TO CAPTURE OR ELECTRIFY? AN ENVIRONMENTAL, ECONOMIC AND SOCIAL COMPARISON OF DECARBONISATION ROUTES FOR ETHYLENE PRODUCTION

IMPERIAL

By Defne Nihal Ertugrul

LAIDLAW SCHOLARS

BACKGROUND

- Ethylene is a major petrochemical building block produced predominantly through **steam cracking**.
- Steam cracking is highly energy-intensive because the hydrocarbon feedstock must be heated to very high temperatures in a furnace. [1,2]
- Conventional crackers rely on **fuel combustion**, generating significant direct CO_2 emissions.
- Decarbonising the furnace is therefore an important opportunity for reducing the carbon footprint of ethylene production. [1,3]
- Three furnace-level pathways are considered in this study:

Furnace Carbon Capture and Storage (CCS) → Electrification → SMR hydrogen + CCS

- Their performance differs across **environmental, economic and social dimensions**, meaning that GHG reduction alone does not provide a complete basis for technology selection.

RESEARCH GAP

- Existing studies often assess individual decarbonisation technologies, but few compare electrification, SMR hydrogen with CCS, and furnace CCS using integrated environmental, economic, and social criteria for ethylene production.

AIM & RESEARCH QUESTIONS

Aim: To compare three furnace-level decarbonisation pathways for European naphtha-based ethylene production across environmental, economic and social performance.

RESEARCH QUESTIONS

- How do Furnace CCS, Electrification and SMR H_2 + CCS compare for the production of 1 kg of ethylene?
- Which pathway performs best under the base-case multi-criteria decision analysis (MCDA)?
- How does the ranking change with different electricity-grid conditions and decision-maker priorities?

METHODOLOGY

Study Design	Comparative Literature-based Assessment
Functional Unit	1 Kg Ethylene
System Boundary	Cradle-to-gate
Geographic Focus	European Naphtha Cracker
Evidence Base	25 External Sources
Data Period	2015–2026

- **Conventional baseline**
  - 1.82 kg CO_2 e/kg Ethylene

Direct cracker emissions	Share of total footprint	Remaining footprint
0.805 kg CO_2e/kg ethylene	**44%**	**56%**

- **MCDA Weights**

Environmental	Economic	Social
50%	**30%**	**20%**

- Scores were assigned on a **1-5 scale** and aggregated to a **20-100 composite score**. The MCDA is intended as an **illustrative decision-support tool**, not a direct measurement of technology performance.

THREE DECARBONISATION ROUTES

ELECTRIFICATION: Electric heating replaces fuel-fired furnace heat.

Crude oil / gas extraction → Refining to naphtha feedstock → ELECTRIFIED steam cracker furnace → Quench, compression, separation → Product fractionation → ETHYLENE (plus co products: propylene, butadiene, BTX, H_2)

- Uses resistive, RotoDynamic or plasma heating.
- Avoids direct furnace combustion.
- Performance depends strongly on electricity-grid carbon intensity [4–6].

FURNACE CCS : CO_2 is captured from dilute furnace flue gas.

1. Main process

Crude oil / gas extraction → Refining to naphtha → Steam cracker furnace → Separation, fractionation → Ethylene

2. CCS process

Furnace flue gas → CO_2 capture → CO_2 compression → Transport (pipeline, ship) → Geological storage

- Furnace CCS: amine capture on the dilute flue gas.
- Strong near-term emissions reduction.
- Requires CO_2 transport and storage infrastructure.
- Storage: permanence and acceptance risk.
- Capture energy penalty and public acceptance are key issues [3,7,10].

SMR H_2 + CCS: Hydrogen produced by steam methane reforming is used as furnace fuel.

1. Main process

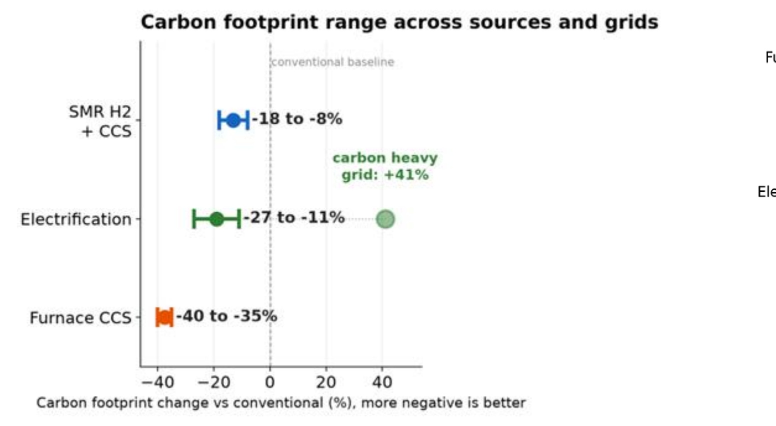
Crude oil / gas extraction → Refining to naphtha → Steam cracker furnace → Separation, fractionation → Ethylene

2. Hydrogen + CCS process

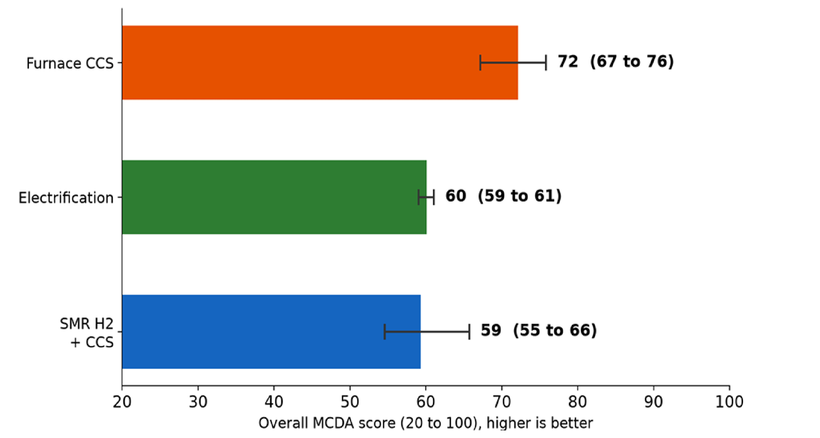
SMR H_2 + CCS → Capture the concentrated reformer CO_2 stream → CO_2 compression → Transport (pipeline, ship) → Geological storage

- Hydrogen is produced by steam methane reforming and used as furnace fuel.
- SMR H_2 + CCS: capture the concentrated reformer CO_2 stream.
- Lowest reported levelised-cost increase.
- Requires hydrogen-production and CO_2 transport and storage infrastructure.
- Storage: permanence and acceptance risk.
- Evidence is less directly comparable with the European naphtha-cracker case [7,8,11].

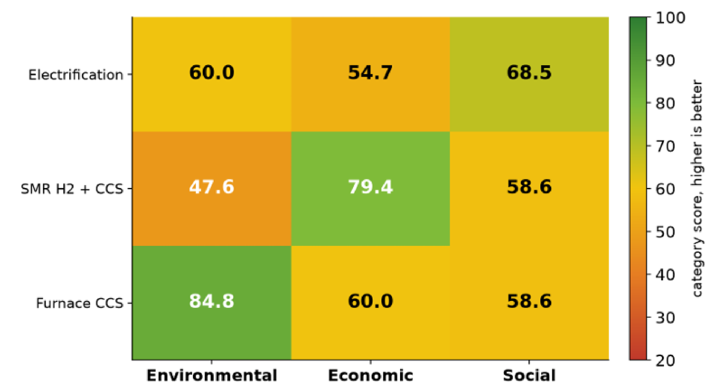
RESULTS



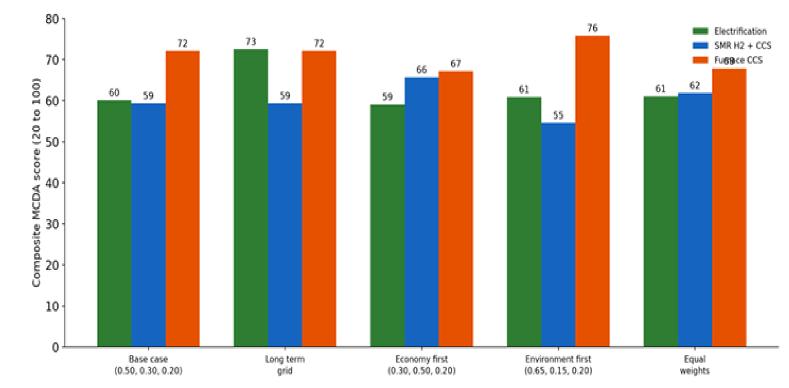
Graph 1: Cradle-to-gate carbon footprint change by route, each against its source's own baseline and so not directly comparable (2.5). Points are midpoints, bars min to max; the faded marker is electrification on a carbon-heavy grid.



Graph 2: Weighted MCDA score by route, on the 20 to 100 scale. Bars are the base case; whiskers are the range across the weighting scenarios (not a statistical uncertainty).



Graph 3: Category score by route on the 20 to 100 scale.



Graph 4: Composite score by route under the base case and the weighting and grid scenarios.

Route	Reported GHG reduction
Furnace CCS	Approximately 35–40%
Electrification	Approximately 11–27% under lower-carbon electricity
Electrification - carbon-heavy grid	Approximately +41% footprint increase
SMR H_2 + CCS	Approximately 8–18%

Table 1. Reported greenhouse gas emissions reductions across the three decarbonisation routes under the relevant electricity-grid scenarios.

Route	Cost increase
Furnace CCS	+6 to +7%
Electrification	+18 to +35%
SMR H_2 + CCS	+3.4%

Table 2. Reported increase in levelised ethylene production cost relative to conventional production for each decarbonisation route.

Route	Cost range
Furnace CCS	70–80 USD/tCO_2 captured
Electrification	≤100 USD/tCO_2 avoided
SMR H_2 + CCS	15–50 USD/tCO_2 captured

Table 4. Reported cost per tonne of CO_2 captured or avoided for each decarbonisation route.

Indicator	Furnace CCS	Electrification	SMR H_2 + CCS
Job creation	**Retains plant jobs**	**−48% to +26% power-system proxy**	**Retains plant jobs**
Human-rights risk	Fossil supply chain	Critical minerals	Fossil supply chain
Public acceptance	Opposition centres on CO_2 storage	Avoids storage step	Opposition centres on CO_2 storage

Table 4. Social indicators used to compare job creation, human-rights risks and public acceptance across the three decarbonisation routes.

DISCUSSION

- **Furnace CCS** achieved the highest base-case score due to its strong GHG reduction and moderate cost increase.
- **Electrification** avoids direct fossil-fuel combustion and CO_2 storage, but its performance depends strongly on electricity carbon intensity.
- **SMR H_2 + CCS** showed the best economic performance but remained dependent on fossil-based hydrogen and effective CO_2 capture.
- Scenario analysis showed that route ranking changes when economic or environmental priorities are given greater weight.
- Furnace CCS is most favourable under the base-case assumptions, while electrification may become more attractive as the electricity grid decarbonises.
- Findings are indicative because the underlying studies use different baselines, process configurations and evidence quality.

LIMITATIONS

- Uneven evidence quality and comparability
- Different feedstocks, regions and system boundaries
- Social and economic proxy data
- Different SMR and electrification configurations

CONCLUSION

Furnace CCS appears to be the most favourable decarbonisation route under the base-case assumptions, achieving the highest overall MCDA score and substantial GHG reductions with a moderate cost increase. Electrification provides a promising long-term option as electricity grids become cleaner, although its performance is highly dependent on electricity carbon intensity. SMR H_2 + CCS offers economic advantages but remains reliant on fossil-based hydrogen production and effective CO_2 capture. Overall, the preferred route depends on the balance between environmental benefits, economic feasibility, infrastructure availability and social acceptance.

Contact Email: dne2@ic.ac.uk

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