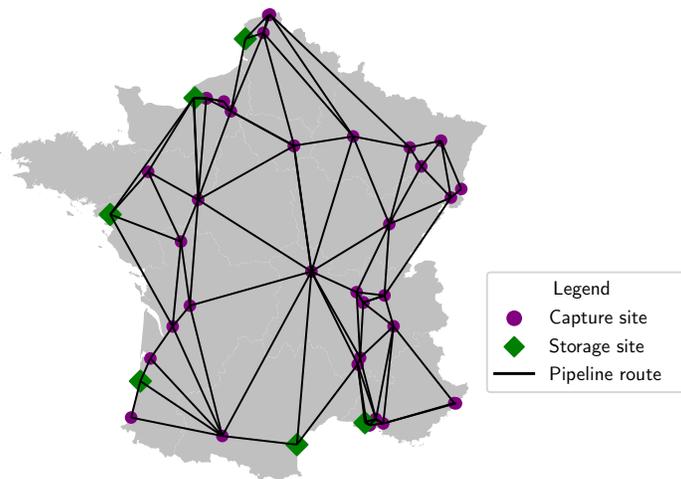


Figure 3: Potential pipeline routes from Delaunay triangulation.

<sup>6</sup>We exclude other types of transportation, as recent developments confirm that transport by pipeline is the most cost-efficient solution for CCS transport (Oeuvray et al., 2024)

Numerous studies quantify the cost of transporting CO<sub>2</sub> by pipeline, but there are wide disparities as shown by Knoope et al. (2013, 2014) and Roussanaly et al. (2014). In network optimization models, studies tend to discretize available pipeline capacities in order to exploit economies of scale (d’Amore & Bezzo, 2017). Here, we adopt the investment cost function calculated in Morbee et al. (2012), which provides the investment cost of a pipeline as a function of length, volumes and terrain factors, thus simplifying the MILP. We then convert this cost into an annualized investment fix cost  $C^{inv,fix}$  and an annualized variable cost  $C^{inv,var}$ , as our model deals with a single representative year. Aside from the investment cost, we consider operation and maintenance cost  $C^{om}$ , see Table 2.

Transport Cost	Value	Source
$C^{inv,fix}$ [M€/ (km·y)]	0.0401	Adapted from Morbee et al. (2012)
$C^{inv,var}$ [M€/ (MtCO <sub>2</sub> ·km·y)]	0.0014	Adapted from Morbee et al. (2012)
$C^{om}$ [M€/ (km·MtCO <sub>2</sub> )]	0.01	Oei et al. (2014)

Table 2: Transportation costs

#### 4.1.4 Cost-minimizing network

We detail the MILP formulation in the Appendix C. Following the MILP, we obtain the cost-minimizing pipeline network presented in Figure 4. To illustrate our methodology, we choose to focus on the northern part of the south east cluster, which is highlighted by the blue box in Figure 4.

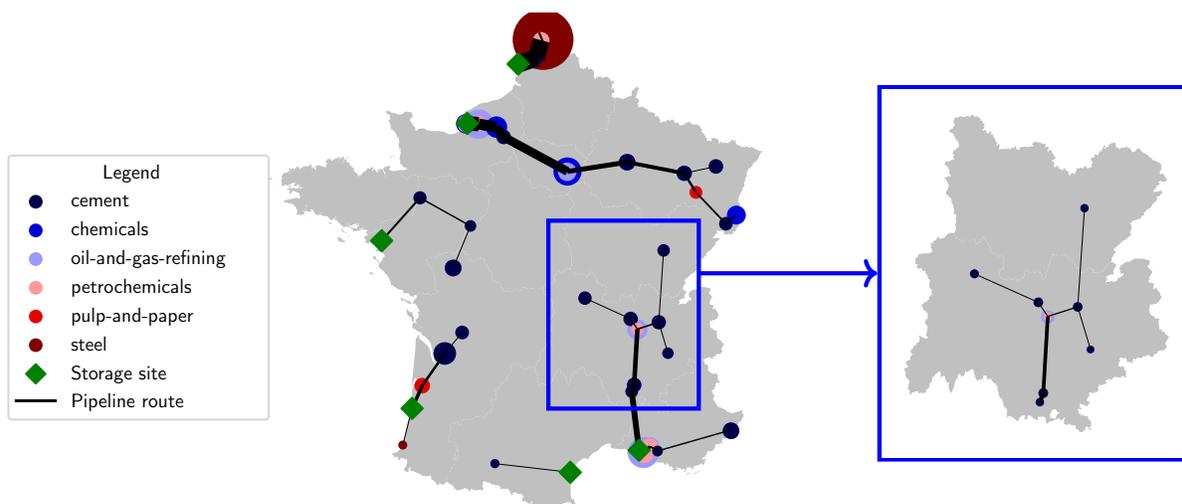


Figure 4: Map of France and northern sites of south-east cluster

Notably, the model’s output corresponds to the clusters described in the French governmental report (Comité national de l’industrie, 2023). A main difference lies in the connection of the eastern Zone Grand Est cluster to the western Le Havre cluster. Indeed, the governmental study assumes that onshore pipelines can transport CO<sub>2</sub> to Germany, unlike our model that can export CO<sub>2</sub> through liquefaction terminals in the West or South of France only.

## 4.2 Results

### 4.2.1 South-East Cluster

For our case study, we apply our methodology to a portion of the south-east cluster. Let us formalize this case study by the problem  $(\mathcal{E}, N, x, P, y) \in \mathbb{E}$ . Without loss of generality, we fix the subsidy budget to  $\mathcal{E} = 170$  and the sink is denoted by  $i_0$ . The other inputs of the model are summarized in Table 3.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$x_i$	18.83	60.55	21.51	18.44	15.44	18.18	10.75	13.13
$P(i)$	$i_0$	$C22$	$C8$	$C33$	$C25$	$C33$	$C26$	$C26$
$y_{iP(i)}$	1.03	7.64	0.04	1.21	4.56	2.34	2.84	6.4

Table 3: Inputs of the case study (in M€/year)

Figure 5 is an illustration of our network to better visualize the tree graph structure and the pipelines’ costs.

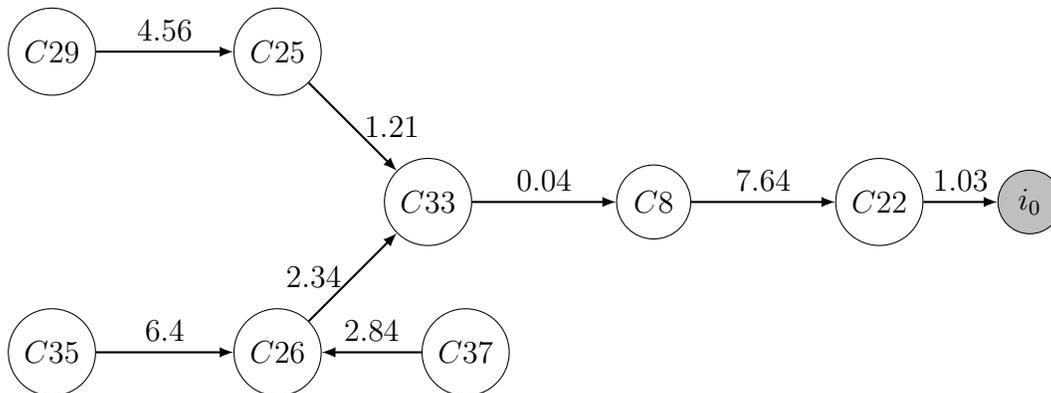


Figure 5: Network and pipelines’ costs

### 4.2.2 Two-step methodology

**Step 1:** Compute the Shapley value of the network game  $(N, v^P)$  associated with our case study problem. According to Proposition 1, the Shapley value divides the cost of each pipeline equally among its upstream emitters. For instance, the cost  $y_{C26C33} = 2.34$  is equally divided among  $C26, C35$  and  $C37$ . Applying this reasoning to each pipeline, i.e., following Algorithm 1, we obtain the Shapley value of the network game, which is given by the second line of Table 4.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$Sh_i(N, v^P)$	0.128	1.219	1.226	1.831	6.391	2.006	4.846	8.406
$c_i$	20.305	61.769	22.736	20.271	21.831	20.186	15.596	21.536

Table 4: First step’s results (in M€/y)

**Step 2:** From the Shapley value obtained in Step 1, we can derive the vector of needs  $c \in \mathbb{R}^8$  (see the third line of Table 4). Each coordinate  $c_i, i \in N$ , of this vector is obtained by summing the capture cost  $x_i$  and the Shapley value  $Sh_i(N, v^P)$  for  $i$ . We have the necessary components to construct the bankruptcy problem  $(N, c, \mathcal{E})$ . Consequently, we can apply solutions to bankruptcy problems to determine subsidy distributions. Additionally, we formulate an alternative bankruptcy problem  $(N, x, \mathcal{E})$  where the network cost are not factored in; specifically, the emitters’ needs are represented solely by their capture costs. This enables us to compare two scenarios: one considering the network and one without, allowing some discussions. The results are compiled in Table 5 (see Appendix D).

### 4.2.3 Interpretations of the results

Observe from Figure 6 that emitters whose emissions pass through many pipelines (upstream emitters) in the transportation network receive more subsidies if their contribution to network cost is considered (i.e.,  $(N, c, \mathcal{E})$ ) compared to the situation where only their capture cost is accounted for (i.e.,  $(N, x, \mathcal{E})$ ). For instance, the distant emitter  $C35$  receives 42% more subsidies in situation  $(N, c, \mathcal{E})$  compared to situation  $(N, x, \mathcal{E})$  through the  $CEA$  solution. Indeed, our methodology favors emitters who are far upstream in the transportation network, as serving them with a pipeline reduces the transportation costs of other emitters.

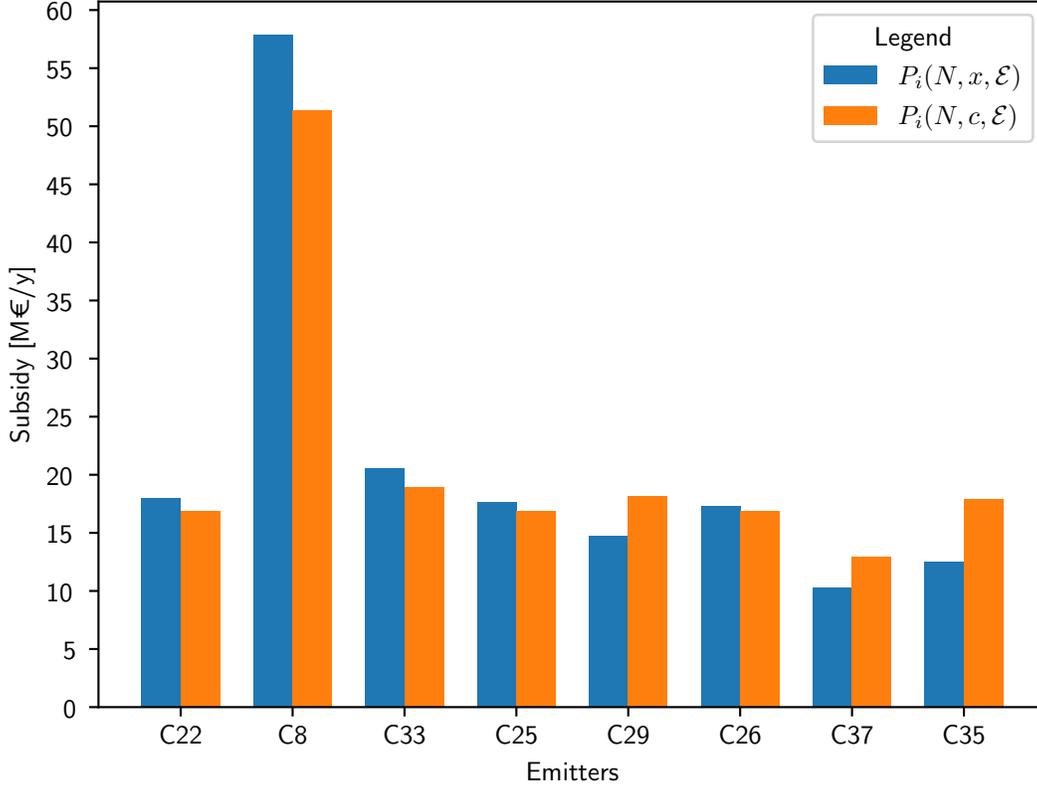


Figure 6:  $P$  results in base case  $(N, c, \mathcal{E})$  and without considering the network  $(N, x, \mathcal{E})$ .

## 5 Discussion

In this section, we discuss some advantages and drawbacks of our methodology. First, in subsection 5.1, we discuss alternative approaches for our methodology’s first and second steps. Second, in subsection 5.2, we suggest future research avenues to study different mechanism designs to implement our methodology.

### 5.1 Methodology modification for future research

For each step of our methodology, we suggest an approach relevant to the current deployment of CCS: for the first stage, we rely on the Shapley value, and for the second stage, we use the Proportional bankruptcy solution. Beyond the approaches applied for each step, our study provides a flexible normative framework for designing a CCS subsidy distribution mechanism. Indeed, alternative approaches are possible for each methodology step, which we detail below.

In the second step, a promising direction for further research is to investigate alternative axioms, leading to different bankruptcy solutions. The choice of an axiom could be motivated by the case study or additional normative considerations. We refer to Thomson (2003) and Thomson (2015) for a deep analysis of bankruptcy solutions and their axiomatic characterizations. For the first step, future studies could replace the Shapley value with their case study’s prevailing T&S tariff. Another possibility consists of applying the Shapley value to minimum cost spanning tree games (see, for instance, Bird (1976), Kar (2002) Bergantiños and Lorenzo-Freire (2008), Bergantiños and Kar (2010), Bogomolnaia and Moulin (2010), Bergantiños and Vidal-Puga, 2010, Trudeau and Vidal-Puga (2019)) and Bergantiños and Vidal-Puga (2021) instead of network games (see Definition 5). The key distinction between network games and minimum cost-spanning tree games lies in their definitions and structures. An exogenously defined cost-minimizing network characterizes a network game. In contrast, a minimum cost-spanning tree game is defined based on the collection of all cost-minimizing networks that sub-coalitions of emitters can generate. Minimum cost-spanning tree games allow for considering counterfactuals in which some coalition of emitters connect themselves to the storage without cooperating with the other emitters (see, for instance, Granot and Huberman (1981), Granot and Huberman (1984) and Granot (1986)). This framework is relevant for studying strategic interaction between emitters and addressing stability issues (see, for instance, Granot and Huberman (1984) and Estévez-Fernández and Reijnierse (2014)). While applying the Shapley value to minimum cost spanning tree games may yield interesting results, the main drawback of this approach is that it becomes harder to compute, as demonstrated by Ando (2012). Other alternative approaches for the first step can be found in Hougaard (2018). More recently, some studies have proposed decomposing the network cost into several components to account for the heterogeneous requirements of infrastructure users (see Van Beek et al. (2024)) or decomposing agents’ demands (or claims) into multiple stages to address differences in emission volume and their impact on network design (see Lowing (2024)).

## 5.2 Implementation of our methodology

A key assumption of this paper is that the public entity distributing the subsidies has perfect information on every emitter’s claim. Under this assumption, the role of the public entity is to distribute subsidies efficiently based on its perfect knowledge of emitters’ capture cost and location. Thus, in our paper, the public entity does not face the preliminary issue of estimating the capture cost of each emitter in order to determine the minimal subsidy budget to support CCS adoption. In this context, the public entity with imperfect

information must develop a mechanism to incentivize emitters to reveal their capture cost. This mechanism will necessarily influence the effectiveness of the subsidy distribution. In this perspective, the Dutch government subsidizes industrial emitters through an auction mechanism. Each emitter’s auction corresponds to its subsidy demand per ton of CO<sub>2</sub> (subsidy intensity) corrected by an emissions intensity factor. The government ranks the auctions in ascending order and subsidizes emitters until the subsidy budget is empty. A greedy emitter could request a higher bid than it claims (by requesting a higher subsidy intensity), but it runs the risk of not being selected. In this way, each emitter is (supposedly) incentivized to submit a bid corresponding to its claim -i.e., its capture cost.

Alternatively, a public entity could roughly estimate capture costs without setting up a mechanism to reveal emitters’ costs. For instance, the Norwegian government runs its CCS flagship project through its company, Gassnova, and is part of the Northern Lights consortium, which manages transportation and storage. In addition to its direct involvement, the Norwegian government has covered 80% of Northern Lights’ costs via state aid agreements (Fattouh et al., 2024). Similarly, Danish emitters can apply to the national CCUS Fund and the NECCS Fund. Depending on its budget and storage target, the government selects emitters through a tendering procedure (European Commission, 2023). In both countries, some grey areas remain: neither country has publicly disclosed the rationale behind the allocation of subsidies.<sup>7</sup> These grey areas do not promote a clear and transparent funding mechanism for future CCS projects. However, transparency in subsidy distribution (i.e., public spending) is a central criterion for the large-scale development of this technology. In this respect, the study by Rode et al. (2023) sets out six principles to guide the development of large-scale CCS. Among these, the fourth principle calls for transparent commitments by government and policymakers.<sup>8</sup>

In light of these examples, setting up a transparent mechanism to reveal emitters’ costs seems desirable to kickstart CCS adoption. Future research could address the impact of gathering information (in auction mechanisms or not) on the efficiency of our methodology. In particular, future research could analyze the efficiency of the subsidy distribution in the investment decision considering the asymmetry of information between emitters and the public entity.

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<sup>7</sup>Likewise, Northern Lights’ remuneration after the first decade of operation is unclear (Nicolle et al., 2023).

<sup>8</sup>Our study aligns with this criterion and directly addresses the second principle, which recommends investing in a common infrastructure.

## 6 Conclusion

In summary, this paper introduces a flexible methodology for distributing subsidies to kickstart the adoption of Carbon Capture and Storage (CCS). By leveraging cooperative game theory and bankruptcy theory, our method efficiently allocates subsidies within budget constraints. Compared to the literature, this methodology has two major advantages. On one hand, the novelty of our methodology lies in considering both the heterogeneous capture costs of emitters and their network locations. On the other hand, future studies or policymakers can customize it according to their normative considerations and their specific case study. Applying this methodology to CCS deployment in France reveals a favorable distribution of subsidies to influential upstream emitters, which is crucial for accelerating CCS adoption. Further research is necessary to validate and refine this methodology for broader application in industrial decarbonization efforts.

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## Appendix A: Proof of Proposition 1

Pick any  $(N, v^P) \in \mathbb{G}(\mathbb{E})$ . According to Dong et al. (2012), the characteristic function  $v^P$  can be decomposed as follows

$$\forall E \subseteq N, \quad v^P(E) = \sum_{j \in N} y_{jP(j)} R^j(E), \quad \text{where} \quad R^j(E) = \begin{cases} 1 & \text{if } E \cap (\hat{P}^{-1}(j) \cup \{j\}) \neq \emptyset, \\ 0 & \text{otherwise.} \end{cases}$$

Observe that, for each  $j \in N$ ,  $(N, R^j)$  can be viewed as a TU-game. Therefore, one can apply the Shapley value on it. Observe that all players in  $\hat{P}^{-1}(j) \cup \{j\}$  have the same marginal contribution in  $(N, R^j)$ . Moreover, observe that all players not in  $\hat{P}^{-1}(j) \cup \{j\}$  have null marginal contributions in  $(N, R^j)$ . By definition of the Shapley value, we obtain

$$\forall i \in N, \quad Sh_i(N, R^j) = \begin{cases} \frac{1}{|\hat{P}^{-1}(j) \cup \{j\}|} & \text{if } i \in \hat{P}^{-1}(j) \cup \{j\}, \\ 0 & \text{otherwise.} \end{cases}$$

By the above mentioned decomposition and by the linearity of the Shapley value, we obtain the desired result

$$\begin{aligned} \forall i \in N, \quad Sh_i(N, v^P) &= \sum_{j \in N} y_{jP(j)} Sh_i(N, R^j) \\ &= \sum_{j \in \hat{P}(i) \cup \{i\}} \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}. \end{aligned}$$

□

## Appendix B: Capture cost data

Assessing the costs associated with capturing CO<sub>2</sub> is challenging due to the limited deployment of this technology (IEA, 2023). Therefore, the scientific literature has mostly favored techno-economic analysis to determine the capture cost for each industrial sector (Antzaras et al., 2023; Leeson et al., 2017; Perpiñán et al., 2023). These studies are nevertheless sensitive to the capture technology considered, the capture rate employed, and the characteristics of the reference industrial site. Thus, each of these studies generally provides a range of values for the capture cost for a given industrial sector rather than a single value. Consequently, the range of values obtained for a given industrial sector can be extensive when

these studies are compared. Hence, studies such as Garcia and Berghout (2019) and Roussanaly et al. (2021) call for a standardization of the methodology of these technico-economic studies.

In the following, we justify the choice of avoidance cost value for each industrial sector presented in Table 1. To this end, we draw in particular on the studies by Leeson et al. (2017) and Roussanaly et al. (2021), which provide a systematic review of these costs in the scientific and grey literature. We compare these costs with more recent studies than Leeson's dedicated to the industrial sector under concern.

## Ammonia

The avoidance capture cost in ammonia production can reach values close to less than ten dollars per ton of CO<sub>2</sub>, as the CO<sub>2</sub> is already in a high purity state. The exact value will then mostly depend of the purity of the CO<sub>2</sub> source and the capture rate. Hence, studies such as Leeson et al. (2017) find an avoidance cost between 3.9 - 45.3 \$/tCO<sub>2,avoided</sub>. The dedicated study by Arora et al. (2018) finds an avoidance cost interval of 11 - 19 \$/tCO<sub>2,avoided</sub> for capture rate varying from 20% to 80%. We assume in our study the conservative value of 20 \$/tCO<sub>2,avoided</sub> with a capture rate of 80%.

## Cement

For the avoidance cost of cement, we mostly refer to the study by Gardarsdottir et al. (2019), part of the European CEMCAP research program. This paper describes the avoidance cost of carbon capture in the cement industry for all types of technologies: MEA, oxyfuel combustion, chilled ammonia, membrane assisted, and calcium looping (integrated or not). For each of these technologies the authors detail the avoidance cost and apply sensitivity analyses. In particular, they show that neither technology has a strong advantage compared to others, and that the cheapest technology depends on the cement plant under consideration. Under their assumptions, they find that oxyfuel is the cheapest technology, with an avoidance cost of 42.4 €/tCO<sub>2,avoided</sub>, for a capture rate of 90%. This result is coherent with studies by the European Joint Research Centre (European Commission. Joint Research Centre., 2023) and the study by Leeson et al. (2017). Yet, the oxyfuel technology's efficiency strongly depends on the cement plant under consideration compared to other post-combustion technologies (Voldsund et al., 2019). Among these, the MEA process is also more technologically mature (Roussanaly et al., 2021). Gardarsdottir et al. (2019) find a cost of

80.2 €/tCO<sub>2,avoided</sub> for the traditional MEA process. This latter result is aligned with other studies such as Garcia and Berghout (2019) and Roussanaly et al. (2017). For a recent assessment of the carbon capture cost of a cement plant, see Antzaras et al. (2023).

Following these considerations, while the avoidance cost of cement could reach 40 €/tCO<sub>2,avoided</sub> through the oxyfuel technology, we assume here that the cost of avoidance is at 50 €/tCO<sub>2,avoided</sub> at a capture rate of 90%.

## Steel

For the avoidance cost of steel, we rely on the dedicated study by Garcia and Berghout (2019). This paper studies publications on the cost of capture in the steel and cement sectors and deduces a common methodology to be adapted in order to be able to compare the results obtained in each of these studies. The paper draws in particular on papers by Leeson et al. (2017), and Kuramochi et al. (2012). Applying their methodology to the IEAGHG (2018) report, the authors find an avoidance cost between €56 and 82€/tCO<sub>2</sub> avoided with a traditional chemical absorption method. We thus retain a cost of 60€/tCO<sub>2,avoided</sub> for an avoidance rate of 90%, which is consistent with the studies by Biermann et al. (2019) and Roussanaly et al. (2014). Note that this cost figure could be decreased for other less mature type of technologies. For a recent assessment of the capture cost of CO<sub>2</sub> in the steel industry, see Perpiñán et al. (2023).

## Pulp & Paper

The study by Onarheim et al. (2017) provides a dedicated study to the avoidance capture cost in the pulp & paper industry. They distinguish this cost depending on the type of the pulp mill. For the Kraft pulp mill, the authors find an avoidance cost of 52–66 €/tCO<sub>2,avoided</sub> while they determine an avoidance cost of 71–89 €/tCO<sub>2,avoided</sub> for the integrated pulp and board mill. The interval depends on the capture rate, varying from 0.6 to 0.9 in both cases. Note that these intervals fall within the intervals found in Leeson et al. (2017) and Roussanaly et al. (2021). Hence, we retain here an avoidance cost of 60 €/tCO<sub>2,avoided</sub> for the pulp and paper sector with a 90% capture rate.

## Refineries and petrochemicals

We observe strong disparities for the avoidance cost for petroleum refineries and petrochemicals. The study by Leeson et al. (2017) assumes an avoidance capture cost of 98\$/tCO<sub>2,avoided</sub> with a 65% capture rate. This value stands between the avoidance cost assumed in the Great Plains Institute whitepaper of 59\$/tCO<sub>2,avoided</sub> (Abramson et al., 2020) and between 145,5 – 189,4€/tCO<sub>2,avoided</sub> retained in Roussanaly et al. (2021). Due to this large interval, we choose a value of 100€/tCO<sub>2,avoided</sub> with a 65% capture rate.

## Appendix C: MILP formulation

We detail here the network optimization program. Since our subsequent subsidy distribution analyses are conducted in a static framework, we solve the optimization program for a representative year. The goal of the following Mixed Integer Linear Program (MILP) is to minimize the cost of the pipeline transportation infrastructure connecting all emitters (set  $N$ ) to storage sites (set  $K$ ), as stated by the objective function (1a). To this end, the model selects the routes for pipelines (through the binary variable  $\delta_p$ ) among the potential pipeline paths provided by the previous Delaunay triangulation (figure 3).

$$\min_{\delta_p, q_p^+, q_p^-} \sum_{p \in P} [C^{inv,fix} \delta_p + C^{inv,var} (q_p^+ + q_p^-) + C^{om} (q_p^+ + q_p^-)] L \quad (1a)$$

$$\text{s.t.} \quad \sum_{p \in P} I_{p,i} (q_p^+ - q_p^-) + Q_i = 0, \quad \forall i \in N, \quad (1b)$$

$$\sum_{p \in P} I_{p,k} (q_p^+ - q_p^-) \geq 0, \quad \forall k \in K, \quad (1c)$$

$$q_p^+ + q_p^- \leq \delta_p M, \quad \forall p \in P, \quad (1d)$$

$$\delta_p \in \{0, 1\}, q_p^+ \geq 0, q_p^- \geq 0, \quad \forall p \in P \quad (1e)$$

For each selected path, the model determines the volumes and directions of the CO<sub>2</sub> that can either be flowing in the positive direction posited for the pipeline  $q_p^+$  or in its reverse direction  $q_p^-$ . Equations (1b) and (1c) are the mass balance equations at emitter nodes and at liquefaction terminals respectively. In these equations,  $Q_i$  stands for the CO<sub>2</sub> captured at node  $i$  (i.e., injected into the transportation network) and  $I_{p,j}$  is an incidence matrix equal to: -1 if pipeline  $p$  starts at node  $j$  ( $j$  can either be a capture site  $i$  or a terminal  $k$ ); to

1 if the pipeline  $p$  arrives at  $j$ ; and to 0 otherwise. Equation (1d) is the big M equation, with  $M = \sum_{i \in N} Q_i$ . This equation guarantees that the model builds a pipeline only if  $\text{CO}_2$  is flowing through it. Equation (1e) states that  $\delta_p$  is a binary variable and that the flow variables are positive. For more details regarding this MILP, see Massol et al. (2018).

## Appendix D: CEA, CEL and additional case study results

This section contains all the numerical results from our case study (see Table D). In particular, we introduce and discuss two additional solutions for bankruptcy problems. This allows us to: (i) propose meaningful alternative solutions to the Proportional solution; (ii) conduct a normative comparison of these solutions (axiomatic characterizations), supported by numerical evidence; and (iii) discuss the various policy implications these solutions may have.

### D.1 Additional content on bankruptcy theory

In addition to the Proportional solution ( $P$ ), we consider the Constrained equal award solution ( $CEA$ ) and the Constrained equal loss solution ( $CEL$ ). The  $CEA$  solution assigns equal awards to all claimants subject to no one receiving more than their claim. The solution follows an iterative process: it distributes resources equally between claimants until each claimant receives an allocation matching the smallest claim. The claimant (or claimants) with the smallest claim leaves (or leave) the distribution process at this stage. The remaining claimants evenly divide the rest of the endowment until reaching the second smallest claim. The process continues until the endowment is empty. At this final stage, one or more claimants received only part of their claims since the endowment is assumed to be lower than the sum of claims. An alternative to the  $CEA$  solution is obtained by focusing on the losses claimants incur (what they do not receive), as opposed to what they receive, and choosing the awards vector at which these losses are equal subject to no one receiving a negative amount. It is called the Constrained equal losses ( $CEL$ ) solution. Similar to the  $CEA$  solution, it follows an iterative process focusing on losses rather than awards.

**Definition 6.** Consider any  $(N, c, \mathcal{E}) \in \mathbb{B}$ .

– The *Constrained equal award* solution *CEA* is defined as

$$\forall i \in N, \quad CEA_i(N, c, \mathcal{E}) = \min\{c_i, \lambda\}, \quad \text{where} \quad \sum_{j \in N} \min\{\lambda, c_j\} = \mathcal{E}.$$

– The *Constrained equal losses* solution *CEL* is defined as

$$\forall i \in N, \quad CEL_i(N, c, \mathcal{E}) = \max\{0, c_i - \lambda\}, \quad \text{where} \quad \sum_{j \in N} \max\{0, c_j - \lambda\} = \mathcal{E}.$$

On the full domain of bankruptcy problems  $\mathbb{B}$ , these two solutions can be characterized by combining axioms conceptually close to those invoked in Theorem 1. The characterizations are due to Yeh (2001). We provide formal expression of these axioms along with their (general) economic interpretations.

1. **Dual claim monotonicity:** for each  $(N, c, \mathcal{E}) \in \mathbb{B}$ , each  $\lambda \in \mathbb{R}_{++}$ , and each  $i \in N$ ,  $f_i(N, \mathcal{E} + \lambda, c + \lambda e_i) - f_i(N, c, \mathcal{E}) \leq \lambda$ .
2. **Conditional full compensation:** For each  $(N, c, \mathcal{E}) \in \mathbb{B}$  and each  $i \in N$ , if  $\sum_{j \in N} \min\{c_j, c_i\} \leq \mathcal{E}$ , then  $f_i(N, c, \mathcal{E}) = c_i$ .
3. **Conditional null compensation:** For each  $(N, c, \mathcal{E}) \in \mathbb{B}$  and each  $i \in N$ , if  $\sum_{j \in N} \max\{0, c_j - c_i\} \geq \mathcal{E}$ , then  $f_i(N, c, \mathcal{E}) = 0$ .

The first axiom is a dual version of Claim monotonicity. It states that if an agent's claim and the total endowment increase by the same amount  $\lambda$ , *ceteris paribus*, then this agent's award should not increase more than this amount  $\lambda$ . The second axiom, Conditional full compensation, ensures that agents with the most reasonable claims are entirely satisfied by the solution. To the contrary, the last axiom, Conditional null compensation, ensures that agents with the most reasonable claims should not be awarded by the solution.

**Theorem 2 (Yeh (2001)).** *A solution  $f$  on  $\mathbb{B}$  is the CEA solution if and only if it satisfies Claim monotonicity and Conditional full compensation.*

**Theorem 3 (Yeh (2001)).** *A solution  $f$  on  $\mathbb{B}$  is the CEL solution if and only if it satisfies Dual claim monotonicity and Conditional null compensation.*

## D.2 Case study results

All the results from our case study are compiled in Table 5. We ran numerical simulations with the three bankruptcy solutions:  $P$ ,  $CEA$ , and  $CEL$  for comparison purposes. For each solution, we considered both scenarios: with and without the network. However, the upcoming discussions only hold on the scenario with the network taken into account, since we already discussed the effect of the network in the core of the paper.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$CEA_i(N, c, \mathcal{E})$	20.305	27.539	22.736	20.271	21.831	20.186	15.596	21.536
$CEL_i(N, c, \mathcal{E})$	16.03	57.49	18.457	15.99	17.55	15.907	11.317	17.257
$P_i(N, c, \mathcal{E})$	16.9	51.41	18.947	16.873	18.172	16.867	12.982	17.926
$CEA_i(N, x, \mathcal{E})$	18.83	53.72	21.51	18.44	15.44	18.18	10.75	13.13
$CEL_i(N, x, \mathcal{E})$	17.97	59.696	20.656	17.586	14.586	17.326	9.896	12.276
$P_i(N, x, \mathcal{E})$	17.999	57.843	20.545	17.638	14.749	17.346	10.268	12.537

Table 5: Methodology results (in M€/year)

Let us discuss the three bankruptcy solutions within the framework of the base problem  $(N, c, \mathcal{E})$ . For clarity, Table 6 below provides the subsidy received by each emitter divided by its claim. In other words, it describes the percentage of each emitter's financial need that is fulfilled by the subsidy. Under  $CEA$ , all the claims of the small emitters are entirely satisfied. In contrast, the large emitter  $C8$  receives less than 50% of its subsidy claims. This phenomenon can be explained by the Conditional full compensation property of the  $CEA$  solution. Note that  $C8$  still receives more than the other emitters due to Claim monotonicity (see Table 5 in Appendix D). Conversely, the  $CEL$  solution favors  $C8$  at the expense of the other emitters who receive between 72% and 82% of their subsidy claims. This phenomenon can be explained by the Conditional null compensation of the  $CEL$  solution. Finally, solution  $P$  distributes normalized subsidies equally among participants. The Non-manipulability property of the solution is evident in this example, as the proportion of subsidy obtained by the emitters is uniform.

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$CEA_i(N, c, \mathcal{E})/c_i$	1	0.446	1	1	1	1	1	1
$CEL_i(N, c, \mathcal{E})/c_i$	0.789	0.931	0.813	0.789	0.803	0.789	0.727	0.802
$P_i(N, c, \mathcal{E})/c_i$	0.833	0.833	0.833	0.833	0.833	0.833	0.833	0.833

Table 6: Normalized subsidy distribution of the base problem.

From a public policy point of view, each of the bankruptcy solutions corresponds to a possible way of overcoming the coordination problem. If the public entity believes that small emitters need more support to invest in the capture and transport of their emissions, then a fair distribution of subsidies is to follow the CEA solution. Conversely, the CEL solution rewards large emitters more. An intermediate solution is to follow the proportional solution. We do not recommend any particular solution in this study. Each solution prescribes different subsidy distributions, each with its own advantages and drawbacks. It is up to the public entity to decide which desirable property (axiom) they would like their solution to satisfy. Note that the computational complexity of each solution is low, so that only normative considerations are needed.

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