

Optimisation of Carbon Capture Utilisation and Storage Supply Chains Under Carbon Trading and Taxation

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ABSTRACT

In recent years, several strategies have been developed to reduce the carbon dioxide (CO₂) released into the atmosphere. Carbon Capture, Storage and Utilisation (CCUS) is one of the proposed solutions. However, CCUS systems are expensive to install and operate. Furthermore, most studies in the literature have focused on CO₂ utilisation and storage separately, without accounting for the effects of other CO₂ emission management strategies. To address this gap, a Mixed Integer Linear Programming (MILP) framework for a supply chain network is developed in this work, incorporating CO₂ storage, utilisation, permit trading, and carbon emission taxation. Multi-criteria decision analysis (MCDA) techniques are implemented to select CO₂-based products for CO₂ utilisation. The MILP framework is set to achieve the maximum environmental and economic performance using a Multi-Objective Optimisation (MOO) approach. This involves using the ϵ -constraint method as a solution procedure to minimise the total cost of the supply chain network while maximising CO₂ reduction. A case study of supply chains in Germany is conducted to demonstrate the applicability of the model. The game theoretical Nash approach is successfully applied to determine the fair trade-off between the two objectives.

Keywords: CCUS Supply Chains, Multi Objective Optimisation, CO₂ Trading and Taxation, Game theoretical Nash Approach.

INTRODUCTION

The UN's International Panel on Climate Change states that the rise in CO₂, which constitutes the majority of greenhouse gas emissions, contributes to global warming and climate change. As a result, scientific research and governmental policies have been working towards the reduction of CO₂ emissions in processes across the board. Carbon Capture Utilisation and Storage (CCUS) is considered to be one of the solutions to lower greenhouse gas emissions. New CCUS routes, such as utilising CO₂ in the production of fuels, chemicals, and building materials, have the potential to use 5 Gt/year of CO₂ [1]. However, this is a challenging task due to the economic costs of developing CCUS products and technologies. Many products can be produced from CO₂ conversion, but not all these CO₂ utilisation reactions have the potential to be implemented profitably at scale. Therefore, implementing cost-effective CCUS supply chain networks at scale will be beneficial in overcoming

the high cost of CO₂ combating development.

LITERATURE REVIEW

Multi-Criteria Decision Analysis (MCDA) is a decision-making methodology that evaluates and ranks a set of CO₂-based products by considering multiple criteria, including environmental, social, and economic aspects. Pacheco et al. [2] conducted a comprehensive assessment of the techno-economic, environmental, and social aspects of 122 CO₂-based chemical compounds. Implementing six different MCDA methods, methanol, dimethyl ether, methane and a couple of other candidates were identified as the best products.

Hasan et al. [3] developed a CCUS network aimed at reducing CO₂ emissions in the United States by 50-80% while minimising the overall cost, incorporating the revenue generated from utilising CO₂ in enhanced oil recovery. The approach involved optimising the selection of the emission sources, capture processes and

materials, pipelines, as well as the CO₂ utilisation/storage amount. Zhang et al. [4] proposed a superstructure in Northeastern China that includes underground storage and the utilisation of CO₂ through several possible conversion paths. Although CO₂ conversion may generate a carbon-neutral cycle, the result emphasised the increased costs with more CO₂ utilisation. A multi-objective optimisation framework was proposed by Leonzio et al. [5] for CCUS deployment, considering cost as the economic performance measure and CO₂ reduction as the environmental performance measure.

In addition to CCUS, various methods exist for carbon emission management, such as introducing carbon pricing. Carbon pricing can take different forms, including carbon taxes or carbon emissions permit trading. The European Union Emissions Trading System (EU ETS), established in 2005, is the oldest cap-and-trade system. This system works by imposing a cap (limit) on the CO₂ that can be emitted from each emission source. Within this cap-and-trade framework, emission sources can buy or sell carbon emission permits to achieve their emission reduction targets in the most cost-effective way [6,7]. Considering the CO₂ market within the scope of carbon management, Zhang et al. [8] developed a mathematical model integrating CCS and carbon trading. Various price levels for excess emissions exceeding the allocated allowances across several power plants in Qatar were considered. To ensure fair competition among these plants, the game theoretic Nash approach was applied to optimise the cost of CCS infrastructure.

In this work, MCDA methods were employed to identify suitable CO₂ utilisation products. Drawing inspiration from the models proposed by Zhang et al. [4] and Zhang et al. [8], a framework was developed for CCUS supply chains incorporating carbon trading and taxation aspects. The ϵ -constraint method was used to achieve both CO₂ reduction maximisation and cost minimisation of the supply chain network. Furthermore, to determine the fair trade-off between the two objectives, the game theoretical Nash approach was applied. A case study focusing on supply chains in Germany was carried out to evaluate the performance of the model.

PROBLEM STATEMENT

Each emission source has a maximum allowable CO₂ emission limit. As shown in the **Figure 1**, the remaining emissions must be managed through CCUS or non-physical carbon management platforms. The first platform involves the physical CO₂ supply chain network, where emissions are captured and sent to utilisation or storage sites. The second platform is the non-physical CO₂ management system, which allows trading CO₂ permits between emission sources or paying a tax to release an excessive amount of CO₂ into the atmosphere.

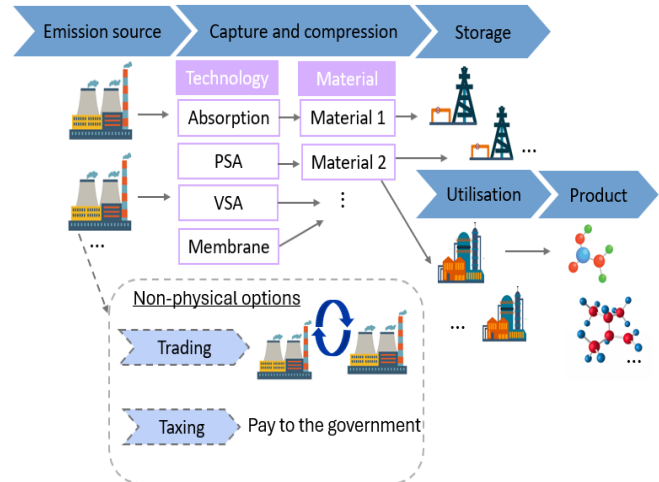


Figure 1. Superstructure of CCUS supply chains under carbon trading and taxation.

The overall supply chain can be stated as follows:

Given: (a) emission sources with their location, annual CO₂ emission and flue gas compositions; (b) combinations of technologies for CO₂ capture and compression with the corresponding materials and cost parameters; (c) cost parameters for the CO₂ transportation via pipelines; (d) locations of CO₂ storage and utilisation sites, their capacities, and the products produced at each utilisation site; (e) for all CO₂ utilisation pathways: unit production costs, selling prices, reactions and conversion rates of products; (f) CO₂ permit price; (g) carbon tax rate.

Determine: (a) CO₂ flow rate to be captured from each selected source; (b) CO₂ capture technology and material for each selected source; (c) storage and utilisation sources to be used and the amount of CO₂ to be utilised/stored; (d) production quantity of each product; (e) pipeline network connecting source and storage/utilisation sites; (f) the quantity of CO₂ permit traded between the emission sources; (g) the amount of CO₂ released into the atmosphere, with the corresponding tax payment made to cover this release; (h) cap percentage for each emission source; (i) the cost of: flue gas dehydration, CO₂ capture and compression, transportation, CO₂ storage, CO₂ permit trading, and the tax payment; (j) Pareto optimal solutions; (k) game-theoretical Nash approach solution.

So as to (a) minimise the total cost; (b) maximise the total CO₂ reduction.

Assumptions: (a) capture plants and CO₂ sources are located in the same place; (b) only one technology-material combination can be selected for CO₂ capture at each source; (c) CO₂ transportation is possible just through pipelines; (d) the production and selling price of the CO₂-based products are fixed; (e) carbon trading occurs within the domestic platform of a country, with no credits being bought or sold internationally; (f) the carbon

tax rate is fixed and uniform across emission sources; (g) a flexible cap is considered for each emission source; (h) carbon permits are traded at a single price.

METHODOLOGY AND MATHEMATICAL FORMULATION

Methodology

Using the combination of four common MCDA methods in the CCUS field (TOPSIS, MARCOS, EDAS, VIKOR) returns a ranked list of all alternative CO₂-based products based on their scores [9]. Each MCDA method determines the rankings using a mathematical scoring system that calculates the distance of each data point from the ideal and negative ideal solutions.

Regarding the supply chain aspect of this paper, the overall problem was formulated as a Mixed Integer Linear Programming (MILP) model which integrates process, tax and trading constraints in addition to accounting for cost calculations. A brief outline of some of the model equations is next given. To facilitate the mathematical formulation, the indices and sets are used as follows: $i \in I$ represents the emission sources, $j \in J$ the CO₂ capture technologies-materials, $k \in K$ the storage and utilisation sites and $p \in P$ represents the CO₂-based products. Furthermore, subset $S \subset K$ is especially for the storage site.

Mathematical Formulation

Objective functions: The supply chain problem is formulated as an MOO model with two objective functions. The first objective, total cost ($Cost$), is minimised and includes the cost of each emission source, $CostI_i$, the production cost of the CO₂-based products, PRC_p , and the revenue from selling the products, Re_p (see equation (2)). The second objective considers the maximisation of the total amount of CO₂ reduction (CR), calculated as the sum of the CO₂ captured and sent to the storage and utilisation sites, CK_{ik} (see equation (4)).

$$\min Cost \quad (1)$$

$$Cost = (\sum_{i \in I} CostI_i) + (\sum_{p \in P} PRC_p - Re_p) \quad (2)$$

$$\max CR \quad (3)$$

$$CR = \sum_{i \in I, k \in K} CK_{ik} \quad (4)$$

Cost calculation: The supply chain cost for each emission source is calculated using equation (5) which consists of several components: the cost of flue gas dehydration, $FDC_{i,j}$; the investment and operational cost of CO₂ capture and compression, $CIC_{i,j}$ and $COC_{i,j}$; the investment and operation cost of transportation, $TIC_{i,k}$ and $TOC_{i,k}$; the cost of CO₂ storage, $SC_{i,k}$; the cost of CO₂ permit trading, CTC_i ; and the tax payment. Ravi et al. [10]

provided detailed mathematical formulations for calculating the costs of flue gas dehydration, CO₂ capture and compression, transportation, and CO₂ storage. All these cost components depend on the amount of CO₂ captured and sent to storage and utilisation sites (CK_{ik}). The tax payment is calculated by multiplying the tax rate per tonne of CO₂ emissions (denoted as the parameter Tax), by the amount of excess CO₂ emissions subject to taxations, $TaxC_i$.

$$CostI_i = (\sum_{j \in J} FDC_{i,j} + CIC_{i,j} + COC_{i,j}) + (\sum_{k \in K} TIC_{i,k} + TOC_{i,k}) + (\sum_{k \in S} SC_{i,k}) + CTC_i + (TaxC_i \cdot Tax) \quad \forall i \in I \quad (5)$$

CO₂ Mass balance: Equation (6) represents the CO₂ mass balance for each emission source. Considering variable emission cap for each source, only $(1 - \varphi_i)$ percent of the total emissions, E_i , from each emission site, can be released into the atmosphere without any consideration. According to the cap, $\varphi_i E_i$ is the amount of CO₂ emission that each emission source should manage using the available options: capturing and sending CO₂ to the storage and utilisation sites, CK_{ik} ; trading CO₂ by selling CO₂ permits to other domestic emission sources, $Tr_{ii'}$, or buying the CO₂ permits from the domestic sources, $Tr_{i'i}$. Another option exists that allows the emission source to pay tax for excess CO₂ emissions ($TaxC_i$).

$$\varphi_i E_i = \sum_k CK_{ik} + \sum_{i'} (Tr_{i'i} - Tr_{ii'}) + TaxC_i \quad \forall i \in I \quad (6)$$

Trading and taxing constraints: Each emission source is not allowed to sell carbon permits to other plants while it is paying taxes and/or buying CO₂ permits from the domestic market. This is facilitated through constraints (7) and (8), in which B is a big number, and the binary variable H_i equals one when an emission source pays a tax and/or purchases permits for excess CO₂ emissions. Furthermore, more than 50% of the CO₂ emissions are constrained to be managed through physical CCUS (see equation (9)).

$$TaxC_i + \sum_{i' \in I} Tr_{i'i} \leq B H_i \quad \forall i \in I \quad (7)$$

$$\sum_{i' \in I} Tr_{ii'} \leq B (1 - H_i) \quad \forall i \in I \quad (8)$$

$$0.5 \sum_{i \in I} \varphi_i E_i \leq CR \quad (9)$$

Process constraints: Equations (10) to (13) represent some of the process constraints in the model. For each emission source, at most one capture technology and material can be selected, as shown in constraint (10). To ensure CO₂ will be captured only if at least one storage and/or utilisation site is chosen, equation (11) is used in which B is a big number. The binary variables, X_{ij} and Y_{ik} , are equal to one when CO₂ is captured from the emission source i with the capture technology material j and sent to the storage and/or utilisation site k . The quantity

of the captured CO₂ is calculated in (12). The symbol FR_{ij} represents the fraction of CO₂ captured from each emission source, which is constrained by an upper-bound f_j^u specific to each capture technology and material, as can be seen in constraint (13).

$$\sum_{j \in J} X_{ij} \leq 1 \quad \forall i \in I \quad (10)$$

$$CK_{ik} \leq B Y_{ik} \quad \forall i \in I, k \in K \quad (11)$$

$$\sum_{k \in K} CK_{ik} = \sum_{j \in J} E_i \cdot FR_{ij} \quad \forall i \in I \quad (12)$$

$$FR_{ij} \leq f_j^u X_{ij} \quad \forall i \in I, j \in J \quad (13)$$

SOLUTION APPROACH

ϵ -Constraint method

An ϵ -constraint method [11] is applied to solve the multi-objective optimisation problem. By keeping one objective as the objective function and the other as a constraint (see formulation (14)), along with equations (2) and (4) to (13), the obtained solutions produce Pareto optimal points, any of which can be selected for the CCUS supply chain.

$$\begin{aligned} \min \quad & \text{Cost} \\ \text{s. t.} \quad & CR \geq \epsilon; \end{aligned} \quad (14)$$

Nash game-theoretic approach

The Nash bargaining approach represents a fair solution for the economic and environmental aspects of the supply chain, given the status quo point. Using this approach, the objective is to maximise the product of the deviations of the optimisation variable cost from the maximum cost ($cost^{quo}$) and the deviation of the optimisation variable CR from the minimum CO₂ reduction (CR^{quo}) shown in equation (15).

$$\text{Max } \mu = (cost^{quo} - cost) (CR - CR^{quo}) \quad (15)$$

The nonlinearity of the above equation causes challenges. To address this, logarithmic operation and separable programming approach are applied by defining piecewise linear functions of n prespecifies grid points, converting the objective function into equation (16). By defining SOS2 variables (z_{1n} and z_{2n}) and the corresponding values for the cost and CO₂ reduction at each grid point (\widehat{cost}_n and \widehat{CR}_n respectively) the nonlinearity is handled. Gjerdrum et al. [12] provides a comprehensive description of game-theoretic Nash approach formulation and linearisation of the Nash objective function. Maximising the Nash variable, μ' , subject to equations (2), (4) to (13), and (16) results in a fair solution for both objectives.

$$\text{Max } \mu' = \sum_n z_{1n} \ln(cost^{quo} - \widehat{cost}_n) + \sum_n z_{2n} \ln(\widehat{CR}_n - CR^{quo}) \quad (16)$$

CASE STUDY

To demonstrate the applicability of the proposed MOO model, a case study of a supply chain network in Germany is conducted. This supply chain network considers 70 power plants with three power generation sources, including coal, oil and gas, as well as 19 storage sites and five utilisation sites. Each utilisation site can either directly convert CO₂ to specific products or use the CO₂ in the production process of that product.

The required data for the emission sources regarding the estimated power generation and latitude and longitude of the power plants are collected from the Global Power Plant Database [13]. Afterwards, CO₂ emission data are obtained for these emission sources using plant efficiency and emission factors. The total CO₂ emission from these 70 sources is 77562 kt/year. An emission management range of 60–80% is considered. Twelve combinations of absorption, membrane, PSA, and VSA-based technologies with different materials are considered for CO₂ capture and compression. Each material-technology combination has upper and lower bounds on the input CO₂ composition it can handle. In this study, the upper bound on the fraction of CO₂ that can be captured, f_j^u , assumed to be 90%.

By applying the MCDA methods, 70 CO₂ utilisation products and pathways are compared across ten criteria, such as product demand, market value, technology readiness level, and others. Methane, cement, and ethylene ranked among the top choices and are selected as the CO₂-based products for the supply chain network of this paper. CO₂ curing in the cement industry especially improves the mechanical properties of cement-based products and transforms CO₂ into thermochemically stable carbonates. In Germany, where cement production is one of the main sources of CO₂ emissions, capturing and re-using CO₂ within cement plants is particularly beneficial. Among the five considered utilisation sites, two of them can produce ethylene, two of them methane and only one of them can be used for cement.

RESULTS AND DISCUSSION

The multi-objective optimisation of the developed MILP model is implemented using Gurobi 11.0.0 in GAMS 46.1.0 with an optimality gap set to 0.1%, using a Dell workstation with Intel® Core™ i9-10980XE CPU @ 3.0 GHz and 128 GB RAM. First, the MOO problem is solved using the ϵ -Constraint method by fixing ϵ to 13 values between CR_{eps}^{min} and CR_{eps}^{max} . The value for CR_{eps}^{min} is obtained through a single optimisation with the objective of

cost minimisation, and the value for CR_{eps}^{max} is obtained with the objective of maximising the CO₂ reduction. The MOO model consists of 21,011 equations and 24,902 variables, of which 2,660 are discrete variables. The entire process to find Pareto optimal solutions (see **Figure 2**) with different values of ϵ takes 90.8 s CPU time with an average of 6.9 s for each iteration. The total cost of the supply chains gradually increases as the amount of CO₂ reduction increases.

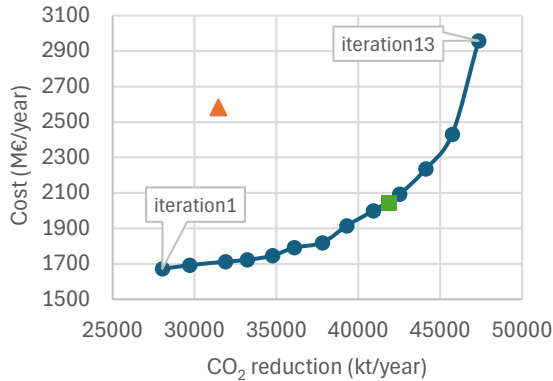


Figure 2. Pareto front and the Nash approach solution: • Pareto optimal; ▲ (CR^{quo} , $cost^{quo}$); ■ Nash result.

Figure 3 illustrates the contribution of each component of the supply chain network to the total cost for some iterations on the Pareto curve. It is important to note that since trading is restricted to the domestic market, the cost of CO₂ permit trading incurred by buyers will be offset by the benefit for the emission sources who sell the permits. Therefore, the net contribution of carbon trading to the total cost of the supply chain network is zero. On another note, the cost of flue gas dehydration, along with the cost of carbon capture and compression, is high, and this creates a trade between cost minimisation and CO₂ reduction because CO₂ capture is one of the bottlenecks of the process. The production cost of CO₂-based products is another economic concern for CCUS. However, the revenue obtained from selling these products can offset the economic challenges of the utilisation processes. The cost of CO₂ storage has a negligible effect on the total costs.

Table 1 represents the amount of CO₂ being covered across different supply chain sections in some iterations that have been chosen to demonstrate the progress of the solver. As CO₂ reduction increases, the contribution of CO₂ utilisation and storage grows, while CO₂ emissions managed through tax payments decrease. By the final iteration on the Pareto front, the amount of CO₂ emissions covered by tax payments reaches zero. However, due to capacity limits for the storage and utilisation sites, CO₂ trading is an important component of CO₂ management to provide the CO₂ mass balance.

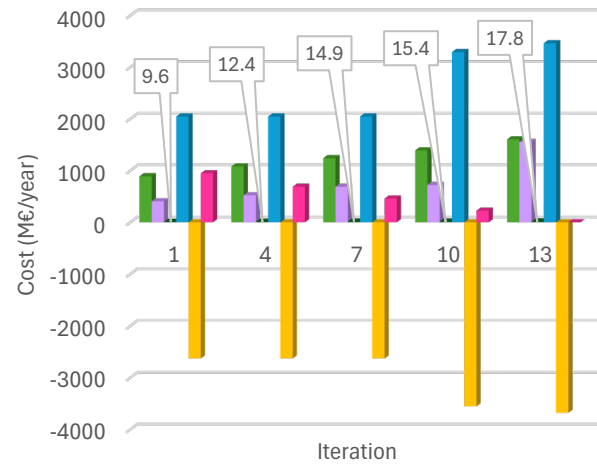


Figure 3. Cost breakdown for selected iterations of the ϵ -Constraint method: total cost of ■ flue gas dehydration and carbon capture and compression; ■ transportation; ■ storage; ■ production of CO₂-based products; ■ revenue from selling the products; ■ taxes.

Table 1. Management paths for CO₂ emissions (Mt/year) in selected iterations and Nash equilibrium.

	Utilisation	Storage	Permit trading	Tax payment
1	10.4	17.6	8.6	18.9
4	10.4	22.8	10.3	13.8
7	10.4	27.4	11.8	9.2
10	14.1	28.4	13.3	4.5
13	14.7	32.7	13.6	0.0
Nash	14.6	27.2	13.5	5.1

In order to find the point where cost and CO₂ reduction are at equilibrium, the game theoretic Nash approach is implemented in the GAMS using the Gurobi solver. The model consists of 21,015 equations and 24,933 variables, of which 2,660 are discrete variables. The number of grid points for the linearisation in equation (16) is 15, the CPU time required to obtain the solution is 6.3 s, and the relative gap obtained was 0.1%. The quo stat point is obtained with a single objective optimisation in a scenario where trading is not allowed, and all emission sources must manage 80% of their total CO₂ emissions. **Table 1** represents the amount of CO₂ being covered through different supply chain sections when the Nash equilibrium strategy is considered. The Nash solution is presented in **Figure 2** with a total cost of 2046.6 M€/year (see **Table 2** for the cost breakdown values) and a CO₂ reduction value of 41859.8 kt/year, of which 35% is achieved through CO₂ utilisation and 65% through storage. Among the 70 emission sources, 10 participate in the CCUS,

using 7 storage sites and 3 utilisation sites to produce 1,660 kt/year of CO₂-based ethylene and cure 1,1791.9 kt/year of cement. s

Table 2. Total cost breakdown of the Nash result.

Cost breakdown	(M€/year)
Dehydration, capture and compression	1357.9
Transportation	634.5
Storage	14.8
Production of CO ₂ -based products	3461.5
Tax payment	256.3
Revenue from selling the products	3678.3

CONCLUSIONS AND FUTURE WORK

A multi-objective MILP modelling framework is presented for the optimisation of carbon capture utilisation and storage supply chains, which is applied to a case study in Germany. The MOO model demonstrates that the total cost of the proposed supply chain network increases nonlinearly with increasing CO₂ reduction quantities. As a guide to decision-makers, the Pareto front of these trade-offs is found. The fair trade-off between these two objectives is determined using the game theoretical Nash approach, and the resulting solution is selected as the optimal strategy in this study. This strategy achieves a CO₂ emissions reduction of approximately 54% from the examined sources, corresponding to ca. 7% of CO₂ of current German emissions. The estimated cost of €2 billion corresponds to ca. 0.05% of German GDP. This is achieved by sending two-thirds of mitigated CO₂ emissions into storage and utilising another third for the production of cement and ethylene. These results rely on assumptions about production, capture, compression, storage and transportation costs, which could affect the profitability of the chosen CO₂ management framework. More investigations and technical progress in these areas will enhance the cost efficiency of the optimal CO₂ management framework.

REFERENCES

1. Baroudi HA, Awoyomi A, Patchigolla K, Jonnalagadda K, Anthony E. A review of large-scale CO₂ shipping and marine emissions management for carbon capture, utilization, and storage. *Applied Energy* 287:116510 (2021).
2. Pacheco KA, Bresciani AE, Alves RM. Multi-criteria decision analysis for screening carbon dioxide conversion products. *J CO₂ Util* 43:101391 (2021).
3. Hasan MMF, Boukouvala F, First EL, Floudas CA. Nationwide, regional, and statewide CO₂ capture, utilization, and sequestration supply chain network optimization. *Ind Eng Chem Res* 53:7489–7506

- (2014).
4. Zhang S, Zhuang Y, Liu L, Zhang L, Du J. Optimization-based approach for CO₂ utilization in carbon capture, utilization, and storage supply chain. *Comp Chem Eng* 139:106885 (2020).
5. Leonzio G, Foscolo PU, Zondervan E. Multi-objective optimization of CCUS supply chains for European countries with higher carbon dioxide emissions. *Phys Sci Rev* 8:1593-1620 (2023).
6. EU Emissions Trading System (EU ETS) — ICAP Carbon Action. <https://icapcarbonaction.com/en/ets/eu-emissions-trading-system-eu-ets> [Accessed 21 Oct 2024].
7. European Commission Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en [Accessed 07 Aug 2024].
8. Zhang D, Alhorr Y, Elsarrag E, Marafia AH, Lettieri P, Papageorgiou LG. Fair design of CCS infrastructure for power plants in Qatar under carbon trading scheme. *International Journal of Greenhouse Gas Control* 56:43–54 (2017).
9. Opricovic S, Tzeng GH. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. *Eur J Oper Res* 156:445–455 (2004)
10. Ravi NK, Van Sint Annaland M, Fransoo JC, Grievink J, Zondervan E. Development and implementation of supply chain optimization framework for CO₂ capture and storage in the Netherlands. *Comp Chem Eng* 102:40–51 (2017).
11. Haimes Y. On a bicriterion formulation of the problems of integrated system identification and system optimization. *IEEE Trans Syst Man Cybern* 1(3):296–297 (1971)
12. Gjerdrum J, Shah N, Papageorgiou LG. Transfer prices for multienterprise supply chain optimization. *Ind Eng Chem Res* 40:1650–1660 (2001)
13. World Resources Institute. <https://www.wri.org/research/global-database-power-plants> [Accessed Aug 2024].

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