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Multiperiod optimisation of a European CCS supply chain under capture-cost uncertainty.

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ABSTRACT

This paper presents a Europe-wide optimisation framework for designing and operating a multi-period Carbon Capture and Storage (CCS) supply chain across Europe. A MATLAB preprocessing pipeline constructs an auditable techno-economic dataset (emission nodes, ports, aquifers, candidate pipeline/shipping arcs and costs) and exports it to a GAMS optimisation model. The planning problem is formulated as a two-stage stochastic MILP, where scenario-independent first-stage decisions select discrete pipeline and shipping capacity bands and port operating modes, while scenario-dependent second-stage decisions allocate capture, transport and sequestration flows. Uncertainty is represented through correlated scenarios of capture unit costs for four capture technologies ($CV = 0.35, \rho = 0.8, N_s = 20$). To address the computational burden induced by inter-temporal binary investments and scenario replication, we apply a two-phase arc-screening heuristic: an LP relaxation on the full network identifies promising corridors, and a reduced MILP is solved on the resulting candidate arc sets. The resulting stochastic model contains 1, 278, 661 continuous variables and 48, 860 binaries and is solved in 1, 347.9 s with a 4.85% optimality gap.

Keywords: Optimization, Supply Chain, Carbon Dioxide Capture, GAMS, Design Under Uncertainty

1. INTRODUCTION

As a consequence of the Paris Agreement reached at the 2015 United Nations Climate Change Conference, 196 Parties pledged to reduce their emissions and to collaborate to limit global temperature rise well below 2 °C above pre-industrial levels, aiming to stay below 1.5 °C [1]. Nonetheless, the climate-change mitigation scenarios presented by the Intergovernmental Panel on Climate Change suggest that even rapid decarbonisation may not be enough to achieve this stringent target [2]. A promising strategy to address both climate and economic challeng-es is the implementation of Carbon Capture and Storage (CCS) [3–5]. CCS is widely recognised as an indispensa-ble technology for limiting global warming below 1.5 °C [6, 7]. Consequently, a significant body of research has focused on designing CCS supply chains in recent years. For instance, [8] proposes a temporal decomposition scheme for CCS supply-chain design.

In this work, a multi-period mixed-integer linear programming (MILP) model for a CCS supply chain across Europe is formulated and solved in full space (i.e., without decomposition) to minimise overall cost under uncertainty. The model is grid-based and spatially explicit, simultaneously optimising capture, multi-mode transport, and geological sequestration nodes over a planning horizon. Transport technologies include onshore pipelines, offshore pipelines, and maritime shipping. Emissions from power, iron and steel and cement industries are projected from the EDGAR database [9]; potential storage comes from JRC/CO2Stop [10]. In the figures 1-4 are shown the regional discretisation used for Europe (Figure 1), the location of the European ports (Figure 2), the place of the aquifers (Figure 3) and the large stationary emission sources considered (Figure 4).

Uncertainty is introduced explicitly in unit capture costs for four technologies—post-combustion (coal), post-combustion (gas), oxy-combustion (coal), and pre-combustion. These four uncertain parameters are correlated, reflecting shared cost drivers; for example, a decrease in coal post-combustion cost is expected to comove with a decrease in gas post-combustion cost.

Compared with Álvarez-Menchero et al. [8], this study (i) expands the spatial scope to continental Europe,

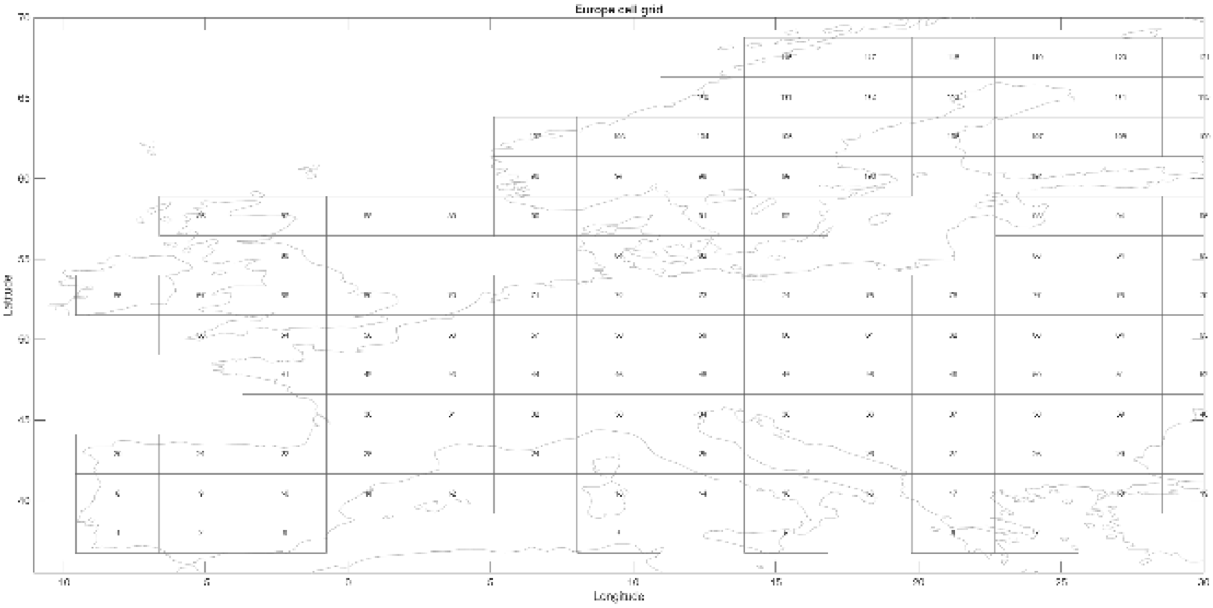

Figure 1. Regional discretization

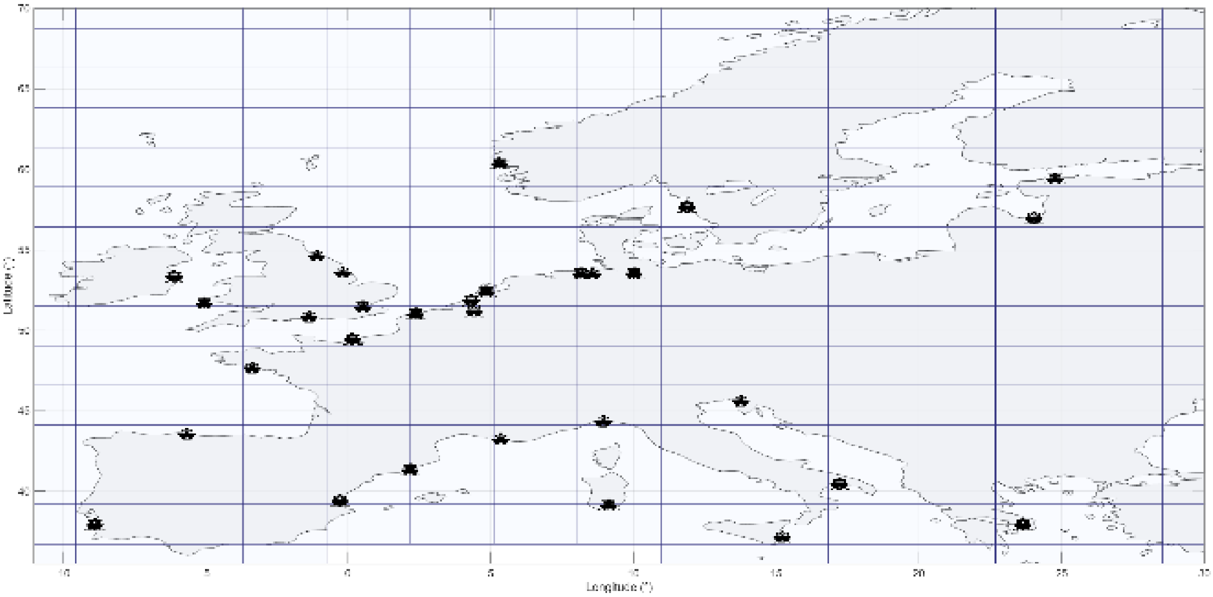

Figure 2. Port locations.

(ii) adds ship transport alongside onshore/offshore pipelines, and (iii) considers correlated uncertainty in the costs of the capture technologies.

2. PROBLEM STATEMENT

2.1 Model formulation

The proposed optimisation model can be interpreted as the interaction of three tightly coupled subproblems:

- a **capture subproblem**, which allocates emissions to capture technologies and enforces a time-dependent capture target;
- a **transport subproblem**, which designs a discrete infrastructure (pipelines and shipping arcs) and routes captured $\mathrm{CO_2}$;
- a **sequestration subproblem**, which injects $\mathrm{CO_2}$ into aquifers under rate and capacity limits.

The overall model is formulated as a two-stage stochastic MILP. The first-stage variables represent *strategic* infrastructure decisions—pipeline and shipping capacity band activations and port operating modes—and are therefore shared across all scenarios. The second-

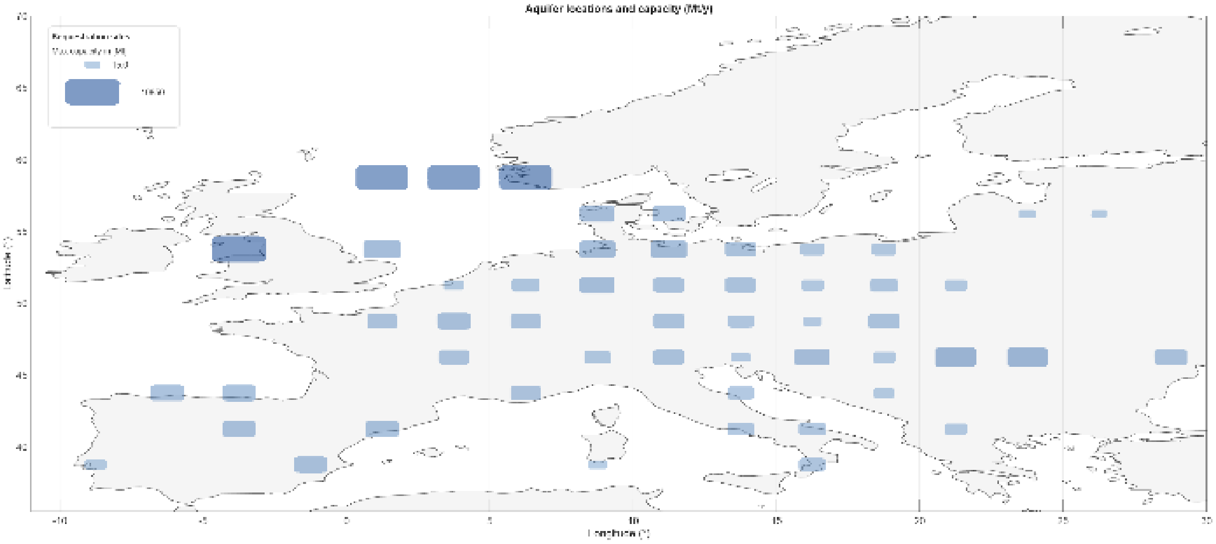

Figure 3. Aquifer locations.

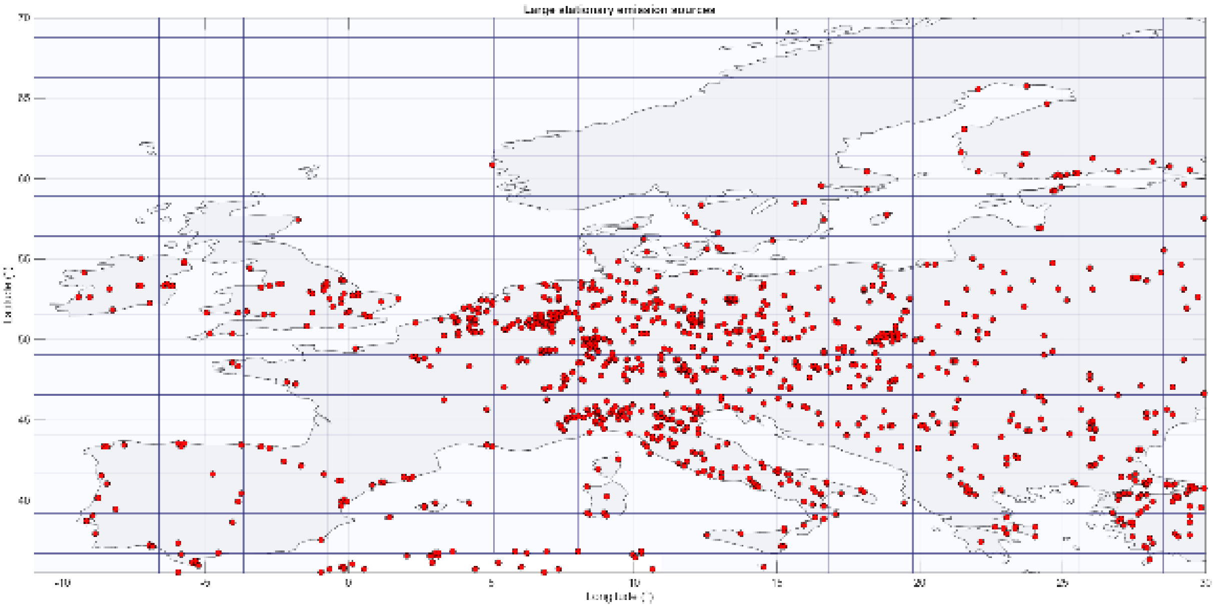

Figure 4. Large stationary emission sources.

stage variables are *operational* and scenario-dependent—capture levels, transported flows, and sequestration—so that the system can adapt to each realisation of uncertain capture costs. The three subproblems are coupled through a node-wise mass balance and an expected-cost objective.

Because the formulation combines (i) large-scale discrete network design and (ii) scenario replication of operational decisions, the full stochastic MILP can become computationally demanding. This motivates the two-phase solution approach presented later (LP screening followed by a reduced MILP).

2.2.1 Capture subproblem

At each emitting node n and year t, the model decides how much CO_2 is processed by each capture technology c, denoted $pCO2_{c,n,t,s}$, and the corresponding captured amount $cCO2_{c,n,t,s}$. Processing is limited by the local emission availability, and by technology-specific feasibility rules (e.g., fuel-share-based envelopes for the power sector).

First, processed CO_2 cannot exceed total emissions:

$$\sum_{c} pCO2_{c,n,t,s} \leq \; E^{total}_{n,t} \;\forall n,t,s \tag{1}$$

Second, technology eligibility is enforced through an admissible envelope $E^{allow}_{c,n,t}$:

$$pCO2_{c,n,t,s} \leq E^{allow}_{c,n,t} \ \forall c,n,t,\mathrm{s} \tag{2}$$

Captured CO_2 is obtained from processed CO_2 via the technology efficiency ce_c:

$$cCO2_{c,n,t,s} = \ ce_c pCO2_{c,n,t,s} \ \ \forall c,n,t,\mathrm{s} \tag{3}$$

Finally, a year-dependent capture target $\alpha(t)$ imposes a minimum captured fraction of total emissions:

$$\sum_n \sum_c cCO2_{c,n,t,s} \geq \ \alpha_t \sum_n E^{total}_{n,t} \ \ \forall t,s \tag{4}$$

In addition to these core constraints, pre-combustion capture is modelled as a niche option through deployment caps. A node-level cap limits the local pre-combustion contribution relative to power emissions:

$$cCO2_{pre^{comb},n,t,s} \leq \ preCapFrac^{node} E^{power}_{n,t} : \forall n,t,s \tag{5}$$

and an EU-wide cap limits aggregate pre-combustion deployment:

$$\sum_n cCO2_{pre^{comb},n,t,s} \leq \ PreCapTotal_t \ \ \forall t,s \tag{6}$$

2.2.2 Transport subproblem

Captured CO_2 can be transported through (i) pipelines on candidate arcs $A_{n,nn}$ and (ii) maritime shipping on candidate port-to-port arcs $SArc_{n,nn}$. Transport capacity is discretised into throughput bands q with bounds $\left[Q^{min}_q, Q^{max}_q\right]$. The activation of a band is controlled by binary variables $y^{pipe}_{q,n,nn,t}$ and $y^{ship}_{q,n,nn,t}$, which are first-stage (scenario-independent) decisions. Operational flows—$qCO2^{pipe}_{q,n,nn,t,s}$ and $qCO2^{ship}_{q,n,nn,t,s}$—are second-stage (scenario-dependent).

Pipeline capacity selection and linking

If a pipeline band is activated, the corresponding flow must remain within the band bounds:

$$qCO2^{pipe}_{q,n,nn,t,s} \geq \ Q^{min}_q y^{pipe}_{q,n,nn,t} \ \ \forall q,(n,nn) \in Aout, \forall t,\mathrm{s} \tag{7}$$

$$qCO2^{pipe}_{q,n,nn,t,s} \leq \ Q^{max}_q y^{pipe}_{q,n,nn,t} \ \forall q,(n,nn) \in Aout, \forall t,\mathrm{s} \tag{8}$$

where $Aout \subseteq A$ excludes arcs whose origin is an aquifer node (aquifers are sinks in the network).

At most one capacity band can be chosen per arc-year:

$$\sum_q y^{pipe}_{q,n,nn,t} \ \leq 1 \ \ \forall (n,nn) \in Aout, t \tag{9}$$

To avoid redundant designs, anti-parallel construction is forbidden:

$$\sum_q y^{pipe}_{q,n,nn,t} \ + \ \sum_q y^{pipe}_{q,nn,n,t} \ \leq \ 1 \ \forall (n,nn) \in A, \ n < nn, \forall t \tag{10}$$

Finally, infrastructure is persistent over time: once activated, it cannot be deactivated in later years:

$$\sum_q y^{pipe}_{q,n,nn,t} \ \geq \ \sum_q y^{pipe}_{q,n,nn,t-1} \ \ \forall (n,nn) \in Aout, \forall t > 1 \tag{11}$$

Shipping capacity selection and linking

Shipping arcs follow the same band-activation logic:

$$qCO2^{ship}_{q,n,nn,t,s} \geq \ Q^{min}_q y^{ship}_{q,n,nn,t} \ \ \forall q,(n,nn) \in SArc, \forall t,\mathrm{s} \tag{12}$$

$$qCO2^{ship}_{q,n,nn,t,s} \leq \ Q^{max}_q y^{ship}_{q,n,nn,t} \ \ \forall q,(n,nn) \in SArc, \forall t,\mathrm{s} \tag{13}$$

with one band per arc-year,

$$\sum_q y^{ship}_{q,n,nn,t} \ \ \leq \ 1 \ \forall (n,nn) \in SArc, \forall t \tag{14}$$

anti-parallel exclusion,

$$\sum_q y^{ship}_{q,n,nn,t} \ + \ \sum_q y^{ship}_{q,nn,n,t} \ \leq \ 1 \ \forall (n,nn) \in SArc, \ n < nn, \forall t \tag{15}$$

and persistence,

$$\sum_q y^{ship}_{q,n,nn,t} \ \geq \ \sum_q y^{ship}_{q,n,nn,t-1} \ \ \forall (n,nn) \in SArc, \forall t > 1 \tag{16}$$

2.2.3 Sequestration subproblem, coupling constraints, and objective function

Sequestration takes place at aquifer nodes. The key coupling between capture, transport and sequestration is the node-wise mass balance, enforced for every node, year, and scenario.

$$\begin{aligned} &\sum_{q,nn:(nn,n)\in A} qCO2^{pipe}_{q,nn,n,t,s} + \sum_{q,nn:(nn,n)\in SArc} qCO2^{ship}_{q,nn,n,t,s} \\ &\qquad + \sum_c cCO2_{c,n,t,s} \\ &= \sum_{q,nn:(n,nn)\in A} qCO2^{pipe}_{q,n,nn,t,s} \\ &\qquad + \sum_{q,nn:(n,nn)\in SArc} qCO2^{ship}_{q,n,nn,t,s} \\ &\qquad + Seq_{n,t,s} \ \forall n,t,\mathrm{s} \end{aligned} \tag{17}$$

Sequestration is further limited by an annual injection cap:

$$Seq_{n,t,s} \leq \ SeqRate \ \forall n,t,s \tag{18}$$

and by finite site capacity over the full horizon:

$$\sum_t Seq_{n,t,s} \leq \ S_n \ \forall n, \forall s \tag{19}$$

Total cost in each year and scenario is the sum of capture, transport, and storage costs. Capture costs are scenario-dependent via $UCC_{c,s}$:

$$TCC(t,s) = \sum_{n,c} UCC_{c,s} \ cCO2_{c,n,t,s} \ \ \forall t,\mathrm{s} \tag{20}$$

Pipeline transport costs are proportional to distance and include an offshore multiplier $aco_{n,nn}$:

$$TTC_{t,s}^{pipe} = \sum_{q} \sum_{(n,nn)\in Aout} qCO2_{q,n,nn,t,s}^{pipe}\ d_{n,nn} UTC_q aco_{n,nn}\ \forall t, s \tag{21}$$

Shipping costs are calculated in the following way:

$$TTC_{t,s}^{ship} = \sum_{q} \sum_{(n,nn)\in SArc} qCO2_{q,n,nn,t,s}^{ship}\ (UTC^{ship,slope} d_{n,nn} + UTC_q^{ship,int})\ \forall t, s \tag{22}$$

Storage costs are linear in injected CO_2, scaled by an offshore storage multiplier:

$$TSC_{t,s} = \sum_{n} Seq_{n,t,s} USC\, USC_n^{off}\ \forall t, s \tag{23}$$

Let $TC_{t,s} = TCC_{t,s} + TTC_{t,s}^{pipe} + TTC_{t,s}^{ship} + TSC_{t,s}$. The objective minimises the expected total cost across the planning horizon using scenario probabilities π_s:

$$\min\ Z = \sum_{s} \pi_s \sum_{t} TC_{t,s} \tag{24}$$

NOMENCLATURE

Sets

t: years {1, 2, ..., 10}

n: nodes {1, 2, ..., 203}

c: capture technology $\{post_{coal}^{comb}, post_{coal}^{comb}, pre^{comb}, oxy^{fuel}\}$

$\mathcal{Q} = \{q1, q2, q3, q4\}$:set of discrete throughput bands, $|\mathcal{Q}| = 4$

q: throughput bands $\{q_1, q_2, q_3, q_4\}$

$\mathcal{S}$:set of scenarios, $|\mathcal{S}| = 20$

s: scenarios $\{s_1, s_2, \ldots, s_{20}\}$

A: set of feasible pipeline arcs

$SArc$: set of feasible shipping arcs (port-to-port)

$pred$: predecessor relation ($(t, tt) \in pred \Rightarrow tt$ precedes t)

PARAMETERS

$coord_{n,p}$:coordinates of node n (degrees)

$d_{n,nn}$:distance between nodes n and nn (km)

$aco_{n,nn}$:offshore pipeline cost multiplier on arc (n, nn) (dimensionless)

$E_{n,t}^{total}$:total emissions [Mt/y]

$E_{n,t}^{power}$:power-sector emissions [Mt/y]

$E_{n,t}^{cement}$:cement-sector emissions [Mt/y]

$E_{n,t}^{steel}$:iron&steel emissions [Mt/y]

α_t:required capture fraction in year t (target on captured CO2

ce_c:capture efficiency of technology c

S_n:total storage capacity at aquifer node n over the horizon [Mt

$SeqRate$:maximum annual injection rate (scalar) [Mt/y]

USC:unit storage (sequestration) cost [€/Mt]

USC_n^{off}:offshore storage cost multiplier at aquifer n (dimensionless

Q_q^{min}:minimum throughput in band q [Mt/y]

Q_q^{max}:maximum throughput in band q [Mt/y]

UTC_q:pipeline unit transport cost in band q [€/Mt·km]

$UTC^{ship,slope}$:shipping distance slope [€/Mt·km]

$UTC_q^{ship,int}$:shipping intercept in band q [€/Mt]

$UCC_{c,s}$:scenario capture unit cost [€/Mt]

π_s: scenario probability, $\sum_{s\in\mathcal{S}} \pi_s = 1$

sh_n^{coal}:coal share of power emissions at node n (dimensionless

sh_n^{gas}:gas share of power emissions at node n (dimensionless

$E_{c,n,t}^{allow}$:eligible-emissions envelope for tech c [Mt/y]

$preCapFrac^{node}$:node-level cap fraction for pre-combustion (dimensionless

$preCapFrac^{EU}$:EU-wide cap fraction for pre-combustion (dimensionless)

$PreCapTotal_t$:EU-wide pre-combustion cap in year t [Mt/y]

Continuous decision variables (scenario - dependent)

$pCO2_{c,n,t,s}$: processed CO2 [Mt/y]

$cCO2_{c,n,t,s}$: captured CO2 [Mt/y]

$qCO2_{q,n,nn,t,s}^{pipe}$: pipeline flow on arc $(n \rightarrow nn)$ [Mt/y]

$qCO2_{q,n,nn,t,s}^{ship}$: shipping flow on arc $(n \rightarrow nn)$ [Mt/y]

$Seq_{n,t,s}$: sequestered CO2 at aquifer node n [Mt/y]

$TCC_{t,s}$: total capture cost [€/y]

$TTC_{t,s}^{pipe}$: pipeline transport cost [€/y]

$TTC_{t,s}^{ship}$: shipping transport cost [€/y]

$TTC_{t,s}$: total transport cost (=pipeline+ship) [€/y]

$TSC_{t,s}$: total storage cost [€/y]

$TC_{t,s}$: total system cost [€/y]

Z: expected objective value [€], $Z = \sum_{s\in\mathcal{S}} \pi_s \sum_{t\in\mathcal{T}} TC_{t,s}$

Binary decision variables (scenario - independent)

$y^{pipe}_{q,n,nn,t} \in \{0,1\}$:1 if pipeline band q is activated on arc $(n \rightarrow nn)$ in year t

$y^{ship}_{q,n,nn,t} \in \{0,1\}$:1 if shipping band q is activated on arc $(n \rightarrow nn)$ in year t

$z^{out}_{n,t} \in \{0,1\}$:port mode (1=ship-export, 0=ship-import)

3. UNCERTAINTY MODELLING.

Uncertainty is introduced in the capture unit costs through a scenario-based representation. Let UCC^{mean}_c denote the nominal capture cost for technology c. We generate a set of scenarios $scen$in MATLAB by sampling correlated cost multipliers with coefficient of variation $CV = 0.35$ and common correlation $\rho = 0.8$ across the four capture technologies (post-combustion coal, post-combustion gas, oxy-combustion coal, and pre-combustion), reflecting shared cost drivers (e.g., energy penalty, solvent/oxygen supply costs, and scale effects). Scenario-specific capture costs are then computed as

$$UCC_{c,s} = UCC^{mean}_c \xi_{c,s} \tag{25}$$

where $\xi_{c,s}$ is the sampled multiplier, and scenario probabilities are taken as uniform. The stochastic MILP minimises the expected total cost, with first-stage infrastructure decisions shared across all scenarios and second-stage operational decisions adapting to each scenario realisation.

4. SOLUTION APPROACH.

As has been mentioned previously, the stochastic CCS network design problem introduced in Section 2 results in a large-scale mixed-integer linear programme (MILP). To keep the model tractable, we adopt a two-phase solution heuristic.

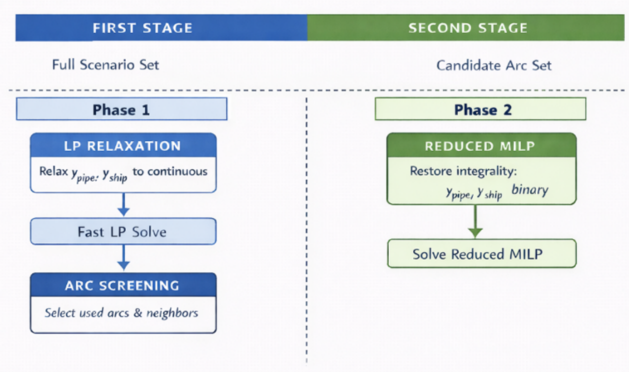

Figure 5. Two-phase heuristic diagram

4.1 Phase 1: LP relaxation on the full scenario set + arc screening

In Phase 1, we solve a *relaxation* of the full stochastic MILP in binaries $y^{pipe}_{q,n,nn,t}$ and $y^{ship}_{q,n,nn,t}$ are relaxed. This converts the original MILP into a large but comparatively fast linear programme (LP) over the full scenario set and the complete set of candidate arcs.

The objective of Phase 1 is to get structural information about where the optimal solution tends to route CO_2. The LP solution provides two key outputs:

- Arcs that carry non-negligible CO_2 flow in at least one time period and scenario are flagged as *used*.
- A conservative candidate set construction. To avoid overly aggressive pruning, we expand the used-arc set by adding a controlled neighbourhood around the endpoints of used arcs (i.e., we keep used arcs and arcs departing from nodes that appear as endpoints of used arcs). This step is critical in practice: it preserves alternative routings that the LP may not select strongly, but that can become essential once integrality is enforced.

The output of Phase 1 is therefore a Candidate Arc Set (for pipelines and for shipping), together with the Phase-1 operational solution (e.g., captured CO_2 levels) that can later be used to stabilise Phase 2.

4.2 Phase 2: reduced stochastic MILP on the candidate arc set

In Phase 2, integrality is restored and the model is solved as a reduced stochastic MILP defined on the Candidate Arc Set identified in Phase 1 (Figure 5).

Phase 2 returns a fully implementable solution: discrete infrastructure investments (pipelines, shipping capacity bands, and port mode), and consistent scenario-dependent operational decisions (capture, transport flows, and sequestration) that meet the decarbonisation targets.

4.3 Validation of the solution method

The proposed solution method was validated on reduced-size instances for which the integrated full-space stochastic MILP could still be solved directly. These simplified instances retained the main structural features of the original problem, including multi-period decisions, uncertainty in capture costs, and the coupling between capture, transport, and sequestration, while reducing the number of nodes, candidate arcs, time periods, and/or scenarios to keep the integrated formulation computationally manageable.

The comparison focused on the consistency of the objective value and on the main first-stage investment decisions, namely the activation of pipelines, shipping

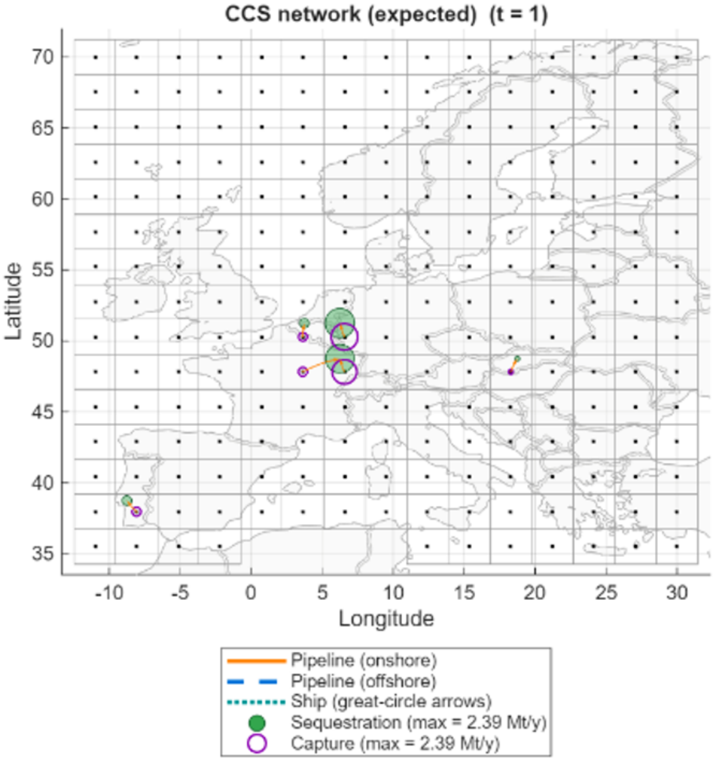

Figure 6. CCS network in year 1

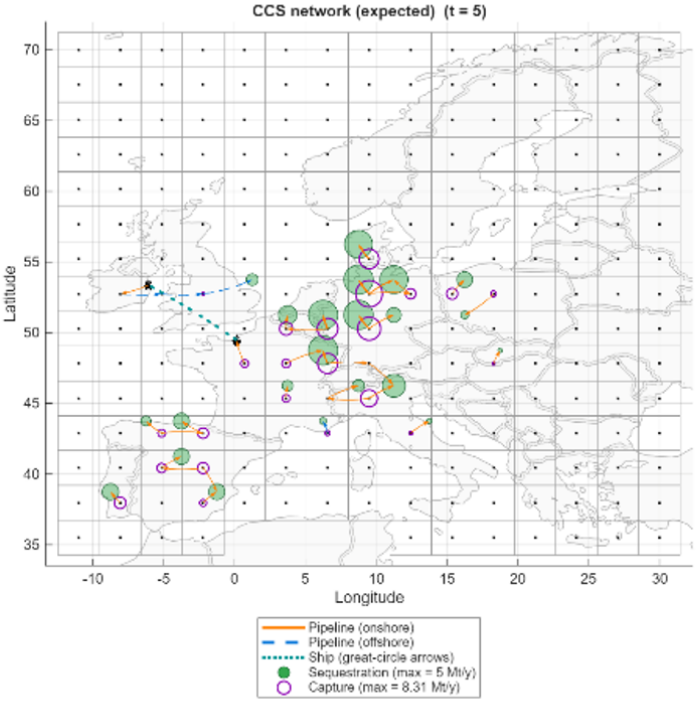

Figure 7. CCS network in year 5

arcs, and capacity levels. The reduced-instance tests showed that the proposed two-phase approach reproduced the same qualitative infrastructure patterns as the integrated model and provided solutions of comparable quality. This confirms that the candidate-arc screening step preserves the key design information required by

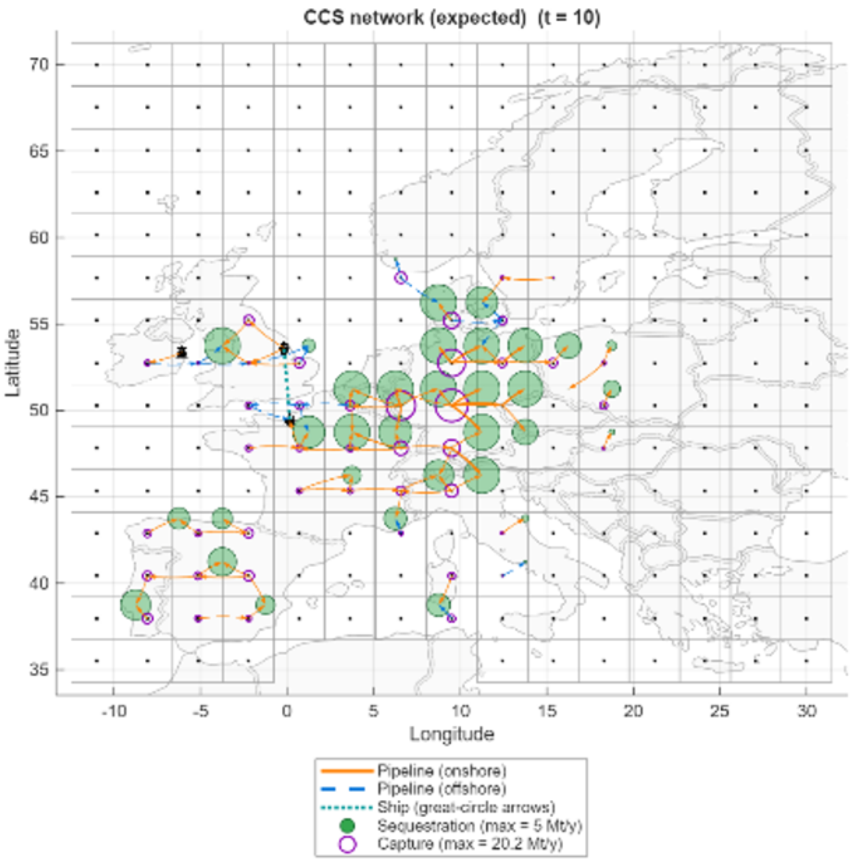

Figure 8. CCS network in year 10

the full-space formulation for the instances examined.

These validation runs were used during model development to verify the soundness of the proposed solution strategy before applying it to the large European-scale cases considered in this work. For such large stochastic instances, the direct solution of the integrated model becomes computationally very demanding. Therefore, the proposed method should be understood as a tractable solution strategy that preserves the essential structure and strategic decisions of the integrated formulation while enabling the treatment of realistically sized case studies.

Table 1. Model size and computational performance

No. of continuous variables	No. of binary variables	Solution time (s)	Optimality gap (%)
1, 278, 661	48, 860	1, 347.9	4.85

5. RESULTS

This section summarises the key outputs of the optimisation. To visualise the spatial evolution of the infrastructure, Figures 6–8 depict the designed CCS network in years 1, 5, and 10, respectively, highlighting how the selected pipeline/shipping corridors and utilised storage sites develop over time. Figure 9 presents the annual captured $\mathrm{CO_2}$ by technology over the 10-year horizon. Figure 10 reports the total annual system cost together with its decomposition into capture, transport, and sequestration contributions. Finally, Table 1 reports the model size and computational performance.

6. CONCLUSION

We developed an integrated MATLAB–GAMS framework for Europe-wide CCS network design that combines multi-technology capture, multimodal transport (pipelines and shipping), and geological storage in a multi-period setting. Capture-cost uncertainty is modelled via correlated scenarios and embedded in a two-stage stochastic MILP, enabling here-and-now infrastructure decisions. To make the large stochastic design problem tractable, a two-phase LP-based arc-screening strategy reduces the candidate transport network before solving the reduced MILP. The approach delivers a feasible time-

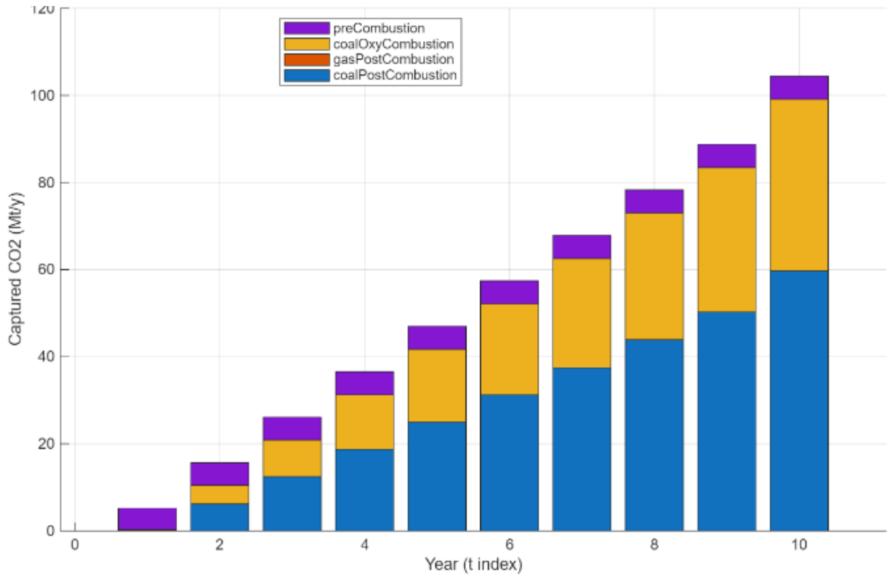

Figure 9. Annual captured CO_2

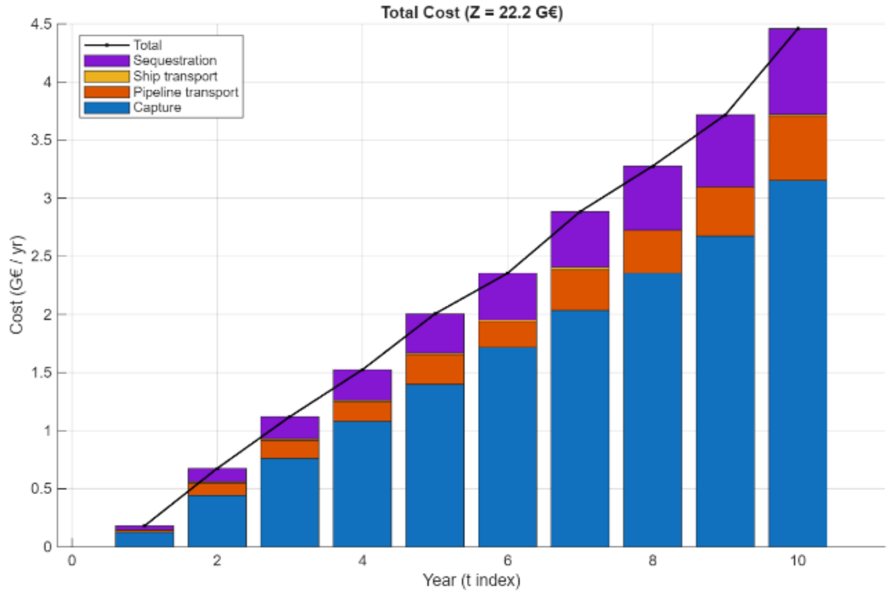

Figure 10. Total annual cost.

evolving infrastructure plan together with technology and cost insights, while achieving practical runtimes for a problem of this scale. Future work will focus on tightening optimality guarantees and extending uncertainty to additional parameters (e.g., transport and storage costs, storage capacity).

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REFERENCES

1. COP-21. In: Paris Agreement, United Nations Framework Convention on Climate, Conference of the Parties 21. Paris, France 2015. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

2. IPCC. Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways. https://www.ipcc.ch/sr15/ (Intergovernmental Panel on Climate Change, 2018).
3. IPCC Special Report on Carbon Dioxide Capture and Storage (eds Metz, B., Davidson, O., de Coninck, H. C., Loos, M. & Meyer, L. A.) Prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC) (Cambridge University Press, Cambridge, UK, 2005).
4. Boot-Handford ME, Abanades JC, Anthony EJ, Blunt MJ, Brandani S, Mac Dowell N, Fernández JR, Ferrari MC, Gross R, Hallett JP, Haszeldine RS, Heptonstall P, Lyngfelt A, Makuch Z, Mangano E, Porter RTJ, Pourkashanian M, Rochelle GT, Shah N, Yao JG, Fennell PS. Carbon capture and storage update. Energy Environ. Sci. 7:130-189 (2014). https://doi.org/10.1039/c3ee42350f
5. Bui M, Adjiman CS, Bardow A, Anthony EJ, Boston A, Brown S, Fennell PS, Fuss S, Galindo A, Hackett LA, Hallett JP, Herzog HJ, Jackson G, Kemper J, Krevor S, Maitland GC, Matuszewski M, Metcalfe IS, Petit C, Puxty G, Reimer J, Reiner DM, Rubin ES, Scott SA, Shah N, Smit B, Trusler JPM, Webley P, Wilcox J, Mac Dowell N. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11:1062-1176 (2018). https://doi.org/10.1039/c7ee02342a
6. Luderer G, Vrontisi Z, Bertram C, Edelenbosch OY, Pietzcker RC, Rogelj J, De Boer HS, Drouet L, Emmerling J, Fricko O, Fujimori S, Havlík P, Iyer G, Keramidas K, Kitous A, Pehl M, Krey V, Riahi K, Saveyn B, Tavoni M, Van Vuuren DP, Kriegler E. Residual fossil CO2 emissions in 1.5–2 °C pathways. Nature Clim Change 8:626-633 (2018). https://doi.org/10.1038/s41558-018-0198-6
7. Boitier B, Nikas A, Gambhir A, Koasidis K, Elia A, Al-Dabbas K, Aliba? ?, Campagnolo L, Chiodi A, Delpiazzo E, Doukas H, Fougeyrollas A, Gargiulo M, Le Mouël P, Neuner F, Perdana S, van de Ven DJ, Vielle M, Zagamé P, Mittal S. A multi-model analysis of the eu's path to net zero. Joule 7:2760-2782 (2023). https://doi.org/10.1016/j.joule.2023.11.002
8. ?lvarez-Menchero JA, Ruiz-Femenia R, Salcedo-Diaz R, Moreno-Palancas IF, Caballero JA. Temporal decomposition scheme for designing large-scale CO2 supply chains using a neural network-based model for forecasting CO2 emissions. Systems and Control Transactions 4:918-923 (2025). https://doi.org/10.69997/sct.193502
9. Joint Research Centre. Emission Database for Global Atmospheric Research (EDGAR). https://edgar.jrc.ec.europa.eu/index.php

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