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By

Andries van Beek, Mirjam Groote Schaarsberg,
Peter Borm, Herbert Hamers, Mattijs Veneman

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TILBURG UNIVERSITY

Cost Allocation in CO2 Transport for CCUS hubs: a Multi-Actor Perspective

A general model to evaluate costs in infrastructure construction

Andries van Beek[a b] Mirjam Groote Schaarsberg[c] Peter Borm[a]
Herbert Hamers[a] Mattijs Veneman[a]

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Abstract

This paper provides a multi-actor perspective on the realization of new infrastructures, motivated by the necessity for infrastructures to support the ongoing climate and energy transition in general, and CO2 transport infrastructures for carbon capture, utilization and storage (CCUS) in particular. We develop a general model to represent infrastructures that allows for a unique decomposition into 'elementary infrastructure components' based on heterogeneous user requirements. Notably, it incorporates a cost function with a very generic and adaptable structure, for which we can still explicitly determine the costs of each individual component. As a direct consequence an intuitive cost allocation rule is obtained: equal component cost sharing. This allocation rule is in line with existing game-theoretic concepts and satisfies the desirable properties of advantageous scaling and coalitional rationality. Advantageous scaling guarantees that the costs allocated to each existing user do not increase if the number of users grows larger and coalitional rationality ensures that there is no subgroup of infrastructure users that would have a financial reason to object to the cost allocation. Additionally, we examine the application of our model to a prospective CO2 transport infrastructure for CCUS in the port of Rotterdam and the adjoining industry area.

Keywords: industrial decarbonization, regional CO2 transport hubs, multi-actor infrastructure, cost allocation

1 Introduction

The importance of reducing CO2 emissions to limit human-induced climate change is widely acknowledged (IPCC, 2022). Transforming energy-intensive industries plays a key role in this reduction of CO2 emissions (or 'decarbonization'), as they account for 20% of all CO2 emissions (IEA, 2020). New and adapted infrastructures[1] are necessary for a successful and timely industrial transformation (de Bruyn et al., 2020; Janipour et al., 2020; Fu et al., 2018).

In this paper we provide a multi-actor perspective on these necessary new infrastructures. We develop a generic model to represent infrastructures and analyze the nature of the corresponding *construction* costs. In particular, this model is 'component-based' to account for the heterogeneous requirements of the users of an infrastructure. By decomposing an infrastructure into a unique component structure, we explicitly differentiate between users based on whether they require, e.g., CO2 conditioning for re-use, or offshore transport. Importantly, we identify and adopt a cost function with a very general structure, for which we can explicitly determine the costs of each individual component. Although the generality of the cost function allows for a wide range of applications within infrastructure construction problems, it is developed primarily

[a]CentER, Department of Econometrics & Operations Research, Tilburg University, P.O. Box 90153, 5000 LE Tilburg, The Netherlands
[b]Corresponding author. E-mail address: a.j.vanbeek@tilburguniversity.edu
[c]Strategic Business Analysis, TNO, P.O. Box 96800 2509 JE Den Haag, the Netherlands

[1]Hydrogen transport and distribution, heat distribution, reinforced electricity grids and CO2 transport infrastructures are primary topics in national, European and worldwide climate change plans.

with a specific application in mind, namely CO2 transport infrastructures for carbon capture, utilization and storage (CCUS). This is a potentially effective, but also heavily debated pathway towards decarbonization. A significant part of this paper is dedicated to a discussion of such a CO2 transport infrastructure in the port of Rotterdam and the adjoining industry area. The case study most prominently illustrates the type of application our model allows.

Before moving to the more general contributions of our research, we start with a discussion of these carbon capture related technologies and explain the need for a multi-actor perspective in the CO2 transport infrastructure application. Carbon capture and storage (CCS) is the process of capturing waste carbon dioxide, transporting it to a storage site, and depositing it. The aim of CCS is to prevent the release of large quantities of CO2 into the atmosphere. Carbon capture and utilization (CCU) is the process of capturing carbon dioxide to be recycled for further usage. CCU aims to convert the captured carbon dioxide into more valuable substances or products. Detz and van der Zwaan (2019) and IEA (2020) expect a future increase of CO2 demand by industry for, e.g., production of blue hydrogen and methane. In new large scale carbon capture projects CCS and CCU are often combined into CCUS projects. CCUS recently gained more traction. Plans for significant investments in CCUS technologies can be found in European industrial transformation strategies (EC, 2020), in the World Energy Outlook (IRENA, 2021), but also in national plans such as in the UK and in the Netherlands. IEA (2020) dedicate a special technology outlook on the role of CCUS in decarbonization of energy-intensive industries. They conclude that CO2 reduction targets probably cannot be achieved without the carbon capture option, and that many technologies necessary for CCU and especially CCS seem to be fully developed. In many regions, CCUS could be a cost effective solution for decarbonization of such industries. However, IEA (2020) warns: "Infrastructure to transport and store CO2 safely and reliably is essential for rolling out CCUS technologies." They recommend the further development of shared CO2 transport and storage infrastructures in a regional industrial hub or cluster. This cluster approach is not a coincidence. Energy-intensive industries often use the same spatial characteristics (e.g., harbor), each other's products (e.g., intermediates), or shared infrastructures (e.g., steam network). The existence of these clusters provides both opportunities and barriers for the necessary industry transition (see, e.g., Janipour et al. (2020) and Fu et al. (2018)). Accordingly, Quarton and Samsatli (2020) explain that significant stakeholder collaboration is required for CCUS investments and implementation. In case of CCUS technologies, both CO2 emitters and CO2 users could benefit from a CO2 transport infrastructure, but they do not have the same requirements regarding, e.g., the quality of the CO2 or the transport capacity to a storage site. Given these differences in user requirements, it is important to consider how to *allocate* the total construction costs of such an infrastructure to the different users. This requires a multi-actor perspective, explicitly taking into account the heterogeneity of different (potential) users.

Of course, appropriate cost allocation is not the only enabler of such a CO2 transport infrastructure, but we believe it is one of the key aspects of collaboration on infrastructure construction. It is desirable that the cost allocation method keeps existing users on board, since a significant majority of cluster participants need to go along with infrastructural investments for its successful realization. If all users are asked for cost contributions based on, e.g., only total transport capacity of the network, some of them might very well decide not to participate in the CO2 network. A 'no' from a subgroup of CO2 network users in a regional industrial cluster will increase investment costs for remaining users, which in return can result in a 'no' from another group of potential CO2 network users. On top of maintaining interested parties on board, appropriate cost allocation methods can even increase the number of participants of the CO2 network and thus speed-up the decarbonization of an industrial cluster. Indeed, SER (2019) mentions that decarbonization investments from heavy emitters can create traction or a 'piggyback effect' on small emitters. A piggyback effect for new entrants may only be admissible if their entrance is also beneficial to the existing group of users. This is the case if the cost allocation method satisfies the property *advantageous scaling*: the costs allocated to each existing user do not increase if the number of users grows larger. Further, to keep the existing users of the infrastructure on board, it is essential that partial cooperation is not profitable. This is ensured by *coalitional rationality*. This property implies that the cost allocation is stable against coalitional deviations: no subgroup of the existing users has a financial reason to object to the cost allocation, because none of these subgroups can benefit from splitting off from the group of existing users. The *equal component cost sharing rule* we propose for infrastructure construction problems in general and CO2 transport infrastructures in particular satisfies both advantageous scaling and coalitional rationality. It is based on the idea that participants (equally) pay only for those infrastructure components that they use.

Having established the need for a multi-actor perspective on CO2 transport infrastructures specifically, we now discuss the more general contributions of our paper. User requirements towards new infrastructures usually differ over several characteristics, like transport radius, capacity, and conditioning. That is why we introduce so-called *component-based infrastructure cost problems* in which we construct an infrastructure that satisfies all user requirements over an arbitrary number of characteristics. Our modeling is based on the mathematical ability to uniquely decompose an infrastructure into a component structure such that each infrastructure component is either required by a user in its entirety, or not required at all. Each *Elementary Infrastucture Component* (`EIC`) will represent a unique part[2] of the potential infrastructure that may or may not be required by the users. Consequently, the infrastructure that is required by a group of users is given by a set of `EIC`s.

We identify and adopt a generic function to determine the total infrastructure construction costs for a given set of requirements. This cost function is constructed in such a way that it can be easily adapted to many different types of infrastructures. In particular, it allows for both continuous and discrete (categorical) characteristics, and for costs to be assigned to any combination of characteristics. Discrete characteristics can represent characteristics that, e.g., only depend on whether or not a user requires a certain specification. Importantly, despite the generic structure of the cost function, we are able to derive the costs of each individual `EIC`. The (minimal) costs for any group of users can then straightforwardly be determined as the sum of the costs of the required `EIC`s. Hence, using our component-based analysis of infrastructures, we are able to uniquely decompose an infrastructure into `EIC`s, assign a cost to each `EIC`, and for each `EIC` we can pinpoint exactly which users need this component. From this, as a natural follow-up, a way of allocating costs is derived: the *equal component cost sharing rule*. For each required component, the costs are divided equally among all users that require this component.

This allocation mechanism is completely in line with existing fairness principles and procedures as provided within the game-theoretic allocation literature. In particular, conceptually, our allocation proposal follows Littlechild and Thompson (1977), who develop a model for allocating the costs of an aircraft landing strip to different types of users, in such a way that users only pay for the part of the strip that they require. Their model and the corresponding cost allocation method are based on a single characteristic of the infrastructure, namely the length of the landing strip. Kuipers et al. (2013) introduce highway games for allocating construction costs of a highway to its users, taking into account that users may require different parts of the highway and ensuring that users only pay for those highway stretches that they require. There are several extensions or adaptations of highway games in which user requirements differ over two characteristics, see, e.g., Sudhölter and Zarzuelo (2017) for an overview of highway games and properties of different types of allocation methods. Our allocation mechanism in a collaborative infrastructure construction setting adds to this work by allowing user requirements to differ over any positive number of characteristics, instead of only two.

To further reflect on the role of game theory in the analysis of industrial clusters, Gedai et al. (2012) argue that game-theoretical models could help understand decision making in industrial clusters. Massol et al. (2018) use cooperative games to model CCS deployment specifically. They investigate the policy and economic conditions needed for a largest possible adoption of CCS technologies and networks, and to determine the break-even price for CCS adoption. Tan et al. (2016) and Andiappan et al. (2016) introduce cost allocation methods for newly developed multi-company industrial clusters, based on models from cooperative and non-cooperative game theory. In particular, both papers look at optimizing and allocating total cluster costs, including multiple infrastructures, for new sites.

We emphasize, however, that the main theoretical contribution and novelty of our paper lies in the component-based modeling of infrastructures and in the definition of a cost function with a very generic structure, for which we can still determine the costs per component. The equal component cost sharing rule then simply is a natural follow-up that satisfies the desirable properties of advantageous scaling and coalitional rationality.

To complement the theoretical results in the technical section of the paper, we subsequently study the specific case of a CO2 transport infrastructure for CCUS-hubs in the port of Rotterdam area in some detail.

[2]We remark that `EIC`s need not always directly correspond to physical components of the infrastructure, they are used to decompose the entire 'system'.

Here, we show how to transform a general description of such an infrastructure and its cost drivers into a component-based infrastructure cost problem and we apply the equal component cost sharing rule. We also demonstrate the workings of the properties of advantageous scaling and coalitional rationality. Finally, since the cost parameters in our case study are based on rough estimates, we analyze the behavior of the equal component cost sharing rule in various additional cost scenarios. In particular, we consider two scenarios in which either the fixed or the variable costs turn out to be higher than expected. Additionally, we consider a scenario in which the cost function changes more fundamentally, where certain costs depend on two characteristics instead of one. In each scenario, we find that the changes to the cost allocation accurately reflect which players 'should' be most affected by the changes. For example, distant emitters are most affected by increased variable transport costs, and additional costs to condition CO2 for re-use are only allocated to those that actually require conditioning for re-use. The final scenario also demonstrates the adaptability of the cost function in a more general way.

The paper is organized as follows. Section 2 discusses the CO2 transport infrastructure case as a specific application of our model, considering its users and their requirements towards this infrastructure. In Section 3 we formally define our component-based infrastructure model, discussing the `EIC`s, the cost function, and the equal component cost sharing rule and its properties. In Section 4 we apply the general model to our case study. Section 5 concludes.

2 CO2 Transport Infrastructure: Users, Requirements and Costs

Currently there are (at least) 12 regional open CO2 transport hubs under development globally. In this section, we provide a qualitative description of the case of a CO2 transport infrastructure inspired by a large CCUS project in an industrial cluster in the Netherlands, specifically the Porthos initiative in the Rotterdam port area (Porthos, 2022). After a brief overview of the basic elements of a CO2 transport infrastructure, we consider the potential users of this specific infrastructure and their heterogeneous requirements, and how these requirements drive the infrastructure construction costs.

The port authority of Rotterdam and two partners have set out to develop an open, collaborative and long term CO2 network that facilitates transport, storage and re-use of CO2. A sketch of such a CCUS transport infrastructure network can be found in Figure 1. The basic idea is that captured CO2 is gathered onshore at the different industry sites through a network of feeders and (a) main transport pipeline(s). After the gathering of the CO2 there are roughly two options. The gathered CO2 is either transported through a main transport pipeline towards the shore where it will be conditioned (pressure and temperature) for offshore transport towards identified storage fields close to the Rotterdam harbour industrial complex (see, e.g., EBN and Gasunie (2018) for potential CO2 storage fields in the Dutch North Sea), or it will be conditioned (pressure, temperature and purity) for re-use purposes and transported through a transport pipeline to sites that use CO2 as feedstock. The capacity of the main pipelines determine the capacity of the transport network. The blue lines in Figure 1 represent the CO2 transport network for a CCUS hub.

The following CO2 infrastructure users are in scope for this open network. First, the *heavy emitters*: the large scale (petro)chemical producers that see no short term cost effective alternative to CO2 emission reduction. They benefit from a large scale CO2 infrastructure with long term storage facilities. Second, the *distant emitters*: heavy emitters to be found a bit further away from the Rotterdam port area, such as in the Moerdijk area or the Zeeland chemical industrial cluster (DNVGL, 2020). They have similar requirements towards a CO2 transport network as heavy emitters, but they would require a larger onshore transport radius of the pipelines as the identified offshore storage fields are closest to the Rotterdam industrial complex. *Small emitters*: small petrochemical producers that do not aim for a large transport capacity. For them investing in carbon capture technologies might become attractive because of the availability of shared CO2 transport infrastructure. Next to the emitters, there are also potential users of the captured CO2. *Hydrogen producers* and *greenhouses*: these users of CO2 also require a smaller capacity and they are not interested in offshore transport to storage facilities, but they do have some more conditioning requirements for the CO2, e.g., its purity needs to be higher than for common onshore transport purposes. Hence, there are two levels

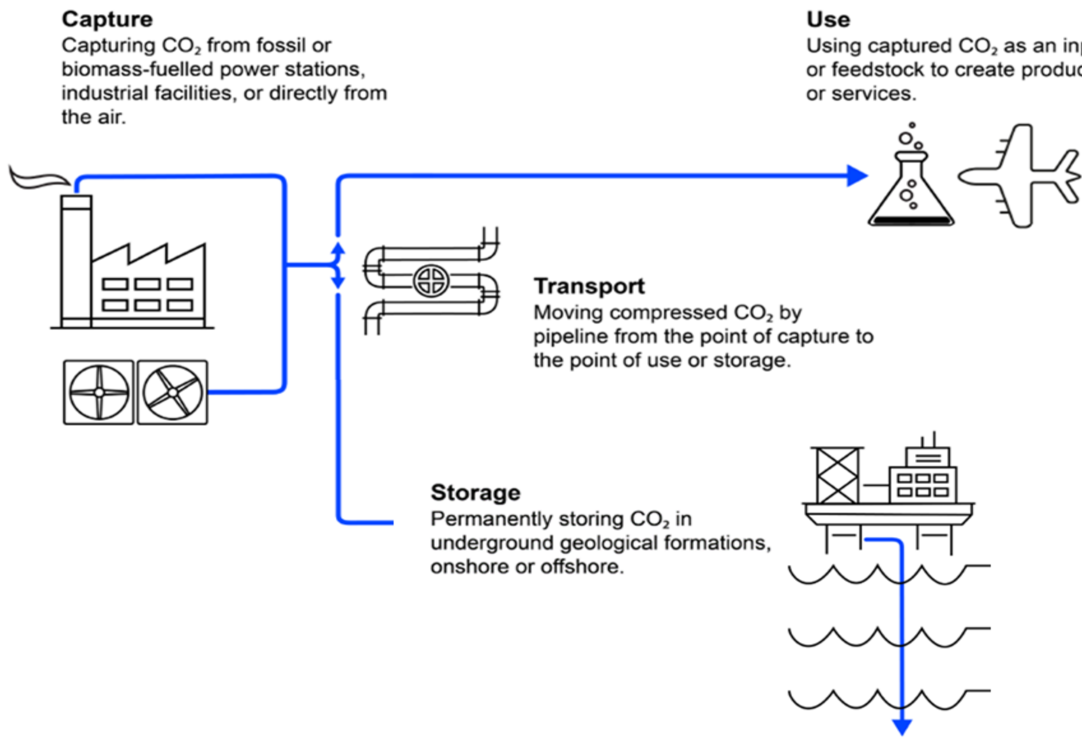

Figure 1: *Schematic overview of CCUS hub, adapted from IEA (2020).*

of conditioning that can be required for onshore transport: standard conditioning for onshore transportation and conditioning for re-use purposes. Table 1 gives a summary of the potential users and their heterogeneous requirements towards the CO2 transport infrastructure.

user	onshore transport radius	offshore transport	capacity	conditioning
heavy emitters	Large Rotterdam area	yes	large	standard
distant emitters	Zeeland area	yes	large	standard
small emitters	Large Rotterdam area	yes	small	standard
greenhouses	Large Rotterdam area	none	small	highly purified
hydrogen producers	Small Rotterdam area	none	small	highly purified

Table 1: *Stylized description of the user requirements for a regional CO2 transport infrastructure.*

Next, we discuss how these requirements drive the infrastructure construction costs. A more detailed argumentation is given at the start of Appendix C. The costs consist of fixed (system) and variable (pipeline) costs. Following Serpa et al. (2011), we express a linear relationship between the costs and the pipeline length (i.e., required transport radius), where the specific cost parameters depend on the terrain (onshore or offshore) and the transport capacity. Further, because conditioning mostly occurs in separate stations, we assume that conditioning requirements only influence the fixed portion of the costs, together with the capacity. Finally, offshore transport requires more advanced conditioning than standard onshore transport (so there is actually a third option for the conditioning). These conditioning costs are included in the fixed costs for offshore transport.

With this application in mind, Section 3 presents a general framework for the component-based analysis of such infrastructures and their costs, with a natural cost allocation rule as a direct result. Finally, we remark that several users in Table 1 are not yet part of the core group of interested participants, while they could benefit from the use of such a transport infrastructure. Both DNVGL (2020) and the Rotterdam port authority have sketched potential future connections to the more distant emitters and future CO2 users in their CO2 transport infrastructure plans. The potential addition of users is a reason to look for cost allocation methods that satisfy the *advantageous scaling* property: adding new users to the project might raise the total construction costs, but it will not result in a cost allocation increase for any of the original users. Further, *coalitional rationality* ensures that there is no financial reason for any subgroup of users to split off from the group and carry on independently. Both properties will be formally defined in Section 3.3, where we also show that they are satisfied by the cost allocation rule we propose.

3 Component-Based Analysis of Infrastructure Construction Problems

In this section, we introduce the theoretical framework to perform a component-based analysis of infrastructure construction problems, also from a cost allocation perspective.

3.1 Elementary Infrastructure Components in Infrastructure Problems

The situation in which players have different requirements for certain characteristics of an infrastructure that must be constructed, is referred to as an *infrastructure problem.* Formally, we define such a problem with the tuple

$$(N, M, X),$$

where N represents a finite player set, $M = \{1, \ldots, m\}$ represents a finite set of characteristics, and X represents a requirement matrix of which the rows correspond to N and the columns to M, such that the cell in the i-th row and k-th column, $X_i^k \in \mathbb{R}_+$, indicates the value that player $i \in N$ requires for characteristic $k \in M$.

Let (N, M, X) be an infrastructure problem. We denote the column of X with respect to $k \in M$ by X^k. For any $k \in M$, $Z^k = \{X_i^k | \ i \in N\}$ is defined as the set of unique values in X^k, and $n^k = |Z^k|$ denotes the number of distinct requirements for characteristic k. Then, $\tilde{X}^k \in \mathbb{R}_+^{n^k}$ is the vector containing the elements of Z^k sorted in increasing order. To emphasize, for any $k \in M$ and $\alpha_k \in \{1, \ldots, n^k\}$, $\tilde{X}^k_{\alpha_k}$ represents the α_k-th lowest value required by the players of the k-th characteristic. Moreover, we set $\tilde{X}^k_0 = 0$ for all $k \in M$.

Using this notation, an *Elementary Infrastructure Component* (`EIC`) is defined by

$$C^{\alpha_1, \ldots, \alpha_m} = \prod_{k=1}^{m} [\tilde{X}^k_{\alpha_k - 1}, \tilde{X}^k_{\alpha_k}],$$

where $\alpha_k \in \{1, \ldots, n^k\}$ for any $k \in M$.[3] Essentially, the origin (i.e., the point of the `EIC` with the lowest values of all characteristics) of $C^{\alpha_1, \ldots, \alpha_m}$ is $(\tilde{X}^1_{\alpha_1 - 1}, \ldots, \tilde{X}^m_{\alpha_m - 1})$ and the 'end point' (i.e., the point of the `EIC` with the highest values of all characteristics) is $(\tilde{X}^1_{\alpha_1}, \ldots, \tilde{X}^m_{\alpha_m})$. In this way, we define a total of $\prod_{k=1}^m n^k$ `EIC`s. We let $\mathcal{C} = \{C^{\alpha_1, \ldots, \alpha_m} | \ \alpha_k \in \{1, \ldots, n^k\}, k \in M\}$ denote the collection of all `EIC`s.

Each `EIC` represents a unique part of the potential infrastructure, in such a way that each player either requires the entire `EIC`, or does not require it at all. Comparing two `EIC`s with the same values for all characteristics except one, the `EIC` with a higher value for one characteristic comes on top of the `EIC` with lower value for this characteristic, it does not replace the `EIC` with lower value. To clarify this in the context of a CO2 transport network, consider Figure 2. The figure illustrates a 2-player infrastructure problem with two characteristics, radius and capacity, in which player A requires a network with large capacity in a short radius, while player B requires a smaller capacity, but a longer radius. In this example, the `EIC` corresponding to the top-left square represents the *additional* capacity required by player A, compared to player B, within the short radius. That is why player A requires both the 'small capacity' and the 'large capacity' square. Importantly, not all of the components in $\mathcal{C}$ are necessarily required by the player set N. In the example, we define an `EIC` corresponding to a large capacity over the longer radius as well, but this is clearly not required by either of the players.

[3] We remark that if $\tilde{X}^k_1 = 0$ for some $k \in M$, one dimension of certain components starts and ends at the same point: $\tilde{X}^k_0 = \tilde{X}^k_1 = 0$. This does not lead to any issues.

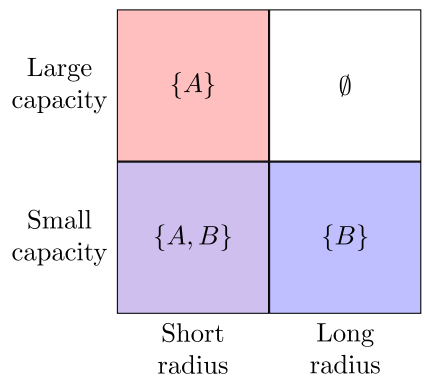

Figure 2: *Example of an infrastructure problem with two players (A and B) and two characteristics (radius and capacity). In each square, the set of players who require this square is given.*

Concretely, we say that an `EIC` is required by the player set N if and only if there is at least one player in N who requires the corresponding characteristic values for *all* characteristics. So, the corresponding (minimal) set $A(N)$ of all `EIC`s required by N is formally defined by

$$A(N) = \{C^{\alpha_1,\dots,\alpha_m} \in \mathcal{C} |\ \exists i \in N \text{ such that } \forall k \in M \text{ we have } X_i^k \geq \tilde{X}_{\alpha_k}^k\}. \quad (1)$$

The set $A(N)$ is also referred to as the *minimal* infrastructure that N requires. In Figure 2, $A(N)$ is given by the three colored squares.

3.2 Component-Based Infrastructure Cost Problems

In this section, we discuss the costs corresponding to an infrastructure problem, thereby defining the *component-based infrastructure cost problem*. To be able to determine the exact costs of a required infrastructure, we first define the general cost function $\kappa : Z^1 \times \cdots \times Z^m \to \mathbb{R}$ that gives the construction costs of a so-called *boxlike* infrastructure. Here, it is important to clarify the difference between a minimal and a boxlike infrastructure. In a minimal infrastructure, determined by $A(N)$ for player set N, the required value of one characteristic may decrease as another characteristic increases. In Figure 2 for example, the required capacity decreases from large to small as the radius increases from short to long. In a boxlike infrastructure, all characteristic values are fixed. In the example, κ would be used to reflect the costs of a network with a fixed capacity level and a fixed radius, it is not suitable to directly determine the costs of a network with capacity levels that vary depending on the radius. Graphically, κ determines the costs corresponding to any rectangle drawn from the bottom left corner, but not (directly) the total costs corresponding to the three colored squares in Figure 2.

However, the crucial feature of the general cost function κ is that through its definition one can derive a closed-form formula for the construction costs incurred due to the 'presence' of each `EIC` individually. Using this, we find the *minimal* infrastructure construction costs by summing the costs of all `EIC`s in $A(N)$.

Before formally defining κ, it is good to briefly discuss its general structure. The cost function allows for both continuous and discrete (categorical) characteristics. Where a continuous characteristic (like onshore transport radius) could take any non-negative value, a discrete characteristic can take a restricted set of values (like 0 and 1, depending on whether a player requires CO2 conditioning for re-use). On top of characteristics that are discrete by nature, such discrete characteristics may also be useful to represent characteristics that are in fact continuous, but for which the (unit) costs are grouped into certain categories, or an exact cost function is uncertain or difficult to determine in practice. By dividing the required values of such a characteristic into categories, it suffices to only find cost estimates for when the characteristic is, say, 'small' or 'large'. For example, cost estimates exist for a CO2 transport infrastructure with specific capacity levels (e.g., 2.5Mt/y and 10Mt/y), but a continuous cost function for any capacity level may be significantly harder to determine (and perhaps unnecessary).

For every combination of continuous and discrete characteristics, we define a coefficient based on the discrete characteristics that determines the slope of a linear relation between the costs and the product of the continuous characteristics for this particular combination. We then sum over all combinations of characteristics to obtain the total cost function. Of course, not every specific combination of characteristics necessarily leads to additional costs, so many of the coefficients may be zero.

Definition 3.1
Let (N, M, X) be an infrastructure problem and partition M into a set of continuous characteristics M_C and a set of discrete characteristics M_D, so that $M_C \cup M_D = M$ and $M_C \cap M_D = \emptyset$. Then, we let

$$I = (N, M, X, \kappa)$$

denote a component-based infrastructure cost problem, with

$$\kappa(z_1, ..., z_m) = \sum_{K \subseteq M_C} \sum_{L \subseteq M_D} \beta_K(\{z_k\}_{k \in L}) \prod_{k \in K} z_k,$$

where $z_k \in Z^k$ for all $k \in M$.

Note that each cost coefficient β_K is essentially a function of the discrete characteristics in L, so that the cost coefficient takes different values depending on the specific values of the characteristics in L. For cost coefficients that do not depend on any discrete characteristic, we set $\beta_K(\emptyset) = \beta_K$.

Example 3.1
To illustrate a component-based infrastructure cost problem $I = (N, M, X, \kappa)$, we now consider a general infrastructure problem based on Table 1, in which users have different requirements for four characteristics of a regional CO2 transport infrastructure. In particular, the characteristics are the onshore and offshore transport radius, the capacity of the network, and the conditioning of the CO2, respectively represented by $M = \{1, 2, 3, 4\}$. As discussed previously, cost estimates may only be available for specific capacity levels rather than continuously for any capacity level. Therefore, the third characteristic will be treated as a discrete characteristic. The same holds for the fourth characteristic, so that $M_C = \{1, 2\}$ and $M_D = \{3, 4\}$. Written out in full, the cost function has 16 terms:

$$\begin{aligned}
\kappa(z_1, z_2, z_3, z_4) = \beta_\emptyset \quad & + \beta_\emptyset(z_3) & + \beta_\emptyset(z_4) & + \beta_\emptyset(z_3, z_4) \\
+ \beta_{\{1\}} z_1 \quad & + \beta_{\{1\}}(z_3) z_1 & + \beta_{\{1\}}(z_4) z_1 & + \beta_{\{1\}}(z_3, z_4) z_1 \\
+ \beta_{\{2\}} z_2 \quad & + \beta_{\{2\}}(z_3) z_2 & + \beta_{\{2\}}(z_4) z_2 & + \beta_{\{2\}}(z_3, z_4) z_2 \\
+ \beta_{\{1,2\}} z_1 z_2 \quad & + \beta_{\{1,2\}}(z_3) z_1 z_2 & + \beta_{\{1,2\}}(z_4) z_1 z_2 & + \beta_{\{1,2\}}(z_3, z_4) z_1 z_2,
\end{aligned}$$

where $z_k \in Z^k$ for all $k \in M$. Many of the coefficients (and thereby the corresponding terms in κ) may be equal to zero, as will be discussed in Example 3.2. △

Clearly, cost function κ has a very generic structure, that can be adapted to reflect various infrastructure contexts. Despite this, it still allows the costs to be analyzed on a per component basis. Specifically, to analyze the costs of more sophisticated infrastructures, for which the requirement of a characteristic may vary for different values of other characteristics, we can derive the costs $\lambda(C^{\alpha_1,...,\alpha_m})$ of each individual `EIC` $C^{\alpha_1,...,\alpha_m} \in \mathcal{C}$. These costs can be iteratively determined on the basis of cost function κ, or, equivalently, using the closed-form expression (2), presented in Theorem 3.2, based on the inclusion-exclusion principle. In this theorem, we show that using (2) for the costs of each `EIC`, the costs of *any* boxlike infrastructure equal the sum of the costs of all `EIC`s within this 'box'. We illustrate the workings of all elements of this theorem in Example 3.2. Its proof is deferred to Appendix A.

Theorem 3.2
Let $I = (N, M, X, \kappa)$ be a component-based infrastructure cost problem. Let the costs $\lambda(C^{\alpha_1,...,\alpha_m})$ of an `EIC` *$C^{\alpha_1,...,\alpha_m} \in \mathcal{C}$ be given by*

$$\lambda(C^{\alpha_1,...,\alpha_m}) = \sum_{M_C^\alpha \subseteq K \subseteq M_C} \quad \sum_{M_D^\alpha \subseteq L \subseteq M_D} b^{\alpha_1,...,\alpha_m}(K, L) \prod_{k \in K} \left(\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k - 1}\right), \tag{2}$$

where $M_C^\alpha = \{k \in M_C |\ \alpha_k > 1\}$ *and* $M_D^\alpha = \{k \in M_D |\ \alpha_k > 1\}$*, and*

$$b^{\alpha_1,\ldots,\alpha_m}(K, L) = \sum_{T \subseteq M_D^\alpha} (-1)^{|T|} \beta_K\big(\{\tilde{X}^k_{\alpha_k}\}_{k \in L \setminus T}, \{\tilde{X}^k_{\alpha_k - 1}\}_{k \in T}\big) \tag{3}$$

for all $M_C^\alpha \subseteq K \subseteq M_C$ *and* $M_D^\alpha \subseteq L \subseteq M_D$*. Then, for all* $\zeta_k \in \{1, ..., n^k\}$*,* $k \in M$*,*

$$\kappa(\tilde{X}^1_{\zeta_1}, ..., \tilde{X}^m_{\zeta_m}) = \sum_{k \in M} \sum_{\alpha_k \in \{1,\ldots,\zeta_k\}} \lambda(C^{\alpha_1,\ldots,\alpha_m}).$$

Example 3.2
We now illustrate Theorem 3.2 by means of an example of a component-based infrastructure cost problem with $M_C = \{1, 2\}$ and $M_D = \{3, 4\}$, and cost function

$$\kappa(z_1, z_2, z_3, z_4) = \beta_\emptyset(z_3, z_4) + \beta_{\{1\}}(z_3) z_1 + \beta_{\{1,2\}} z_1 z_2, \tag{4}$$

where $z_k \in Z^k$ for all $k \in M$. Going back to the CO2 transport infrastructure context of Example 3.1, the first term in (4) corresponds to fixed costs depending on the capacity level and the level of conditioning in the network. The second term represents costs that increase linearly in the onshore transport radius, where the slope of this linear relation depends on the capacity level. The final term represents variable costs based on the product of the onshore and offshore transport radius, for which the cost coefficient is constant, independent of the discrete characteristics. In Section 4, we provide a full case study using a more realistic cost function for such a CO2 transport infrastructure.

We calculate the costs of all `EIC`s $C^{\alpha_1,\alpha_2,\alpha_3,\alpha_4} \in \mathcal{C}$ with $\alpha_k \in \{1, 2\}$ for all $k \in M$. Before elaborating on the calculations of a few instructive components, it is good to note that many of the `EIC`s have zero costs. For example, consider the costs of $C^{1,2,1,2}$. In (2), we only sum over $K \subseteq \{1, 2\}$ and $L \subseteq \{3, 4\}$ such that $M_C^\alpha = \{2\} \subseteq K$ and $M_D^\alpha = \{4\} \subseteq L$. However, note that there is no non-zero coefficient in (4) for which both $\{2\} \in K$ and $\{4\} \in L$. Therefore, the costs of this `EIC` simply equal zero. A similar argument can be made for $C^{1,2,2,1}$ and $C^{2,1,1,2}$, and all `EIC`s with $\alpha_k = 2$ for three or four characteristics $k \in M$. All non-zero costs of the `EIC`s are given in Table 2.

`EIC`	λ(`EIC`)
$C^{1,1,1,1}$	$\beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1) + \beta_{\{1\}}(\tilde{X}^3_1)\tilde{X}^1_1 + \beta_{\{1,2\}}\tilde{X}^1_1\tilde{X}^2_1$
$C^{1,1,1,2}$	$\beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_2) - \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1)$
$C^{1,1,2,1}$	$\beta_\emptyset(\tilde{X}^3_2, \tilde{X}^4_1) - \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1) + \big(\beta_{\{1\}}(\tilde{X}^3_2) - \beta_{\{1\}}(\tilde{X}^3_1)\big)\tilde{X}^1_1$
$C^{1,2,1,1}$	$\beta_{\{1,2\}}\tilde{X}^1_1(\tilde{X}^2_2 - \tilde{X}^2_1)$
$C^{2,1,1,1}$	$\beta_{\{1\}}(\tilde{X}^3_1) \cdot (\tilde{X}^1_2 - \tilde{X}^1_1) + \beta_{\{1,2\}} \cdot (\tilde{X}^1_2 - \tilde{X}^1_1)\tilde{X}^2_1$
$C^{1,1,2,2}$	$\beta_\emptyset(\tilde{X}^3_2, \tilde{X}^4_2) - \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_2) - \beta_\emptyset(\tilde{X}^3_2, \tilde{X}^4_1) + \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1)$
$C^{2,1,2,1}$	$\big(\beta_{\{1\}}(\tilde{X}^3_2) - \beta_{\{1\}}(\tilde{X}^3_1)\big)(\tilde{X}^1_2 - \tilde{X}^1_1)$
$C^{2,2,1,1}$	$\beta_{\{1,2\}} \cdot (\tilde{X}^1_2 - \tilde{X}^1_1)(\tilde{X}^2_2 - \tilde{X}^2_1)$

Table 2: *All non-zero costs of* `EIC`*s* $C^{\alpha_1,\alpha_2,\alpha_3,\alpha_4} \in \mathcal{C}$ *with* $\alpha_k \in \{1, 2\}$ *for all* $k \in M$*, based on cost function (4).*

For $C^{1,1,1,1}$, we have $M_C^\alpha = M_D^\alpha = \emptyset$, so we sum over all $K \subseteq \{1, 2\}$ and $L \subseteq \{3, 4\}$ in (2). However, $\lambda(C^{1,1,1,1})$ will only consist of three terms, corresponding to the combinations of K and L with non-zero coefficients, namely $K = \emptyset$ and $L = \{3, 4\}$, $K = \{1\}$ and $L = \{3\}$, and $K = \{1, 2\}$ and $L = \emptyset$. Since $M_D^\alpha = \emptyset$, we restrict to $T = \emptyset$ in (3) for both $L = \{3\}$ and $L = \{3, 4\}$. For $L = \emptyset$, we use the fact that

$$b^{\alpha_1,\ldots,\alpha_m}(K, \emptyset) = \beta_K$$

for any $K \subseteq M_C$. Further, we use that $\tilde{X}^k_0 = 0$ for all $k \in M$, which yields[4]

$$\begin{aligned}
\lambda(C^{1,1,1,1}) &= (-1)^0\beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1) + (-1)^0\beta_{\{1\}}(\tilde{X}^3_1) \cdot (\tilde{X}^1_1 - \tilde{X}^1_0) + \beta_{\{1,2\}} \cdot (\tilde{X}^1_1 - \tilde{X}^1_0)(\tilde{X}^2_1 - \tilde{X}^2_0) \\
&= \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1) + \beta_{\{1\}}(\tilde{X}^3_1) \cdot (\tilde{X}^1_1 - 0) + \beta_{\{1,2\}} \cdot (\tilde{X}^1_1 - 0)(\tilde{X}^2_1 - 0) \\
&= \beta_\emptyset(\tilde{X}^3_1, \tilde{X}^4_1) + \beta_{\{1\}}(\tilde{X}^3_1)\tilde{X}^1_1 + \beta_{\{1,2\}}\tilde{X}^1_1\tilde{X}^2_1.
\end{aligned}$$

[4]In the first term, corresponding to $K = \emptyset$, we also use the convention that the empty product equals one.

To further illustrate the workings of (3), essentially representing the inclusion and exclusion of cost parameters, we consider the costs of `EIC` $C^{1,1,2,2}$ next. Since $M_D^\alpha = M_D = \{3,4\}$, we only consider $L = \{3,4\}$, for which $K = \emptyset$ gives the only non-zero coefficient. However, in this case $b^{1,1,2,2}(\emptyset, L)$ consists of four terms, corresponding to $T = \emptyset$, $T = \{3\}$, $T = \{4\}$, and $T = \{3,4\}$, respectively:

$$\begin{aligned}\lambda(C^{1,1,2,2}) &= (-1)^0\beta_\emptyset(\tilde{X}_2^3, \tilde{X}_2^4) + (-1)^1\beta_\emptyset(\tilde{X}_1^3, \tilde{X}_2^4) + (-1)^1\beta_\emptyset(\tilde{X}_2^3, \tilde{X}_1^4) + (-1)^2\beta_\emptyset(\tilde{X}_1^3, \tilde{X}_1^4)\\ &= \beta_\emptyset(\tilde{X}_2^3, \tilde{X}_2^4) - \beta_\emptyset(\tilde{X}_1^3, \tilde{X}_2^4) - \beta_\emptyset(\tilde{X}_2^3, \tilde{X}_1^4) + \beta_\emptyset(\tilde{X}_1^3, \tilde{X}_1^4).\end{aligned}$$

Finally, we consider `EIC` $C^{2,1,2,1}$. Since $M_C^\alpha = \{1\}$ and $M_D^\alpha = \{3\}$, the only combination of K and L with a non-zero coefficient and $M_C^\alpha \subseteq K$ and $M_D^\alpha \subseteq L$ is $K = \{1\}$ and $L = \{3\}$, for which $b^{2,1,2,1}(\{1\},\{3\}) = \beta_{\{1\}}(\tilde{X}_2^3) - \beta_{\{1\}}(\tilde{X}_1^3)$. Using this, we directly find the closed-form expression for the costs of this `EIC`, namely

$$\lambda(C^{2,1,2,1}) = \big(\beta_{\{1\}}(\tilde{X}_2^3) - \beta_{\{1\}}(\tilde{X}_1^3)\big)(\tilde{X}_2^1 - \tilde{X}_1^1).$$

The remaining costs in Table 2 can be calculated in the same way. Indeed, we find that the costs of *any* boxlike infrastructure equal the sum of the costs of all `EIC`s within this box. For example, one readily verifies that

$$\begin{aligned}&\lambda(C^{1,1,1,1}) + \lambda(C^{1,1,1,2}) + \lambda(C^{1,1,2,1}) + \lambda(C^{1,2,1,1}) + \lambda(C^{2,1,1,1}) + \lambda(C^{1,1,2,2}) + \lambda(C^{1,2,1,2}) + \lambda(C^{1,2,2,1})\\ &+ \lambda(C^{2,1,1,2}) + \lambda(C^{2,1,2,1}) + \lambda(C^{2,2,1,1}) + \lambda(C^{1,2,2,2}) + \lambda(C^{2,1,2,2}) + \lambda(C^{2,2,1,2}) + \lambda(C^{2,2,2,1}) + \lambda(C^{2,2,2,2})\\ &= \beta_\emptyset(\tilde{X}_2^3, \tilde{X}_2^4) + \beta_{\{1\}}(\tilde{X}_2^3)\tilde{X}_2^1 + \beta_{\{1,2\}}\tilde{X}_2^1\tilde{X}_2^2 = \kappa(\tilde{X}_2^1, \tilde{X}_2^2, \tilde{X}_2^3, \tilde{X}_2^4). \qquad \triangle\end{aligned}$$

To determine the total construction costs $c(N)$ of the minimally required infrastructure of player set N, we simply sum the costs of all `EIC`s in $A(N)$, i.e.,

$$c(N) = \sum_{C^{\alpha_1,\ldots,\alpha_m} \in A(N)} \lambda(C^{\alpha_1,\ldots,\alpha_m}).$$

In a component-based infrastructure cost problem $I = (N, M, X, \kappa)$, non-negativity of the costs of each `EIC` is guaranteed if cost function κ satisfies a natural condition. We describe such problems as component-based infrastructure cost problems with *regular* κ. The results in Section 3.3 will use the non-negativity of each `EIC`'s costs.

Definition 3.3
Let $I = (N, M, X, \kappa)$ be a component-based infrastructure cost problem. Then, we say κ is regular if

$$b^{\alpha_1,\ldots,\alpha_m}(K, L) \geq 0$$

for any $\alpha_k \in \{1,\ldots,n^k\}$, $k \in M$ and all K, L such that $M_C^\alpha \subseteq K \subseteq M_C$ and $M_D^\alpha \subseteq L \subseteq M_D$, where $M_C^\alpha = \{k \in M_C |\ \alpha_k > 1\}$ and $M_D^\alpha = \{k \in M_D |\ \alpha_k > 1\}$.

In the context of Example 3.1 and using cost function (4), the regularity requirements on κ boil down to the following conditions on the underlying cost coefficients. Next to non-negativity of all cost coefficients, regularity entails that the cost coefficient of onshore transport does not decrease as the capacity level increases. Further, the cost coefficient corresponding to the fixed costs cannot decrease when the capacity level increases and conditioning remains at the lowest level, or when the level of conditioning increases with the capacity fixed at its lowest level. Lastly, this fixed costs coefficient must be such that the additional costs of conditioning CO2 for re-use do not decrease as the capacity level of the network grows, and vice versa. All requirements seem to be reasonable.

3.3 The Equal Component Cost Sharing Rule

The *equal component cost sharing rule* γ is an allocation mechanism that follows naturally from the component-based analysis of infrastructure construction costs. Specifically, γ divides the total costs $c(N)$ corresponding to a component-based infrastructure cost problem $I = (N, M, X, \kappa)$ over the players in N, such that the costs of each required `EIC` are equally divided over the players who require that component.

To properly define the equal component cost sharing rule, we let $N^{\alpha_1,\dots,\alpha_m} = \{i \in N |\ X_i^k \geq \tilde{X}_{\alpha_k}^k\ \forall k \in M\}$ denote the set of players in N who require component $C^{\alpha_1,\dots,\alpha_m} \in \mathcal{C}$. Using this, $A(\{i\}) = \{C^{\alpha_1,\dots,\alpha_m} \in \mathcal{C} |\ i \in N^{\alpha_1,\dots,\alpha_m}\}$ is defined as the set of EICs that a player $i \in N$ requires in I. Finally, we denote the class of all component-based infrastructure cost problems by $\mathcal{I}$.

Definition 3.4
The equal component cost sharing rule γ on $\mathcal{I}$ is defined by setting

$$\gamma_i(I) = \sum_{C^{\alpha_1,\dots,\alpha_m} \in A(\{i\})} \frac{\lambda(C^{\alpha_1,\dots,\alpha_m})}{|N^{\alpha_1,\dots,\alpha_m}|}$$

for all $I = (N, M, X, \kappa) \in \mathcal{I}$ and any $i \in N$.

For each player, the allocated costs are based only on the costs of the components that this player actually requires. Hence, the definition of γ is such that players 'only pay for what they need'. Moreover, if players require the same set of components, they pay the same.

We will show that the equal component cost sharing rule satisfies the properties of coalitional rationality and advantageous scaling, if the component-based infrastructure cost problem is such that cost function κ is regular.

Let f be a cost sharing rule on $\mathcal{I}$. Intuitively, the *coalitional rationality* property states that for any component-based infrastructure cost problem $I = (N, M, X, \kappa) \in \mathcal{I}$, no coalition $S \subseteq N$ has a (financial) reason to object to the cost allocation $f(I)$, because no coalition can benefit from splitting off from the grand coalition N: for any $S \subseteq N$, the total costs allocated to the players in S are below or equal to the costs of the minimal infrastructure $A(S)$ that S requires. Put differently, the cost allocation is stable against coalitional deviations. Note that this property is strongly related to the cooperative game-theoretic notion of the core (Gillies (1959), see Ray and Vohra (2015) for a more extensive discussion of the core).

A coalition S requires an EIC if at least one player in S requires the EIC. Formally, $A(S) = \{C^{\alpha_1,\dots,\alpha_m} \in \mathcal{C} |\ S^{\alpha_1,\dots,\alpha_m} \neq \emptyset\}$, where $S^{\alpha_1,\dots,\alpha_m} = \{i \in S |\ C^{\alpha_1,\dots,\alpha_m} \in A(\{i\})\}$ denotes the set of players in S who require EIC $C^{\alpha_1,\dots,\alpha_m} \in \mathcal{C}$.

Coalitional rationality *Let f be a cost sharing rule on $\mathcal{I}$. Then, f satisfies coalitional rationality on $\mathcal{I}$ if*

$$\sum_{i \in S} f_i(I) \leq \sum_{C^{\alpha_1,\dots,\alpha_m} \in A(S)} \lambda(C^{\alpha_1,\dots,\alpha_m})$$

for all $I = (N, M, X, \kappa) \in \mathcal{I}$ and all $S \subseteq N$.

Next, we define *advantageous scaling* for a cost sharing rule f on $\mathcal{I}$. This property states that the costs allocated to each player can only decrease if the player set N grows larger.

Advantageous scaling *Let f be a cost sharing rule on $\mathcal{I}$. Then, f satisfies advantageous scaling on $\mathcal{I}$ if*

$$f_i(\bar{I}) \leq f_i(I)$$

for all $I = (N, M, X, \kappa) \in \mathcal{I}$ and $\bar{I} = (\bar{N}, M, \bar{X}, \kappa) \in \mathcal{I}$ such that $N \subseteq \bar{N}$ and[5] *$X_j = \bar{X}_j$ for all $j \in N$, and for all $i \in N$.*

Theorem 3.5
The equal component cost sharing rule γ satisfies coalitional rationality and advantageous scaling on $\mathcal{I}$, if κ is regular.

Before applying our cost sharing rule in a case study, we remark that one can define a cooperative cost game (N, c_I) corresponding to a component-based infrastructure cost problem $I = (N, M, X, \kappa)$ by setting

[5] Recall that X_j, $j \in N$, denotes the j-th row of matrix X.

$c_I(S) = \sum_{C^{\alpha_1,\ldots,\alpha_m} \in A(S)} \lambda(C^{\alpha_1,\ldots,\alpha_m})$. In this way, $c_I(S)$ reflects the total costs of the minimal infrastructure $A(S)$ that a coalition $S \subseteq N$ requires. Interestingly, it can then be shown that the equal component cost sharing rule $\gamma(I)$ coincides with the Shapley value (Shapley, 1953) of the cost game (N, c_I). In fact, if κ is regular, one can show that the cost game is 'concave', from which it directly follows that the Shapley value is in the core and that the (extended) Shapley value is a so-called population monotonic allocation scheme (Sprumont, 1990). The former directly implies coalitional rationality, where the latter implies advantageous scaling. In Appendix B, we provide an explicit and direct proof of Theorem 3.5 without relying on the translation into a cooperative game and more general game-theoretical results.

4 Component-Based Infrastructure Cost Problems Applied to CO2 Transport Infrastructures

In this section, we apply the technical model of Section 3 to the specific case of CO2 transport infrastructure for CCUS-hubs in the port of Rotterdam area described in Section 2. This section follows the steps as sketched in Figure 3. We first convert the qualitative problem description of Section 2 into a component-based infrastructure cost problem, and determine the required set of EICs and their costs. Subsequently, we discuss the results with respect to cost allocation using the equal component cost sharing rule, also considering alternative scenarios for the cost parameters.

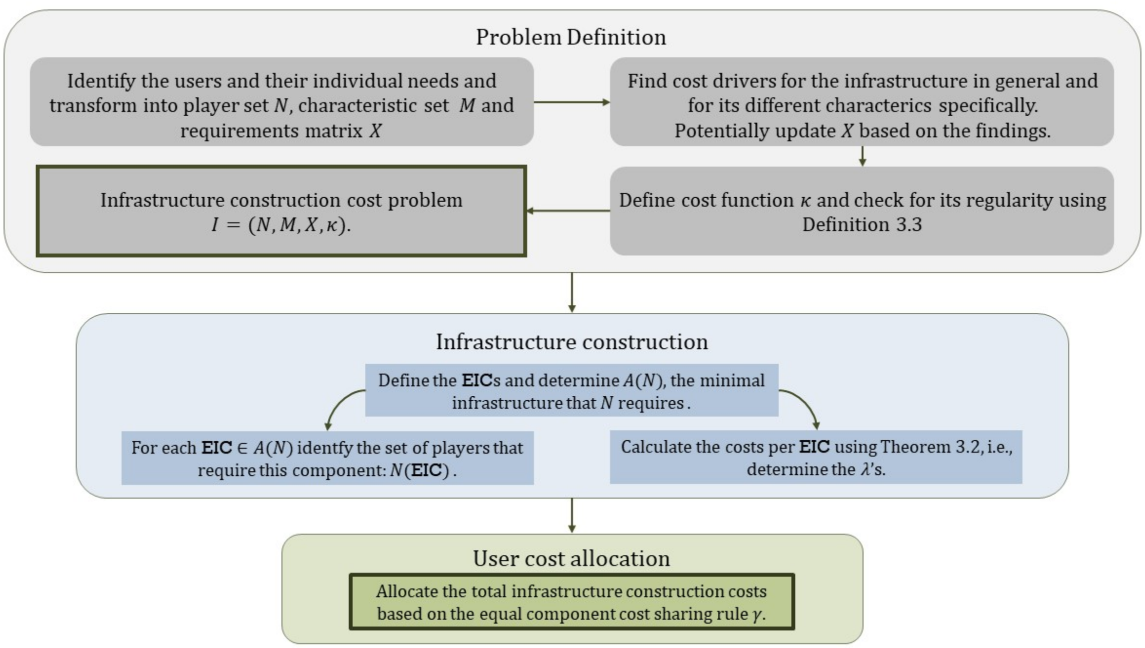

Figure 3: *Steps for applying component-based analysis and equal component cost sharing rule to a multi-actor infrastructure construction problem.*

4.1 CO2 Transport EICs and Their Costs

The general problem description of Section 2 can be transformed into a formal component-based infrastructure cost problem. The player set is represented more compactly using numbers: $N = \{1, 2, 3, 4, 5\}$, corresponding to the players 'Heavy Emitters', 'Distant Emitters', 'Small Emitters', 'Greenhouses', and 'Hydrogen producers', respectively. Furthermore there are four infrastructure component characteristics for which the users have different requirements, hence $M = \{1, 2, 3, 4\}$. Table 3, a quantified version of Table 1, gives the entries for our requirement matrix X.

$N \downarrow$	$M \rightarrow$	onshore transport radius 1	offshore transport radius 2	capacity 3	conditioning 4
heavy emitters	1	30	30	2	1
distant emitters	2	80	30	2	1
small emitters	3	30	30	1	1
greenhouses	4	30	0	1	2
hydrogen producers	5	10	0	1	2

Table 3: *Transformation of Table 1 into entries for requirement matrix X.*

The first two characteristics, onshore and offshore transport radius, are expressed in kilometers. The third characteristic, transport capacity, is in this application represented by discrete options: 1 reflects a small capacity (around 2.5 Mt/y), and a 2 reflects a larger network with higher capacity (around 10 Mt/y). Finally, the fourth characteristic is related to the conditioning of CO2, is also discrete and can take two values: this characteristic is 2 if the corresponding player re-uses CO2 (and thereby requires additional conditioning w.r.t. pressure, temperature and purity), and 1 otherwise.

The elementary infrastructure components corresponding to this CO2 transport infrastructure are defined on the basis of the vectors of unique requirements (sorted in increasing order) for each characteristic, namely

$$\tilde{X}^1 = \begin{bmatrix} 10 \\ 30 \\ 80 \end{bmatrix}, \tilde{X}^2 = \begin{bmatrix} 0 \\ 30 \end{bmatrix}, \tilde{X}^3 = \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \text{ and } \tilde{X}^4 = \begin{bmatrix} 1 \\ 2 \end{bmatrix}.$$

Next, we present how these infrastructure characteristics drive the construction costs. This part continues with the findings on the CO2 transport cost drivers from Section 2: the CO2 infrastructure construction cost function is a combination of onshore costs and offshore costs; and those costs consist of a fixed and a variable portion. For a detailed derivation of the cost function parameter values, the β's in Section 3, we refer to Appendix C.

The *costs of onshore transportation* are determined by a fixed and variable portion. The value of the fixed cost parameter is determined by the value of characteristics 3 and 4, i.e., capacity and level of conditioning. The variable cost parameter is determined by the requirement for characteristic 3, capacity, only. The higher the required transport capacity, the higher the costs per km. Formally, we have

$$\kappa_{\text{onshore}}(z_1, z_3, z_4) = {}^{6} \begin{cases} 6 + 0,6z_1 & \text{if } z_3 = 1 \text{ and } z_4 = 1, \\ 8 + 0.75z_1 & \text{if } z_3 = 2 \text{ and } z_4 = 1, \\ 42 + 0.6z_1 & \text{if } z_3 = 1 \text{ and } z_4 = 2, \\ 94 + 0.75z_1 & \text{if } z_3 = 2 \text{ and } z_4 = 2, \end{cases}$$

with $z_1 \in \{10, 30, 80\}$, $z_3 \in \{1, 2\}$ and $z_4 \in \{1, 2\}$. Thus, an onshore transport radius of 10 kilometers ($z_1 = 10$) with 2.5 Mton capacity ($z_3 = 1$) and standard conditioning ($z_4 = 1$), costs $6 + 0.6 \cdot 10 = 12$ million euros, while the same 10 kilometers with 2.5 Mton capacity and conditioning for re-use purpose ($z_4 = 2$) cost $42 + 0.6 \cdot 10 = 48$ million euros.

Offshore transportation costs are also determined by a fixed and variable portion. The values of both the fixed and the variable cost parameter are determined only by the value of characteristic 3 (i.e., transport capacity), as the conditioning that partly determines the fixed costs is the same for all offshore transport. However, we only want to add (fixed) offshore costs if the players actually make use of offshore transportation, i.e., if their required offshore length is greater than 0. For the variable cost portion this happens instantly as the cost parameter will be multiplied by the required offshore length. For the fixed costs portion we achieve

[6] For readability purposes of this section, the cost function is presented in a conditional breakdown, and the characteristic values z_3 and z_4 are included in the conditions only. Recall that $z_3 = 1$ and $z_3 = 2$ represent a small (2.5 Mt/y) and large (10 Mt/y) capacity, respectively, and $z_4 = 1$ and $z_4 = 2$ represent standard conditioning and conditioning for re-use, respectively.

this using the indicator variable X^5 with, for all $i \in N$, $X_i^5 = 1$ if $X_i^2 > 0$ and 0 otherwise.[7] One can interpret these costs as the required costs for transfer and compressor stations when going from onshore to offshore transportation. Formally, we have

$$\kappa_{\text{offshore}}(z_2, z_3, z_5) = \begin{cases} 1.2z_2 + 38z_5 & \text{if } z_3 = 1, \\ 1.6z_2 + 64z_5 & \text{if } z_3 = 2, \end{cases}$$

with $z_2 \in \{0, 30\}$, $z_3 \in \{1, 2\}$ and $z_5 \in \{0, 1\}$. Note that here the first term represents the variable costs and the second term the fixed.

For the total cost function of our CO2 transport infrastructure application we have

$$\begin{aligned} \kappa(z_1, z_2, z_3, z_4, z_5) &= \kappa_{\text{onshore}}(z_1, z_3, z_4) + \kappa_{\text{offshore}}(z_2, z_3, z_5) \\ &= \begin{cases} 6 + 0.6z_1 + 1.2z_2 + 38z_5 & \text{if } z_3 = 1 \text{ and } z_4 = 1, \\ 8 + 0.75z_1 + 1.6z_2 + 64z_5 & \text{if } z_3 = 2 \text{ and } z_4 = 1, \\ 42 + 0.6z_1 + 1.2z_2 + 38z_5 & \text{if } z_3 = 1 \text{ and } z_4 = 2, \\ 94 + 0.75z_1 + 1.6z_2 + 64z_5 & \text{if } z_3 = 2 \text{ and } z_4 = 2, \end{cases} \end{aligned}$$

with $z_1 \in \{10, 30, 80\}$, $z_2 \in \{0, 30\}$, $z_3 \in \{1, 2\}$, $z_4 \in \{1, 2\}$ and $z_5 \in \{0, 1\}$. It can be shown that κ is regular, so that the costs of each `EIC` are non-negative.

As a result, using the vectors $\tilde{X}^1, \tilde{X}^2, \tilde{X}^3$, $\tilde{X}^4$ and $\tilde{X}^5$, and the specific context of this CO2 transport infrastructure, we find that $A(N)$ consists of exactly 11 elementary infrastructure components with non-zero costs.[8] Table 4 gives, for each of these components, the `EIC`, the corresponding set of players $N(\texttt{EIC})$ that requires it, the costs $\lambda(\texttt{EIC})$, and an interpretation. It is clear from this `EIC`-decomposition that not all infrastructure components are required by all players. The requirements from players 1 and 2 coincide in many `EIC`s, while players 4 and 5 are only interested in the first two `EIC`s and one `EIC` dedicated to re-use conditioning. This last one is not of interest to the other three players.

`EIC`	$N(\texttt{EIC})$	$\lambda(\texttt{EIC})$	Interpretation
$C^{1,1,1,1,1}$	{1, 2, 3, 4, 5}	12	onsh. transp. [km 0-10] with small cap. and no re-use cond.
$C^{2,1,1,1,1}$	{1, 2, 3, 4}	12	onsh. transp. [km 10-30] with small cap. and no re-use cond.
$C^{3,1,1,1,1}$	{2}	30	onsh. transp. [km 30-80] with small cap. and no re-use cond.
$C^{1,1,2,1,1}$	{1, 2}	3.5	onsh. transp. [km 0-10] with increased cap. and no re-use cond.
$C^{2,1,2,1,1}$	{1, 2}	3	onsh. transp. [km 10-30] with increased cap. and no re-use cond.
$C^{3,1,2,1,1}$	{2}	7.5	onsh. transp. [km 30-80] with increased cap. and no re-use cond.
$C^{1,1,1,1,2}$	{1, 2, 3}	38	conversion to offsh. transp. with small cap.
$C^{1,1,2,1,2}$	{1, 2}	26	conversion to offsh. transp. with increased cap.
$C^{1,2,1,1,1}$	{1, 2, 3}	36	offsh. transp. [km 0-30] with small cap.
$C^{1,2,2,1,1}$	{1, 2}	12	offsh. transp. [km 0-30] with increased cap.
$C^{1,1,1,2,1}$	{4, 5}	36	cond. for re-use, small cap.

Table 4: *Each `EIC` with non-zero costs required in the CO2 transport network, with the set of players that requires it, its costs, and an interpretation. Onsh. = onshore, offsh. = offshore, transp. = transport, cap. = capacity, cond. = conditioning.*

Having completed the decomposition into `EIC`s, Theorem 3.2 can now be used to derive the costs per `EIC`. The exact mathematical expressions of the costs $\lambda(\texttt{EIC})$ per `EIC` can be found in Table 11 in Appendix D. Using these derivations, we readily find all costs per `EIC` in $A(N)$, as summarized in the third column in Table 4. If we sum the costs of all `EIC`s, we find that $c(N) = 216$ million euros, the construction costs for the minimal infrastructure that N requires. One can also see that these 216 million euros can be split in

[7]This is a simple dummy variable that does not have a meaningful impact on the interpretation or structure of the model, while ensuring fixed costs for offshore transportation are only included when applicable. As a consequence, however, the resulting `EIC`s will be based on 5 characteristics instead of 4. Note that $\tilde{X}^5 = [0\ 1]^\top$.

[8]Formally there are 48 `EIC`s, 12 of which have non-zero costs. However, this 12th `EIC` with non-zero costs, $C^{1,1,2,2,1}$, is not required by any of the users, since there is no user that requires both a large transport capacity and re-use conditioning.

104 million euros onshore infrastructure construction costs and 112 million euros offshore infrastructure construction costs. The next section discusses how to allocate these costs over the CO2 transport infrastructure users.

4.2 Component-Based Cost Allocations for CO2 Transport Infrastructure

In this section, we apply the equal component cost sharing rule γ to allocate the total CO2 infrastructure construction costs $c(N) = 216$ over its different users. The basic idea of equal component cost sharing is that the costs of each `EIC` in $A(N)$ are equally shared among the group of users of this component. For example, the costs of `EIC` $C^{1,1,1,1,1}$ are allocated equally to all players, whereas only player 2 pays for $C^{3,1,1,1,1}$, a component corresponding to the longer transport radius only the distant emitters require. In this way, combining the information from columns 2 and 3 in Table 4 directly provides the cost allocation that follows from this rule, namely

$$\gamma(I) = {}^{9}(52.3, 89.8, 30.1, 23.4, 20.4).$$

The remainder of this section demonstrates the use of the equal component cost sharing method in two ways. First, we vary the set of players that are using the CO2 transport network, in order to show the attractiveness of the rule's properties coalitional rationality and advantageous scaling. Second, we consider three additional cost scenarios to show the adaptability of the general cost function κ and to show that one can easily attribute particular cost increases to specific players.

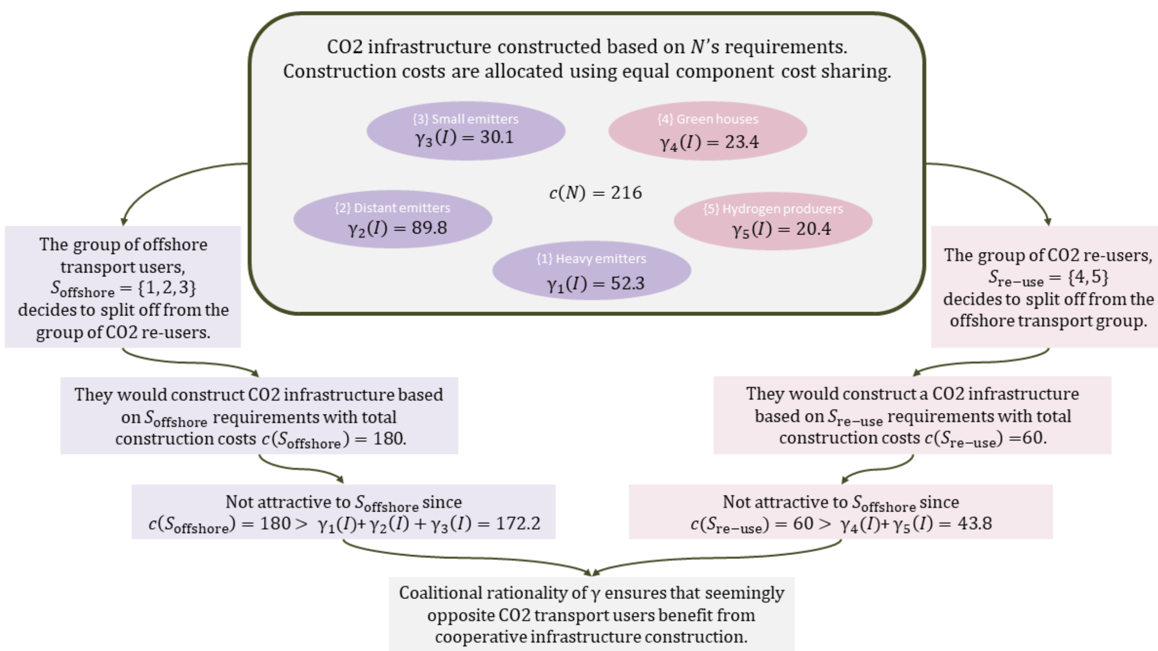

Figure 4: *Coalitional rationality: what would happen if the offshore or the re-use coalition would split off and decide to construct their own CO2 infrastructure?*

Varying the player set

The player set N consists of five typical potential users of CO2 infrastructure. Within this group of 5, there are 2 logical groups that might find some common ground in their requirements and also in the things they do *not* need. The heavy, distant and small emitters each require offshore transport infrastructure, while they do not require any conditioning for re-use. The greenhouses and hydrogen producers need conditioning

[9] All costs are rounded to (at most) one decimal place in this section.

for re-use purposes, while they do not require any offshore transport. In Figure 4 we describe what would happen if either the 'offshorers' or the CO2 re-users would split off from N.

Let $S_{\text{offshore}} = \{1, 2, 3\}$ be the offshore subgroup that splits off from N and constructs a CO2 transport infrastructure that only satisfies their subgroup's requirements. Compared to N, S_{offshore} no longer requires $C^{1,1,1,2,1}$, so that $c(S_{\text{offshore}}) = 216 - 36 = 180$. Thus, if the offshore subgroup would build an infrastructure that only satisfies their requirements it would cost them 180 million euros. This is higher than the approximately $52.3 + 89.8 + 30.1 = 172.2$ million euros that are allocated to them in the setting where an infrastructure is constructed for all players in N.

Alternatively if the re-use subgroup $S_{\text{re-use}} = \{4, 5\}$ would split off, they require only $C^{1,1,1,1,1}$, $C^{2,1,1,1,1}$, and $C^{1,1,1,2,1}$, with total construction costs $c(S_{\text{re-use}}) = 60$ million euros. This is significantly more than the approximately $23.4 + 20.4 = 43.8$ million euros in the case of constructing and sharing an CO2 transport infrastructure for the total group of users N.

Due to the *coalitional rationality* property of the equal component cost sharing rule γ, these seemingly opposite subcoalitions $S_{\text{offshore}} = \{1, 2, 3\}$ and $S_{\text{re-use}} = \{4, 5\}$ are not better of if they construct and share a CO2 transport infrastructure for only their subgroup. This does not only hold for these two coalitions, but for any potential coalitional deviation.

Next, we analyze the effect of adding players. For this, the new starting point of analysis is a situation in which only the 'local' players cooperate to construct a CO2 transport infrastructure and the distant emitter, player 2, is not involved. The component-based infrastructure problem $I = (N, M, X, \kappa)$ we have analyzed so far would instead be a problem without player 2. Figure 5 illustrates what would happen if this local coalition would consider letting the distant emitter, player 2, join this local group.

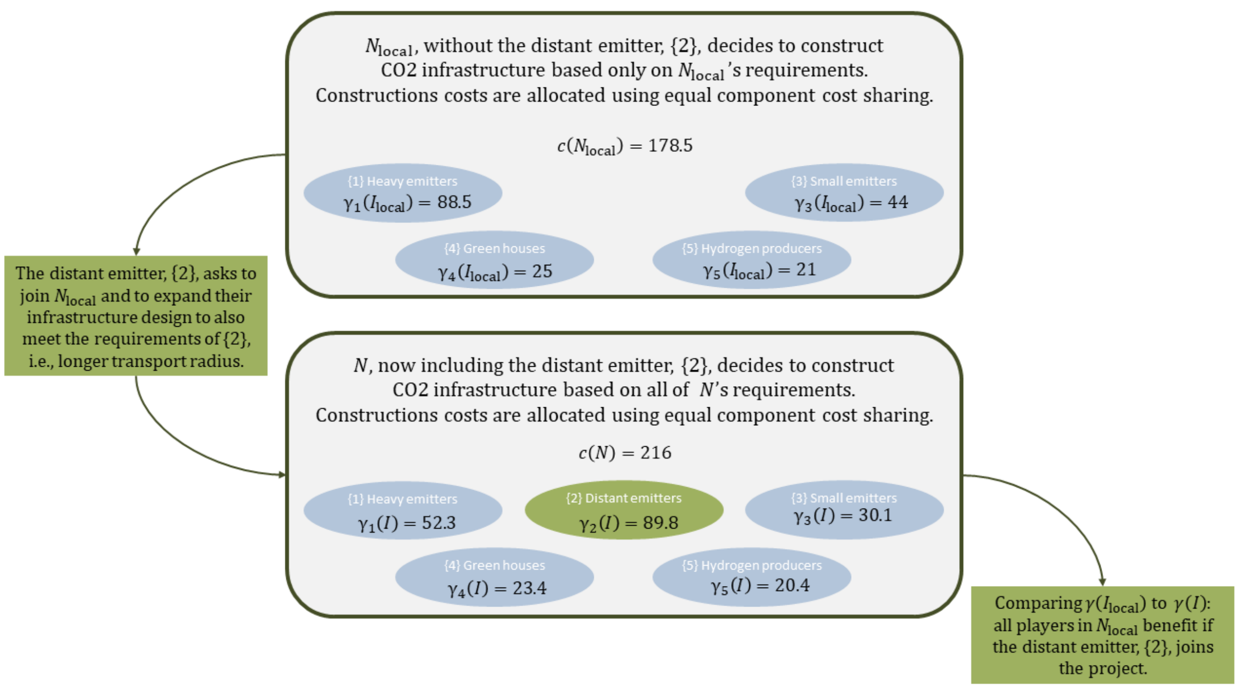

Figure 5: *Advantageous scaling: what would happen if the local coalition would extend its coalition and infrastructure design to the more distant CO2 transport user?*

Formally, we then consider the component-based infrastructure problem $I_{\text{local}} = (N_{\text{local}}, M, X_{-2}, \kappa)$, with $N_{\text{local}} = \{1, 3, 4, 5\}$ and where X_{-2} represents the matrix X without its second row. Since the absence of player 2 has no effect on the requirements of any of the other players or on the cost function κ, we can use Table 4 to determine the total costs of the player set N_{local} and the allocation of these costs according to the equal component cost sharing rule, and we find that $c(N_{\text{local}}) = 178.5$. Applying the equal component cost sharing rule to this component-based CO2 infrastructure problem yields

$$\gamma(I_{\text{local}}) = (88.5, 44, 25, 21).$$

Comparing $\gamma(I)$ to $\gamma(I_{\text{local}})$, it becomes apparent that all players in the local group would benefit if the distant emitter, player 2, joins the project. This addition to the player set from N_{local} to N would lead to a decrease in the costs allocated to all four 'local' players, as anticipated based on the *advantageous scaling* property. The difference is most notable for players 1 and 3, since the first three players share a requirement for costly offshore transportation. Therefore, players 1 and 3 benefit greatly from sharing the corresponding costs with player 2. In case of player 1, this effect is reinforced much further by the fact that player 2 is the only other player who requires high transport capacity.

Varying the costs

CCUS is one of the key enabling technologies for accelerating and realizing decarbonization of industries. New insights in costs and cost drivers, especially of shared CO2 transport infrastructures, will emerge every year. The parameters that we use are based on non-recent studies and the estimates are rough (cf. Appendix C). That is why we extend our application with three extra cost parameter scenarios. This section not only shows the impact on cost allocations to the players, but it also shows that if better, more recent or more accurate data becomes available, one can easily update the cost model and its parameters. The following scenarios are considered:

- a scenario VAR↑ 25% where all variable cost parameters values are 25 percent higher;
- a scenario FIX↑ 25% where all fixed cost parameters are 25 percent higher;
- a scenario REUSE+VAR in which the conditioning for re-use also leads to increased variable onshore transportation costs.

In all three cases, the other parameter values remain the same. The adaptations of the cost function parameters used in κ that follow from these three scenarios are given in Table 5. The third cost scenario REUSE+VAR shows the adaptability of the cost function of a component-based infrastructure cost problem. In this REUSE+VAR scenario, the conditioning for re-use ($z_4 = 2$) does not just lead to fixed costs, but also increases the variable costs of onshore CO2 transport. It means that parameter "Onshore VAR 2.5 Mton" is split into "Onshore VAR 2.5 Mton standard" with original value 0.6, the variable costs for onshore transport with standard conditioning, and "Onshore VAR 2.5 Mton re-use", the new variable costs for onshore transport with re-use conditioning, with value 1.[10]

cost parameter description	baseline	VAR ↑ 25%	FIX ↑ 25%	REUSE+VAR
Onshore VAR 2.5 Mton	0.6	0.75	0.6	-
Onshore VAR 2.5 Mton standard	-	-	-	0.6
Onshore VAR 2.5 Mton re-use	-	-	-	1
Onshore VAR 10 Mton	0.75	0.94	0.75	0.75
Onshore FIX 2.5 Mton standard	6	6	7.5	6
Onshore FIX 10 Mton standard	8	8	10	8
Onshore FIX 2.5 Mton re-use	42	42	52.5	42
Onshore FIX 10 Mton re-use	94	94	117.5	94
Offshore VAR 2.5 Mton	1.2	1.5	1.2	1.2
Offshore VAR 10 Mton	1.6	2	1.6	1.6
Offshore FIX 2.5 Mton	38	38	47.5	38
Offshore FIX 10 Mton	64	64	80	64

Table 5: *Cost parameters for different cost scenarios as used in the cost function κ of the* `EIC` *application to CO2 transport infrastructure problems.*

The extra variable cost driver in the third scenario leads to a change in the costs of the `EIC` $C^{1,1,1,2,1}$, since we need to account for the variable re-use conditioning costs. Since player 4 and 5 have different transport

[10] This new parameter value is for illustrative purposes only.

radius requirements, it also leads to one new EIC with non-zero costs in $A(N)$: $C^{2,1,1,2,1}$. This component is only required by player 4 and represents the extra 20 kilometer transport radius needed by player 4, relative to player 5. The costs per EIC in each of the three scenarios are outlined next to the baseline in Table 6.

EIC	N(EIC)	baseline	FIX↑ 25%	VAR↑ 25%	REUSE+VAR
$C^{1,1,1,1,1}$	{1, 2, 3, 4, 5}	12	13.5	13.5	12
$C^{2,1,1,1,1}$	{1, 2, 3, 4}	12	12	15	12
$C^{3,1,1,1,1}$	{2}	30	30	37.5	30
$C^{1,1,2,1,1}$	{1, 2}	3.5	4	3.875	3.5
$C^{2,1,2,1,1}$	{1, 2}	3	3	3.75	3
$C^{3,1,2,1,1}$	{2}	7.5	7.5	9.375	7.5
$C^{1,1,1,1,2}$	{1, 2, 3}	38	47.5	38	38
$C^{1,2,1,1,1}$	{1, 2, 3}	36	36	45	36
$C^{1,1,2,1,2}$	{1, 2}	26	32.5	26	26
$C^{1,2,2,1,1}$	{1, 2}	12	12	15	12
$C^{1,1,1,2,1}$	{4, 5}	36	45	36	40
$\mathbf{C^{2,1,1,2,1}}$	{4}	-	-	-	8
$c(N)$		216	243	243	228

Table 6: *Costs per* EIC *in four different scenarios for the CO2 transport cost drivers.*

Note that for cost scenarios FIX↑ 25% and VAR↑ 25%, the costs of all EICs except $C^{1,1,1,1,1}$ and $C^{1,1,2,1,1}$ either increase 25%, or do not change. This occurs because all these components correspond to a part of the infrastructure that leads to either only additional fixed costs (e.g., additional fixed costs for conditioning) or only additional variable costs (e.g., additional variable onshore transport costs). We also remark that the total costs are 243 million euros in both scenarios. This is merely a coincidence: in the baseline cost scenario the total costs $c(N) = 216$ consist of exactly 108 fixed costs (42+8-6+64) and 108 variable costs, so the total costs increase an equal amount in both scenarios.

Using Table 6, one can readily apply the equal component cost sharing rule to find the cost allocations given in Table 7.

player	baseline	FIX↑ 25%	VAR↑ 25%	REUSE + VAR
heavy emitters	52.3	59.3 (↑ 13.3%)	58.4 (↑ 11.7%)	52.3 (↑ 0%)
distant emitters	89.8	96.8 (↑ 7.8%)	105.3 (↑ 17.2%)	89.8 (↑ 0%)
small emitters	30.1	33.5 (↑ 11.5%)	34.1 (↑ 13.5%)	30.1 (↑ 0%)
greenhouses	23.4	28.2 (↑ 20.5%)	24.5 (↑ 4.5%)	33.4 (↑ 42.7%)
hydrogen producers	20.4	25.2 (↑ 23.5%)	20.7 (↑ 1.5%)	22.4 (↑ 9.8%)

Table 7: *Cost allocations based on the equal component cost sharing rule for the construction costs of a CO2 transport infrastructure in four different cost scenarios.*

Several interesting observations can be made here. The equality of the total costs for the scenarios FIX↑ 25% and VAR↑ 25% allows for a 'fair' comparison of the corresponding cost allocations. The equal component cost sharing rule behaves as we would expect. It is clear that the players who require conditioning for re-use (4 and 5) are relatively most affected by an increase in fixed costs, since this is a relatively large part of their (allocated) costs. Similarly, the distant emitters are most affected by the increase in variable costs, due to their large onshore transport radius.

For the REUSE+VAR cost scenario, only the players who require conditioning for re-use purposes face an increase in allocated costs. The larger requirement for onshore transport radius of player 4 compared to player 5 means the former is affected more by the increase in variable costs.

5 Concluding Remarks

Motivated by the necessity for new infrastructures to support the ongoing climate and energy transition in general, and CO2 transport infrastructures for CCUS in particular, we develop a general model for infrastructure construction from a multi-actor perspective. We account for the heterogeneous requirements of the users for the characteristics of an infrastructure by mathematically decomposing this infrastructure into so-called elementary infrastructure components (`EIC`s). The main theoretical contribution of this paper lies in Definition 3.1 accompanied by Theorem 3.2: we define a cost function that supports the component-based modeling of infrastructures, as despite its generic structure we can still determine the costs per `EIC`. An additional advantage of Theorem 3.2 is that it directly results in a natural cost allocation rule: the equal component cost sharing rule of Definition 3.4. This allocation rule also satisfies the desirable properties of coalitional rationality and advantageous scaling (Theorem 3.5), under the reasonable requirement of regularity of the cost function (Definition 3.3).

As demonstrated in Section 4, the theoretical framework is very suitable to model the specific case of a CO2 transport infrastructure for CCUS-hubs in the port of Rotterdam area presented in Section 2. However, its use is not restricted to CO2 transport infrastructures. One could further validate the general model in additional case studies, since the generic structure of the cost function allows for it to be adapted to different types of infrastructures.

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Appendix A Proof of Theorem 3.2

Let $\zeta_k \in \{1, ..., n^k\}$ for all $k \in M$. We show that the costs of the corresponding boxlike infrastructure, as determined by $\kappa(\tilde{X}^1_{\zeta_1}, ..., \tilde{X}^m_{\zeta_m})$, equal the sum of the costs of all `EIC`s within this box. Concretely, we show that

$$\kappa(\tilde{X}^1_{\zeta_1}, ..., \tilde{X}^m_{\zeta_m}) = \sum_{k\in M} \sum_{\alpha_k \in \{1,...,\zeta_k\}} \lambda(C^{\alpha_1,...,\alpha_m}), \tag{5}$$

where, as given in (2),

$$\lambda(C^{\alpha_1,...,\alpha_m}) = \sum_{M_C^\alpha \subseteq K \subseteq M_C} \sum_{M_D^\alpha \subseteq L \subseteq M_D} b^{\alpha_1,...,\alpha_m}(K,L) \prod_{k\in K} \big(\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k - 1}\big). \tag{6}$$

In (6), for all $\alpha_k \in \{1,...,\zeta_k\}$, $k \in M$, we sum over all $K \subseteq M_C$ and $L \subseteq M_D$ such that $M_C^\alpha = \{k \in M_C|\ \alpha_k > 1\} \subseteq K$ and $M_D^\alpha = \{k \in M_D|\ \alpha_k > 1\} \subseteq L$, i.e., for all $k \in M$ such that $\alpha_k > 1$ we have $k \in K \cup L$. Put differently, we only sum over $K \subseteq M_C$ and $L \subseteq M_D$ if $\alpha_k = 1$ for all $k \in M \setminus (K \cup L)$. Consequently, we may rewrite

$$\sum_{k\in M} \sum_{\alpha_k \in\{1,...,\zeta_k\}} \lambda(C^{\alpha_1,...,\alpha_m}) = \sum_{K\subseteq M_C} \sum_{L\subseteq M_D} \sum_{k\in K\cup L} \sum_{\alpha_k\in\{1,...,\zeta_k\}} b^{\alpha_1,...,\alpha_m}(K,L) \prod_{k\in K} \big(\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k-1}\big),$$

where $\alpha_k = 1$ for all $k \in M \setminus (K \cup L)$.

Recall that

$$\kappa(\tilde{X}^1_{\zeta_1}, ..., \tilde{X}^m_{\zeta_m}) = \sum_{K\subseteq M_C} \sum_{L\subseteq M_D} \beta_K(\{\tilde{X}^k_{\zeta_k}\}_{k\in L}) \prod_{k\in K} \tilde{X}^k_{\zeta_k}$$

and

$$b^{\alpha_1,...,\alpha_m}(K,L) = \sum_{T\subseteq M_D^\alpha} (-1)^{|T|} \beta_K\big(\{\tilde{X}^k_{\alpha_k}\}_{k\in L\setminus T}, \{\tilde{X}^k_{\alpha_k-1}\}_{k\in T}\big).$$

We can now show that (5) holds by showing that

$$\beta_K\big(\{\tilde{X}^k_{\zeta_k}\}_{k\in L}\big) \prod_{k\in K} \tilde{X}^k_{\zeta_k} = \sum_{k\in K\cup L} \sum_{\alpha_k\in\{1,...,\zeta_k\}} \sum_{T\subseteq M_D^\alpha} (-1)^{|T|} \beta_K\big(\{\tilde{X}^k_{\alpha_k}\}_{k\in L\setminus T}, \{\tilde{X}^k_{\alpha_k-1}\}_{k\in T}\big) \prod_{k\in K} \big(\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k-1}\big)$$

for all $K \subseteq M_C$ and all $L \subseteq M_D$.

Let $K \subseteq M_C$ and let $L \subseteq M_D$. Note that we can analyze the terms corresponding to continuous characteristics separately from those corresponding to discrete characteristics, by consecutively showing

$$\beta_K\big(\{\tilde{X}^k_{\zeta_k}\}_{k\in L}\big) = \sum_{k\in L} \sum_{\alpha_k\in\{1,...,\zeta_k\}} \sum_{T\subseteq M_D^\alpha} (-1)^{|T|} \beta_K\big(\{\tilde{X}^k_{\alpha_k}\}_{k\in L\setminus T}, \{\tilde{X}^k_{\alpha_k-1}\}_{k\in T}\big) \tag{7}$$

and

$$\prod_{k\in K} \tilde{X}^k_{\zeta_k} = \sum_{k\in K} \sum_{\alpha_k\in\{1,...,\zeta_k\}} \prod_{k\in K} (\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k-1}).$$

The latter can be straightforwardly shown by recursively using the telescoping sum $\sum_{\alpha_k\in\{1,...,\zeta_k\}} \big(\tilde{X}^k_{\alpha_k} - \tilde{X}^k_{\alpha_k-1}\big) = \tilde{X}^k_{\zeta_k} - \tilde{X}^k_0 = \tilde{X}^k_{\zeta_k}$ for all $k \in K$.

It remains to show that (7) holds. For this, we show that any $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ such that $\eta_k \in \{1,...,\zeta_k\}$ for all $k \in L$ cancels out on the right-hand side of (7), except when $\eta_k = \zeta_k$ for all $k \in L$.

Let $\eta_k \in \{1,...,\zeta_k\}$ for all $k \in L$. Let $U = \{k \in L|\ \eta_k \in \{1,...,\zeta_k - 1\}\}$ denote the set of discrete characteristics in L that do not equal their ζ_k-th value. Note that we always add the term $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ once, irrespective of U, by considering $\eta_k = \alpha_k$ for all $k \in L$ and $T = \emptyset$ on the right hand side of (7). Next, if $|U| \geq 1$, we subtract $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ exactly $|U|$ times, namely whenever $\eta_l = \alpha_l - 1$ for some $l \in U$, $\eta_k = \alpha_k$ for all other $k \in U \setminus \{l\}$, and $T = \{l\}$ (so that $(-1)^{|T|} = -1$). Then, if $|U| \geq 2$, we add $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ exactly $\binom{|U|}{2}$ times, namely whenever $\eta_l = \alpha_l - 1$ and $\eta_m = \alpha_m - 1$ for $l, m \in U$, $\eta_k = \alpha_k$ for all other $k \in U \setminus \{l, m\}$, and $T = \{l, m\}$ (so that $(-1)^{|T|} = 1$). This process continues until we arrive at $\eta_k = \alpha_k - 1$ for all $k \in U$ and $T = U$, so that we add or subtract $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ once more, depending on $(-1)^{|U|}$.

More generally, $\beta_K\big(\{\tilde{X}^k_{\eta_k}\}_{k\in L}\big)$ is counted exactly $\sum_{r\in\{0,...,|U|\}} (-1)^r \binom{|U|}{r}$ times. Hence, we can apply the binomial theorem

$$(x+y)^n = \sum_{k\in\{0,...,n\}} \binom{n}{k} x^{n-k} y^k$$

for any non-negative integer n. In particular, we use $x = 1$, $y = -1$, and $n = |U|$. We find zero whenever $|U| \geq 1$, and one for $|U| = 0$. Hence, only one term does not cancel out on the right-hand side of (7), namely the term corresponding to $U = \emptyset$, and it is added exactly once. Since this term is $\beta_K\big(\{\tilde{X}^k_{\zeta_k}\}_{k\in L}\big)$, we see that (7) holds, which completes the proof.

Appendix B Proof of Theorem 3.5

Here, we show that the equal component cost sharing rule γ satisfies coalitional rationality and advantageous scaling on $\mathcal{I}$, if κ is regular.

For coalitional rationality, let $I = (N, M, X, \kappa) \in \mathcal{I}$ with regular κ and let $S \subseteq N$. Then,

$$\begin{aligned}
\sum_{i\in S} \gamma_i(I) &= \sum_{i\in S} \sum_{C^{\alpha_1,\dots,\alpha_m}\in A(\{i\})} \frac{\lambda(C^{\alpha_1,\dots,\alpha_m})}{|N^{\alpha_1,\dots,\alpha_m}|} \\
&= \sum_{C^{\alpha_1,\dots,\alpha_m}\in \mathcal{C}} |S^{\alpha_1,\dots,\alpha_m}| \frac{\lambda(C^{\alpha_1,\dots,\alpha_m})}{|N^{\alpha_1,\dots,\alpha_m}|} \\
&\leq \sum_{\substack{C^{\alpha_1,\dots,\alpha_m}\in \mathcal{C}:\\ S^{\alpha_1,\dots,\alpha_m}\neq\emptyset}} \lambda(C^{\alpha_1,\dots,\alpha_m}) \\
&= \sum_{C^{\alpha_1,\dots,\alpha_m}\in A(S)} \lambda(C^{\alpha_1,\dots,\alpha_m})
\end{aligned}$$

where the inequality follows from the fact that the costs of each `EIC` are non-negative (since κ is regular) and $S^{\alpha_1,\dots,\alpha_m} \subseteq N^{\alpha_1,\dots,\alpha_m}$ for all $\alpha_k \in \{1, \dots, n^k\}$, $k \in M$.

To see that γ satisfies advantageous scaling if κ is regular, consider $I = (N, M, X, \kappa) \in \mathcal{I}$ and $\bar{I} = (\bar{N}, M, \bar{X}, \kappa) \in \mathcal{I}$ with regular κ such that $N \subseteq \bar{N}$ and $X_j = \bar{X}_j$ for all $j \in N$, and let $i \in N$. It is good to note that $\bar{\mathcal{C}}$ contains more components than $\mathcal{C}$ if a new player also brings new requirements. Since the costs of player i can only be affected by `EIC`s that i requires, i is not affected by new components that only the new players require. However, a new requirement may 'split' an existing component that i requires into 'subcomponents'. We will not formally define such splits, but instead provide an intuitive argument why this never increases the costs of player i. Clearly, the costs of the original component equal the sum of the costs of the subcomponents. If a subcomponent is not required by a new player, the corresponding costs are divided over the same set of players in N as before, so this does not affect the costs of i. If a subcomponent is required by a new player, the costs of this subcomponent are divided over more players than before, thereby lowering the costs of i (here, we also use the non-negativity of the costs of each `EIC`). It follows that $\gamma_i(\bar{I}) \leq \gamma_i(I)$.

Appendix C Cost Drivers and Parameter Values of CO2 Transport Infrastructure Application

In this appendix, we first review literature concerning the main cost drivers in the construction of a CO2 transport infrastructure. Then, we derive the cost parameter values used in Section 4 on the basis of two selected studies.

Van der Linden (2019) estimates that for the regional CCUS cluster in Rotterdam investments in the range of 300 to 400 million euros are necessary. A year later, in a more extensive study, these costs have been re-estimated to 400 to 500 million euros (DNVGL, 2020). CO2 transport infrastructure is a significant (but not the only) portion of these roughly estimated investment costs. Capital cost estimates are highly variable (Akbilgic et al., 2015), depending, e.g., on which cost components are aggregated to calculate total capital costs. Though there are different factors driving the costs, often only estimates of total costs are presented. There is also a stream of literature developing detailed cost models for different CCUS network components, see Knoope (2015) for a review. These detailed models can be used to optimize pipeline configurations such as pipeline diameter and choice of materials based on, e.g., geological and economic conditions. These studies are, however, often focused on a single component (e.g., only considering compression cost drivers or offshore pipeline cost drivers), rather than an entire CO2 transport infrastructure like we aim to analyze. Two exceptions are summarized in Mallon et al. (2013): a 2011 report from the Zero Emmission Platform (ZEP, 2011) on CO2 transport costs and in the same year a technical study from JRC into CO2 pipeline costs (Serpa et al., 2011).

The cost drivers and the corresponding parameter values we consider in our application are mainly based on these two studies. We choose these sources for our cost estimates for various reasons: they are readily available, are most consistent with the cost driver relations found in the literature, and cover a range of CO2 transport infrastructure designs with varying characteristics. Although ZEP's and JRC's cost estimates as absolute numbers might no longer be accurate, they do provide insight in the relative changes in investment costs due to changes in type of terrain (onshore or offshore), transport capacity, or transport radius.

ZEP presents total transport cost estimates for different combinations of pipeline length and yearly transport capacity. They also perform a simple sensitivity analysis, where they conclude that investment costs account for circa 90% of total CO2 transport costs, the relation between costs and transport length is almost linear, and the actual use of the transport pipeline does (almost) not influence the costs as long as it does not exceed its maximum capacity.

Serpa et al. (2011) state that the capital costs of a CO2 pipeline system consist of pipeline material and installation costs, and costs for system equipment such as pumping and filtering stations and (digital) control systems. They develop a heuristic and simplified approach to estimate CO2 pipeline costs. They express a linear relationship between costs and pipeline length, where the specific cost parameters depend on the terrain (onshore or offshore), the yearly transport capacity and the quality of CO2.

Next, we discuss the derivation of the cost parameter values used in the application in Section 4. Recall from Section 2 and Section 4.1 that, based on the aforementioned two studies, we consider costs consisting of fixed (system) and variable (pipeline) costs, for both onshore and offshore transportation. There is a linear relationship between the costs and the required transport radius, where the specific cost parameters depend on the terrain and the transport capacity. Further, conditioning requirements only influence the fixed portion of the costs[11], together with the capacity.

Since CCUS is one of the key enabling technologies for accelerating and realizing decarbonization of industries, new insights in costs and cost drivers, especially of shared CO2 transport infrastructures, will emerge regularly. The parameters that we use are based on non-recent studies and the estimates are rough. Therefore, we present our parameter derivation in such a way that if better, more recent or more accurate data becomes available, one can easily adapt the cost parameters.

What parameters?

In Section 4.1, it becomes clear that we only need to find 10 different cost parameters for the corresponding total cost function. We have continuous characteristics 'onshore transport radius' and 'offshore transport radius', $M_C = \{1, 2\}$, and discrete characteristics 'transport capacity' and 'CO2 conditioning', $M_D = \{3, 4\}$. Finally from the entries in the requirement matrix X we see that both discrete variables only take two values.

Onshore cost parameters

We start with the cost parameters for onshore transportation. In Table 8, we combine ZEP's and JRC's transport cost estimates into one table.

JRC's data refer to pipeline costs only, while ZEP's data refer to total pipeline system costs. Since, we use this data only for inspirational and exemplary purposes, we combine this data without further corrections for potential price level differences. First, we interpolate the JRC data to find that for 10 Mt/y capacity the pipeline costs per km are approximately 0.735 million euros.

We combine JRC's variable cost estimates corresponding to 2.5 Mt/y and 10 Mt/y with ZEP's data

[11] It is not clear how exactly the conditioning requirements influence the infrastructure construction costs. Unfortunately, Knoope (2015) concludes in her CO2 infrastructure cost model review that cost models for pumping stations (related to conditioning of the CO2) are not validated, and also EBN (2018) notes that there is no reference cost known for pumping stations. Mallon et al. (2013) apply a cost model to estimate the investments costs of pumping stations, but the actual investment costs seem to be 3 to 5 times higher than its estimates.

Capacity (Mt/y)	per km (JRC)	10 km feeders (ZEP)	180 km spine (ZEP)
2.5	0.59	11.5	147
5	0.64		
10		15	226
15	0.83		

Table 8: *Onshore transport pipeline system cost estimates in million euros for different combinations of pipeline length and yearly transport capacity, based on Annex 3 from ZEP (2011) and Table 10 from Serpa et al. (2011).*

to find approximations for the fixed costs, in the following way. The 10 km feeders are seen as a simple onshore transport system that is sufficiently conditioned for transportation to the shore - conditioning level 1. Hence, we estimate fixed costs for this type of pipeline at approximately $11.5 - 10 \cdot 0.59 = 5.6$ million euros for a small yearly capacity and $15 - 10 \cdot 0.735 = 7.65$ for a large capacity. The 180 km spine from ZEP is seen as a system that has a more advanced conditioning level due to the long distance, and is re-use ready - conditioning level 2. Again using the two variable cost parameters, the corresponding fixed costs are estimated in a similar way, which yields approximately 40.8 and 93.7 for small and large capacity, respectively.

Offshore cost parameters
Next, we consider offshore system costs. Again, we use a combination of JRC and ZEP data.

Capacity (Mt/y)	per km (JRC)	180 km spine (ZEP)
2.5	1.18	250
5	1.28	
10		338
15	1.78	

Table 9: *Offshore transport pipeline system cost estimates in million euros for different combinations of pipeline length and yearly transport capacity, based on Annex 3 from ZEP (2011) and Table 10 from Serpa et al. (2011).*

Using a similar linear interpolation approach as with the onshore cost parameter estimations, we find offshore variable costs of approximately 1.18 and 1.53 for small and large capacity, respectively, and use this to derive the corresponding offshore fixed costs estimates of approximately 37.6 and 62.6.

Parameters for application
The parameter estimates used in Section 4 are summarized under 'baseline' in Table 10. As explained previously, the derived cost function parameters are rough estimates based on rather non-recent sources. To avoid the impression of working with accurate cost estimates, we round up all estimates. In this table, we also present the first two scenarios in which the cost parameters differ, as discussed in Section 4.2.

Appendix D Detailed Calculations of Section 4.1

In Section 4, we only show a numerical breakdown of cost function κ for the component-based infrastructure cost problem, by providing different cost functions depending on the capacity level and the level of conditioning. This is simply a more intuitive representation of a more general cost function as formulated in Definition 3.1. In particular, we have

$$\kappa(z_1, z_2, z_3, z_4, z_5) = \beta_{\emptyset}(z_3, z_4) + \beta_{\{1\}}(z_3)z_1 + \beta_{\{2\}}(z_3)z_2 + \beta_{\{5\}}(z_3)z_5, \tag{8}$$

with $z_1 \in \{10, 30, 80\}$, $z_2 \in \{0, 30\}$, $z_3 \in \{1, 2\}$, $z_4 \in \{1, 2\}$ and $z_5 \in \{0, 1\}$. The coefficient values are derived in Appendix C and summarized in Table 10. Using the more general notation, we have $\beta_{\emptyset}(1, 1) = 6$, $\beta_{\emptyset}(2, 1) = 8$, $\beta_{\emptyset}(1, 2) = 42$, $\beta_{\emptyset}(2, 2) = 94$, $\beta_{\{1\}}(1) = 0.6$, $\beta_{\{1\}}(2) = 0.75$, $\beta_{\{2\}}(1) = 1.2$, $\beta_{\{2\}}(2) = 1.6$, $\beta_{\{5\}}(1) = 38$ and $\beta_{\{5\}}(2) = 64$.

cost parameter description	name in κ	baseline	VAR $\uparrow$ 25%	FIX $\uparrow$ 25%
Onshore VAR 2.5 Mton	$\beta_{\{1\}}(1)$	0.6	0.75	0.6
Onshore VAR 10 Mton	$\beta_{\{1\}}(2)$	0.75	0.94	0.75
Onshore FIX 2.5 Mton Cond1	$\beta_{\emptyset}(1,1)$	6	6	7.5
Onshore FIX 10 Mton Cond1	$\beta_{\emptyset}(2,1)$	8	8	10
Onshore FIX 2.5 Mton Cond2	$\beta_{\emptyset}(1,2)$	42	42	52.5
Onshore FIX 10 Mton Cond2	$\beta_{\emptyset}(2,2)$	94	94	117.5
Offshore VAR 2.5 Mton	$\beta_{\{2\}}(1)$	1.2	1.5	1.2
Offshore VAR 10 Mton	$\beta_{\{2\}}(2)$	1.6	2	1.6
Offshore FIX 2.5 Mton	$\beta_{\{5\}}(1)$	38	38	47.5
Offshore FIX 10 Mton	$\beta_{\{5\}}(2)$	64	64	80

Table 10: *Cost parameters, in million euros, for different cost scenarios as used in the cost function κ of the component-based infrastructure cost problem applied to CO2 transport infrastructure problems.*

To calculate the costs of all EICs, as summarized in Table 4, we use Theorem 3.2. Here, we extend this table such that we also show the final expression of the costs in terms of the coefficients, as given in Table 11, and we include the previously omitted costs of $C^{1,1,2,2,1}$. To clarify the final expressions, we further illustrate the calculations of two components. We omit some of the details that were already discussed in Example 3.2, since the calculations are largely analogous, even though we have a different cost function and an additional characteristic. Also, we are now able to fill in the actual values of the characteristics.

EIC	$\lambda(\texttt{EIC})$	
$C^{1,1,1,1,1}$	$\beta_{\emptyset}(1,1) + \beta_{\{1\}}(1) \cdot 10$	$= 12$
$C^{2,1,1,1,1}$	$\beta_{\{1\}}(1) \cdot (30 - 10)$	$= 12$
$C^{3,1,1,1,1}$	$\beta_{\{1\}}(1) \cdot (80 - 30)$	$= 30$
$C^{1,1,2,1,1}$	$\beta_{\emptyset}(2,1) - \beta_{\emptyset}(1,1) + \big(\beta_{\{1\}}(2) - \beta_{\{1\}}(1)\big) \cdot 10$	$= 3.5$
$C^{2,1,2,1,1}$	$\big(\beta_{\{1\}}(2) - \beta_{\{1\}}(1)\big) \cdot (30 - 10)$	$= 3$
$C^{3,1,2,1,1}$	$\big(\beta_{\{1\}}(2) - \beta_{\{1\}}(1)\big) \cdot (80 - 30)$	$= 7.5$
$C^{1,1,1,1,2}$	$\beta^{\{3\}}_{\{5\}}(1) \cdot 1$	$= 38$
$C^{1,1,2,1,2}$	$\big(\beta_{\{5\}}(2) - \beta_{\{5\}}(1)\big) \cdot 1$	$= 26$
$C^{1,2,1,1,1}$	$\beta_{\{2\}}(1) \cdot 30$	$= 36$
$C^{1,2,2,1,1}$	$\big(\beta_{\{2\}}(2) - \beta_{\{2\}}(1)\big) \cdot 30$	$= 12$
$C^{1,1,1,2,1}$	$\beta_{\emptyset}(1,2) - \beta_{\emptyset}(1,1)$	$= 36$
$C^{1,1,2,2,1}$	$\beta_{\emptyset}(2,2) - \beta_{\emptyset}(1,2) - \beta_{\emptyset}(2,1) + \beta_{\emptyset}(1,1)$	$= 50$

Table 11: *All non-zero costs of* EICs *for the case study of Section 4.*

We first consider $\lambda(C^{1,1,1,1,1})$. Since $M^{\alpha}_C = M^{\alpha}_D = \emptyset$, we sum over all $K \subseteq \{1,2,5\}$ and $L \subseteq \{3,4\}$ in (2). Since there are four combinations of K and L with non-zero coefficients in (8), $\lambda(C^{1,1,1,1,1})$ would in principle consist of four terms. However, note that $\tilde{X}^2_1 = \tilde{X}^5_1 = 0$, because the lowest required offshore transport radius is zero (and the binary characteristic indicating whether offshore transport is required is zero as well then), and recall that $\tilde{X}^k_0 = 0$ for all $k \in M$. Consequently, we find

$$\begin{aligned}
\lambda(C^{1,1,1,1,1}) &= \beta_{\emptyset}(\tilde{X}^3_1, \tilde{X}^4_1) + \beta_{\{1\}}(\tilde{X}^3_1) \cdot (\tilde{X}^1_1 - \tilde{X}^1_0) + \beta_{\{5\}}(\tilde{X}^3_1) \cdot (\tilde{X}^5_1 - \tilde{X}^5_0) + \beta_{\{2\}}(\tilde{X}^3_1) \cdot (\tilde{X}^2_1 - \tilde{X}^2_0) \\
&= \beta_{\emptyset}(1,1) + \beta_{\{1\}}(1) \cdot (10 - 0) + \beta_{\{5\}}(1) \cdot (0 - 0) + \beta_{\{2\}}(1) \cdot (0 - 0) \\
&= \beta_{\emptyset}(1,1) + \beta_{\{1\}}(1) \cdot 10 \\
&= 12.
\end{aligned}$$

Next, consider $\lambda(C^{3,1,2,1,1})$. Since $M^{\alpha}_C = \{1\}$ and $M^{\alpha}_D = \{3\}$, the only combination of K and L with a non-zero coefficient and $M_C^\alpha \subseteq K$ and $M_D^\alpha \subseteq L$ is $K = \{1\}$ and $L = \{3\}$.[12] Therefore,

$$\begin{aligned}
\lambda(C^{3,1,2,1,1}) &= b^{3,1,2,1,1}(\{1\},\{3\}) \cdot (\tilde{X}_3^1 - \tilde{X}_2^1) \\
&= \big(\beta_{\{1\}}(\tilde{X}_2^3) - \beta_{\{1\}}(\tilde{X}_1^3)\big) \cdot (\tilde{X}_3^1 - \tilde{X}_2^1) \\
&= \big(\beta_{\{1\}}(2) - \beta_{\{1\}}(1)\big) \cdot (80 - 30) \\
&= 0.15 \cdot 50 \\
&= 7.5.
\end{aligned}$$

Observe that if we sum all costs given in Table 11, we get

$$266 = \beta_\emptyset(2,2) + \beta_{\{1\}}(2) \cdot 80 + \beta_{\{5\}}(2) \cdot 1 + \beta_{\{2\}}(2) \cdot 30 = \kappa(80,30,2,2,1).$$

More generally, the costs of any boxlike infrastructure equal the sum of the costs of all EICs within this box. Finally, we remark that $C^{1,1,2,2,1}$ is not required by any player, since no individual player requires both the highest capacity level and the highest level of conditioning. Hence, $C^{1,1,2,2,1} \notin A(N)$, which is why this component was omitted in Section 4. All other EICs are required by at least one player, as shown in Table 4. Summing all corresponding costs, we find $c(N) = 216$ million euros of construction costs for the minimal infrastructure that N requires.

[12] This line of reasoning can also be used to show that only twelve out of 48 EICs have non-zero costs, since for all other EICs there does not exist a combination of K and L such that $M_C^\alpha \subseteq K \subseteq M_C$ and $M_D^\alpha \subseteq L \subseteq M_D$ with a non-zero coefficient.