The Minimal Methanol Economy as a Gap-Filler for High Electrification Scenarios

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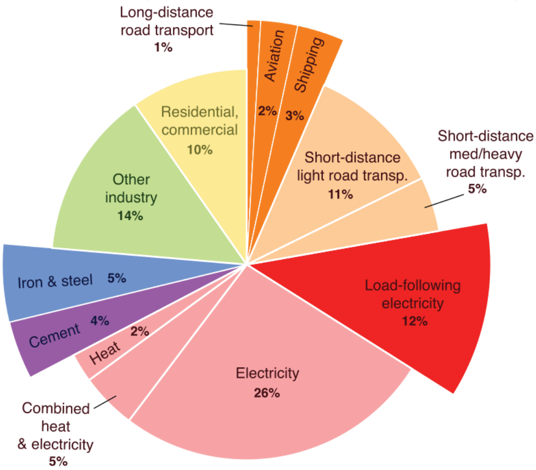
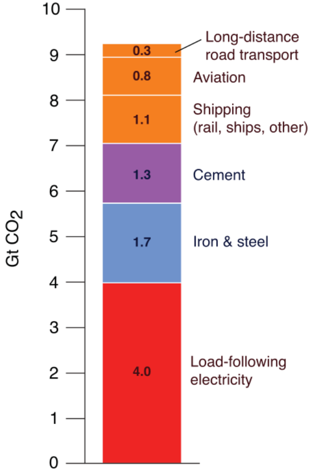
Electrifying sectors like land transport and building heating is a cost-effective strategy for decarbonisation. For harder-to-abate sectors that require fuels for their density or chemical properties, like long-haul aviation, shipping, backup power or iron ore reduction, electrolytic hydrogen and its derivatives are often proposed as part of a `hydrogen economy'. However, hydrogen itself is challenging to transport and store because of its small molecule size and low volumetric density; the build-up of a pipeline network needs close coordination with demand, supply and storage. We present a `minimal methanol economy' as an alternative concept for filling the gaps that electrification cannot reach. As a liquid at ambient conditions, methanol is easy to transport and store; it scales down to low-volume use cases without the lumpiness of hydrogen pipelines; it is a better drop-in fuel to replace methane; it can help integrate decentralised biomass wastes and residues into the energy system; it is needed anyway in large volumes as a feedstock for industry and transport fuels. We show in an energy system model for Europe that deep decarbonisation has lowest cost when hydrogen can be widely transported and used for backup power and heat, but a methanol-based system is only \bneuro{24} more expensive in the default scenario (3\% of system costs). This small increase is robust across varying assumptions about carbon sequestration, green imports and biomass availability. We argue that this modest expense is justified because methanol avoids many of the challenges in scaling up and regulating hydrogen infrastructure.

Source: Glaum et al, 2025

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



A Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)



B Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)

Source: Davis et al, 2018

But which hydrogen demand sectors really need actual hydrogen?

All potential hydrogen demand sectors can be served by **electrification** or 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.

Challenges with hydrogen

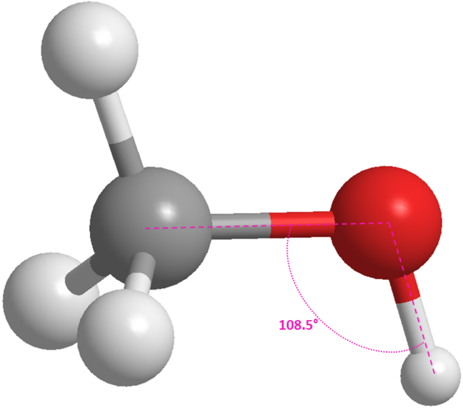
A hydrogen economy comes with **several challenges**:

- The molecule **size is small**, making it easy to leak and e.g. embrittle steel
- The **volumetric density** is low, making storage and transport difficult
- Salt deposits necessary easy underground storage in caverns are **not widely available**
- Vehicular transport is **costly**, pipeline network is necessary
- Hydrogen is an **indirect greenhouse gas** with GWP100 of 11.6 ± 2.8
- The widespread usage of a new gas requires a **coordinated scale-up** of lumpy **GW-scale** pipelines, storage, supply and demand

Introducing methanol

Methanol, the simplest alcohol CH_3OH, can fit the bill for many non-electric sectors.

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

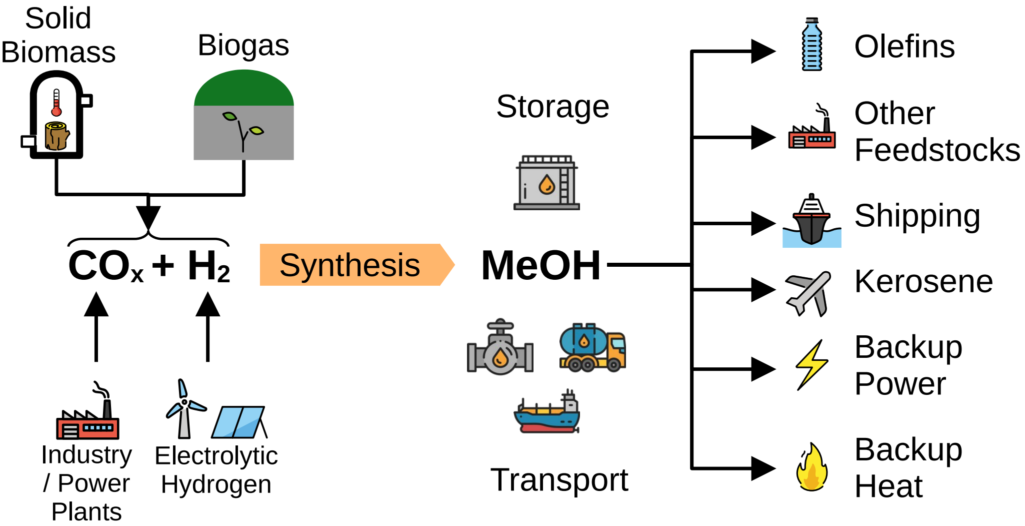


Source: Wikipedia; Yves Meur

Idea: ‘Electrification plus minimal methanol economy’

- **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 rest (backup power & heat, shipping, aviation, chemical industry)
- Methanol is more easily **storeable and transportable** than hydrogen (liquid at RTP)
- Methanol **scales down** to MW-scale use cases 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)

Methanol as platform for hard-to-electrify



Source: Glaum et al, 2025

Explore in energy model PyPSA-Eur for net zero CO_2 emissions

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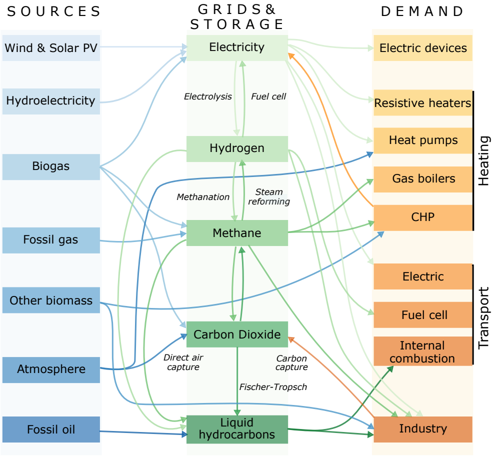
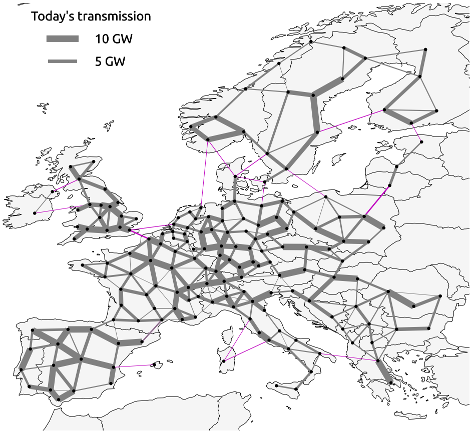
Use **full energy system model** PyPSA-Eur with net zero CO_2 emissions, hourly modelling, 100 regions, biomass limited to wastes and residues, 200 $MtCO_2/a$ limit on sequestration.





Five main scenarios remove gaseous energy networks

Scenarios contrast **gap-fillers for power and heat**: hydrogen, methane and methanol.

- **All Networks (all)**: both hydrogen and methane transmission networks.
- **Only Methane Network (CH_4)**: only methane transmission network.
- **Only Hydrogen Network (H_2)**: only hydrogen transmission network.
- **No Gaseous Fuel Networks (none)**: neither hydrogen nor methane transmission networks, but does allow local distribution of hydrogen and methane inside the regions.
- **Minimal Methanol Economy (min. MeOH)**: neither hydrogen nor methane transmission networks, and forbids gaseous distribution inside the regions. Hydrogen may only be used captively inside industrial facilities for ammonia, steel, methanol and kerosene production. No methane is produced and biomass cannot be used directly in power plants. Methanol must be used for all backup heat and power plants.

All scenarios allow the transport of oil, methanol, biomass, carbon dioxide and electricity.

Methane and Hydrogen Networks for ‘All Networks’ scenario

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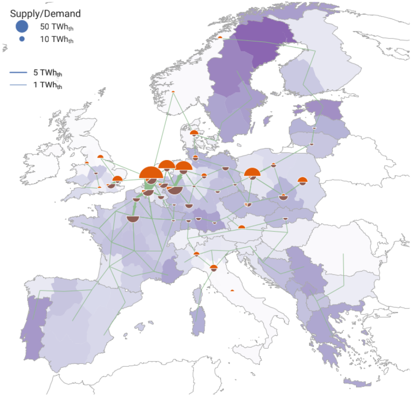
Gas network serves backup power & heat; **H_2 network** serves steel, ammonia and methanol.



Production

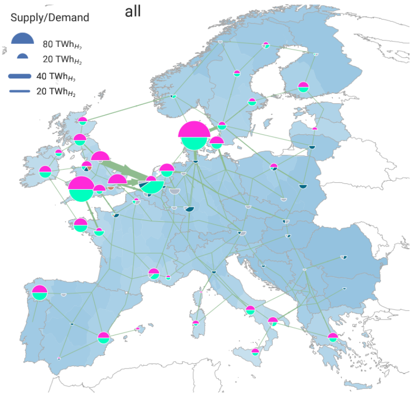
methane import

Consumption

open-cycle gas turbine

urban central gas CHP

urban decentral gas boiler



Production

H_2 electrolysis

methanol steam reforming

Consumption

DRI

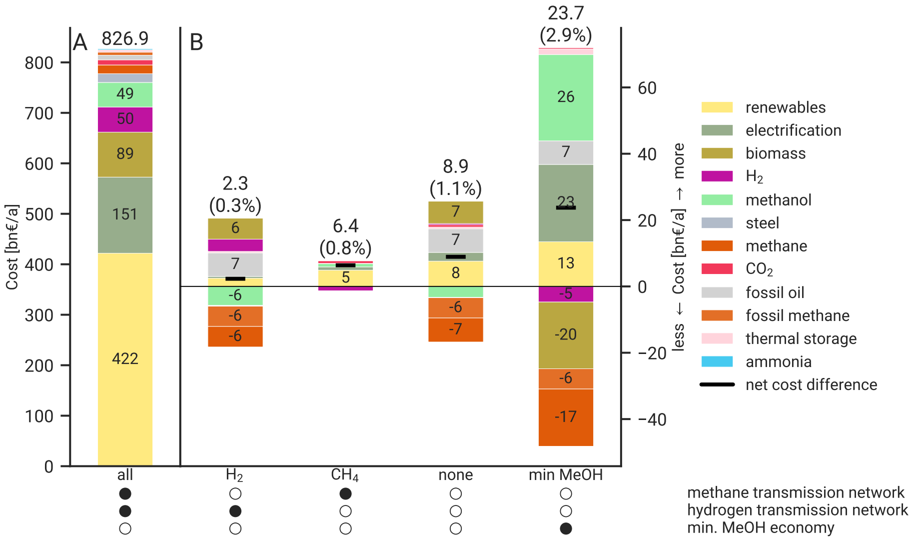
Haber-Bosch

methanol-to-kerosene

methanolisation

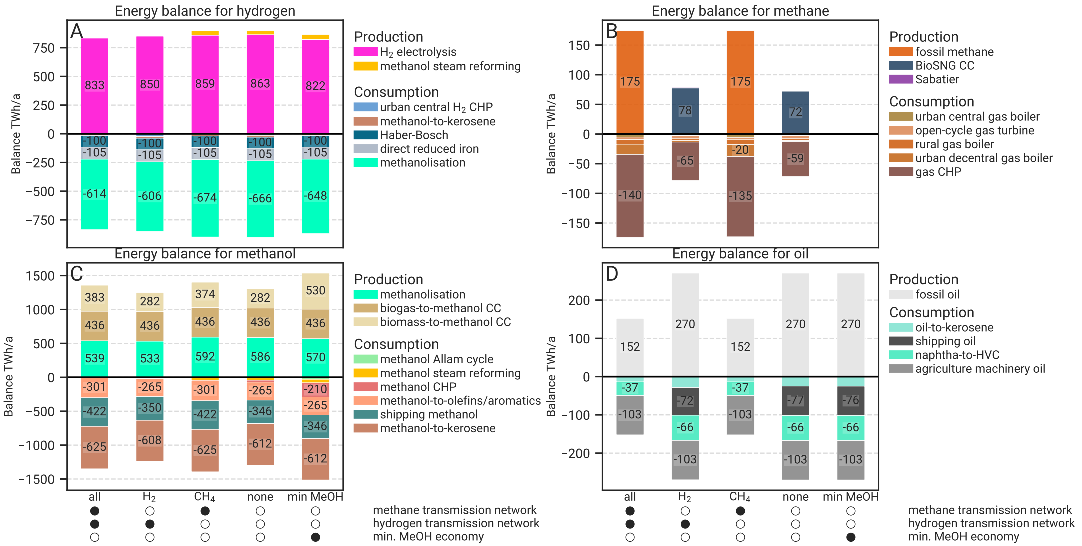
Source: Glaum et al, 2025

Scenario system cost comparison: methanol only 3% more expensive



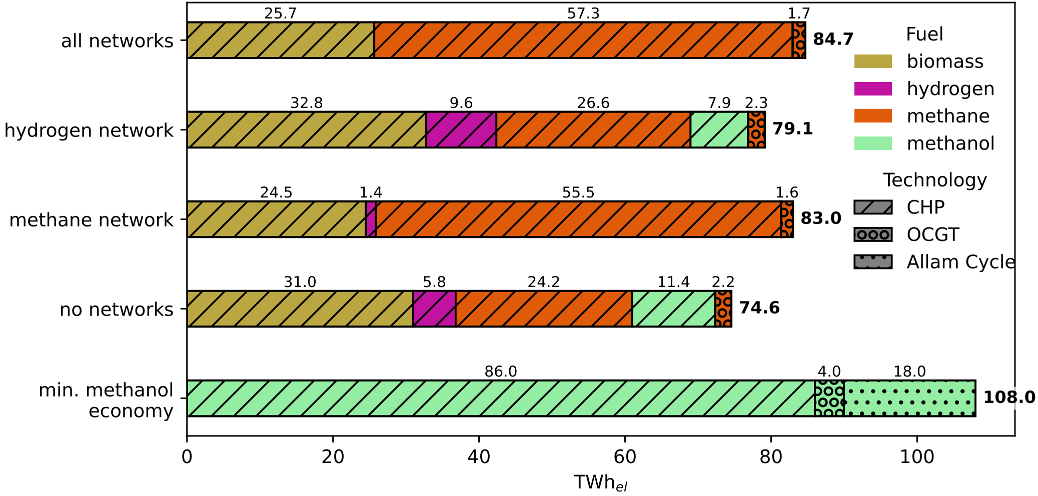
Source: **Glaum et al, 2025**

Energy balances: methanol use by shipping, MtO/A/K, backup



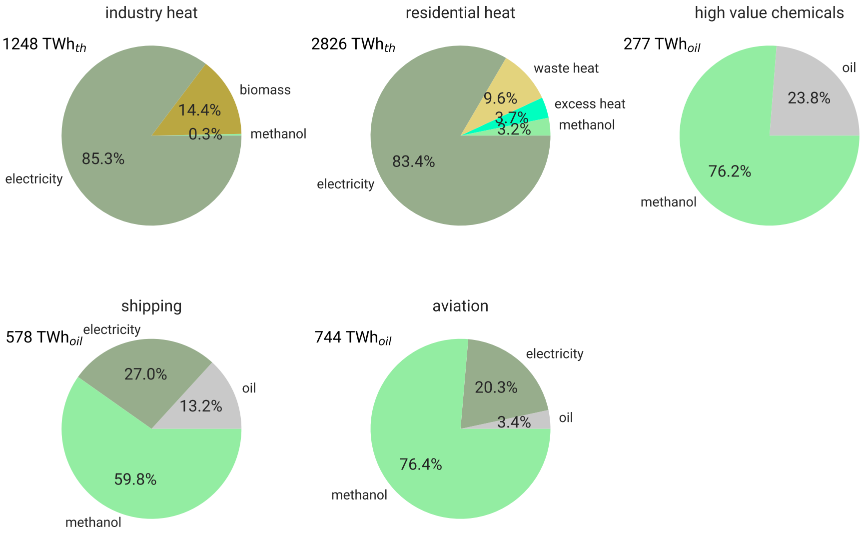
Source: **Glaum et al, 2025**

Dispatchable generation: switch from biomass+gas to methanol



Source: Glaum et al, 2025

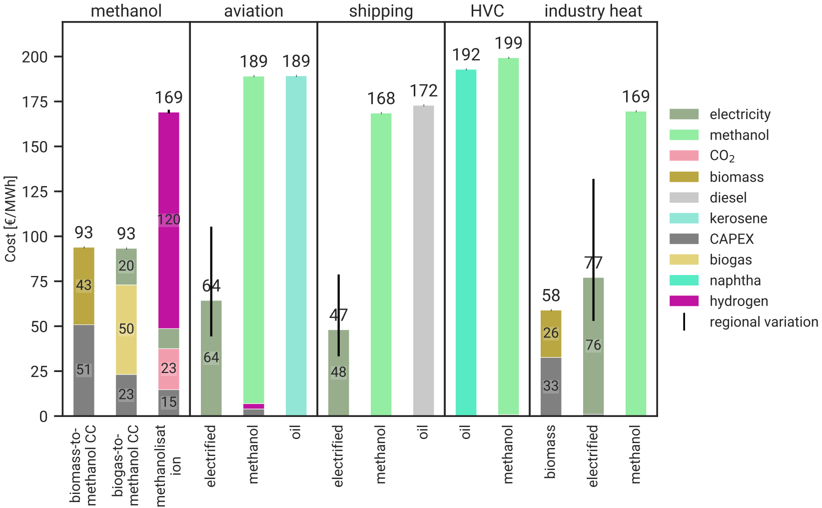
Final energy supply dominated by electricity and methanol



Source: **Glaum et al, 2025**

Production costs for different end use sectors

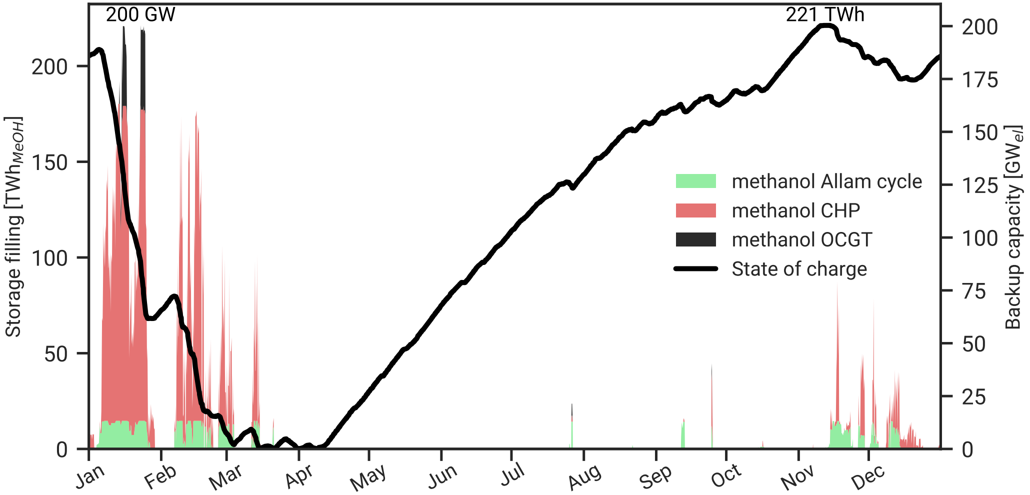
Biomethanol can be supplemented with green hydrogen to use excess CO_2: **e-biomethanol**.



Source: Glaum et al, 2025

Methanol for backup power is used rarely

Backup power runs during **cold dark wind lulls**, primarily CHP to support district heating.



Source: **Glaum et al, 2025**

Biomethanol production is spread around the continent

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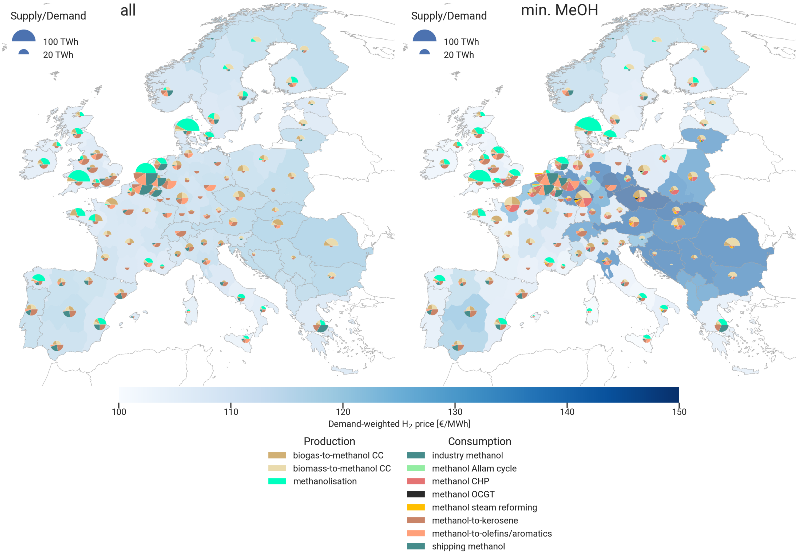

Source: Glaum et al, 2025

Sensitivity (CO_2 network, relocation, imports, sequestration, biomass)

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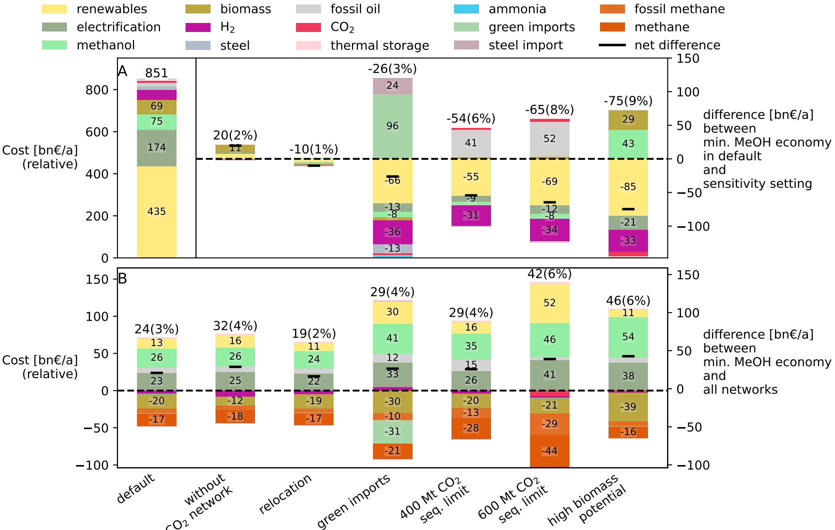
Cost increase to minimal methanol economy (bottom row) **robust across sensitivity analysis**.

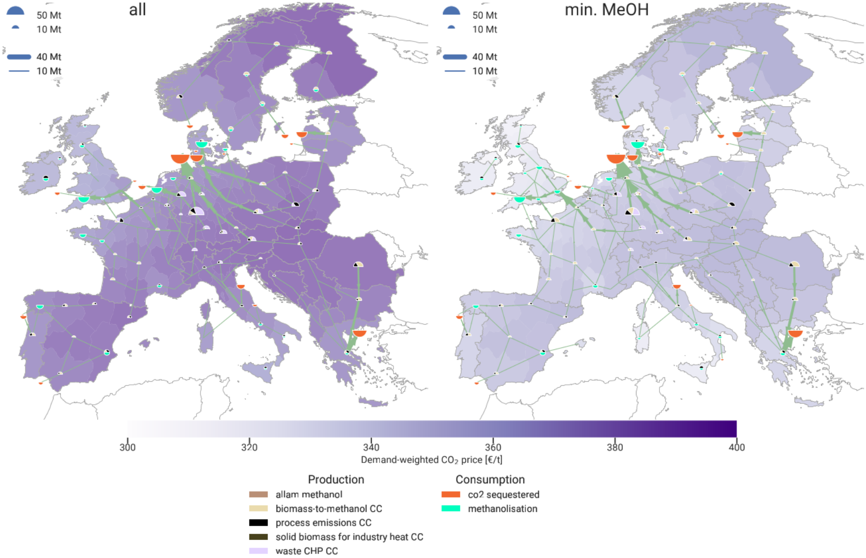


Source: Glaum et al, 2025

- Methanol is a **scaleable and flexible** solution for hard-to-electrify sectors and carbon management (e.g. absorbing sustainable carbon from decentral biomass)
- Green methanol will be needed in **large volumes** for shipping, chemicals and aviation, especially if sequestration capacity is scarce
- A **minimal methanol economy** avoids long-distance transport of methane or hydrogen in pipelines, and uses methanol instead of these gases in remaining uses
- Using methanol in this way as a **gap filler** for backup power and heat is only **24 billion euros per year (3% of system cost)** more expensive than a methane/hydrogen system
- Methanol **de-links the scale-up** of infrastructures (storage, pipelines), avoids frictions of hydrogen, is a **drop-in replacement** for methane, allows **easier regulation**

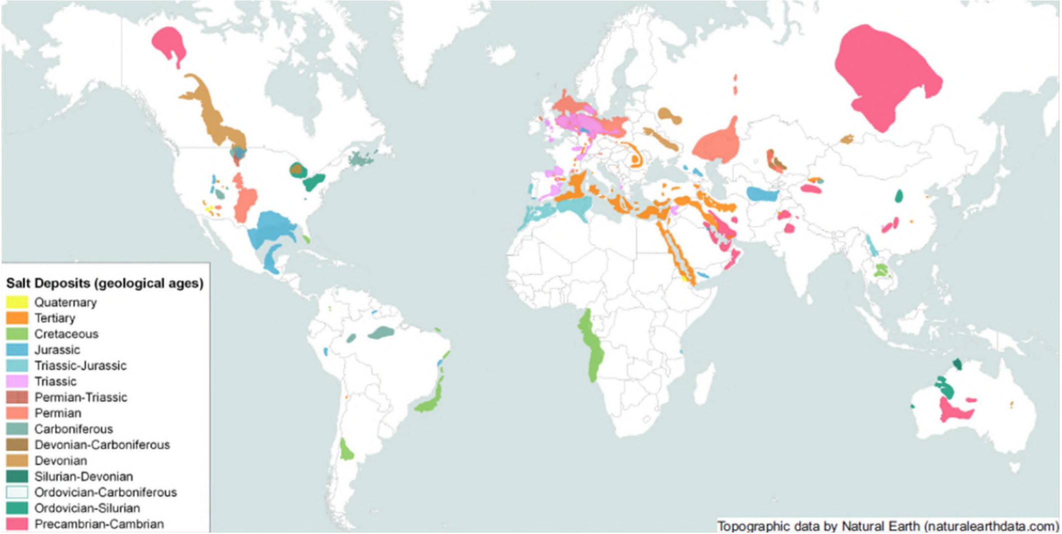
Backup

CO_2 network



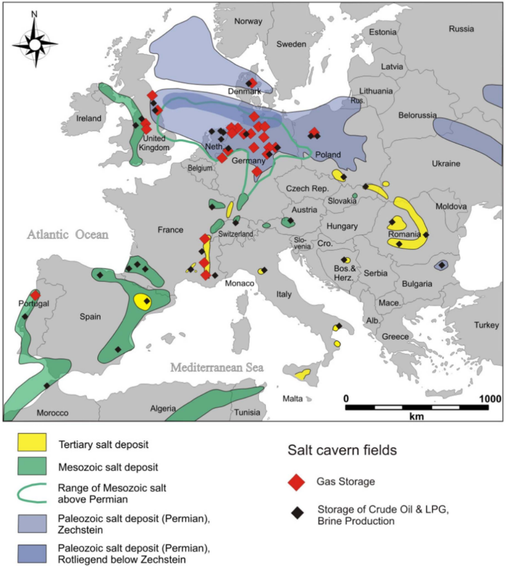
Source: **Glaum et al, 2025**

Problem: salt deposits for hydrogen caverns are highly localised



Source: Solution Mining Research Institute

Zoom on salt deposits in Europe and US



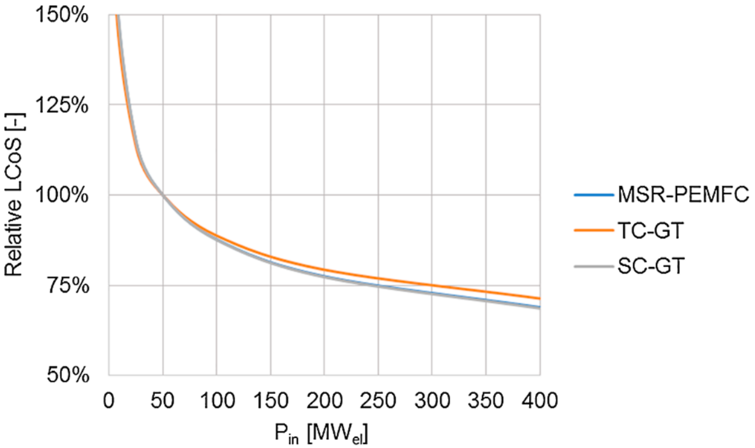
Large methanol tanks can be built cheaply anywhere

- 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

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.

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**.

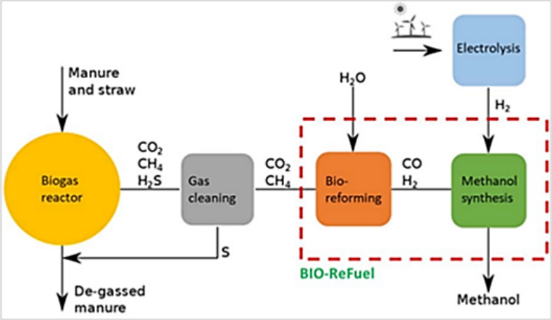


Figure 4: The process flow of bio-methanol production
Source: Lemvig Biogas

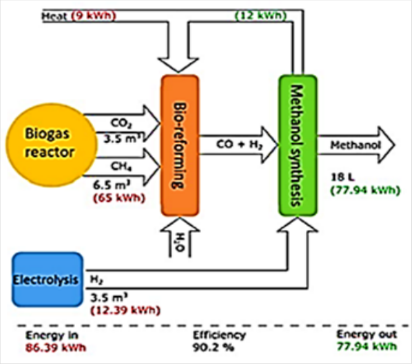


Figure 5: Energy balance
Source: Lemvig Biogas

Source: IEA Bioenergy

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)