An optimisation model for the design of multi-modal CO_2 transportation in carbon capture and storage supply chain

Fengyuan (Felix) Zhang, Elena Catalanotti, Sergey Martynov*, Richard T.J. Porter, and Haroun Mahgerefteh*

Department of Chemical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom
Corresponding Emails: s.martynov@ucl.ac.uk, h.mahgerefteh@ucl.ac.uk

1 Motivation and objectives

The design and deployment for an economical, safe and reliable CO_2 transport network connecting emitters and geological storage locations presents a major barrier to CCS implementation. Costs of CO_2 transport modes (by pipelines, ships, trains and trucks) vary across CCS projects. The combination of CO_2 transport modes can provide a more efficient and flexible solution for the future CO_2 transport systems [1, 2].

- Objective 1: Develop a Mixed-Integer Linear Programming (MILP) model to optimise the design of a multi-modal CO_2 transportation chain for CCS.
- Objective 2: Apply the MILP model to a case study of CO_2 transport from the Thomas Zement cement plant in Germany to a storage site in the North Sea off the coast of Norway.

2 Methodology

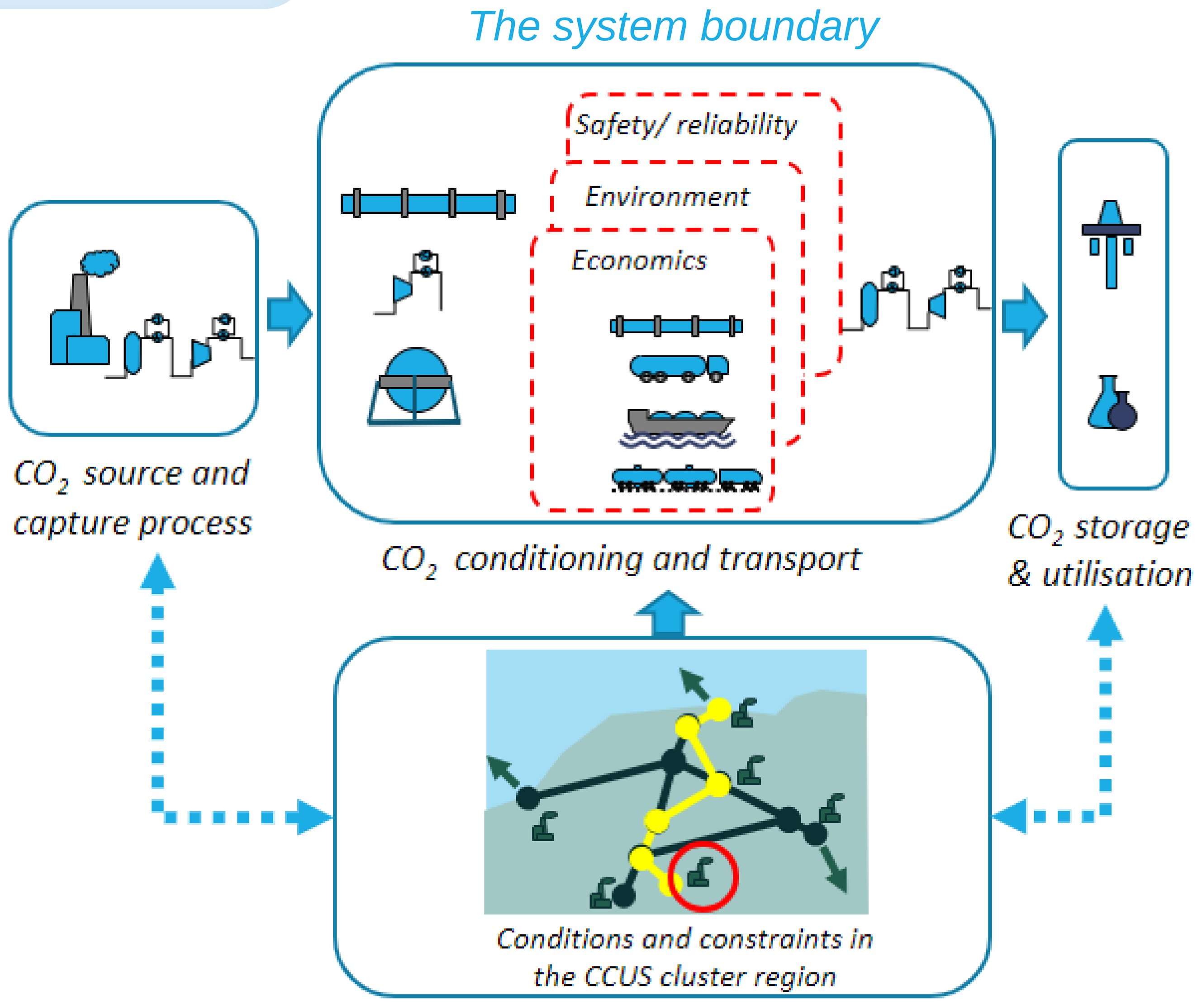

Figure 1. Schematic diagram of multi-modal CO_2 transportation and the system boundary.

- The MILP model of multi-modal CO_2 transport network:

$$\min_{xy}\left(\boldsymbol{c}'\boldsymbol{x}+\boldsymbol{d}'\boldsymbol{y}\right)$$

subject to

$$\mathbf{A}\boldsymbol{x}+\mathbf{B}\boldsymbol{y}=\boldsymbol{b}$$

$$\boldsymbol{x}\geq\mathbf{0}\in\mathbb{R}^{N},\ \boldsymbol{y}\in\{0,1\}^{M}$$

where ***c'*** and ***d'*** are the objective functions for variables ***x*** and ***y***; **A** and **B** are the corresponding constraint matrices; ***x*** is the continuous decision variable in a real number field ℝ and ***y*** is the binary decision variable.

- The cost objective function:

$$\min\sum_{t=0}^{\tau}\frac{C_t+O_t}{(1+r)^t}$$

where C_t and O_t are the CAPEX and OPEX of CO_2 transportation, r is the discount rate, $\tau \leq T$ is the number of years in calculation, and T is the total number of years considered in the analysis.

3 Case study for the cement plant

- **Thomas Zement plant**, CO_2 emissions of 1 Mt /year
- **Three transit ports**, buffer storage installed at the port
- **Offshore storage** in the North Sea
- Transport modes:
  - LP Pipeline - gas phase (20ºC, 25 bar)
  - HP Pipeline - dense phase (20ºC,130 bar)
  - Truck (-30ºC, 15 bar)
  - Train (-30ºC, 20 bar)
  - Ship (-30ºC, 7 bar or 15 bar)

Figure 2. Locations of the plant, ports and storage sites.

4 Results: CAPEX and OPEX of multi-modal CO_2 transport

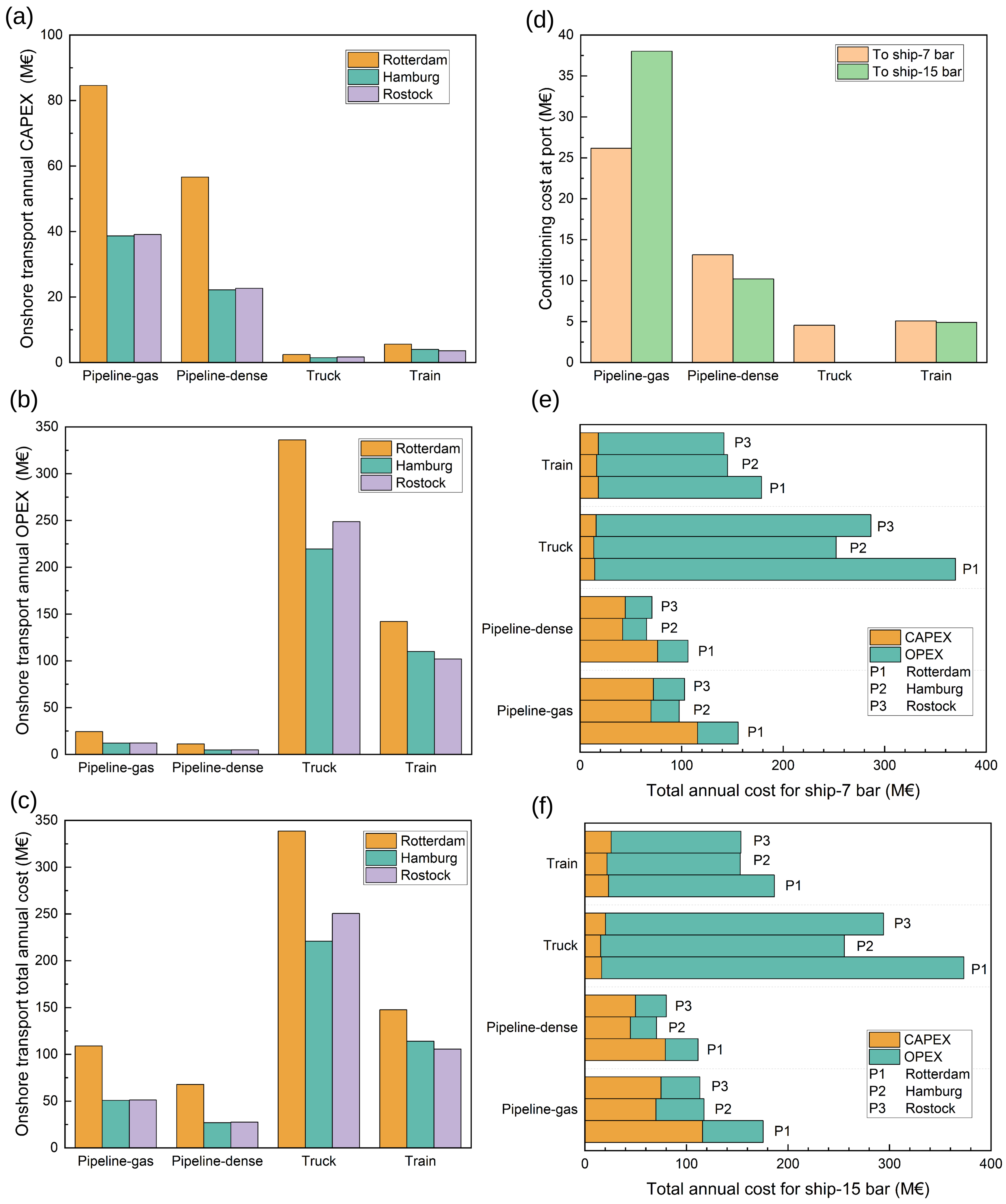

Figure 3. CAPEX and OPEX of multi-modal CO_2 transport. (a) CAPEX for onshore transport; (b) OPEX for onshore transport; (c) Annual CAPEX+OPEX for onshore transport; (d) Conditioning cost at transit ports; (e) Total transport cost by ship at 7 bar; (f) Total transport cost by ship at 15 bar.

5 Key findings and conclusions

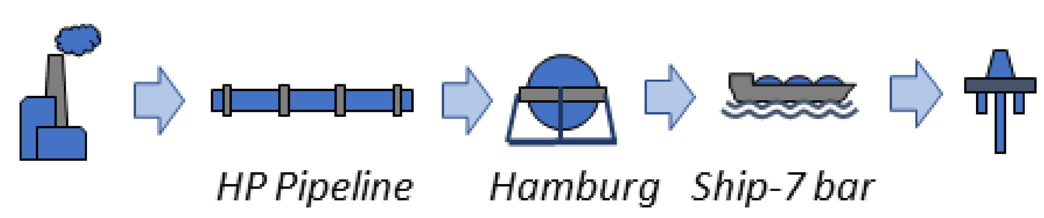

Figure 4. The optimal transportation combination for Thomas Zement plant.

- Onshore CO_2 transportation by **Truck** has the **minimum annual CAPEX**.
- Onshore CO_2 transportation by **HP Pipeline** has the **minimum OPEX**.
- **Total onshore** transport cost appears minimum of 26.9 M€ by **HP Pipeline**.
- Transit port **Hamburg** is best for multi-modal transportation (Fig. 3e & 3f).
- Total cost of offshore shipping at **7 bar** is lower than for shipping at **15 bar**.
- The optimal total cost of CO_2 transportation is **65.5 M€/y** (Figs. 3e and 4).

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[2] Gabrielli, P., et al., Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: cost of resilience. Int. J. of Greenh. Gas Control, 2022. 121: p. 103797.