E-biofuels reduce the cost of achieving emissions targets in hard-to-electrify sectors

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Motivation

Reaching net-zero emissions requires climate-neutral fuels for hard-to-electrify sectors such as aviation and shipping. ReFuelEU Aviation requires 70% sustainable aviation fuel by 2050, half of it synthetic. Each established option has limits: biofuels keep only about 30% of the biogenic carbon in the fuel, e-fuels need costly CO_2 capture and hydrogen, and continued fossil use must be offset by scarce geological carbon storage. **E-biofuels add renewable hydrogen directly to biofuel production to turn the excess biogenic carbon into fuel**, yet their role in a net-zero European energy system and their place in EU fuel regulation remain unclear.

Method

- Sector-coupled European energy system model **PyPSA-Eur**: 39 nodes, 3-hourly resolution, 2040 technology costs, net-zero emissions target by 2050.
- E-biofuel routes: e-biomass-to-liquid, e-biomethanol, e-bioSNG and e-biogas-to-methanol.
- Scenarios: CO_2 sequestration capacity of 140–1000 Mt/a × with / without e-biofuels × with / without ReFuelEU fuel mandates.
- **Why focus on carbon sequestration?** Geological CO_2 storage decides how much fossil fuel can remain in a net-zero system, offset by carbon removal, and therefore how valuable biogenic carbon is. Its scale-up is highly uncertain: the EU targets 250 Mt/a by 2040, but the accessible capacity is unclear.

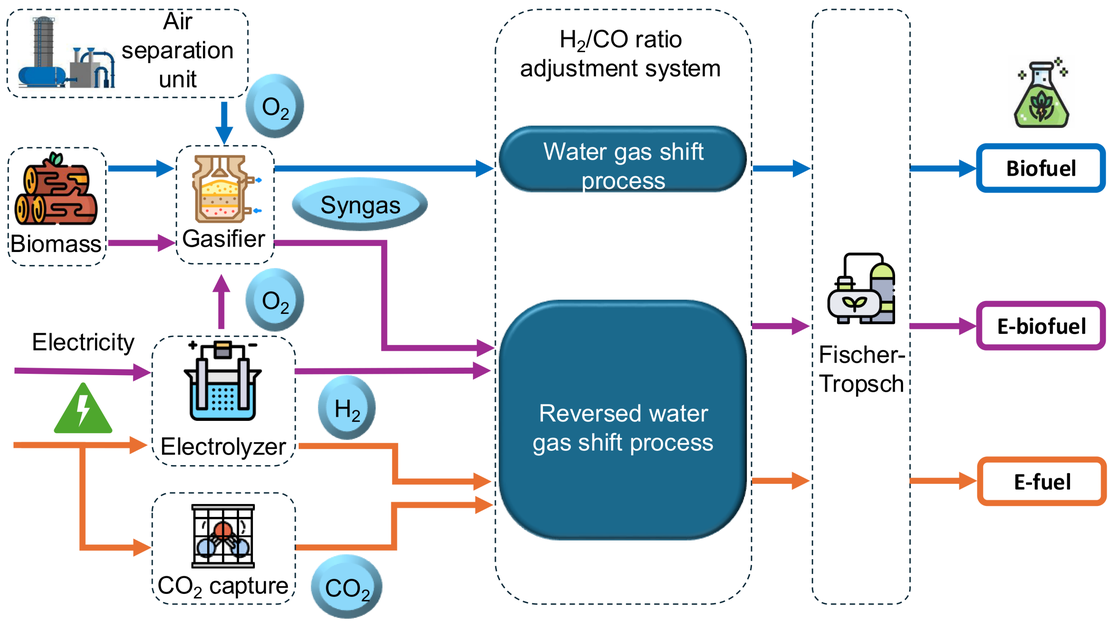

Figure 1. **Three renewable liquid-fuel pathways:** biofuels, e-biofuels (biomass + H_2) and e-fuels (H_2 + captured CO_2).

Key findings

- E-biofuels become cost-effective **the more fossil fuels are phased out**. With CO_2 sequestration of 300 Mt/a or less, they dominate liquid-fuel supply.
- They reduce total system cost by up to **2.7%** (23 B€/a) and liquid fuel system cost by **11%**.
- Including them decreases fuel conversion capital by **27%** and carbon capture capacity by **28%**, and lower the CO_2 price by up to **16%**.
- **Mechanism:** adding H_2 directly to biogenic carbon is cheaper than capturing, transporting and synthesising CO_2 into e-fuels, which rank last in the merit order.
- **Policy:** under ReFuelEU mandates, e-biofuels become the main compliance option, displacing most e-fuels and keeping system cost **1.2–3.1%** lower.

Lower risk, not only lower cost. E-biofuels can be built **step by step on existing biofuel plants**: start with biofuels today and add hydrogen once green hydrogen and carbon storage availability become clearer. This incremental path **hedges against uncertainty** in biomass, hydrogen and CO_2 storage, and reduces the risk of stranded assets.

Policy implications

- EU legislation (Renewable Energy Directive, ReFuelEU) does not explicitly recognise e-biofuels and favours less efficient e-fuels.
- The hydrogen-derived share of e-biofuels should count as a renewable fuel of non-biological origin, giving a technology-neutral and more cost-effective path to the mandates.

Paper, data and code

Zhang, Y., Millinger, M., Hedenus, F., Pettersson, K., Brown, T. *E-biofuels reduce the cost of achieving emissions targets in hard-to-electrify sectors.* arXiv:2604.12080 (2026).

Model code: `https://github.com/yun-long-zhang/pypsa-eur/tree/electrobiofuel`

Results data: `https://zenodo.org/records/18985101`

Acknowledgements

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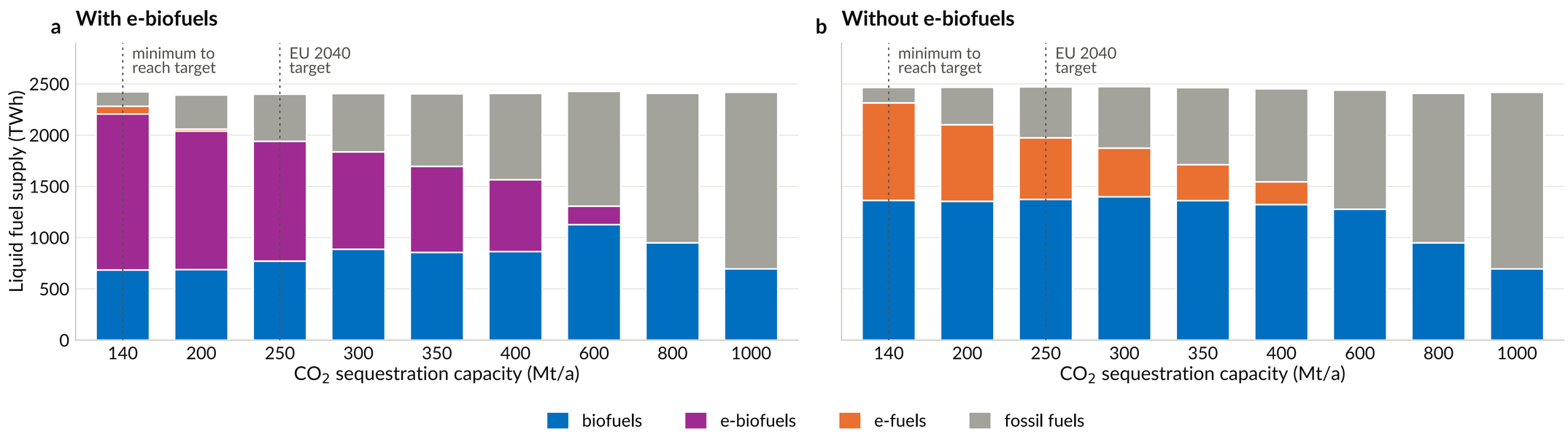

Figure 2. **E-biofuels replace e-fuels and part of the biofuels when carbon storage is scarce.** Liquid-fuel supply in Europe under different annual CO_2 sequestration potentials, (a) with and (b) without e-biofuels (no fuel mandates).

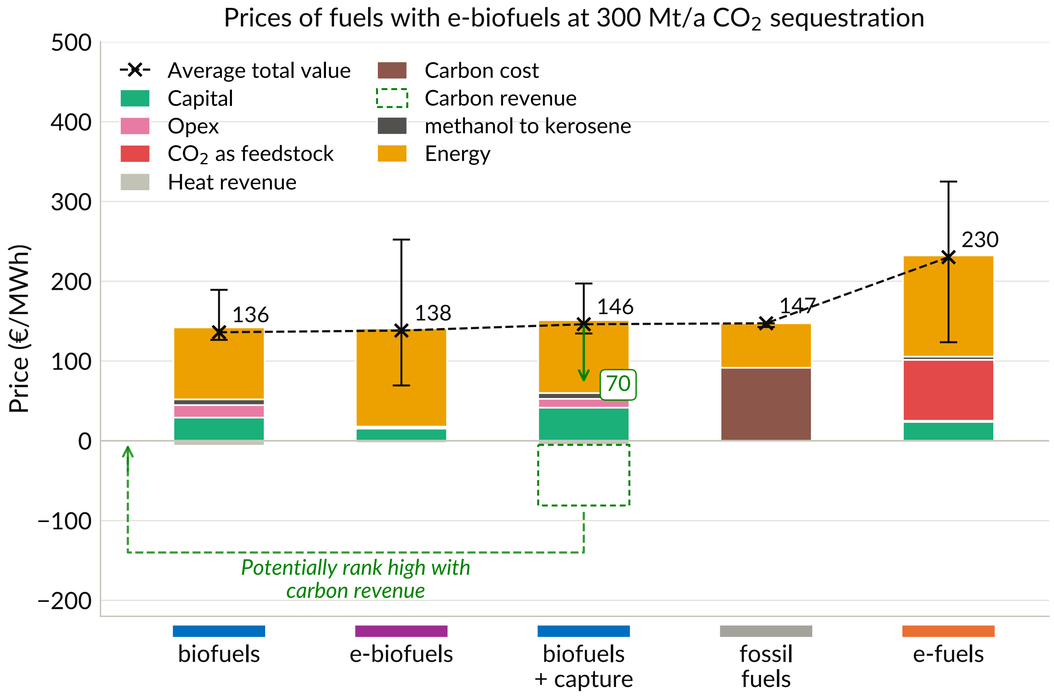

Figure 3. **Carbon system value governs the liquid-fuel merit order.** E-biofuels (138 €/MWh) are on par with biofuels and cheaper than fossil fuels and e-fuels (230 €/MWh). Error bars show the spread of energy costs across nodes and time steps.

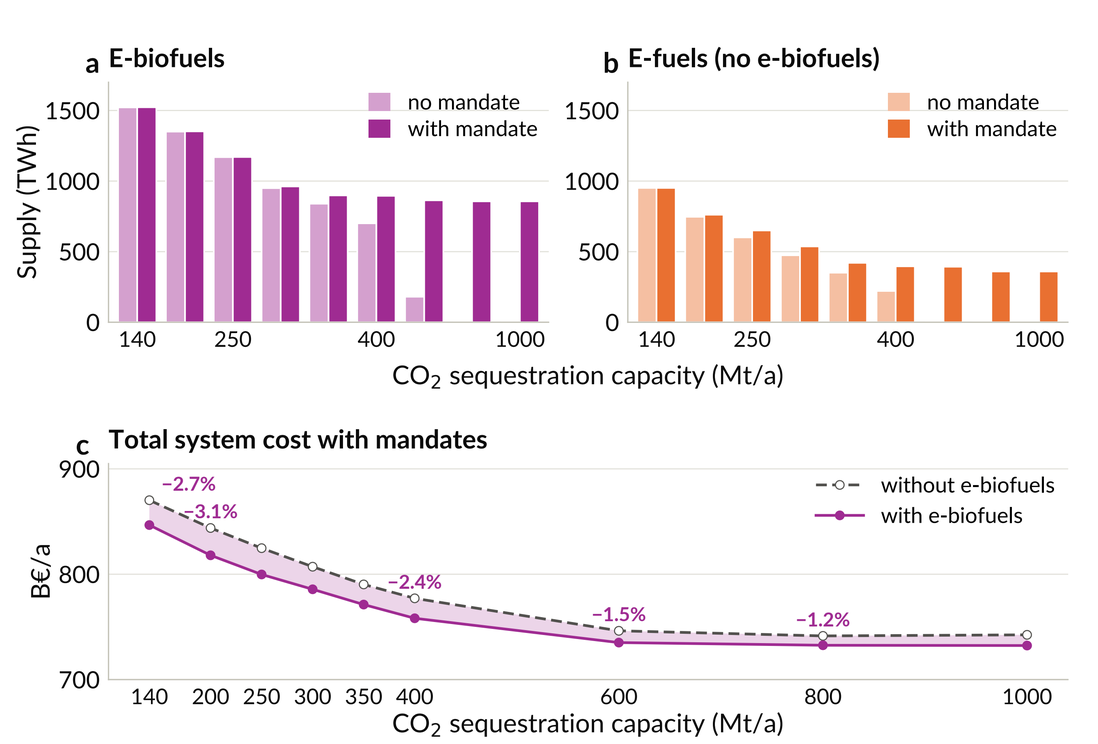

Figure 4. **Under ReFuelEU mandates, e-biofuels become the main compliance option.** (a) E-biofuel supply and (b) e-fuel supply in the system without e-biofuels, with and without fuel mandates. (c) Total system cost under mandates, with and without e-biofuels.

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