Bridging Economic, Environmental, and Safety Performance: Multi-Objective Optimisation of CCUS Supply Chains

Hourissa Soleymani Babadi, and Lazaros G. Papageorgiou*

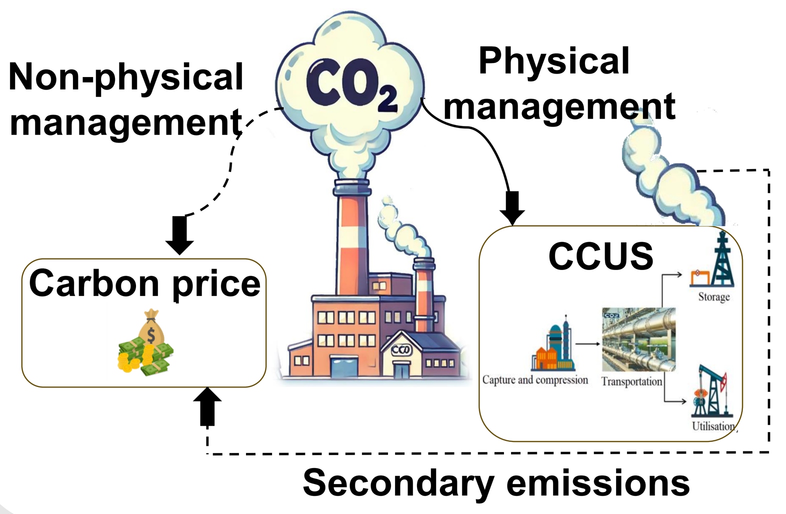
The Sargent Centre for Process Systems Engineering, UCL (University College London), Torrington Place, London WC1E 7JE, UK

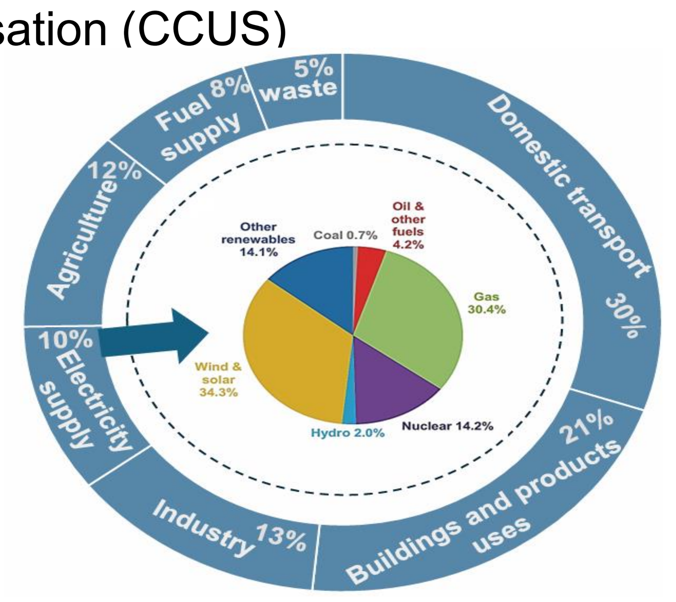
* Corresponding author. E-mail: l.papageorgiou@ucl.ac.uk

UCL

Introduction and Motivation

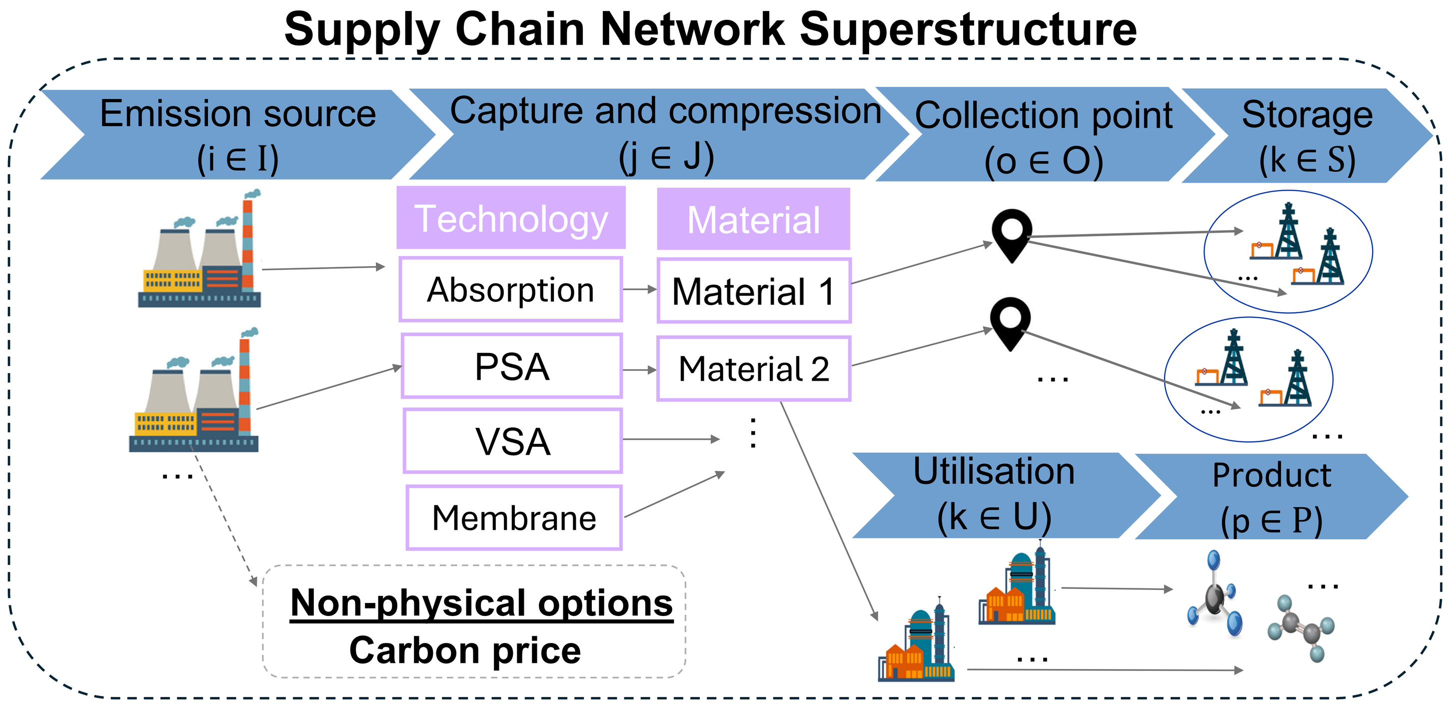
- Net-Zero emissions target to be met by 2050
- Carbon Capture, Storage and Utilisation (CCUS)
- Carbon pricing

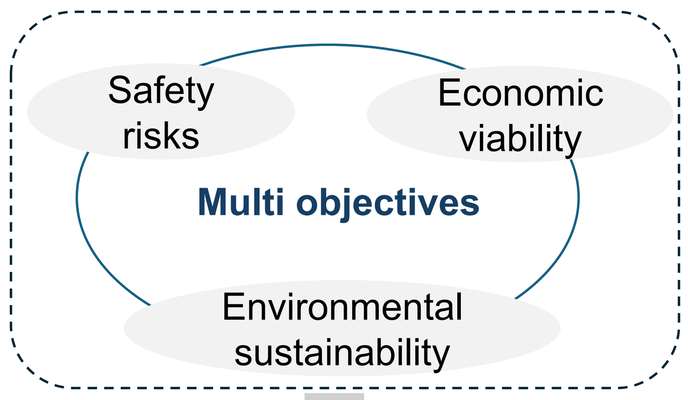




UK Greenhouse gas emissions by sector [1]
Electricity generated by fuel in 2024 [2]

Supply Chain Network Superstructure





Robust decision support for policymakers and industry stakeholders

Mathematical Model

❖ Supply Chain Optimisation Framework

Given

- **Emission and Sites Data:** Nodes location, emission volumes, storage/utilisation capacities
- **Techno-Economic Parameters:** Capture options, materials, transport, and cost parameters
- **Market and Policy:** Product economics, carbon price unit cost

Determine the optimal

- **Flow rates of CO_2 captured, stored, utilised**
- **Technology/material choice**
- **Network decisions**

So as to: **Minimise**
Total cost
CO_2 emission
Safety hazard

❖ Mathematical Model

Objective Functions

$$Min\ Cost = Capture + Transportation + Storage + Carbon\ pricing + Utilisation\ cost - Utilisation\ revenue$$

$$Min\ Emission = Not\ Captured\ CO_2 + Secondary\ emissions$$

$$Min\ Safety\ Hazard^{[3]} = \sum_i \sum_j TI_j^{cap} \frac{E_i\, FR_{ij}}{CR^{min}} + \sum_i \sum_j \left(TI^{tran} + TI_k^{sink}\right) \frac{CK_{ik}}{CR^{min}}$$

Mixed Integer Linear Programming (MILP)

What are the optimal configurations?
✓ **Augmented ε-constraint method**
What is the fair trade off solution?
✓ **Nash game theoretic approach**

Process Constraints

- Maximum storage/production capacity

$$\sum_i CK_{ik} \le MSC_k\ /years \qquad \forall k \in S$$

$$\sum_i \sum_p \sigma_p^{Product}\, CUP_{ikp} \le MPC_k \qquad \forall k \in U$$

CO_2 Balances

- CO_2 capture flow rate

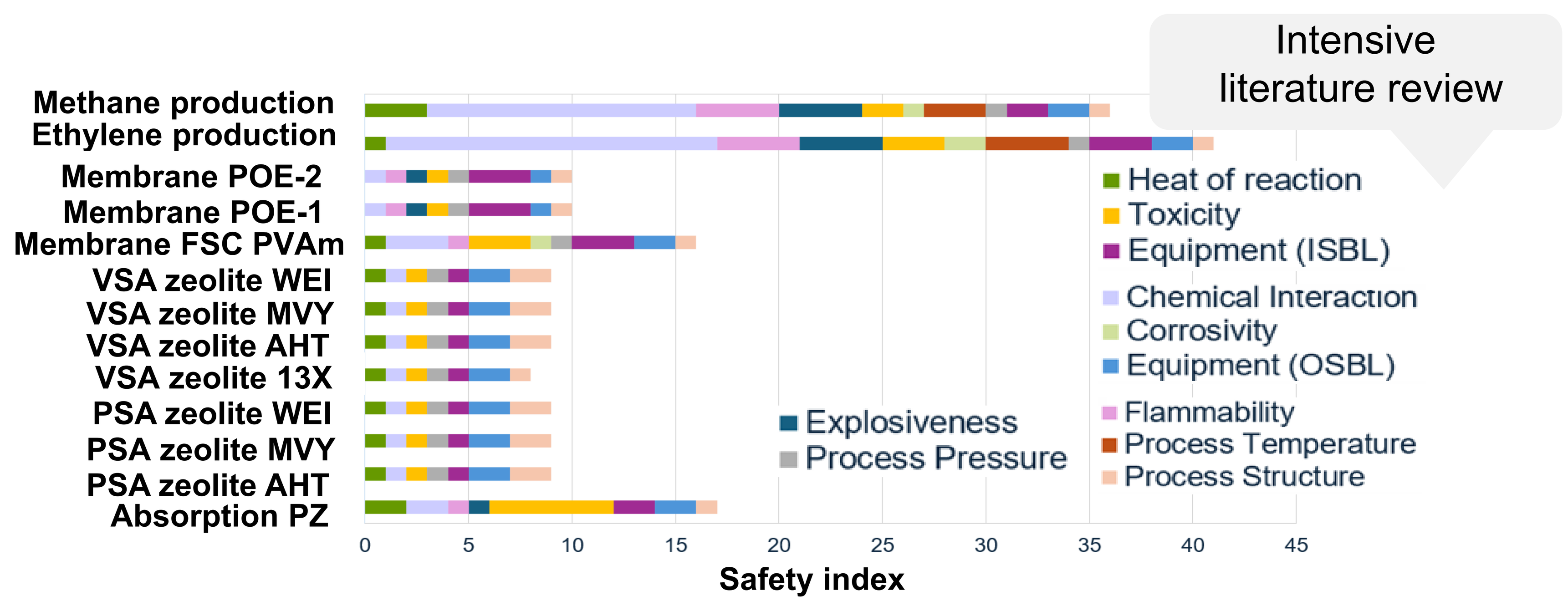
$$\sum_k CK_{ik} = \sum_j E_i\, FR_{ij} \qquad \forall i \in I$$

- CO_2 flow rate for the utilisation section

$$CK_{ik} = \sum_p CUP_{ikp} \qquad \forall i \in I, k \in U$$

Variable:
CK_{ik} CO_2 mass flow rate
CUP_{ikp} CO_2 flow rate for utilisation
FR_{ij} Captured CO_2 fraction

Parameter:
CR^{min} Minimum CO_2 reduction capacity
E_i CO_2 emissions mass flow rate
MSC_k Maximum storage capacity
MPC_k Maximum production capacity
TI_j^{cap} Safety index for CO_2 capture
TI^{tran} Safety index for transportation
TI_k^{sink} Safety index for storage/utilisation
$\sigma_p^{Product}$ Product conversion factor



Breakdown of inherent safety indices for some CCUS network modules

Case Study and Computational Results

❖ CO_2 supply chain under CCUS and carbon pricing in Great Britain

34 power plants and cement factories → Total CO_2 emission of **27.23 Mt/year**
4 utilisation sites (products: Methane, Ethylene), 10 offshore storage sites
12 combination of capture technologies and materials

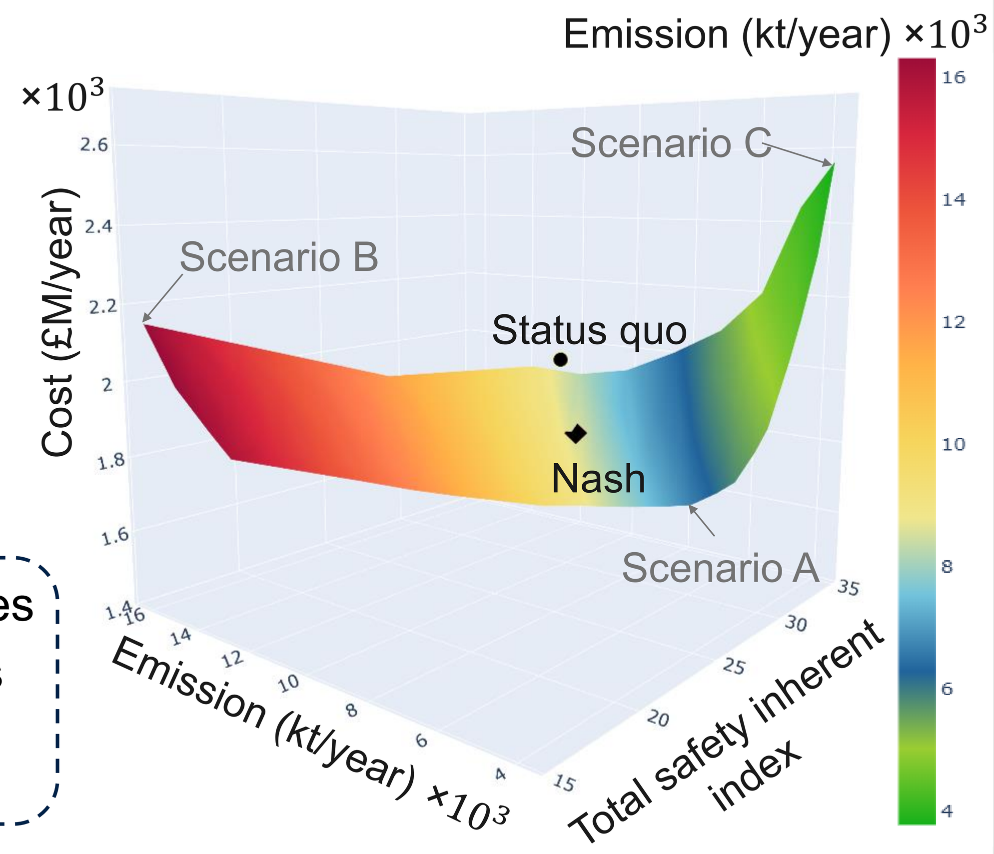
❖ Solution procedure

Gurobi Solver ; using GAMS

Pareto front solutions

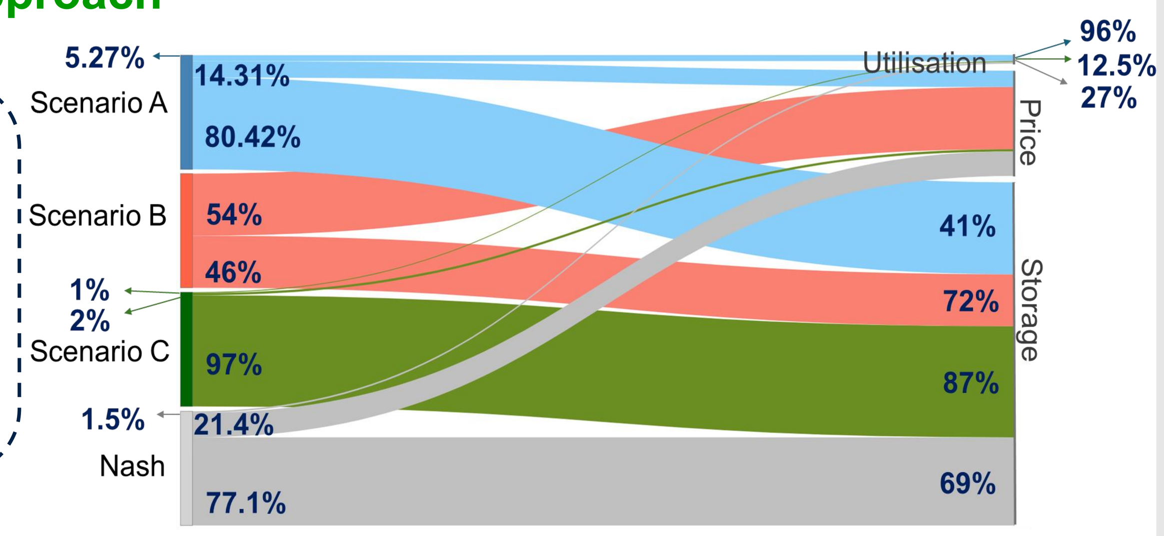
Scenario	Emphasise
A	on economic aspect
B	on environmental aspect
C	on safety aspect

- Trade-offs among the key objectives
- Profitable CO_2 utilisation pathways often cause higher secondary emissions and safety risks



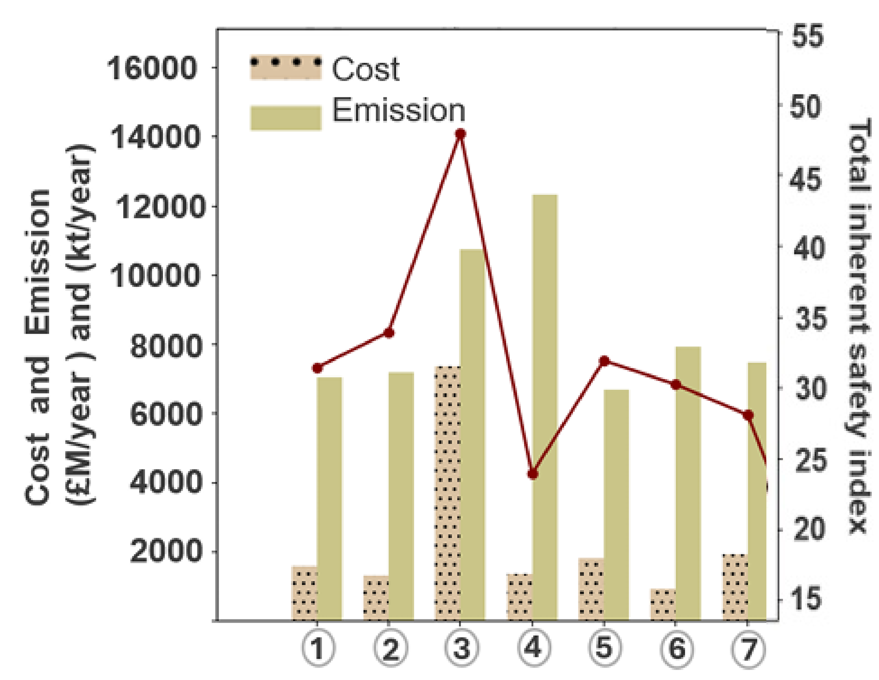
Nash game-theoretic approach
Fair trade off

- Financial implications of CCUS deployment
- Carbon pricing improves cost and safety without delivering major emission cuts



CO_2 management strategy

Comparative analysis



Electricity price
Carbon price
CO_2 Utilisation capacity

1. Original scenario
2. Low capacity scenario
3. High capacity scenario
4. Low carbon price
5. High carbon price
6. Low electricity price
7. High electricity price

Concluding Remarks

- Pareto-optimal solutions across economic, environmental, and safety criteria, guiding sustainable and scalable CCUS configurations toward net-zero industries
- Identification of an industry-relevant fair trade-off using the Nash bargaining approach to support balanced CCUS network selection
- What-if analyses highlighting CO_2-product capacity, carbon price, and electricity price as key drivers influencing CCUS performance and industrial investment

References:
[1] Department for Energy Security and Net Zero, 2024 UK greenhouse gas emissions, provisional figures.
[2] Department for Energy Security and Net Zero, UK energy in brief 2025.
[3] Oqbi, M., Véchot, L. and Al-Mohannadi, D.M., 2025. Safety-driven design of carbon capture utilization and storage (CCUS) supply chains: A multi-objective optimization approach. Computers & Chemical Engineering, 192, p.108863.

Author Information & Affiliations:


Hourissa Soleymani Babadi


Prof. Lazaros Papageorgiou

Sargent Centre for Process Systems Engineering