Methanol for hard-to-electrify sectors: example of ultra-long-duration energy storage

Tom Brown (TU Berlin), Johannes Hampp (IEA, ex-PIK)
t.brown@tu-berlin.de, Department of Digital Transformation in Energy Systems, TU Berlin

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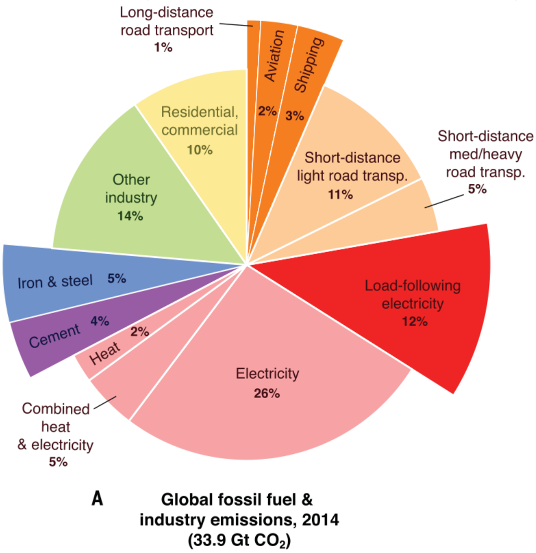
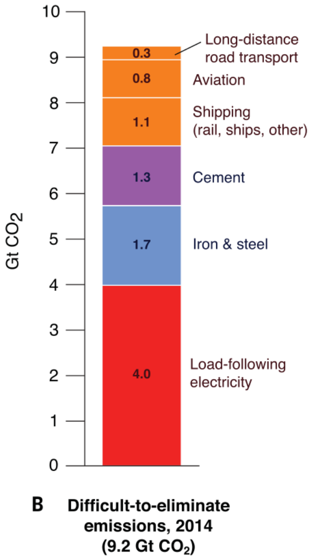
Arguments for a Minimal Methanol Economy

Hydrogen: a solution for sectors that can't be electrified?





Source: Davis et al, 2018

But which hydrogen demand sectors really need actual hydrogen?

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All potential hydrogen demand sectors can **be served by hydrogen derivatives** (e-fuels like ammonia, methanol, etc.) that are easier to transport and store.

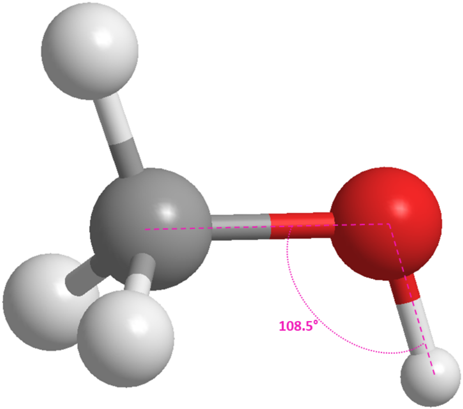
sector	alternatives if hydrogen not available
heavy duty trucks	electrify
iron direct reduction	do reduction close to ore / in cluster
ammonia	synthesise close to hydrogen source
high value chemicals	methanol or naphtha
process heat	electrify/use e-fuels
shipping	methanol or ammonia
aviation	kerosene from methanol or Fischer-Tropsch
backup power & district heat	use derivative fuels (methane, methanol)

$\Rightarrow$ There is **no strict need** for hydrogen outside of industry clusters.

Introducing methanol

Methanol, the simplest alcohol CH_3OH, can fit the bill for many of these sectors.

Advantages: liquid, easy to store/transport, widely traded, burns cleanly. Don't drink it!



Source: Wikipedia; Yves Meur

Idea: ‘Electrification plus minimal methanol economy’

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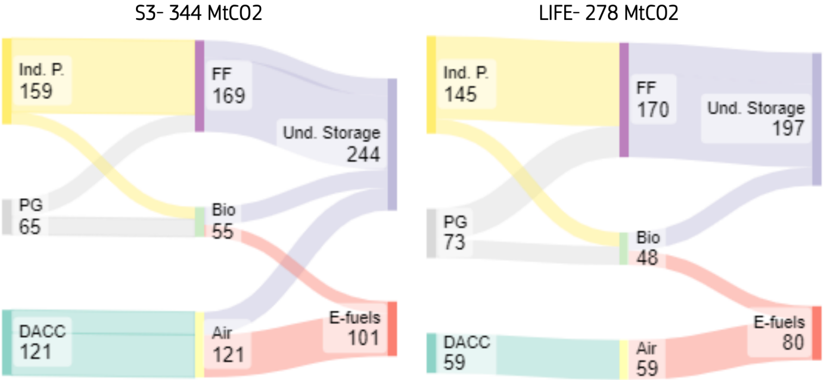
- **Electrify** as much as possible
- Use hydrogen in cluster for **sectors where really needed** (ammonia, iron ore reduction)
- Where it is difficult or slow to scale up hydrogen (e.g. delays in building pipeline network, technical problems with pipelines or turbines), consider **methanol instead**
- Methanol is more easily **storeable and transportable** than hydrogen (liquid at RTP)
- Methanol **scales down** to MW-scale without lumpiness of big infrastructure (frictions and non-linearities not seen by models)
- (E-)biomethanol can absorb sustainable carbon from **decentral biomass and wastes**, then be used directly in industry or dense fuels (carbon management)
- **Cycle carbon** whereever possible (e.g. in power sector, industry and shipping)

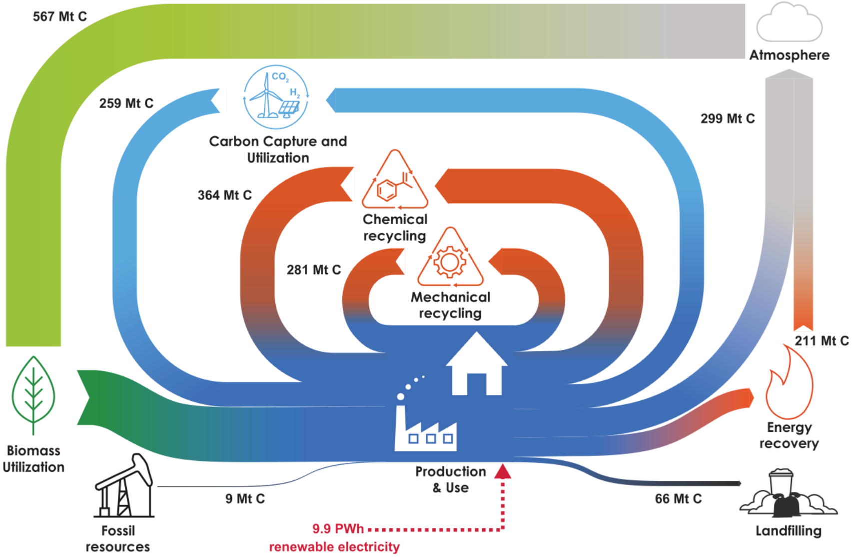
What we definitely need: carbon management



Note: "Ind. P." stands for Industrial processes and include fossil carbon from industrial processes as well as carbon of biogenic origin coming from the upgrade of biogas to biomethane. "FF" stands for "fossil fuels". "PG" stands for "power generation". "Bio" refers to CO2 produced by the combustion of biomass in power generation and produced during the upgrade of biogas into biomethane. "DACC" stands for "Direct Air Capture of CO2", for underground storage (DACCS) or use in efuels.

Source: European Commission 2040 target impact assessment, 2024

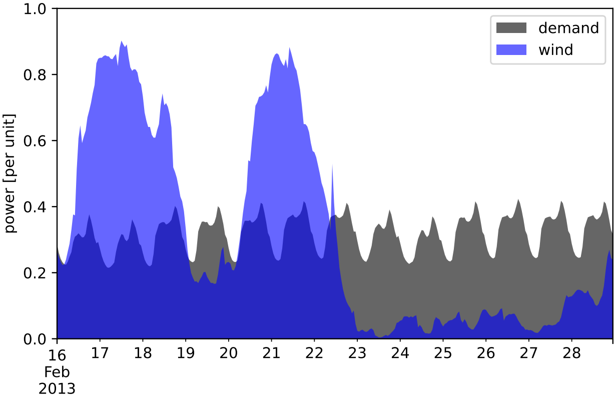
What we definitely need: carbon management



Source: Meys et al, 2021

Backup Power and Heat from Methanol with Carbon Cycling

With only wind and solar, need long-duration storage



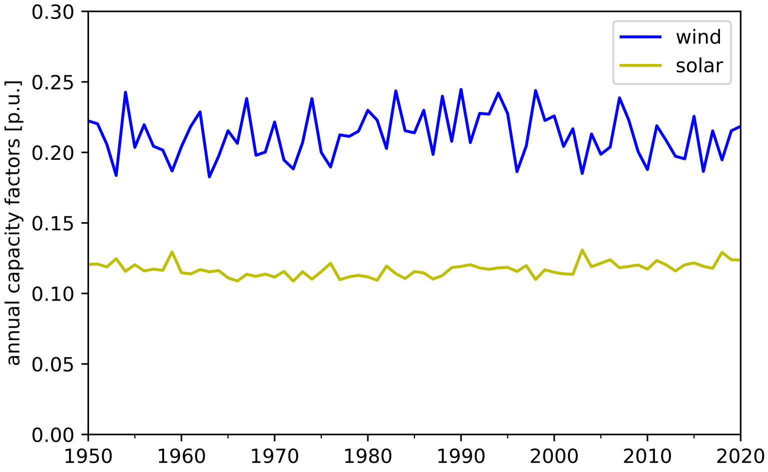
- Variability of wind and solar requires storage for **multiple days**
- Batteries cost 150-250 €/kWh, only suitable for a few hours
- Hydrogen pressure vessels cost 15-50 €/kWh, still too expensive
- **Underground salt caverns** for hydrogen cost 0.1-0.5 €/kWh, suitable for long-duration storage, **dominant concept in research**

Source: Irish wind and load data

Inter-annual variations of wind and solar

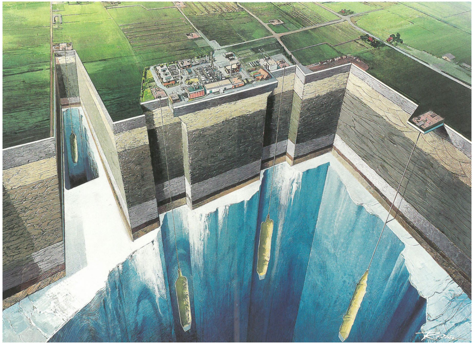
Particularly wind shows decadal cycles and strong **inter-annual variability**.

$\Rightarrow$ Need **ultra-long-duration energy storage** (ULDES), i.e. $>$ 100 hours.

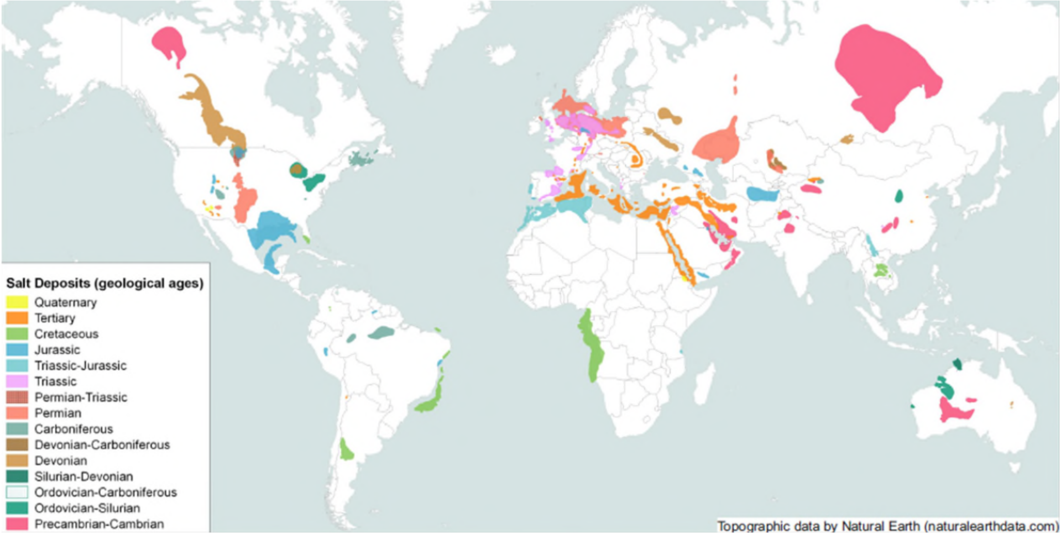


Source: Example of Germany

Many countries plan to store hydrogen in **solution-mined salt caverns** and transport hydrogen in **pipelines** (can reuse fossil gas infrastructure for both).

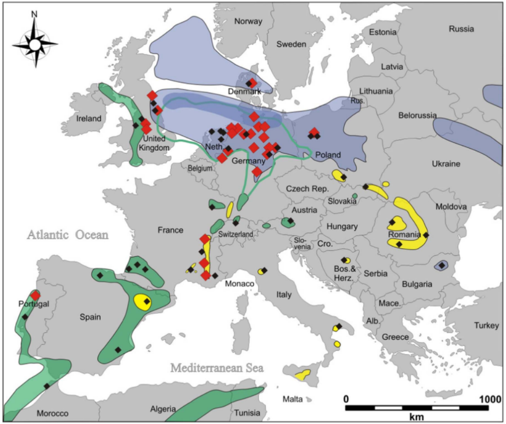


Problem: salt deposits for hydrogen caverns are highly localised



Source: Solution Mining Research Institute

Zoom on salt deposits in Europe and US



Tertiary salt deposit

Mesozoic salt deposit

Range of Mesozoic salt above Permian

Paleozoic salt deposit (Permian), Zechstein

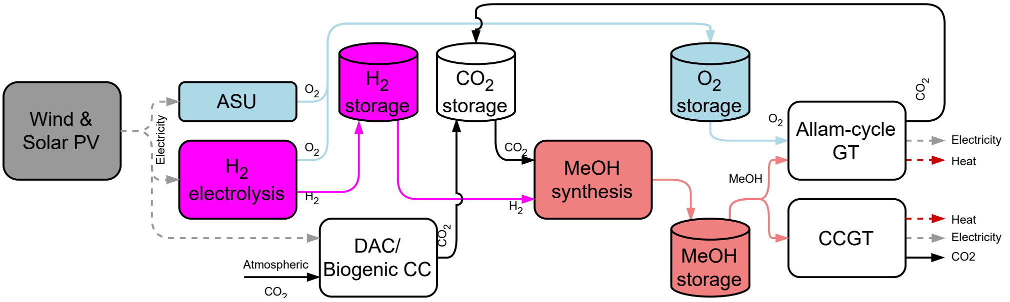
Paleozoic salt deposit (Permian), Rotliegend below Zechstein

Salt cavern fields

Gas Storage

Storage of Crude Oil & LPG, Brine Production

Store energy as **methanol**; combust methanol in pure **oxygen** from electrolysis in **Allam cycle turbine**; capture **carbon dioxide** and then cycle for more methanol synthesis.



Large methanol tanks can be built cheaply anywhere

- 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
- CO_2 and O_2 stored cryogenically
- Can be dimensioned to provide **resilience** against low wind years, volcanos and infrastructure outages

Source: **Wikipedia**

All components are demonstrated at scale

A 50 MW_{th} Allam cycle turbine **already operating for years** in Texas; 300 MW_{el} plants to be commissioned by 2026. George Olah Renewable Methanol plant in Iceland commissioned in 2011 produces 4000 tons per year. Megaton methanol plants run in China on gasified coal.

Source: NET Power, Carbon Recycling International

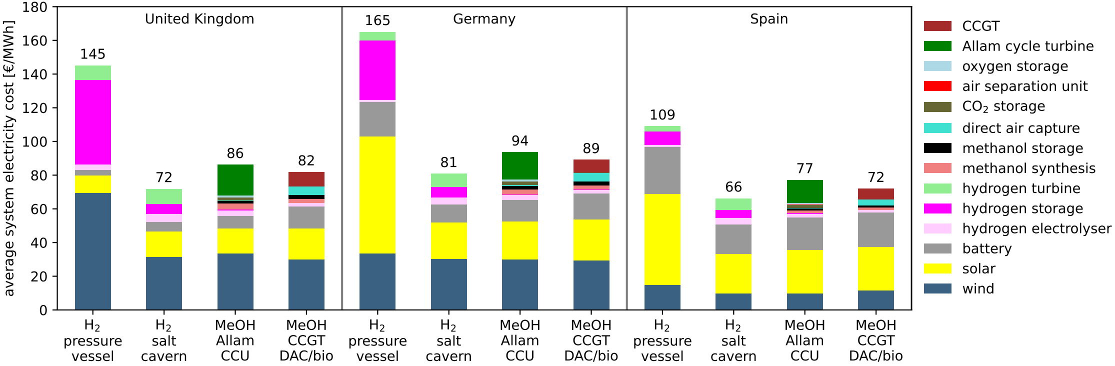
Study design

Optimise wind, solar, batteries plus one of following chemical carriers over **71 historical weather years** (1950-2020) for Germany, Spain and UK in open-source PyPSA.

- **H_2 pressure vessel** - hydrogen storage in aboveground steel pressure vessels
- **H_2 salt cavern** - hydrogen storage in underground salt caverns (round-trip $\sim$ 38%)
- **MeOH Allam CCU** - methanol storage, all storage in aboveground steel tanks or pressure vessels, CO_2 captured from Allam cycle turbine (round-trip $\sim$ 35%)
- **MeOH CCGT DAC/bio** - methanol storage, all storage in aboveground steel tanks or pressure vessels, CCGT without CO_2 capture instead of Allam, all CO_2 for methanol synthesis from direct air capture (or biogenic sources)

Average electricity costs: UK, Germany, Spain

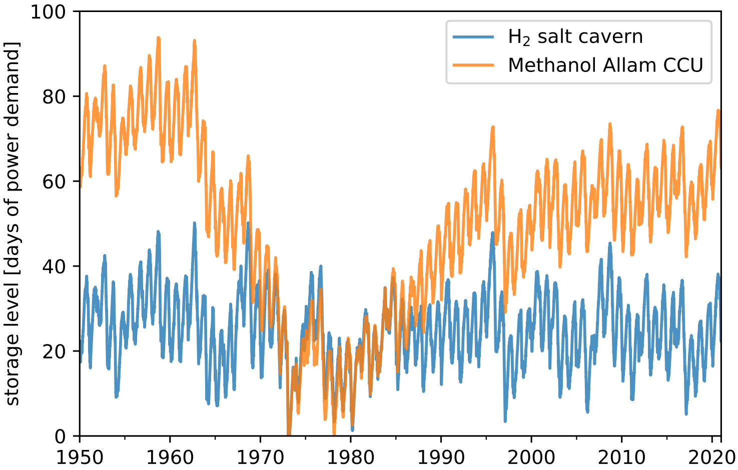
Methanol system **much cheaper** than H_2 pressure vessels where caverns not available; still 16-20% more expensive than salt caverns, but if Allam cycle costs reduce, only 6-7% more.



Source: Brown & Hampp 2023

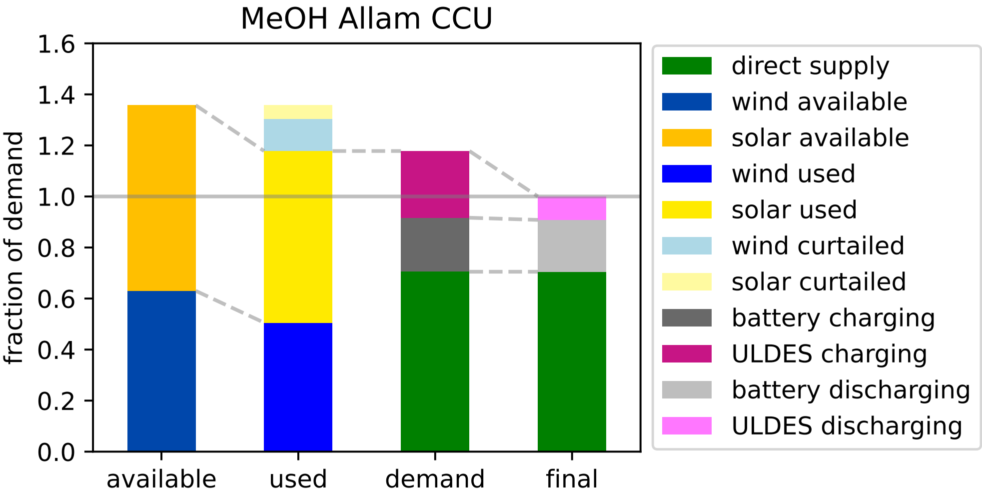
Filling levels of storage in days of electricity demand

Methanol stored over many years for **multi-year reductions in wind output**. Storage large enough to cover **92 days** of electricity demand.



Source: Brown & Hampp 2023

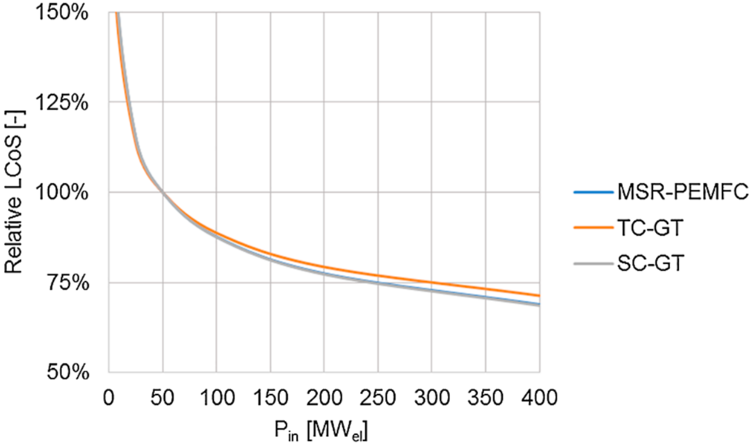
13% of available wind and solar is curtailed, a further 13% lost in storage conversion.



Source: Brown & Hampp 2023

Scaleability down to 200 MW

Economies of scale remain down to 200 MW (electrolyser power). ⇒ Interesting for **smaller autarkic regions**, such as islands or data centres. Also good for **fast, modular iteration**.



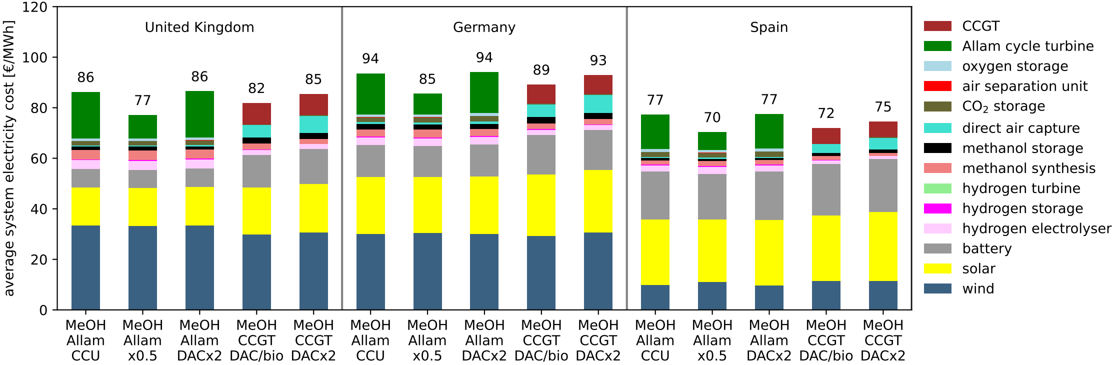
Source: Baak et al, 2018

Pros and cons versus other chemical storage

- **Methane**: similar costs and efficiencies to methanol, can re-use existing infrastructure like methanol. Disadvantage of requiring pressurisation for storage and transport, leakage as greenhouse gas, needs GW economies of scale, could prolong fossil gas.
- **Ammonia**: has advantage of avoiding carbon cycle. But toxic, needs cryogenic storage, storage and transport is highly regulated, ammonia turbines have low TRL, nitrogen oxide emissions mean mitigation necessary.
- **Liquid hydrogen**: LH_2 requires constant cooling power, less attractive for ULDES.
- **Liquid organic hydrogen carrier**: LOHC similar to methanol storage, but more expensive and lower TRL. Waste heat from power generation can be used for dehydrogenation.

Sensitivity to cost assumptions

Effects of halving Allam cycle investment cost (from 1832 €/kW to 916 €/kW), doubling DAC investment cost (raises CO_2 cost in Germany from 202 €/tCO_2 to 316 €/tCO_2).



Source: Brown & Hampp 2023

Sensitivity to flexibility assumptions

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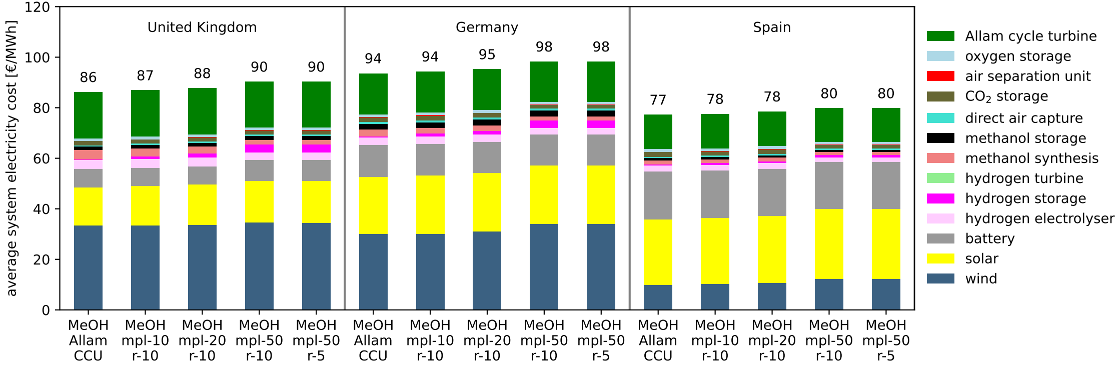
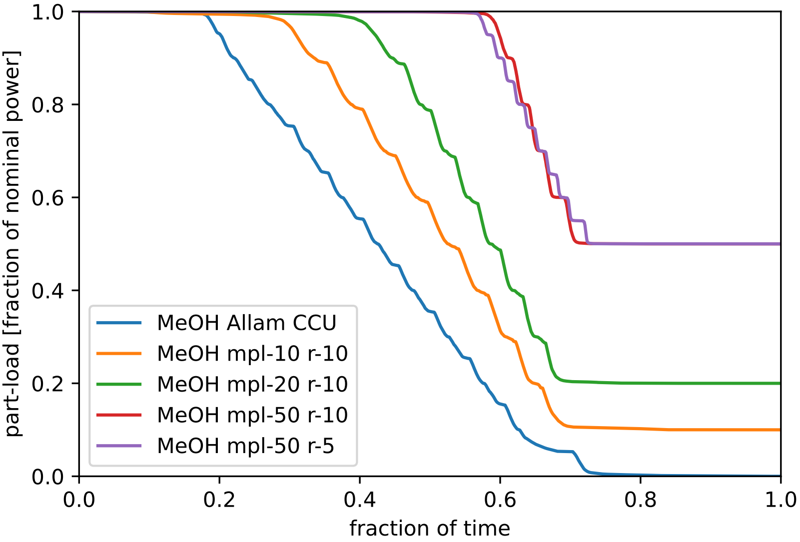
Fossil methanol synthesis typically runs with high capacity factors. Here we explore varying the minimum part load level (from 0% to 50%) and the hourly ramping limit (from 10% to 5%).



Source: Brown & Hampp 2023

Partload with different flexibility assumptions



Source: **Brown & Hampp 2023**

Avoiding cycling carbon dioxide and direct air capture

In short-term can take CO_2 from e.g. biogas, or convert all biogas to **e-bio-methanol**. But mid-term this CO_2 is needed by shipping, aviation and industry ⇒ **better to cycle if possible**.

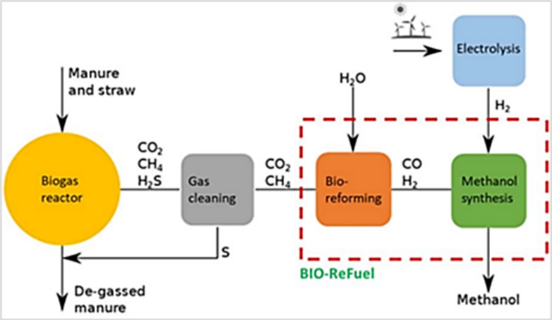


Figure 4: The process flow of bio-methanol production
Source: Lemvig Biogas

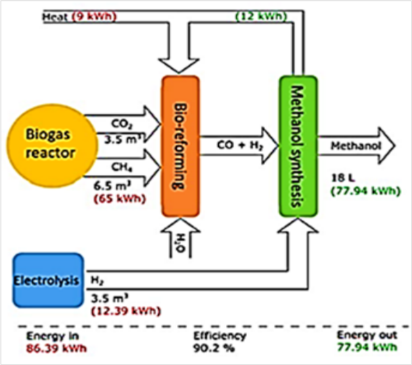
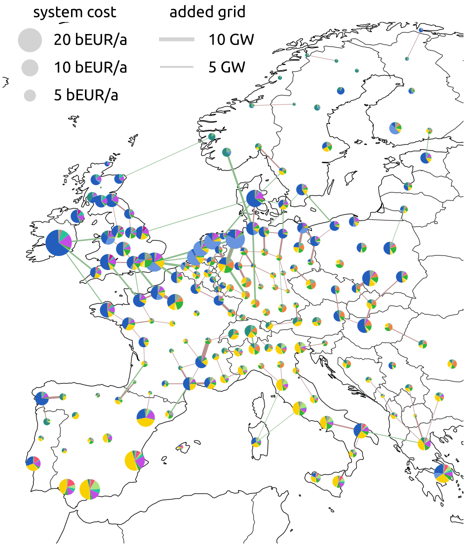
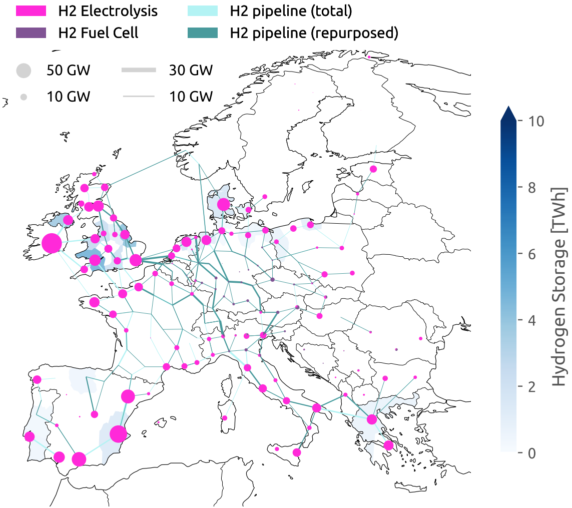


Figure 5: Energy balance
Source: Lemvig Biogas

Source: **IEA Bioenergy**

Next step: test in sector-coupled model PyPSA-Eur





Source: **Neumann et al, 2023**

Conclusions

Conclusions

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- Methanol is a **scaleable and flexible** solution for hard-to-electrify sectors and carbon management (from biomass to industry/fuels)
- Systems built on wind and solar will need **long-duration** storage both for variability and **resilience** against rare extreme events
- Where salt deposits are not available, **methanol storage** provides an attractive alternative, whereby carbon is **captured and cycled back** to synthesis
- System costs are **much lower** than using hydrogen pressure vessels; costs are 6-20% higher than with hydrogen caverns, depending on cost assumptions
- By providing storage for many days, a methanol-based system is **resilient** against low-wind years, volcano eruptions and infrastructure interruptions
- **Further research** needed on synthesis flexibility, Allam cycle and system integration

Backup

More information

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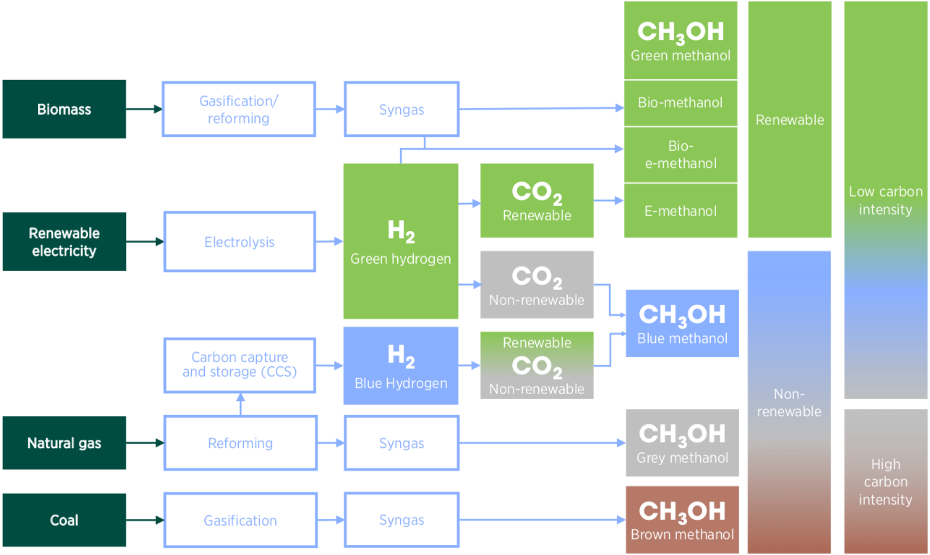
All input data and code for PyPSA-Eur is open and free to download:

1. `https://github.com/pypsa/pypsa`: The modelling framework
2. `https://github.com/pypsa/pypsa-eur`: The European model

Publications (selection):

1. F. Neumann, E. Zeyen, M. Victoria, T. Brown, *"The Potential Role of a Hydrogen Network in Europe,"* Joule (2023), **DOI**, **arXiv**.
2. M. Victoria, E. Zeyen, T. Brown, *"Speed of technological transformations required in Europe to achieve different climate,"* Joule (2022), **DOI**, **arXiv**.
3. M. Victoria, K. Zhu, T. Brown, G. B. Andresen, M. Greiner, *"Early decarbonisation of the European energy system pays off,"* Nature Communications (2020), **DOI**, **arXiv**.
4. T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, *"Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system,"* Energy 160 (2018) 720-739, **DOI**, **arXiv**.
5. J. Hörsch, F. Hofmann, D. Schlachtberger and T. Brown, *"PyPSA-Eur: An open optimization model of the European transmission system,"* Energy Strategy Reviews (2018), **DOI**, **arXiv**
6. T. Brown, J. Hörsch, D. Schlachtberger, *"PyPSA: Python for Power System Analysis,"* Journal of Open Research Software, 6(1), 2018, **DOI**, **arXiv**.
7. D. Schlachtberger, T. Brown, S. Schramm, M. Greiner, *"The Benefits of Cooperation in a Highly Renewable European Electricity System,"* Energy 134 (2017) 469-481, **DOI**, **arXiv**.

Methanol routes



Source: IRENA, 2022

What about methane and direct use of bioenergy?

Methane

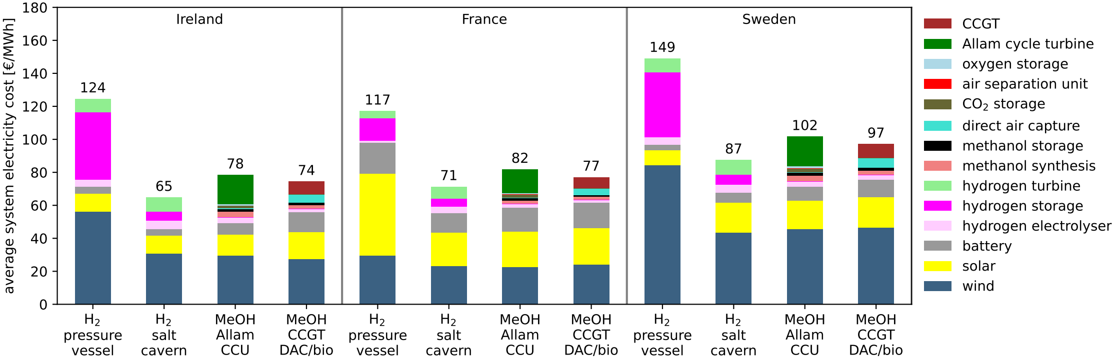
- There are very few sectors that need methane (beyond building heating until phase out is complete), whereas methanol has many uses; $CH_4 \Rightarrow$ lumpy pipelines
- Methane should be avoided in transport because of engine slippage, and in general because of leakage (possible to regulate, but in practice difficult)

Direct use of bioenergy

- Uses should be prioritised to: industrial feedstock, dense fuels for aviation and shipping, and carbon dioxide removal
- All of these needs can be met either with pure CO_2 (CDR) or methanol (MtO/A, MtK)
- Soak up all carbon close to source with biogas and e-H_2 in bio-e-methanol plants, or cellulosic ethanol, or gasification+synthesis
- Rare usage in CHP $\Rightarrow$ want low-capex plant using homogenous fuel (i.e. avoid solids)

Average electricity costs: Ireland, France, Sweden

Similar results in Ireland, France and Sweden.



Source: Brown & Hampp 2023