RESILIENT – Resilient Energy System Infrastructure Layouts for Industry, E-Fuels and Network Transitions

https://resilient-project.github.io/

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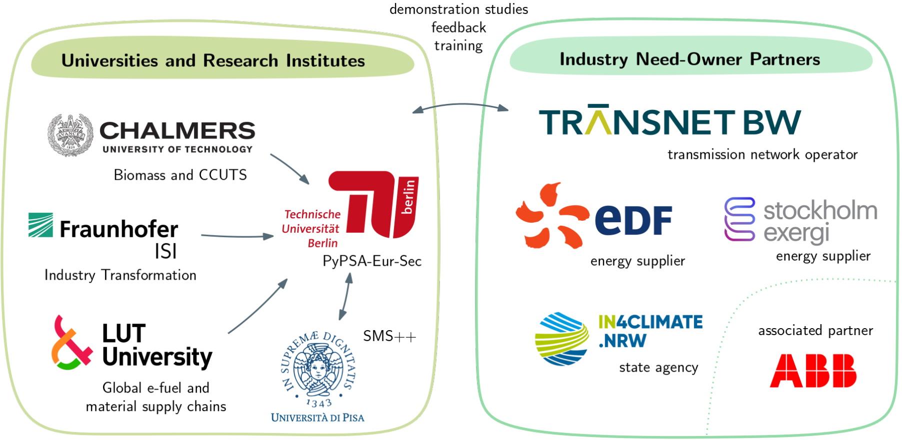
Collegial exchange with dena — 06 November 2025

Supported by: Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag

RESILIENT project partners



Funded through the **CETPartnership 2022** call and by the **German Federal Ministry for Economic Affairs and Energy (BMWE)** for the German project partners.

Source: https://resilient-project.github.io/

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Working packages

WP1 – TUB
Project Leadership

WP2
Methods for Resilient Planning under Strategic Uncertainties

- Development of stochastic optimisation framework SMS++
- Development of multi-vector energy system model PyPSA-Eur-Sec

WP3
Datasets and Model Improvements on Industry, Biomass and E-Fuels

- Industry Transition Paths: Fuel and Process Switching
- Carbon Management and the Role of Biomass
- Global Green Fuel and Material Markets

WP4
Case Studies and Model Demonstrations for Need-Owners

- France's future energy system in the European network
- Grid planning and industry transition in Western Germany
- Carbon and e-fuel strategies for Sweden and Finland

WP5
Outreach, Communication and Dissemination

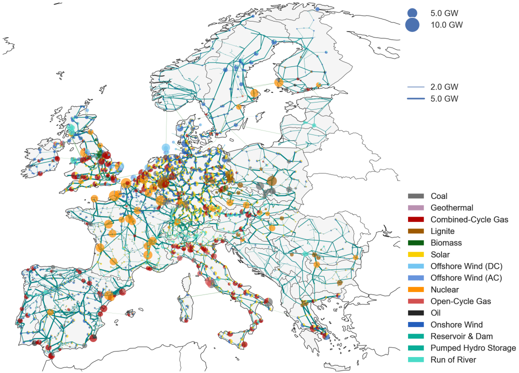
- engagement with more need-owners
- training events and documentation

WP6
Reporting & Knowledge Community Standard WP

Source: https://resilient-project.github.io/

PyPSA-Eur: A sector-coupled energy system model for Europe

- Spatially and temporally highly resolved linear optimisation model covering the **European continent**,
- Based on the open-source framework **PyPSA**,
- Includes **existing power plant fleet**, **renewable potentials**, and **availability time series**,
- Includes the **electrical transmission grid** from 220 kV to 750 kV (AC, including Ukraine) and from 150 kV (DC), with the option to enable planned grid expansion projects (TYNDP and German NEP), as well as the gas network,
- Maintained by the Department of Digital Transformation in Energy Systems at **TU Berlin**.



Source: https://pypsa-eur.readthedocs.io

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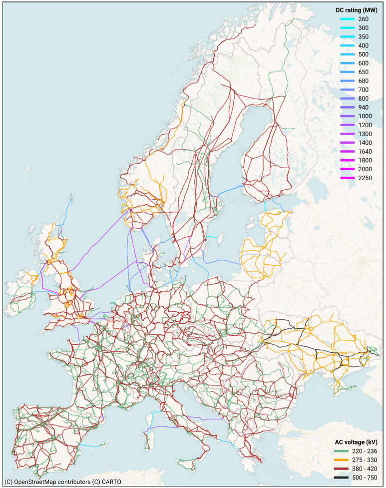
Electricity high-voltage grid based on OpenStreetMap (OSM)

- Dataset contains a topologically connected representation of the European high-voltage grid (220 kV to 750 kV) constructed using OpenStreetMap data
- Heuristic cleaning process was used to for lines and links where electrical parameters are incomplete, missing, or ambiguous
- Close substations within a radius of 500 m are aggregated to single buses
- Unique transformers are added for each voltage pair in a substation
- AC lines mapped using pandapower's standard line type library. In default version, nominal capacity is set to 70 % of the technical capacity to account for n-1 security approximation
- Includes all 38 European HVDC connections with their nominal rating that are commissioned as of 2024



Source: Xiong, Fioriti, Neumann, Riepin, Brown (2025): https://www.nature.com/articles/s41597-025-04550-7

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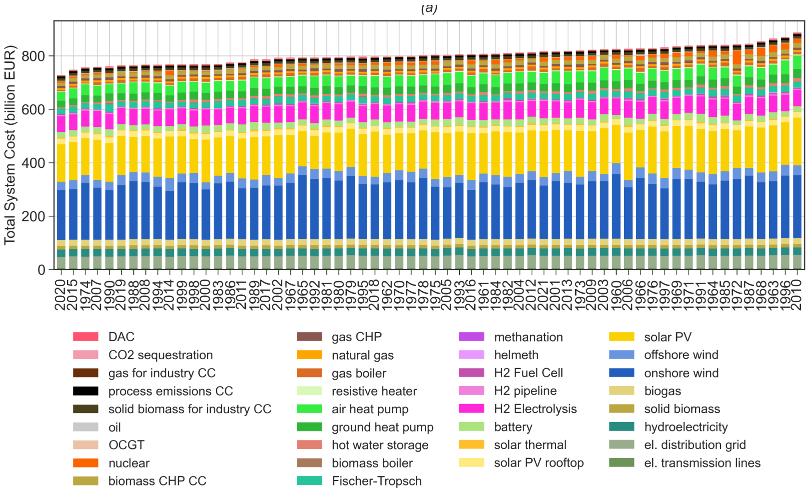
System cost variations for different underlying **weather years**



Source: Gøtske, Andresen, Neumann, Victoria, 2024; https://www.nature.com/articles/s41467-024-54853-3

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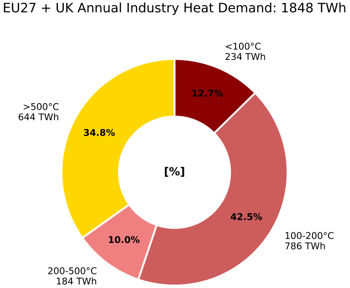
Extending PyPSA-Eur: Representing industrial heating by temperature band

- PyPSA-Eur represents **industrial decarbonisation** by allowing a shift to alternative, low-carbon production pathways.
- In its current form, the model does not track the **end-use of inputs**; in particular, it does not distinguish between heat use and feedstock use.
- The ongoing work introduces this distinction by tracking feedstock and temperature-specific heat uses, enabling the model to **endogenously** simulate cost-optimal decarbonisation pathways.



Motivation: PCI-PMI projects

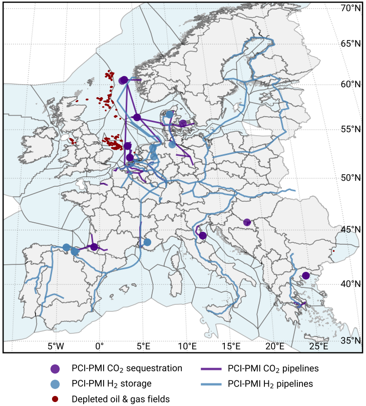
What are PCI-PMI projects?

- Projects of Common Interest (PCIs) are key **cross-border infrastructure projects** that link the energy systems of EU countries
- Projects of Mutual Interest (PMIs) include cooperations with countries outside the EU
- Intend "to help the EU achieve its **energy policy and climate objectives**: affordable, secure and sustainable energy for all citizens and the long-term decarbonisation of the economy in accordance with the **Paris Agreement**"
- "Potential overall benefits of the project must outweigh its costs"
- Given their **lighthouse character**, these projects are highly likely to be implemented.
- Large infrastructure projects (incl. PCI-PMI) are however commonly facing delays due to permitting, procurement bottlenecks, etc.

1 What is the long-term value of PCI-PMI projects in supporting the EU's climate and energy policy targets, and what are the associated costs?

2 What are the costs of adhering to the EU policy targets, even when the implementation of PCI-PMI projects is delayed?

Project map



Source: Preprint Xiong, Brown, Riepin (2025): https://doi.org/10.48550/arXiv.2507.01860

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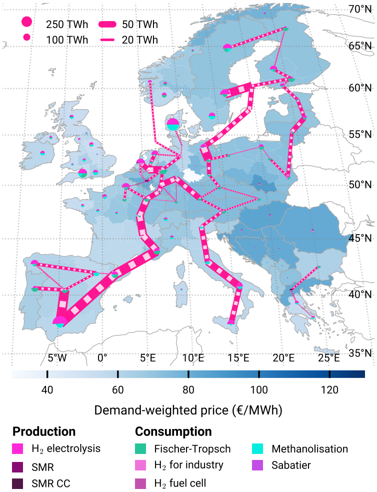
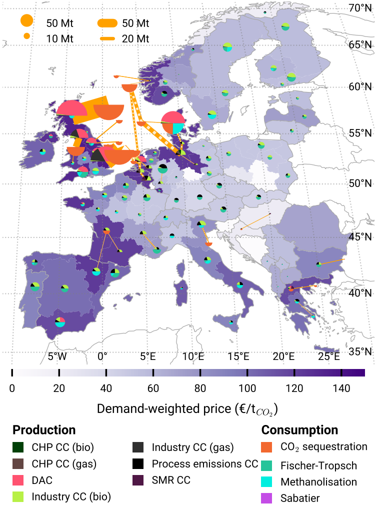
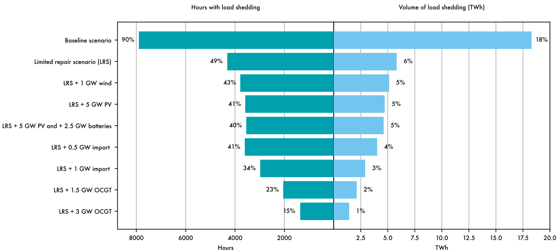
PCI-PMI H_2 and CO_2 infrastructure projects

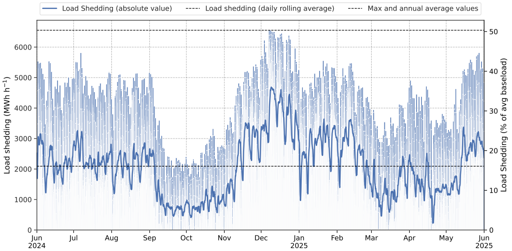


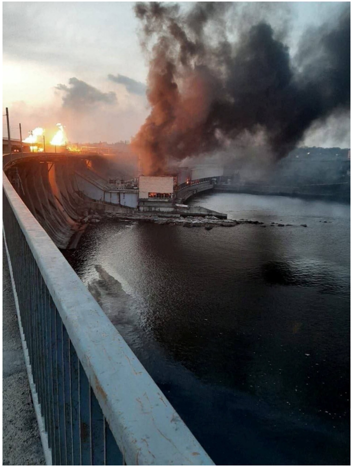


Source: Preprint Xiong, Brown, Riepin (2025):
https://doi.org/10.48550/arXiv.2507.01860

Mitigating Ukraine’s Looming Electricity Crisis







Source: Photo by Reuters (credit: Denys Shmyhal); graphs from https://ssrn.com/abstract=4930511

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Idea: Electrification plus minimal methanol economy

- **Electrify** as much as possible.
- Use hydrogen in clusters for **sectors where really needed** (ammonia, iron ore reduction).
- Use **methanol as a gap-filler** for the remaining sectors (backup power & heat, shipping, aviation, chemical industry).
- Methanol is more easily **storable and transportable** than hydrogen (liquid at RTP).
- Methanol **scales down** to MW-scale use cases without the lumpiness of large infrastructure (frictions and non-linearities not captured by models).
- (E-)biomethanol can absorb sustainable carbon from **decentralised biomass and waste sources**, and can then be used directly in industry or for dense fuels (carbon management).

Resilience: Network restoration after a blackout

- Electrified building heating and transport make **resilient system design** paramount
- Can each region black-start and run for two weeks during **system restoration** after a full blackout? During a cold wind lull?
- Are we sure gas or hydrogen networks would function during a blackout? Electronics in compressor stations are vulnerable, cf. Texas in Feb 2021 for unexpected issues.

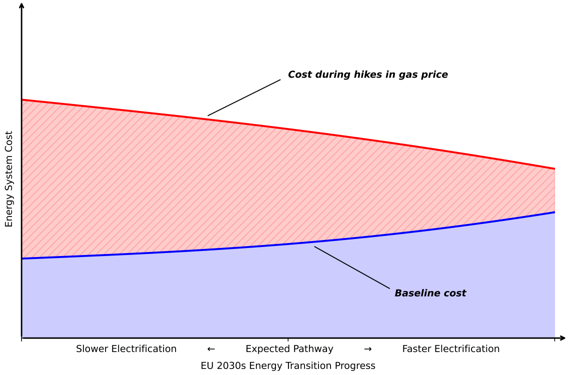
Source: https://www.netztransparenz.de/de-de/Systemdienstleistungen/Versorgungswiederaufbau

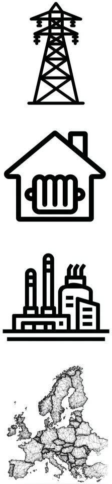
Simple, robust solution: Peaker capacity with methanol tanks

- Put turbines or motors to cover **winter peak** in each region, next to a giant **methanol tank**
- Can also run as **synchronous condenser** to provide reactive power, fault current, inertia
- Methanol tanks cost just 0.01-0.05 €/kWh
- Single 200,000 m^3 tank can store **880 GWh**
- Can be built **anywhere**, take up little space
- Can be dimensioned to provide **resilience** against low wind years, volcanos, infrastructure outages, sabotage, blackouts

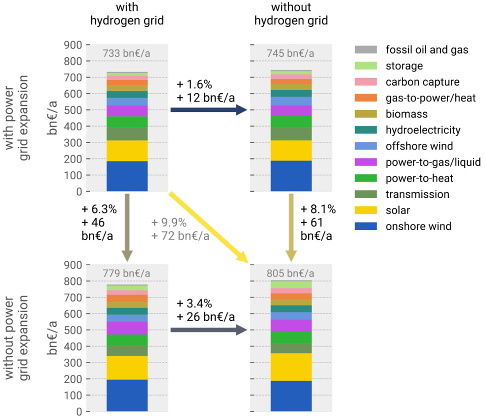
Source: https://www.netztransparenz.de/de-de/Systemdienstleistungen/Versorgungswiederaufbau

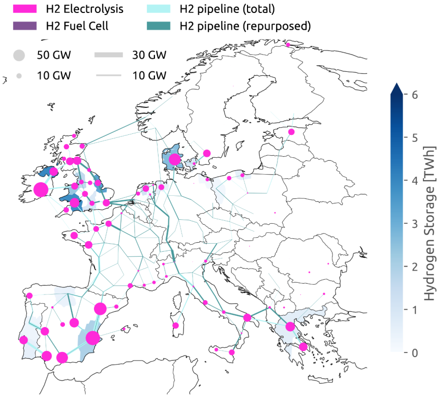
Upcoming: Resilience against gas shocks through EU electrification





Electricity vs. hydrogen network expansion





→ Hydrogen grid **reduces system costs**, but **electricity grid expansion is more attractive.**

Source: Neumann, Zeyen, Victoria, Brown:
https://doi.org/10.1016/j.joule.2023.06.016

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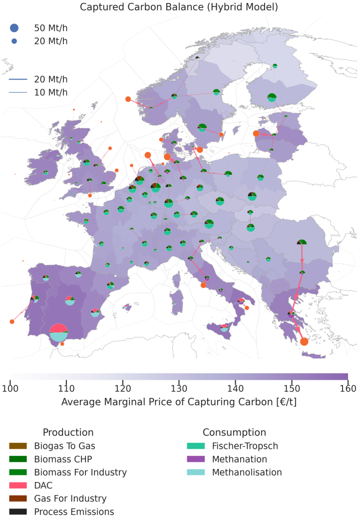
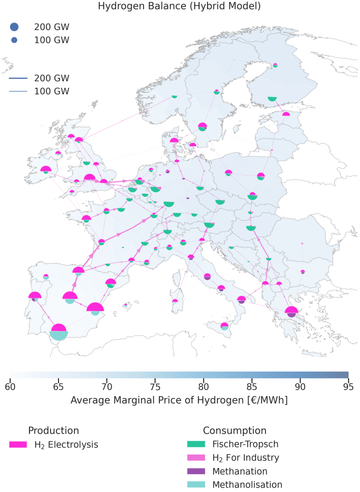
Transport H_2 to CO_2 or CO_2 to H_2 locations?

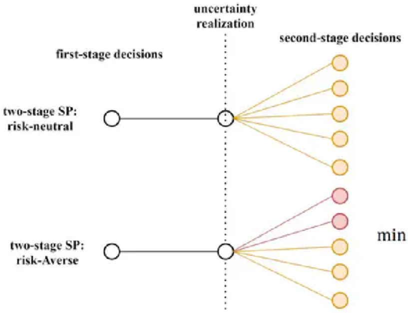




Source: Hofmann, Tries, Neumann, Zeyen, Brown (2025):
https://www.nature.com/articles/s41560-025-01752-6

PyPSA v1.0: Stochastic and risk-averse optimisation

Two-stage stochastic optimisation (first investments, then uncertainty on e.g. gas price or hydrogen volume) allows for **Conditional Value-at-Risk (CVaR)** formulation of risk aversion.



$$\min IC + \sum_{s=1}^{S} p_s \cdot OC_s$$

$$\min IC + (1-\omega) \sum_{s=1}^{S} p_s \cdot OC_s + \omega \cdot \mathrm{cvar}$$

Source: https://docs.pypsa.org/latest/user-guide/v1-guide/?h=stochastic

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About project: `https://resilient-project.github.io/`
About PyPSA ecosystem: `https://pypsa.org/`

Project overview

- **Problem description**: The world is in a phase of **uncertainty** and **transformation** (geopolitics, energy transition, climate change); scenarios with single deterministic solutions are no longer sufficient.
- **Project goal**: Development and demonstration of tools for resilient planning of the energy transition for industry, e-fuels, and networks.
- Builds on the already established, open-source, and globally used multi-vector energy system model **Python for Power System Analysis (PyPSA)**.
- **Methodological focus**: Optimisation under uncertainty (stochastic and robust), decomposition methods, and heuristics for resilience.
- **Case studies**: **Industrial transition in North Rhine-Westphalia**, grid planning in Baden-Württemberg, e-fuels in Scandinavia, and climate extreme events in France.

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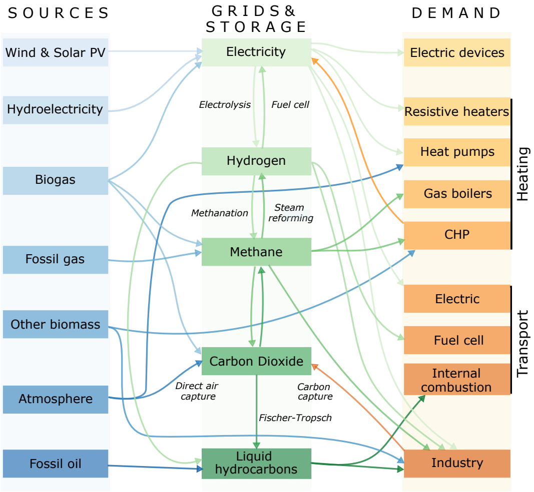
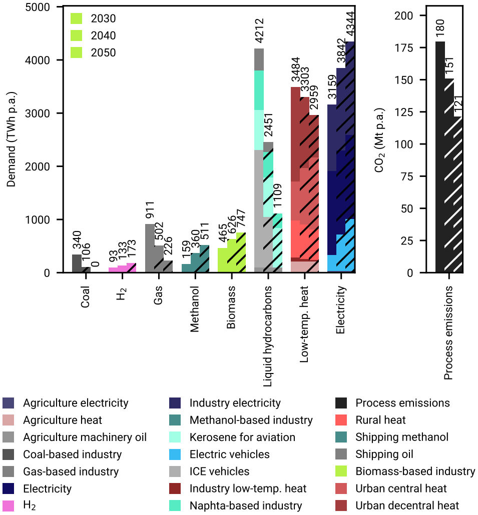
PyPSA-Eur: A typical model setup

- Including sectors **power, heat, transport, industry, feedstock** and **agriculture**
- Minimising **total system costs** (investment and operation), including generation, transmission, storage, and power-to-X
- Resolving to **100-200 regions**
- **1- to 3-hourly** resolution over **one year**
- **Net-zero emission pathway** by 2050
- Built-in **scenario manager** to handle multiple scenarios and/or **stochastic optimisation**



Source: https://pypsa-eur.readthedocs.io

Exogenous demand per sector



- Demand for electricity, heat, gas, biomass, and transport is regionally and temporally resolved
- ICE vehicles in land transport expected to fully phase out in favour of EV by 2050
- Demand for methanol and hydrocarbons, including kerosene primarily driven by shipping, aviation, and industry sector (not spatially resolved)
- Unabatable process emissions from industry sector, e.g. cement, also considered
- CO_2 sequestration cost assumed at €15/tCO_2 (mid-range estimate)

Source: Preprint Xiong, Brown, Riepin (2025): https://doi.org/10.48550/arXiv.2507.01860

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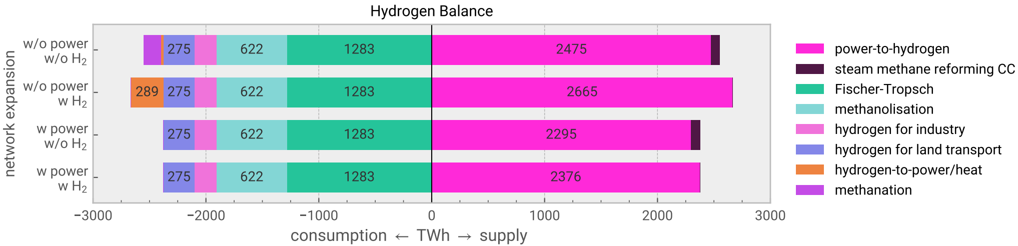
Why H_2? Most H_2 is used for derivative fuels and chemicals



Mostly **green electrolytic hydrogen supply**. **Few direct uses of hydrogen** in the energy system, but it is used to synthesise other fuels and chemicals:

- ammonia for fertilizers
- direct reduced iron for steelmaking
- shipping and aviation fuels
- precursor to high-value chemicals
- backup heat and power supply
- some heavy duty land transport

Source: Neumann, Zeyen, Victoria, Brown (2023): https://doi.org/10.1016/j.joule.2023.06.016

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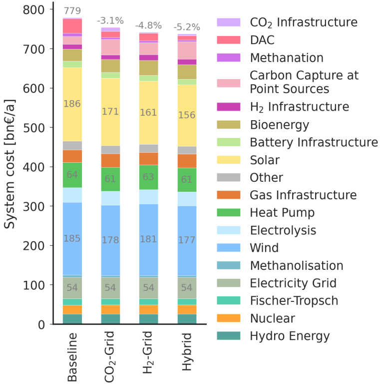
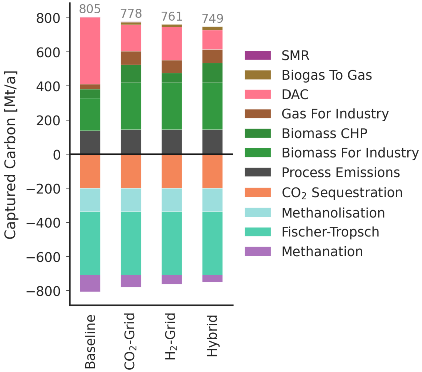
Carbon management: Capture, use, transport and sequestration





- **CCS** for process emissions (for instance, in cement industry)
- **CCU** for e-synfuels and e-chemicals (in particular, shipping, aviation, plastics)
- **CDR** for unabatable and negative emissions (to offset imperfect capture rates)

Source: Hofmann, Tries, Neumann, Zeyen, Brown (2024):
https://www.nature.com/articles/s41560-025-01752-6

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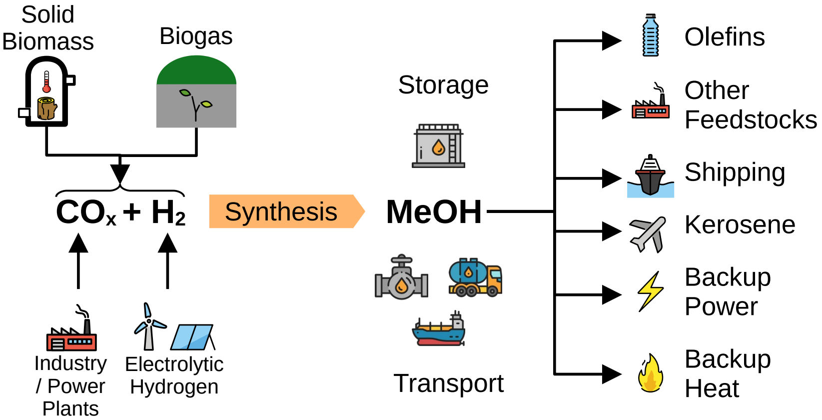
Methanol as platform for had-to-electrify



Source: Preprint Glaum, Neumann, Millinger, Brown (2025): https://doi.org/10.48550/arXiv.2505.09277