Multi actor decision models for transformation of industrial clusters

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1 Introduction

Industrial sectors are often organized in regional clusters. Reasons for their clustering can be found in the use of same spatial characteristics (e.g. harbor), use of each other's products (e.g. intermediates) or sharing facilities (e.g. steam network). In addition, they often have the same group of suppliers and customers, regional access to employees with appropriate skills and knowledge, and they experience that (pre-competitive) cooperation can boost productivity, innovation and 'new business'. This is also referred to as the cluster effect by Porter (1990).

The Netherlands have five energy-intensive regional industrial clusters (RICs). The climate agreement of June 2019 states that the Netherlands will realize a reduction of 49% of CO_2 emissions (with respect to 1990) in 2030 (Rijksoverheid (2019)). For the industry sector this reduction is equal to circa 19.5 Megaton (Mt). Targets for 2050 are set at an emission level of nearly zero. Preferably these targets are met while maintaining employment levels and factors that attract and keep (new and sustainable) business. The five RICs have each set their own cluster targets. van der Linden (2019) describes and analyzes these cluster targets, later on refined by Tan et al. (2016). Three reduction options are necessary for all clusters to achieve the goals; (i) CO_2 capture and storage, (ii) sustainable electrification of processes and (iii) large-scale use of hydrogen for high-temperature heat and feed-stock. These reductions options all require new or adapted energy infrastructure to comply with new energy demand profiles of the RICs. These infrastructures are a crucial component for successful energy transition in industrial clusters.

Circa 75% of the CO_2 emissions of the Dutch industry are produced by twelve large companies, 4 refineries, 1 steel factory and 7 chemical factories, which are located in the beforementioned RICs. These 'big twelve' can, according to SER (2019), have a pioneering role in the regional value chain and should be seen as the ones in the position to accelerate the energy transition in industry. The 2019 climate agreement, a typical Dutch agreement between government industry and societal organisations, also lists a set of possible policy measures and instruments to facilitate and speed up the transition in industrial clusters. A strong regional cluster approach is mentioned as an important accelerator. The companies that are part of the RICs benefit from the current forms of cooperation. At the same time they, like most other companies, make investment decisions based on individual business economic trade-offs. Policy instruments and measures, as mentioned by the SER (2019), can influence the decisions of the industry directly or indirectly, but the actual sustainable transformation(s) is the result of multiple individual decisions on company level.

This individual (business economic) trade-off is however rather complicated. There are many external developments, policy, markets and technology performance, (see Fu et al. (2018) for a more elaborate analysis about the factors which influence the adoption of sustainable process technologies) of which it is not clear in which direction they are going. But there are also developments within the cluster that severely hinder the ease of decision making. Janipour et al. (2020), based on an in depth study of multiple RICs, describes this as *heavy system integration* and is found as one of the main sources of carbon lock-in of those clusters. This internal dependence is perhaps the most pressing but also the most contradictory of them all: the past and current successful collaboration and cross company process optimization within a RIC are hindering future investment decisions in decarbonization technologies. Because (i) some technologies are only feasible if it is a group decision, and (ii) the individual pay-off for feasible technologies strongly depends on the decisions of other cluster members. That is why we argue for adding a multi-actor perspective to the decision making regarding (regional) industrial decarbonization.

There exist numerous studies and policy reports on the decarbonization options for, see *e.g.* Bataille et al. (2018) for an extensive overview. Also in the Dutch context studies focus on feasibility and effectiveness of decarbonization options, *cf.* Altenburg et al. (2021) and a series of PBL reports on decarbonization options of subsets of industries. However, these studies and their underlying models focus on techno-economic trade-offs from a system perspective, while an industrial cluster consists of multiple actors with different objectives, value creation processes and dependencies: an actor perspective is much needed as well. Neglecting this actor perspective in analysing and selecting decarbonization options can result in sub optimal choices, non robust choices or the lack of choice at all. This decision dependency is listed as one of the five bottlenecks for successful transformation by (TNO, 2020).

While Janipour et al. (2020) and Fu et al. (2018) also argue for the need for an actor perspective, they do not point to specific modelling or research approach potential sources of carbon lock in, Gedai et al. (2012) and Gedai et al. (2015) are one of the first to argue the potential use of interactive decision theory in the modeling and analyses of industrial clusters. The basic idea here is that cluster participants will make individual trade-offs based on what best serves their own value creation process, but that total value creation in a cluster increases if cluster participants coordinate and make joint investments in e.g. new infrastructure. Later on Tan et al. (2016) and Andiappan et al. (2016) use the suggested modelling approach from interactive decision theory to find fair and robust cost benefit allocation or negotiation framework for participants in a new eco-industrial park under development. We continue with this line of thinking. Our work serves a starting point for including an multi-actor perspective in industrial decarbonization. Instead of presenting a single model we present different variants of multi-actor decision modelling. In Section 2 we start by modelling decarbonization of RICs as a multi actor decision problem using the concepts from cooperative game theory. For this we use a simple value function for the industrial actors, in which decisions are based on a weighted combination of investments costs and emmissions abated. We present a basic versions and a version in which regulation could influence the individual actor's valuation of the options. Next, in Section 3 we use the work of Tan et al. (2016) (strongly based on Maali (2009)) as a starting point for allocating costs and benefits of a clusters choice. We find that this single point solution concept could have some disadvantages and therefore we also present the negotiation space: a set of potential value allocation solutions that cluster participants could use in their negotiation process. In Section 4 we present a use case, and illustrate the models and allocation method with this use case. Finally, as our work serves as a first step, in Section 5 we shortly discuss our work and make recommendations for next steps.

2 Decarbonization of RICs as a multi-actor decision problem

Decarbonization of RICs is not only a cost effectiveness optimization problem, it is also a multi actor decision problem. In this section we model the decarbonization of RICs as a a multi actor decision problem. We start with an example inspired by current decision problems of Dutch RICs.

Example 1. Consider a simplified regional industrial cluster, consisting of three organizations, A, B and C. All three organizations are facing a similar decision problem towards decarbonization of their industrial process. Company A emits circa 2 megaton CO_2 on a yearly basis, B emits circa 1.5, and company C roughly 2.5. Decarbonization will require a significant investment, but it will also save them future CO_2-taxes. Each of them can decarbonize using the following options:

(i) invest in carbon capture technology. This option is only effective if the organization also has access to a CO2 transport infrastructure that transports the captured CO2 to a use or storage site.

(ii) invest in new processes that uses hydrogen as feedstock or as energy carrier. This option is only effective if the organization also has access to hydrogen distribution infrastructure.

(iii) invest in other individually focussed measures, such as process electrification that are less dependent on significant infrastructure investments.

(iv) do nothing at all.

In Table 1 you can find the investment costs (in million euros) and emission reductions (in kilotons) for each of the decarbonization options for the different organizations. The first two options are options that contribute most significantly to CO2 emission reduction. But those options are also heavily infrastructure dependent. Without available CO2 transport pipelines, carbon capture is not a realistic option. So for these two first options to succeed, investments in infrastructure are also necessary and therefore included in the trade-off. This infrastructure component does not depend on the number of player investing in the decarbonization option, and you can find them in the last row of Table 1 as additional fixed cost for carbon capture and hydrogen. Because of this fixed cost component, coordinated and cooperative decision making seems logical. If A and B invest in carbon capture and C would go for hydrogen, this would reduce emmissions by $1800 + 1425 + 2250 = 5475$ kilotons, and cost them $300 + 250 + 1200 + 400 + 900 = 3050$. While, if they would all go for carbon capture they would still reduce emissions by 5475 ktons, but it would cost them only $300 + 250 + 1200 + 400 = 2150$. Hence the total costs and benefits of the individually chosen decarbonization options depend on everyone elses choices as well.

Table 1: Example of a use case.

Companies	Decarbonisation options							
	Do nothing		Electrification		CCUS		Hydrogen infrastructure	
	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)
A	0	0	1600	910	1800	300	1600	300
B	0	0	900	550	1425	250	1050	250
C	0	0	1250	500	2250	400	2250	400
	Fixed cost:	0	Fixed cost:	0	Fixed cost:	1200	Fixed cost:	900

In the remainder of this section we present two versions of our multi actor decarbonization decision model.

2.1 Basic model

A RIC decarbonization decision problem is given by the tuple (N, X, E, C, z, b, k). The set $N = \{1, \ldots, n\}$ represents a group of organisations that each can choose from a set X of decarbonization strategies. Every organization can choose only one decarbonization strategy. For each strategy $x \in X$ and company $i \in N$, the matrices $E \in \mathbb{R}^{N \times X}$ and $C \in \mathbb{R}^{N \times X}$ contain the emission reductions ($e_{i,x}$) and costs ($c_{i,x}$) if i decides to implement strategy x. The vector $z \in \mathbb{R}^X$ contains the associated fixed costs for all the decarbonization strategies, irrespective of the number of participants. Note that z_x can be 0 for some of the individual strategies. For group solutions, such as hydrogen infrastructure and CCUS, these are nonzero and it would make sense to collaborate on these decarbonization strategies as the fixed costs are rather high. Let us continue with the parameter vectors b and k. For that we need a bit more context. Depending on their business strategies companies might differ in their valuation of emission reduction or abatement costs. This could be based on CO_2 taxation and can have a social, stakeholder or marketing component. The vectors $b, k \in \mathbb{R}^N$ represent the individual weights of the different organizations in N towards impacts on either emissions reductions (b) or cost increase (c). This results in the following valuation of a company $i \in N$ for investing in option $x \in X$

$$b_i \cdot e_{i,x} - k_i \cdot (c_{i,x} + z_x).$$

Hence, any organization $i \in N$ would chose the strategy $\hat{x} \in X$ such that

$$\hat{x} = \underset{x \in X}{\operatorname{argmax}}[b_i \cdot e_{i,x} - k_i \cdot (c_{i,x} + z_x)]. \tag{1}$$

However, when the group of organizations is looking at the decision problem from a collaborative point of view, formulating the optimization problem becomes a bit more cumbersome. Individually, each organization can only chose for one decarbonization strategy. Also in a coalitional context there is room for only one decarbonization strategy per organization, but organizations can choose for the same decarbonization strategy and attain economies of scale through sharing the fixed costs of those strategies. Game theory offers an analytical framework for analyzing situations for creating and allocating shared costs and benefits: cooperative transferable utility games. In such a TU-game one considers all options of all the different subcoalitions of N, what could it minimally create without the rest of N. These coalitional values can be used as reference points or boundary points for setting allocation rules of the total group benefit. Before introducing the RIC decarbonization game, we introduce some coalitional concepts corresponding to the RIC-decarbonization problem. Later on in Section 3 we will discuss different allocation methods.

Let Π^S be the set that contains all possible choice combinations of coalition members of $S \subset N$. Take $\sigma^S \in \Pi^S$, then $\sigma^S : S \to X$ and $\sigma^S(i)$ denotes the choice of player of $i \in S$ for a certain decarbonization strategy $x \in X$ and it is possible that for any $\{i, j\} \in S$, $\sigma^S(i) = \sigma^S(j)$. For convenience we introduce for any $S \subset N$ and any $\sigma^S \in \Pi^S$

$$Y(\sigma^S) = \{x \in X | \exists i \in S \text{ with } \sigma^S(i) = x\}, \tag{2}$$

$$T_x(\sigma^S) = \{i \in S | \sigma^S(i) = x\}, \tag{3}$$

Thus, Y represents the set of strategies chosen by coalition $S \subset N$ and T_x the subset of players chosing strategy $x \in X$. Furthermore we introduce some coaliational aggregates of the matrices E and C, for all $S \subset N$ and option $x \in X$

$$e(S, x) = \sum_{i \in S} e_{i,x} \text{ and} \tag{4}$$

$$c(S, x) = \sum_{i \in S} c_{i,x}. \tag{5}$$

Now we can introduce the RIC decarbonization game $G = (N, v)$ corresponding to a RIC decarbonization decision problem (N, X, E, C, z, b, k). The characteristic function $v : \mathbb{R}^{2^N} \to \mathbb{R}$ with $v(\emptyset) = 0$ assigns a value to each coalition $S \subset N$. These coalitional values can be used to describe the potential benefits a coalition $S \subset N$ can achieve without the players outside of that coalition. For the individual coalitions we can easily derive v from (1). We have that for all $i \in N$

$$v(\{i\}) = \max_{x \in X} [b_i \cdot e_{i,x} - k_i \cdot (c_{i,x} + z_x)]. \tag{6}$$

Then, for all $S \subset N$ we have that

$$v(S) = \max_{\sigma^S \in \Pi^S} \sum_{x \in Y(\sigma^S)} [b_S \cdot e(T_x(\sigma^S), x) - k_S \cdot (c(T_x(\sigma^S), x) + z_x)]. \tag{7}$$

Where b_S and k_S are the coalitional weights towards emission reductions and cost increase. The choice of b_S and k_S is rather arbitrary. We opt for setting b_S and k_S as the averages of the individual weights of the coalition members. Thus for all $S \subset N$

$$b_S = \frac{\sum_{i \in S} b_i}{|S|} \qquad \text{and} \qquad k_S = \frac{\sum_{i \in S} k_i}{|S|}. \tag{8}$$

However, one can redefine these and choose for weighted averages based on e.g. the annual turnover of the companies. Through (7) we see a coalition as if it were a single decision making entity that bases its decision on the total emission reductions and costs and average indicators b_S and k_S. In the extension of our basic model in the next subsection we also consider potential differences between companies within a coalitions and we account for beforehand set rules (regulation) on allocations of emissions and costs towards the different coalitional members. Figure 1 shows an overview of the basic model.

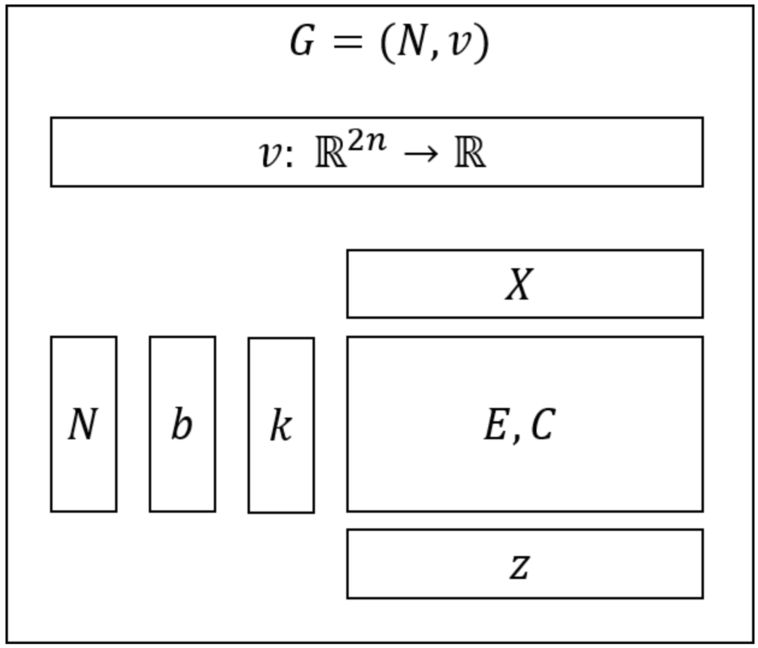

Figure 1: Overview of the basic model.

We finalize the description of the basic model with an example.

Example 2. Let us go back to the RIC decarbonization situation of Example 1. We extend Table 2 with individual weights.

Table 2: Continuation of the example in Table 1.

Companies	b	k	Decarbonisation options							
			Do nothing		Electrification		CCUS		Hydrogen infrastructure	
			Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)
A	0.60	1.0	0	0	1600	910	1800	300	1600	300
B	0.55	1.0	0	0	900	550	1425	250	1050	250
C	0.50	1.3	0	0	1250	500	2250	400	2250	400
			Fixed cost:	0	Fixed cost:	0	Fixed cost:	1200	Fixed cost:	900

This results in the following description of the RIC decarbonization situation

$$N = \{A, B, C\} \qquad X = \{\text{Do nothing}, \text{Electrification}, \text{CCUS}, \text{Hydrogen infrastructure}\}$$

$$C = \begin{pmatrix} 0 & 910 & 300 & 300 \\ 0 & 550 & 250 & 250 \\ 0 & 500 & 400 & 400 \end{pmatrix} \qquad E = \begin{pmatrix} 0 & 1600 & 1800 & 1600 \\ 0 & 900 & 1425 & 1050 \\ 0 & 1250 & 2250 & 2250 \end{pmatrix}$$

$$b = \begin{pmatrix} 0.60 & 0.55 & 0.50 \end{pmatrix}^T \qquad k = \begin{pmatrix} 1.0 & 1.0 & 1.3 \end{pmatrix}^T$$

$$z = \begin{pmatrix} 0 & 0 & 1200 & 900 \end{pmatrix}$$

If company A individually chooses for the decarbonization strategy electrification, then he would value this as

$$b_A \cdot e_{A,elec} - k_A(c_{A,elec} + z_{elec}) = 0.60 \cdot 1600 - 1.0 \cdot (910 + 0) = 50.$$

Similarly, company A values CCUS as $0.60 \cdot 1800 - 1.0 \cdot (300 + 1200) = -420$, hydrogen as $0.60 \cdot 1600 - 1.0 \cdot (300 + 900) = -240$ and doing nothing as 0. Hence, $v(\{A\}) = 50$ and A will choose for electrification. With similar calculations and reasoning we find that B and C, on an individual basis, will choose to do nothing, $v(\{B\}) = 0$ and $v(\{C\}) = 0$.

Let us continue with the decision problem of coalition $\{A, B\}$. There are $|X| \cdot |X| = 16$ options that coalition $\{A, B\}$ can choose from. These 16 options form the set $\Pi^{\{A,B\}}$ consisting of the elements (Do nothing, Do nothing), (Do nothing, Electrification), ... up until (H2, H2). Let $\sigma^{\{A,B\}} = (\text{Electrification}, \text{Do nothing})$. This means that A chooses electrification and B chooses to do nothing. Then Y, the set of strategies chosen by a coalition, is equal to

$$Y(\sigma^{\{A,B\}}) = \{\text{Electrification}, \text{Do nothing}\}$$

and the T_x, the sets of coalitions choosing option $x \in X$, are equal to

$$\begin{aligned} T_{\text{Do nothing}}(\sigma^{\{A,B\}}) &= \{B\}, \\ T_{\text{Electrification}}(\sigma^{\{A,B\}}) &= \{A\}, \\ T_{\text{CCUS}}(\sigma^{\{A,B\}}) &= \emptyset, \\ T_{\text{H2}}(\sigma^{\{A,B\}}) &= \emptyset. \end{aligned}$$

Based on (8) we derive that $b_S = (0.60 + 0.55)/2 = 0.575$ and $k_S = (1.0 + 1.0)/2 = 1.0$. We can use b_S and k_S to calculate the value for each $\sigma^{\{A,B\}}$. Again, let $\sigma^{\{A,B\}} = (\text{Electrification}, \text{Do nothing})$, then we obtain a combined value of $0.575 \cdot (1600 + 0) - 1.0 \cdot ((910 + 0) + (0 + 0)) = 10$. This value is lower than the sum of the individual values. This is caused by b_S and k_S being average weights and it shows that this definition does not always result in realistic approaches for coalitional values. This problem will be solved in the regulation extended model, but for now we continue with another option, A and B both invest in CCUS. The coalitional value is equal to $0.575 \cdot (1800 + 1425) - 1.0 \cdot ((300 + 250) + 1200) = 104.375$. Similar, the coalitional value when A and B invest in hydrogen is equal to 73.75. The coalitional values of the other $\sigma^{\{A,B\}} \in \Pi^{\{A,B\}}$ are negative. The maximum value is obtain when A and B invest in CCUS together, hence $v(\{A, B\}) = 104.375$.

Similarly we obtain that coalition $\{A, C\}$ chooses to invest in hydrogen infrastructure together, $v(\{A, C\}) = 277.5$. The coalition $\{B, C\}$ chooses to have B do nothing and C electrification with a coalition value of 81.25. This is again an odd result, as in the individual cases B and C both decided to do nothing. Due to the higher valuation of B of emission reductions, $b_B > b_C$, and lower disliking of costs, $k_B < k_C$, C chooses for electrification when collaborating with B.

Finally, for the grand coalition $v(\{A, B, C\}) = 660$, where the strategy of hydrogen infrastructure was slightly favored over CCUS.

Table 3 shows an overview of the choices that are made by each coalition, together with the coalitional value.

Table 3: Choices of each coalition for the small example using the simple model.

Coalition S	**Choice** $\hat{\sigma}^S$	**Coalitional value** $v(S)$
A	A: Electrification	50.00
B	B: Do nothing	0.00
C	C: Do nothing	0.00
A, B	A: CCUS, B: CCUS	104.38
A, C	A: Hydrogen, C: Hydrogen	277.50
B, C	B: Do nothing, C: Electrification	81.25
A, B, C	A: Hydrogen, B: Hydrogen, C: Hydrogen	660.00

2.2 Regulation extended model

In the previous section we introduced the basic setting of RIC decarbonization decision problems and their corresponding games. We have also observed that due to the individual differences in valuation of effects it is not straightforward to determine coalitional values. Too simple approaches can result in odd or unrealistic results.
Therefore we extend the basic model to adjust for these indivdual valuations of coalitional effects. We introduce the set $\mathcal{R}$ of potential rules for RIC decarbonization decisions. A rule combination $R \in \mathcal{R}$, consist of a rule $re : 2^N\backslash\{\emptyset\} \times X \to \mathbb{R}^N$ for allocating emission reductions and a rule $rc : 2^N\backslash\{\emptyset\} \times X \to \mathbb{R}^N$ for allocating costs. If coalition S decides to invest in option x, then re and rc describe how the total emission reduction and costs should be allocated to all companies in the coalition.

Let (N, X, E, C, z, b, k) be a RIC decarbonization decision problem and take a rule combination $R \in \mathcal{R}$ with $R = [re, rc]$. Then, we define $G^R = (N, w)$ to be the corresponding regulated RIC decarbonization game with for all $S \subset N$

$$w(S) = \max_{\sigma^S \in \Pi^S} \sum_{x \in Y(\sigma^S)} \sum_{i \in T_x(\sigma^S)} [b_i \cdot re_i(T_x, x) - k_i \cdot rc_i(T_x, x)]. \tag{9}$$

In this we consider the following combinations of possible regulation, see Table 4. There are two rules for emission reduction and two rules for cost, so in total there are four possible combinations of re and rc. One could think of many other ways of allocating emission reductions and costs among coalitions.

Given a coalition $S \subset N$ and a choice $\sigma^S \in \Pi^S$, these regulation rules allocate the emission reduction and cost over the players in S. For ease of notation we will use $\sigma^S(i) = x$.
The first emission rule, re^{self}, allocates each company its own emission reduction,

$$re_i^{prop}(S, \sigma^S) = e_{i,x}.$$

For the second emission rule, re^{prop}, the emission reduction is allocated proportionally to the variable cost among the companies investing in the same option,

$$re_i^{prop}(S, \sigma^S) = \frac{c_{i,x}}{c(T_x(\sigma^S), x)} e(T_x(\sigma^S), x).$$

If company i is the only company investing in option x, then $c(T_x(\sigma^S), x) = c_{i,x}$ and $e(T_x(\sigma^S), x) = e_{i,x}$, such that $re_i^{prop}(S, \sigma^S) = e_{i,x} = re_i^{prop}(S, \sigma^S)$. In that case, the two rules have the same allocation.

The first cost rule, rc^{propS}, allocates each company its own variable costs and allocates the fixed costs proportionally to the emission reductions of the companies investing in the same option,

$$rc_i^{propS}(S, \sigma^S) = c_{i,x} + \frac{e_{i,x}}{e(T_x(\sigma^S), x)} z_x.$$

The second cost rule, rc^{propT}, allocates the total cost proportionally to the emission reductions of the companies investing in the same option,

$$rc_i^{propT}(S, \sigma^S) = \frac{e_{i,x}}{e(T_x(\sigma^S), x)} (c(T_x(\sigma^S), x) + z_x).$$

If company i is the only company investing in option x, then both rules boil down to $c_{i,x} + z_x$.

Table 4: Overview of the regulation

Emission regulation	**Description**	**Mathematical expression**
re^{self}	Emissions reduction allocated to company itself	$e_{i,x}$
re^{prop}	Emissions reduction allocated proportionally to variable cost among companies investing in same option	$\frac{c_{i,x}}{c(T_x(\sigma^S),x)} e(T_x(\sigma^S), x)$
Cost regulation	**Description**	**Mathematical expression**
rc^{propS}	Variable costs allocated to company itself, fixed costs allocated proportionally to emission reduction among companies investing in same option	$c_{i,x} + \frac{e_{i,x}}{e(T_x(\sigma^S),x)} z_x$
rc^{propT}	Total costs allocated proportionally to emissions reduction among companies investing in same option	$\frac{e_{i,x}}{e(T_x(\sigma^S),x)} (c(T_x(\sigma^S), x) + z_x)$

Example 3. Let us go back to Example 2. We have a RIC decbarbonization decision problem provided by the information in Table 2. We will now define the corresponding regulated RIC decarbonization game for different rule combinations from Table 4.

We consider the coalition $S = \{A, B\}$ investing in CCUS together, $\sigma^{\{A,B\}} = (\text{CCUS}, \text{CCUS})$. With rule re^{self}, A gets allocated $re^{self}_A(\{A, B\}, \sigma^{\{A,B\}}) = 1800$ and B gets allocated $re^{self}_B(\{A, B\}, \sigma^{\{A,B\}}) = 1425$. With re^{prop} the emission reduction is allocated proportionally to the variable costs of A and B. The variable costs of A and B are 300 and 250. So, A receives $\frac{300}{300+250} = \frac{6}{11}$ of the total emission reduction and B receives $\frac{5}{11}$. The total emission reduction is 3225 kton, so $re^{prop}_A(\{A, B\}, \sigma^{\{A,B\}}) = 1759$ and $re^{prop}_B(\{A, B\}, \sigma^{\{A,B\}}) = 1466$. The reasoning for this rule would be that B gets allocated more kton with re^{prop}, because the variable costs of B are relatively higher.

For the cost allocation we start with rc^{propS}. If A and B decide to invest in CCUS together, then A is allocated its own variable costs of 300 M€ and B its own 250 M€. The fixed costs are allocated proportional to the emission reductions of A and B, 1800 and 1425 respectively. A is allocated $1200 \cdot 1800/(1800 + 1425) \approx 670$ M€ and B $1200 \cdot 1425/(1800 + 1425) \approx 530$ M€. In total A gets allocated 970 M€ and B 780 M€. With rc^{propT} the total costs are allocated proportionally over the companies investing in the same option, A gets allocated $(300 + 250 + 1200) \cdot 1800/(1800 + 1425) \approx 977$ and B $(300 + 250 + 1200) \cdot 1425/(1800 + 1425) \approx 773$. B gets allocated lower costs with this rule because the emission reduction of B is relatively low.

The coalitional value is equal to the sum of the individual values of the companies within the coalition. When A and B invest in CCUS together, with regulation $R = (re^{self}, rc^{propS})$, then A is allocated 1800 kton and 970 M€ and B is allocated 1425 kton and 780 M€. The individual values are calculated with the indiviual b and k of the companies in the coalition, 0.60 and 1.0 for A and 0.55 and 1.0 for B. The individual value of A is equal to $0.60 \cdot 1800 - 1.0 \cdot 970 \approx 110$ and the individual value of B is equal to $0.55 \cdot 1425 - 1.0 \cdot 780 \approx 4$. The coalitional value is equal to 114. With $R = (re^{self}, rc^{propT})$ the individual value is 103 for A and 10 for B. With $R = (re^{prop}, rc^{propS})$ the individual value is 86 for A and 26 for B. With $R = (re^{prop}, rc^{propT})$ the individual value is 79 for A and 33 for B. We can clearly see the effect of choosing different types of regulation.

Table 5 shows an overview of the choices made by the coalitions for the four different rule combinations from Table 4. In the final four columns one can find the corresponding coalitional shown as well. In all subcoaltions of N the rule combination does not influence the coalitional choice and has only minor impact on coalitional value. For the grand coalition, however, this is not the case. The rule combination (re^{prop}, rc^{propS}) leads to invest in hydrogen together, while for the other rule combinations they invest in CCUS together.

Table 5: Overview of choices and coalitional values for all coalitions for the four regulated games based on the information from Table 2 and the rules of Table 4: $R_1 = (re^{self}, rc^{propS})$, $R_2 = (re^{self}, rc^{propT})$, $R_3 = (re^{prop}, rc^{propS})$, $R_4 = (re^{prop}, rc^{propT})$.

Coalition	**Rule combination**	**Coalitional Choice**	**Coalitional value**			
			R_1	R_2	R_3	R_4
A	R_1-R_4	Electrification	50.0	50.0	50.0	50.0
B	R_1-R_4	Do nothing	0.0	0.0	0.0	0.0
C	R_1-R_4	Do nothing	0.0	0.0	0.0	0.0
A, B	R_1-R_4	CCUS	113.72	113.72	111.70	111.70
A, C	R_1-R_4	Hydrogen	207.21	204.48	212.21	209.48
B, C	R_1-R_4	Do nothing	0.0	0.0	0.0	0.0
A, B, C	R_1, R_2, R_4	CCUS	570.80	573.68		567.36
	R_3	Hydrogen			575.23	

3 Allocating RICs decarbonization value creation

The next step after modelling the the multi-actor decarbonization decision problem as cooperative TU game (G and G^R) we can start with diving into potential methods of allocating the created value through RIC decarbonization cooperation.

Let (N, v) be a TU-game, then an allocation $\zeta \in \mathbb{R}^N$ allocates $v(N)$ over all players in N. An allocation method f is a function that maps any TU-game in a given set to a vector in N. For example one could say that $f_i(v, N) = \frac{v(N)}{|N|}$ for all $i \in N$. However, preferably one uses the characteristics of the decision and allocation problem at hand and uses the coalitional values as reference point for constructing fair and appropriate allocation mechanisms. That is why we use inspiration from the mechanism that has been used by Tan et al. (2016) to allocate the cost benefits for a new industrial cluster. This new cluster approach has been based on approach from Maali (2009) that centers around a players relative marginal contribution to coalitional value creation.

In addition to proposing a single solution concept, we also study the so-called negotiation space of RICs: a set of potential solution concepts that would most likely be considered fair or acceptable by the participants. In this, we study the effect of different rules R on the potential negotiation space of the different companies.

3.1 Single point solution concept based on marginal contributions

Let (N, v) be a TU-game. Then, an allocation $\zeta \in \mathbb{R}^N$ is individually rational if

$$\zeta_i \geq v(\{i\}), \qquad \text{for all } i \in N, \tag{10}$$

Individual rationality implies that each company receives at least the value that it could create on its own. An allocation is efficient if

$$\sum_{i \in N} \zeta_i = v(N). \tag{11}$$

Efficiency implies that one allocates precisely the total group value created, not more and not less.

The Maali solution centers around a player's relative marginal contribution μ, defined for all $i \in N$ as

$$\mu_i = \sum_{S \in \{2^N \setminus \emptyset | i \in S\}} \frac{v(S) - v(S \setminus \{i\})}{v(N)}. \tag{12}$$

For each coalition S we determine how much value company i adds to the coalition. Here a a high μ_i implies that a company contributes a lot to the value creation of others through cooperation. The idea is then that every player will receive a part of $v(N)$ that is directly related to its relative marginal contribution. Moreover for each player this direct relation is the same. A dummy variable, λ, is used for this relation and to find λ the following LP problem is formulated.

Maali-allocation method

$$\max \lambda,$$

subject to

$$\begin{aligned} \frac{1}{\mu_i}\zeta_i &\geq \lambda, && i \in N, \\ \zeta_i &\geq v(\{i\}), && i \in N, \\ \sum_{i=1}^{n} \zeta_i &= v(N). \end{aligned}$$

Solving these LP problems results in an allocation in which each player $i \in N$ receives

$$\lambda \cdot \mu_i. \tag{13}$$

With this allocation method, a company with a higher relative marginal contribution will receive a large share and a company with a lower marginal contribution will receive a smaller share, and it is all equally related to their marginal contribution. Both Maali (2009) and Tan et al. (2016) argue that this can be seen as a fair allocation. Furthermore it is relatively easy to find λ.

The results from Maali (2009) only hold for games that are *superadditive*, *i.e.* for which it holds that sum of the value of two disjoint coalitions is smaller or equal to the value of the merger of those two disjoint coalitions. This is very natural condition for any form of coalitional 1 plus 1 is at least two. There is however no guarantee that the basic and rule extended RIC decarbonization games introduced in Section 2 are superadditive. The RIC games in the examples in Sections 2 and 3, and in the extended case in Section 4 are all superadditive.

The allocation method as suggested by Tan et al. (2016) has two disadvantages. First of all, it is a single point solution concept that is based only on the game itself and offers little room for directions for negotiation. E.g. if cluster participants in N would like to deviate from this single point, what direction should they follow. Second of all, the solution is not necessarily a rational solution for all sub coalitions of N. In general it does not satisfy the property of stability, which means that a subgroup of cluster participants, e.g. A and C would be able to create more value with this subgroup than what they would receive from the allocation ζ, thus $v(\{A, C\}) \geq \zeta_A(v) + \zeta_C(v)$.. That is why we present an alternative to this single point concept in the next subsection.

3.2 Negotiation space

Apart from studying single point solution concepts, game theory can also help in revealing sets of potential allocations that satisfy one or multiple properties of fairness. For example, individual rationality can be extended to coalitional rationality or stability. Then, for all $S \subset N$

$$\sum_{i \in S} \zeta_i \geq v(S).$$

Coalitional rationality implies that with allocation ζ no subgroup of players would be able to create more value as a subgroup and thus would have no rational reason to split off. It would result in a stable cooperation. The properties coalitional rationality and efficiency describe a set of potential allocations known as the core of the game $Core(v)$: the set of all coalitionally rational allocations that would result in a stable cooperation.Note that $C(v)$ can be empty. Also in our RIC decarbonization games G and G^R there is no guarantee that the core of the game is nonempty. The remainder of this section only applies to RIC decarbonization situations for which its corresponding decarbonization game has a non-empty core.

We use the core of the game as suggested negotiation space for RICs. Let $G^R = (N, w)$ be a regulation extended RIC decarbonization game, then the negotiation space (NS) for allocating value created is defined as

$$NS(G^R) = \{\zeta \in \mathbb{R}^N | \sum_{i \in N} \zeta_i = w(N), \sum_{i \in S} \zeta_i \geq w(S) \forall S \subset N\} \tag{14}$$

Simply presenting a convex hull of points in an N-dimensional plane will also remain rather vague, that is why we made proxy of this set to present the potential individual negotiation space for each company $i \in N$

$$UB_i(G^R) = \max_{\zeta \in NS(G^R)} \zeta_i,$$

and similarly

$$LB_i(G^R) = \min_{\zeta \in NS(G^R)} \zeta_i.$$

Example 4. Recall Examples 2 and 3, where we determined the choices and coalitional values for each coalition for the simple model and the regulation model for the game described by Table 2. Given the allocation method, we can calculate allocations for the simple and regulation model.

We repeat the choices and coalitional values of the coalitions for the basic model from Table 3. These values can be used to calculate the marginal contributions of the companies. Company A is in four coalitions: $\{A\}$, $\{A, B\}$, $\{A, C\}$ and $\{A, B, C\}$. The marginal contribution of A is equal to

$$\begin{aligned} C_A &= \frac{v(\{A\}) - v(\emptyset)}{v(\{A, B, C\})} + \frac{v(\{A, B\}) - v(\{B\})}{v(\{A, B, C\})} + \frac{v(\{A, C\}) - v(\{C\})}{v(\{A, B, C\})} + \frac{v(\{A, B, C\}) - v(\{B, C\})}{v(\{A, B, C\})} \\ &= \frac{50 - 0}{660} + \frac{104.38 - 0}{660} + \frac{277.50 - 0}{660} + \frac{660 - 81.23}{660} \\ &= 1.53. \end{aligned}$$

Similarly, $C_B = 0.79$ and $C_C = 1.31$. A has the highest marginal contribution. The marginal contribution of C is slightly smaller, while the marginal contribution of B is clearly the smallest.

Coalition	**Choice**	**Coalitional value**
A	A: Electrification	50.00
B	B: Do nothing	0.00
C	C: Do nothing	0.00
A, B	A: CCUS, B: CCUS	104.38
A, C	A: Hydrogen, C: Hydrogen	277.50
B, C	B: Do nothing, C: Electrification	81.25
A, B, C	A: Hydrogen, B: Hydrogen, C: Hydrogen	660.00

Table 6 shows the allocation and the negotiation space for each company. A receives most, followed by C and B gets far less. This is what we would expect from the marginal contributions. We see a similar result for the upper bound of the negotiation spaces. For the lower bound of the negotiation spaces we find the individual values of the companies.

Table 6: Allocation of utility and the negotiation space for the small example using the basic model.

Company	**Allocated value**	**Negotiation space**	
		Min	**Max**
A	278.720	50.0	578.750
B	142.894	0.0	382.500
C	238.386	0.0	555.625

If the upper and lower bounds for the players are rather close, there is little room for negotiation, it could also imply that there is only little benefit for cooperation or only a few players really benefit. The upper and lower bounds, and the size or largeness of the negotiation space can be influenced by the regulations.

Example 5. Table 7 shows the allocation and the negotiation spaces for all companies for the regulation games based on the four rule combinations. The marginal contributions are listed as well, these have been calculated as in the previous example. The allocations differ slightly between the rule combinations, due to slight changes in the marginal contributions.

The coalitional value of the grand coalition differs between the simple and regulation model. The total coalitional value to be allocated in the simple model is 660, while it is 570.8 for the regulated model with $R = (re^{self}, rc^{propS})$. We calculate the percentage that the companies are allocated of the total coalitional value. For the simple model, A is allocated 42%, B is allocated 22% and C is allocated 36%. For the regulated model, A is allocated 47%, B is allocated 22% and C is allocated 31%. This is caused by the fact that a coalitional value is the sum of the individual values. Looking at b and k in Table 2 we see that A values emission reductions the most, while C values these the least. Furthermore, C dislikes costs the most. Consequently, C adds less value to a coalition. This becomes clear in the regulation model, but not in the simple model. As a result, C is allocated less in the regulation model, while A is allocated more.

Table 7: Allocation of value and the negotiation space for the small example using the regulation model. The allocations and negotiation spaces are given for the four rule combinations.

Company	**Rule combination**	**Marginal contribution**	**Allocated value**	**Negotiation space**	
				Min	**Max**
A	R_1	1.65	271.035	50.0	570.80
A	R_2	1.64	271.635	50.0	573.68
A	R_3	1.65	273.042	50.0	575.23
A	R_4	1.65	269.856	50.0	567.37
B	R_1	0.75	122.988	0.0	363.60
B	R_2	0.75	124.858	0.0	369.20
B	R_3	0.74	122.182	0.0	363.02
B	R_4	0.74	120.642	0.0	357.89
C	R_1	1.08	176.782	0.0	457.05
C	R_2	1.07	177.189	0.0	459.93
C	R_3	1.09	180.006	0.0	463.53
C	R_4	1.08	176.868	0.0	455.66

4 Use case and Results

In the previous sections we have introduced a basic and regulated-extended RIC decarbonization decision problems. We have modelled as a cooperative game and we have developed single point solution concept that has been used before in industrial site application, and alternatively we have developed upper and lower bounds for a potential negotation space for participants in the regional. industrial cluster. In this section we present a larger use case and show the results for this use case.

4.1 Use case

The allocation mechanism will be demonstrated with a use case. This use case is based on Chemelot, one of the five industrial clusters in the Netherlands, located in Limburg. On this industrial site, there are a few large companies, and many smaller companies. As mentioned by the SER (2019), larger companies have to be leaders in the industrial transformation, such that smaller companies can follow. Examples of larger companies in Chemelot are OCI Nitrogen and SABIC. We extend on Table 2 to create the use case shown in Table 8.

Table 8: Overview of the data used in the use case.

Companies	b	k	Decarbonisation options							
			Do nothing		Electrification		CCUS		Hydrogen infrastructure	
			Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)	Emission reduction (kton)	Cost (M€)
A	0.60	1.0	0	0	1600	910	1800	300	1600	300
B	0.55	1.0	0	0	900	550	1425	250	1050	250
C	0.50	1.3	0	0	1250	500	2250	400	2250	400
D	0.45	0.9	0	0	10	8	18	4	18	5
E	0.50	1.0	0	0	60	33	95	16	70	20
F	0.80	1.0	0	0	48	36	54	13	48	9
			Fixed cost:	0	Fixed cost:	0	Fixed cost:	1200	Fixed cost:	900

4.2 Results

We continue with the results of the use case. We only use the regulation model for this example. Table 9 shows the choices made by each coalition and the corresponding coalitional values for the four rule combinations. Mostly, the choices are the same for the four rule combinations. The rule combination (re^{prop}, rc^{propS}) (emission reductions are allocated proportionally to variable costs among companies investing in the same option, variable costs are allocated to a company itself, and the fixed costs are allocated proportionally to the emission reductions among companies investing in the same option) differs from the other rule combinations. Whereas for the other rule combinations all coalitions including A, B and C choose for CCUS, for (re^{prop}, rc^{propS}) it differs depending on whether E is also included in the coalition. If E is not included, then the coalition chooses for hydrogen. If E is included in the coalition, then the coalition chooses for CCUS. For rows such as "Coalitions including A and B and excluding C" a range of coalitional values is given, as it described multiple coalitions.

We conclude that the smaller companies do not have a large influence on the choices that the coalitions make. Only when the coalitional values of two choices such as CCUS and hydrogen are close together, a small company can be decisive. These smaller companies depend on the larger companies to be able to invest in CCUS and hydrogen. This is consistent with the SER (2019) statement that large companies have to take a leading role in the industrial transformation. For the larger companies it is beneficial to let the smaller companies participate, since the fixed costs can be divided among more companies. Consequently, the coalitional values increase.

Table 9: Overview of choices and coalitional values for all coalitions for the four regulated games based on use case and the rules of Table 4: $R_1 = (re^{self}, rc^{propS})$, $R_2 = (re^{self}, rc^{propT})$, $R_3 = (re^{prop}, rc^{propS})$, $R_4 = (re^{prop}, rc^{propT})$.

Coalition	**Rule combination**	**Choice**	**Range**	**Coalitional value**			
				R_1	R_2	R_3	R_4
A	R_1-R_4	Electrification		50.0	50.0	50.0	50.0
F	R_1-R_4	Electrification		2.4	2.4	2.4	2.4
Other individual companies	R_1-R_4	Do nothing		0.0	0.0	0.0	0.0
Coalitions including A and B and excluding C	R_1-R_4	CCUS	Min Max	113.75 178.65	113.75 178.65	111.70 180.64	111.70 180.64
Coalitions including A and C and excluding B	R_1-R_4	Hydrogen	Min Max	207.21 259.19	204.48 254.89	212.21 261.45	209.48 257.16
Coalitions including A, B and C	R_1, R_2, R_4	CCUS	Min Max	570.80 636.42	573.68 638.92		567.37 638.02
Coalitions including A, B and C and excluding E	R_3	Hydrogen	Min Max			575.23 606.94	
Coalitions including A, B and C and E	R_3	CCUS	Min Max			601.57 635.53	
All other coalitions	R_1-R_4	Individual choices		Sum of individual values			
A, B, C, D, E and F	R_1-R_4	CCUS		640.08	642.48	638.45	640.85

Table 10: Overview of choices and coalitional values for all coalitions for the four regulated games based on use case and the rules of Table 4: $R_1 = (re^{self}, rc^{propS})$, $R_2 = (re^{self}, rc^{propT})$, $R_3 = (re^{prop}, rc^{propS})$, $R_4 = (re^{prop}, rc^{propT})$.

Coalition	**Rule combination**	**Choice**	**Range**	**Coalitional value**			
				R_1	R_2	R_3	R_4
A	R_1-R_4	Electrification		50.0	50.0	50.0	50.0
F	R_1-R_4	Electrification		2.4	2.4	2.4	2.4
Other individual companies	R_1-R_4	Do nothing		0.0	0.0	0.0	0.0
Coalitions including A and B and excluding C	R_1-R_4	CCUS	Min Max	113.75 178.65	113.75 178.65	111.70 180.64	111.70 180.64
Coalitions including A and C and excluding B	R_1-R_4	Hydrogen	Min Max	207.21 259.19	204.48 254.89	212.21 261.45	209.48 257.16
Coalitions including A, B and C	R_1, R_2, R_4	CCUS	Min Max	570.80 636.42	573.68 638.92		567.37 638.02
Coalitions including A, B and C and excluding E	R_3	Hydrogen	Min Max			575.23 606.94	
Coalitions including A, B and C and E	R_3	CCUS	Min Max			601.57 635.53	
All other coalitions	R_1-R_4	Individual choices		Sum of individual values			
A, B, C, D, E and F	R_1-R_4	CCUS		640.08	642.48	638.45	640.85

Table 11 shows the allocated value to each company for the use case for each rule combination. There are small differences between the allocated values for the different rule combinations. The overall picture remains the same: the big companies A, B and C receive a large share of the value and the small companies D, E and F receive small shares. The negotiation space is also shown. The lower bound is the same for all rules and equal to the individual values of the companies. The upper bound differs slightly, just like the allocated values.

In Example 5 we calculated the allocated values, shown in Table 7, for the small example in Table 2. Recall that the use case is an extension of this small example. We compare the results from Table 11 with the results from Table 7. Due to the presence of the smaller companies, the fixed cost can be divided among more companies. Consequently, the allocated values for A, B and C are higher in Table 11. However, as D, E and F are small companies, relative to A, B and C, the difference in allocated values is not large. This shows that it is beneficial for the larger companies to let the smaller companies participate, but that they have to take a leading role.

Table 11: Overview of the allocated value and the negotiation space for the use case and the four rule combinations: $R_1 = (re^{self}, rc^{propS})$, $R_2 = (re^{self}, rc^{propT})$, $R_3 = (re^{prop}, rc^{propS})$, $R_2 = (re^{prop}, rc^{propT})$.

Company	**Allocated value**				**Negotiation space**							
					Min				**Max**			
	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4
A	294.838	295.245	295.446	295.514	50.0	50.0	50.0	50.0	637.6	640.0	636.0	638.4
B	133.579	135.642	131.621	132.998	0.0	0.0	0.0	0.0	380.8	387.5	376.9	383.6
C	183.340	183.497	183.384	182.967	0.0	0.0	0.0	0.0	461.4	463.8	457.8	460.2
D	1.399	1.345	0.863	0.912	0.0	0.0	0.0	0.0	3.6	3.5	2.9	2.8
E	11.902	11.760	10.718	11.551	0.0	0.0	0.0	0.0	33.9	34.0	31.5	34.1
F	15.026	14.991	16.423	16.907	2.4	2.4	2.4	2.4	31.5	31.1	36.8	36.4

5 Further research

We have explored potential ways of adding a multi-actor perspective to the decision making process of industrial clusters towards decarbonization, based on concepts from interactive decision theory. We have provided a basic and regulation extended model of the multi-actor decision problem, we have analyzed an optimization based solution method and a negotiation based solution space. But we have not yet arrived at conclusions for what approach would work best. We see multiple directions for further research, technical refinement and validation with industry. Underneath we summarize our recommendations for next steps.

Practical - interaction with industry
In both the basic and regulation extended model of RIC-decarbonization problems we have modelled the decision making of individual actors as a weighted trade off between costs and emission reductions. We can improve and refine this value function through interaction with cluster participants, most importantly to also include value creation potential of decarbonization.

Interactive decision theory offers a wide range of solution approaches and extensively researched solution concepts. Through interaction with industry, presenting single-point-solution concepts and property based solution spaces, we can unravel what type of decision support would be helpful in the decision making and negotiation process.

We are also aware that simply making a model, finding the data and presenting the results is not enough to put this multi-actor perspective higher on analysis agenda. The interaction described above should also result in insights of a more agenda-setting nature.

RIC decarbonization modelling
After a first round of feedback with industry we can start refining our RIC decarbonization model. One of the most important next steps would be to work on solution methods (value allocation methods) that are tailored to the needs and wishes of the industrial clusters. The single-point-solution method is based on game-theoretic properties rather than characteristics of RIC decarbonization dynamics. In many cooperative settings, stability, *i.e.* robust towards potential deviations from subsets of actors, is an important requirement for positive decision making. How important is stability for RIC decarbonization decision making and for what kind of deviations should a solution be robust?

Technical
Finally, we have made a few assumptions on mathematical properties of RIC decarbonization problems and their corresponding decarbonization games. But we would rather also assess these basic mathematical properties of RIC decarbonization models. Such as can there be one or multiple solutions for the optimzation problems; under what conditions are RIC decarbonization games superadditive; can we find sufficient conditions for RIC decarbonization games having a core? If so, how large is the core and what does it look like?

References

M. D. Altenburg, K. M. Schure, and K. Blok. Cost-effectiveness of decarbonisation options for the vegetable-oil and -fat industry in the netherlands. *Journal of Cleaner Production*, 306:127270, 2021.

V. Andiappan, R. Tan, and D. Ng. An optimization-based negotiation framework for energy systems in an eco-industrial park. *Journal of Cleaner Production*, 129:496–507, 2016.

C. Bataille, M. Åhman, K. Neuhoff, L. J. Nilsson, M. Fischedick, S. Lechtenböhmer, B. Solano-Rodriquez, A. Denis-Ryan, S. Stiebert, H. Waisman, O. Sartor, and S. Rahbar. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the paris agreement. *Journal of Cleaner Production*, 187:960–973, 2018.

Y. Fu, R. A. Kok, B. Dankbaar, P. E. Ligthart, and A. C. van Riel. Factors affecting sustainable process technology adoption: A systematic literature review. *Journal of Cleaner Production*, 205:226–251, 2018.

E. Gedai, L. Kóczy, and Z. Zombori. Cluster games: A novel, game theory-based approach to better understand incentives and stability in clusters. MPRA Paper 65095, University Library of Munich, Germany, 2012. URL `https://ideas.repec.org/p/pra/mprapa/65095.html`.

E. Gedai, L. Kóczy, G. Meier zu Köcker, and Z. Zombori. About Cooperation, Selfishness and Joint Risks in Clusters. MPRA Paper 65053, University Library of Munich, Germany, 2015. URL `https://ideas.repec.org/p/pra/mprapa/65053.html`.

Z. Janipour, R. de Nooij, P. Scholten, M. Huijbregts, and H. de Coninck. What are sources of carbon lock-in in energy-intensive industry? a case study into dutch chemicals production. *Energy Research & Social Science*, 60:1–9, 2020.

Y. Maali. A multiobjective approach for solving cooperative n-person games. *Electrical Power and Energy Systems*, 31:608–610, 2009.

M. Porter. Competitive advantage of nations. 1990.

Rijksoverheid. Klimaatakoord, 2019.

SER. Nationale klimaataanpak voor regionale industriële koplopers. *SER adviesrapport*, (nr. 06 juni 2019), 2019.

R. Tan, V. Andiappan, Y. Wan, R. Ng, and D. Ng. An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration. *Chemical Engineering Research and Design*, 106:43–58, 2016.

TNO. Energie-infrastructuren 2030: gezamelijk en afgewogen besluiten is urgent, 2020. TNO report R11000.

N. van der Linden. Inventarisatie van de behoefte van de industrieclusters aan grootschalige infrastructuur voor transport van elektriciteit, waterstof, warmte en CO_2 nodig voor het realiseren van klimaatdoelstellingen. *TNO rapport P10550*, 2019.