Energy Infrastructure Planning for Europe's Hydrogen, Import and Carbon Management Strategies

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Spatial mismatches in Europe’s energy transition

1 Best **wind and solar potentials** in the periphery of Europe (or even abroad).

2 **Bottlenecks** in the power network and limited acceptance for reinforcement.

3 **Hydrogen demand** for industry (steel & ammonia) in regions with low potentials.

4 Not all regions have geological conditions to allow for cheap **underground storage**.

5 **CO_2 from point sources** for synthetic fuels located in Europe’s industrial clusters.

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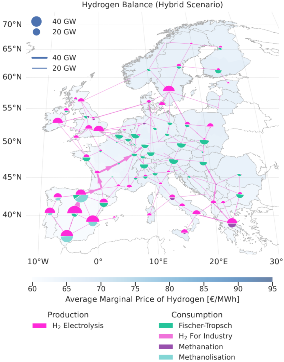
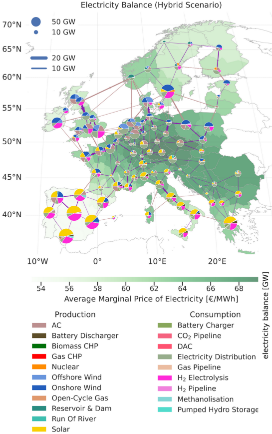
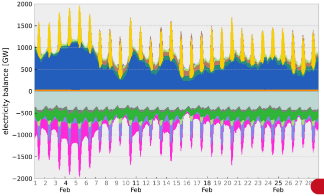
PyPSA-Eur: A sector-coupled open model of the European energy system

Automated workflow to build energy system model of Europe from raw open data:

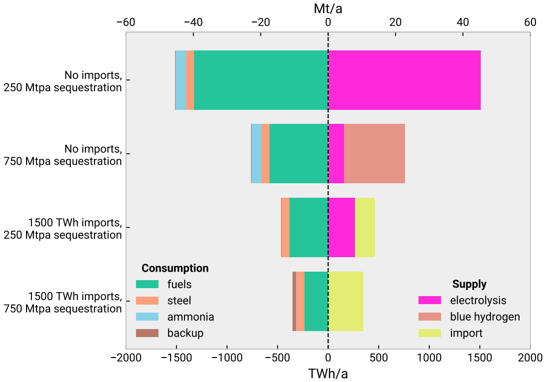
1. Energy balances
2. Power transmission and gas pipelines
3. Geographical data about power plants, industrial sites, LNG terminals
4. Geographical potentials for the expansion of wind, solar, biomass, hydrogen and CO2 storage
5. Time series for energy demand (electricity, heat, transport, industry)
6. Time series for wind and solar production, hydro-power, heat pumps, etc.
7. Techno-economic assumptions







Context: Role of synthetic fuels depends on Europe's import and carbon management strategies

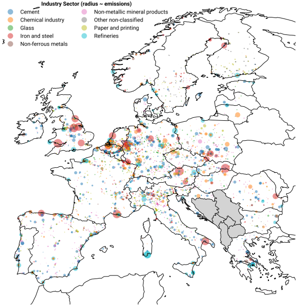


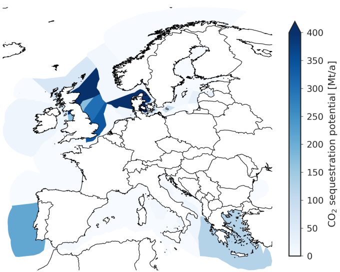
- Most hydrogen used for chemical feedstocks, aviation and shipping fuels.
- With no imports and strict sequestration limits (250 Mt/a), large volumes of **hydrogen-based** e-fuel synthesis.
- With higher **sequestration** limits: substituted by fossil fuels offset by CO_2 removal.
- **Imports** of hydrogen and its derivatives reduce need for domestic hydrogen production.

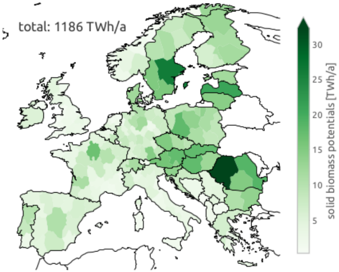
Reference: Own runs from PyPSA-Eur, see `https://pypsa-eur.readthedocs.io`

Ingredient 1: Carbon Dioxide

- **CC** for fossil & biogenic process emissions (e.g. cement) + DAC
- **CU** for e-(bio-)fuels and e-chemicals (in particular, shipping, aviation, plastics)
- **CDR** for unabatable and negative emissions (to offset imperfect capture rates)
- **CT** by pipeline from point sources to CU or CS sites



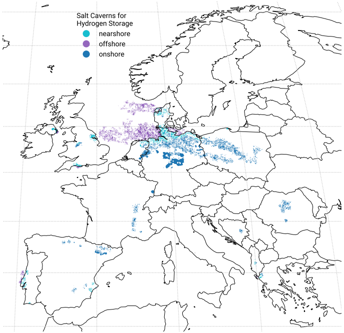


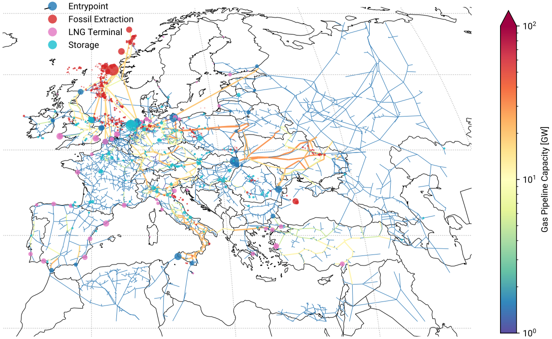


Reference: Hotmaps, ENSPRESO, CO2StoP

Ingredient 2: Hydrogen

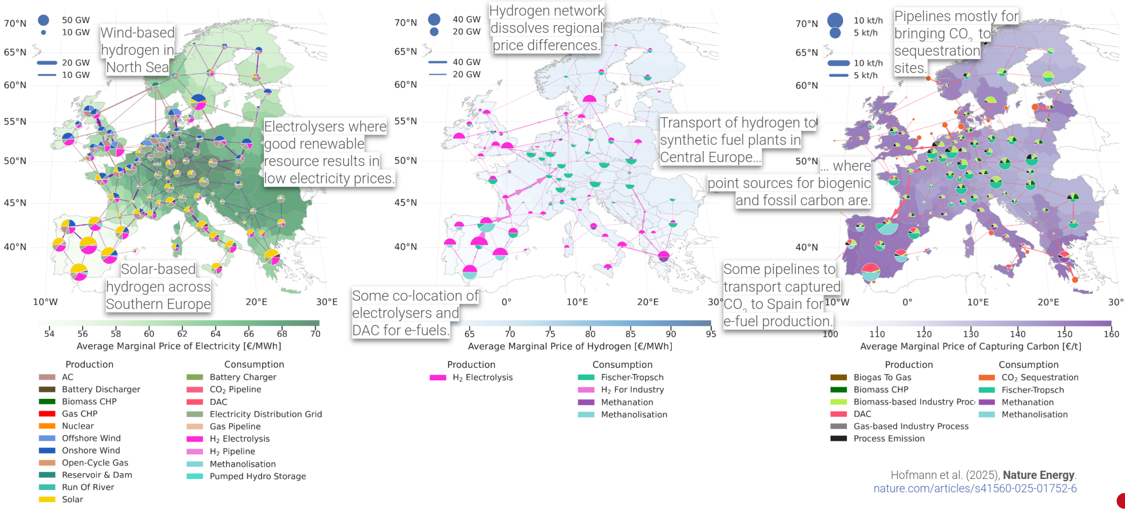
- **storage** in steel tanks or underground salt caverns
- **transport** in new or repurposed pipelines
- **supply** from electrolysis or steam methane reforming (with or without CC)





Reference: SciGRID_gas, `https://www.gas.scigrid.de/`, Pluta et al. (2022), Caglayan et al. (2020)

Transport CO_2 to H_2 or H_2 to CO_2 for fuel synthesis?



Wind-based hydrogen in North Sea

Electrolysers where good renewable resource results in low electricity prices.

Solar-based hydrogen across Southern Europe

Hydrogen network dissolves regional price differences.

Transport of hydrogen to synthetic fuel plants in Central Europe...

Some co-location of electrolysers and DAC for e-fuels.

Pipelines mostly for bringing CO_2 to sequestration sites.

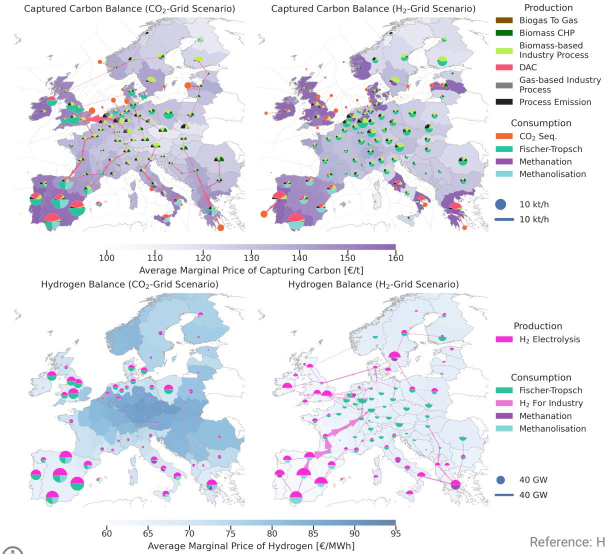
... where point sources for biogenic and fossil carbon are.

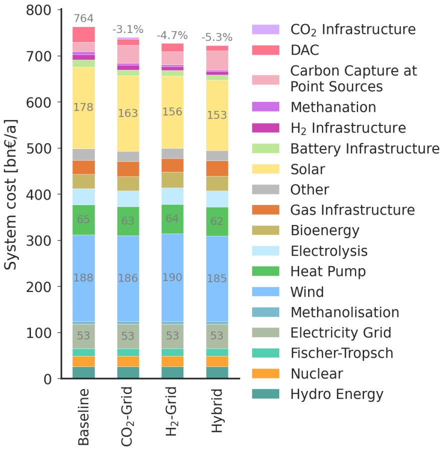
Some pipelines transport captured CO_2 to Spain for e-fuel production.

Hofmann et al. (2025), **Nature Energy**.
nature.com/articles/s41560-025-01752-6

Reference: Hofmann, Tries, Neumann, Zeyen, Brown (2025), **Nature Energy**, `https://www.nature.com/articles/s41560-025-01752-6`

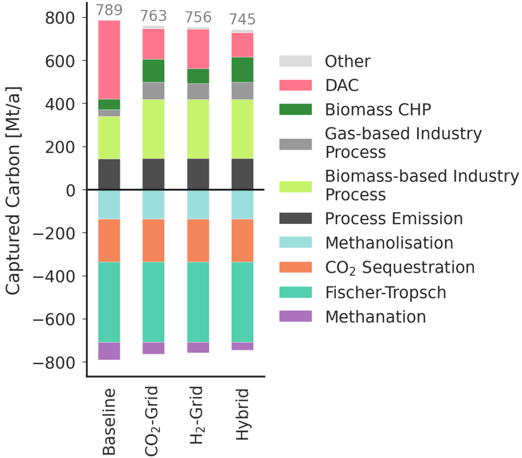
Alternative scenarios with either only CO_2 or H_2 pipelines





Reference: Hofmann, Tries, Neumann, Zeyen, Brown (2025), **Nature Energy**, https://www.nature.com/articles/s41560-025-01752-6

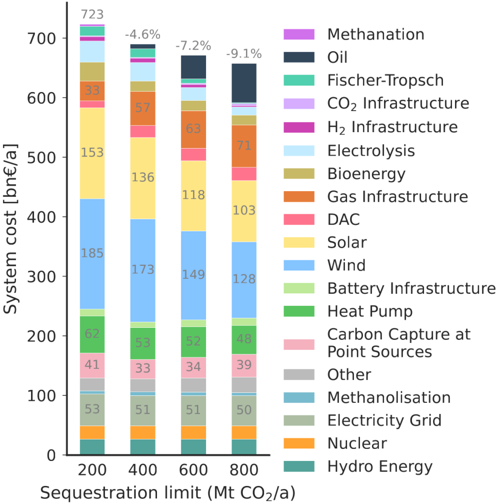
Carbon balances between capture, use, transport and sequestration



- A quarter **CCS** – three quarters **CCU**.
- A quarter **fossil** & **DAC** each – half **biogenic**.
- Carbon capture follows a **merit order**: fossil process emissions first, then high full load biogenic emissions, DAC as **backstop**.
- Network infrastructures for CO_2 and H_2 mainly help with **unlocking regional biogenic carbon** potentials for e(-bio)-fuels.

Reference: Hofmann, Tries, Neumann, Zeyen, Brown (2025), **Nature Energy**, `https://www.nature.com/articles/s41560-025-01752-6`

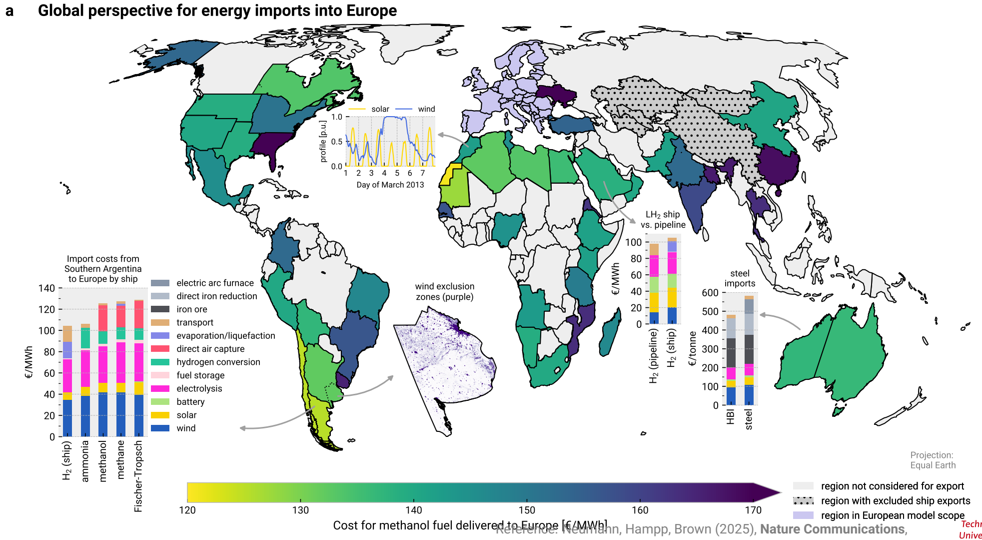
High CCU volumes depend on strictness of CCS limits.



- Results shown allow sequestration of **200 $MtCO_2/a$** for net-zero emission systems.
- European Carbon Management Strategy suggests **250 $MtCO_2/a$**.
- Without exogenous limits, the model would use **$\geq$1000 $MtCO_2/a$** for CCS → biomass / fossil fuels + CDR

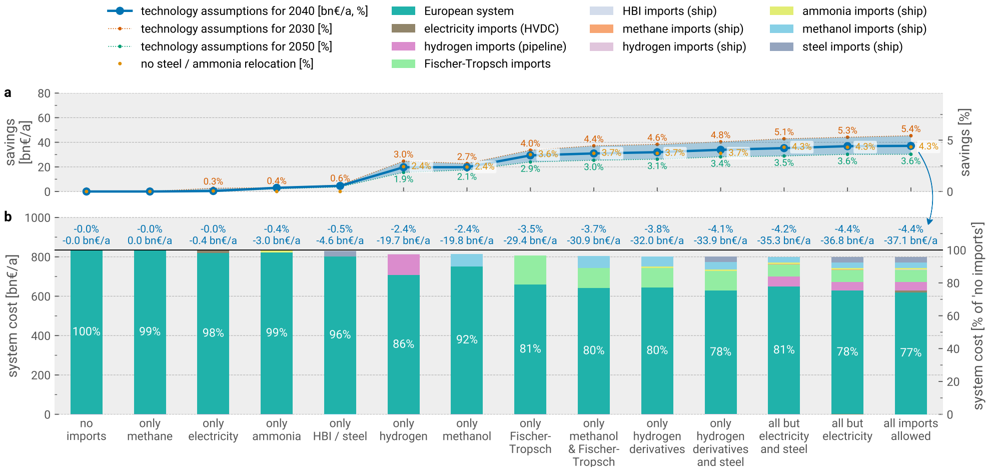
Reference: Hofmann, Tries, Neumann, Zeyen, Brown (2025), **Nature Energy**, `https://www.nature.com/articles/s41560-025-01752-6`

How do green energy imports fit into all this?



Reference: Neumann, Hampp, Brown (2025), **Nature Communications**, https://www.nature.com/articles/s41467-025-60652-1

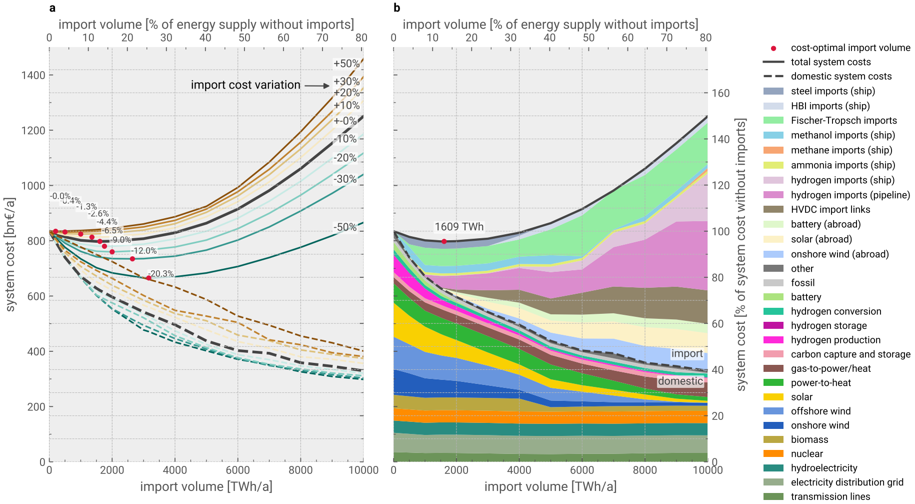
Cost savings depend on used import vectors.



→ In particular, import of carbonaceous H_2-derivatives and steel/HBI reduces costs.

Reference: Neumann, Hampp, Brown (2025), **Nature Communications**, `https://www.nature.com/articles/s41467-025-60652-1`

Diminishing return with increasing import volumes.



Reference: Neumann, Hampp, Brown (2025), **Nature Communications**,
https://www.nature.com/articles/s41467-025-60652-1

Take-Away Messages

1 **H_2 versus CO_2 pipelines:** Comparable in terms of system costs, with slight preference for hydrogen transport. Without both, 5% higher system costs than without both.

2 These networks mainly allow better spatial integration of **point-source carbon** with **cheapest hydrogen sites** for CCU: important with low biomass availability, sequestration and import levels.

3 **Energy imports:** Benefits most clear for imports of 1000-3000 TWh/a, especially for steel / HBI and liquid carbonaceous carriers, but with diminishing returns, centering around system cost savings of 4%.

4 Infrastructure policy needs **coordination** between the various national and European hydrogen, import, biomass, backup power and carbon management strategies.