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

Preprint:

https://arxiv.org/abs/2505.09277

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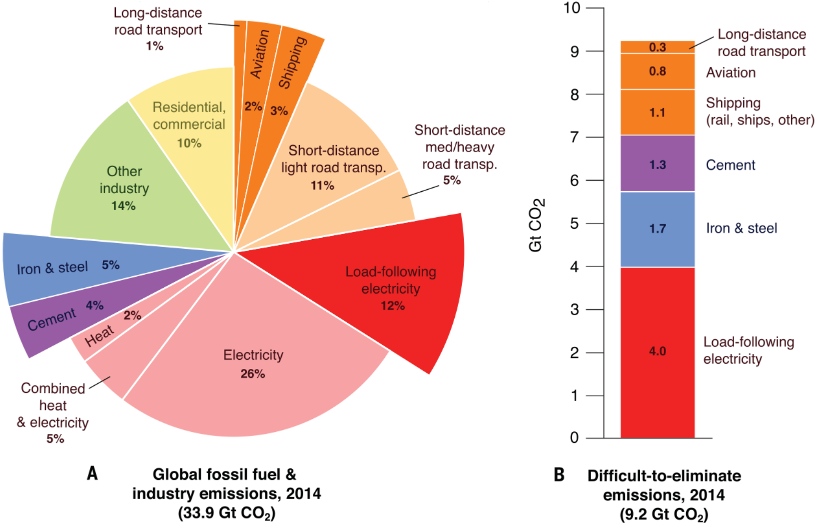
October 17, 2025

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



Reference: Davis et al., 2018

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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
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)

→ There is **no strict need** for hydrogen outside of industry clusters.

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Challenges with hydrogen economy

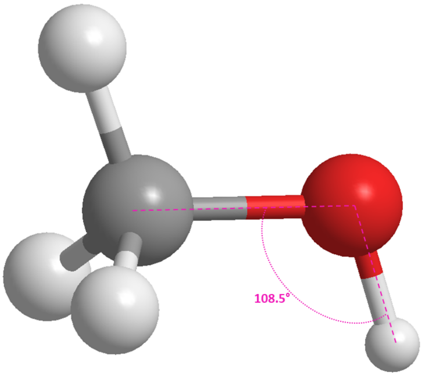
A hydrogen economy comes with **several challenges**:

- 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!



Reference: 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 reduction)
- Use **methanol as a gap-filler** for the rest: shipping, aviation, chemical industry, backup power & heat
- 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)

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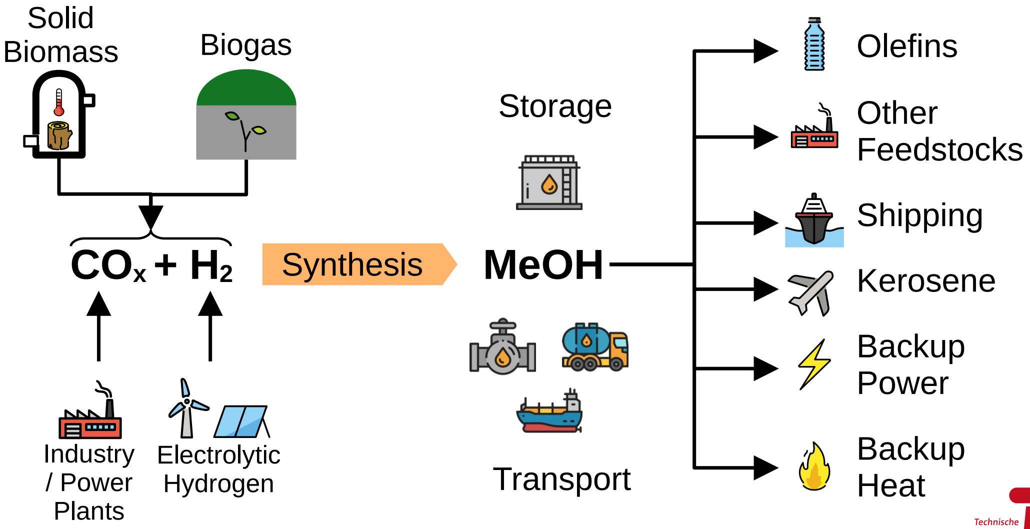
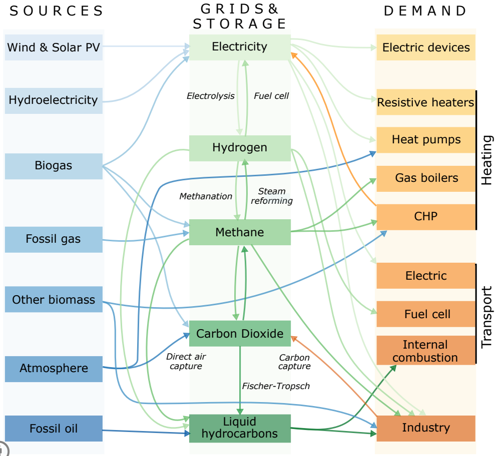
Methanol as platform for what is hard to electrify:

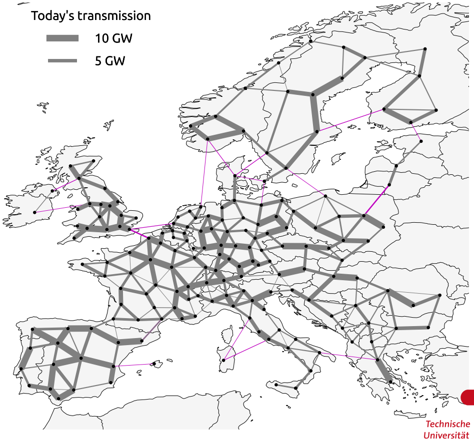


Reference: Glaum et al., 2025 (arxiv:2505.09277)

Explore in PyPSA-Eur energy system model

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.





Reference: PyPSA-Eur

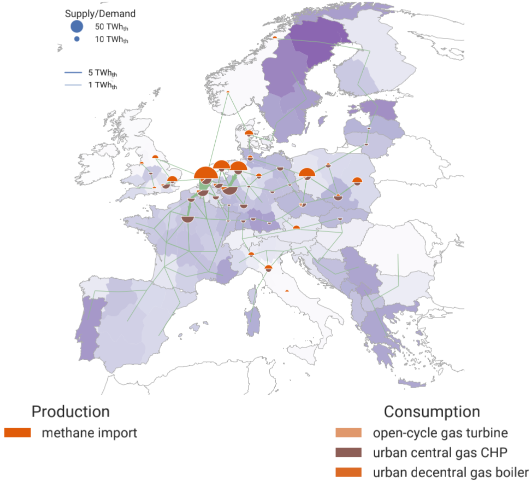
Five main scenarios contrast gap-fillers for backup power & heat

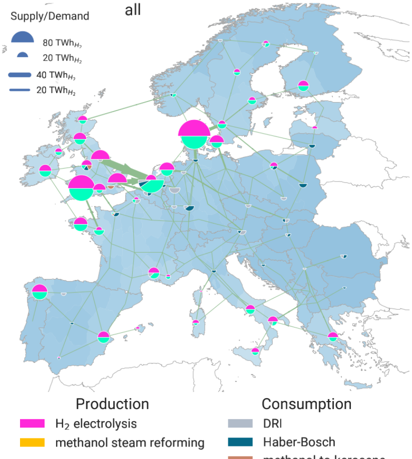
1. **All Networks (all)**: both hydrogen and methane transmission networks.
2. **Only Methane Network (CH_4)**: only methane transmission network.
3. **Only Hydrogen Network (H_2)**: only hydrogen transmission network.
4. **No Gaseous Fuel Networks (none)**: neither hydrogen nor methane transmission networks, but allow local distribution of hydrogen and methane inside regions.
5. **Minimal Methanol Economy (min. MeOH)**:
   - neither hydrogen nor methane transmission nor distribution networks,
   - hydrogen may only be used captively inside industrial facilities (ammonia, steel & MeOH),
   - 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 & electricity.

Methane and hydrogen networks for 'All Networks' scenario

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





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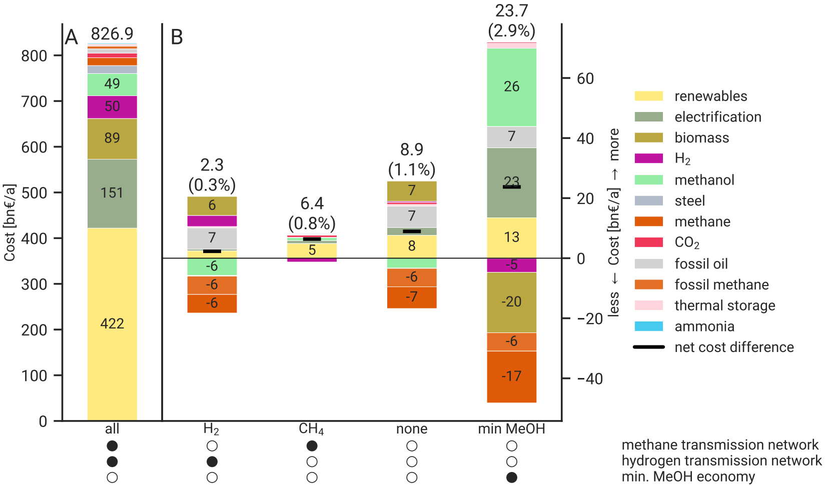
System cost comparison

Minimal methanol economy scenario is only 3% more expensive than cost-optimum.



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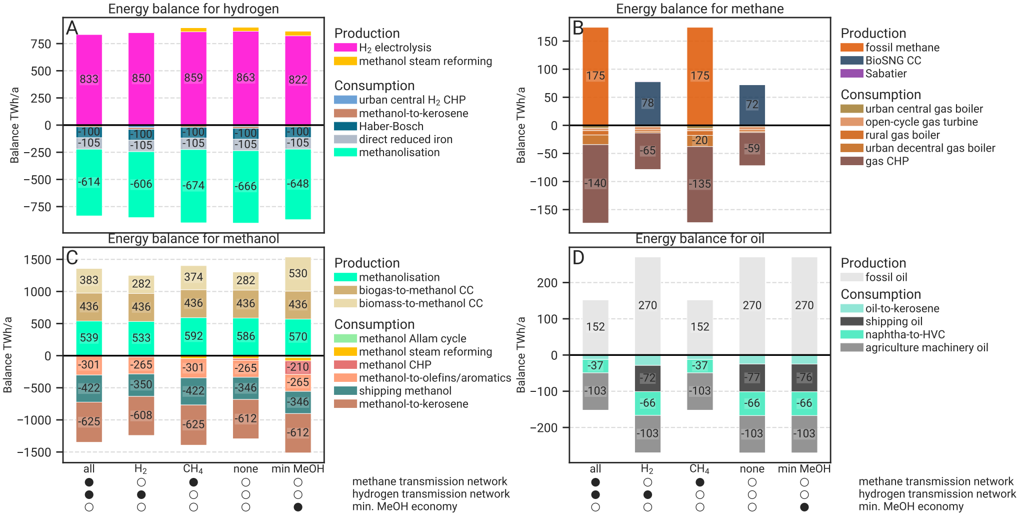
Energy balances: methanol used in shipping, MtO/A/K, backup



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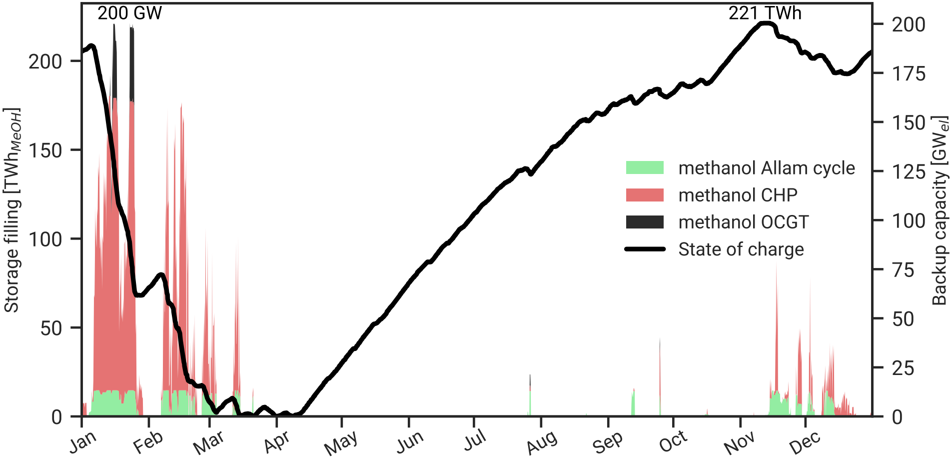
Methanol for backup power/heat is used rarely

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



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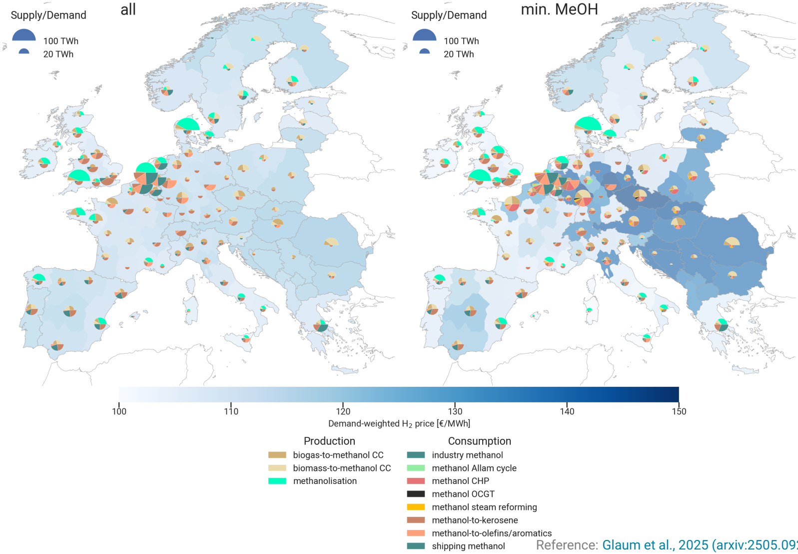
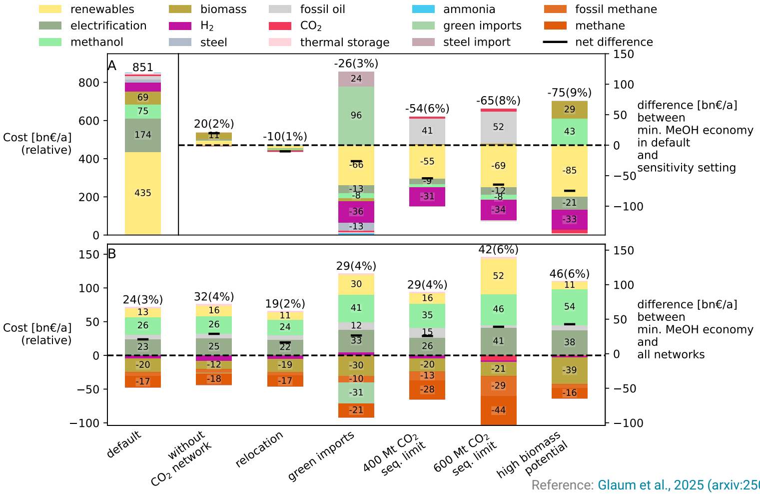
Biomethanol production is distributed across the continent



Reference: Glaum et al., 2025 (arxiv:2505.09277)

Sensitivities: CO_2 network, sequestration, imports, biomass

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



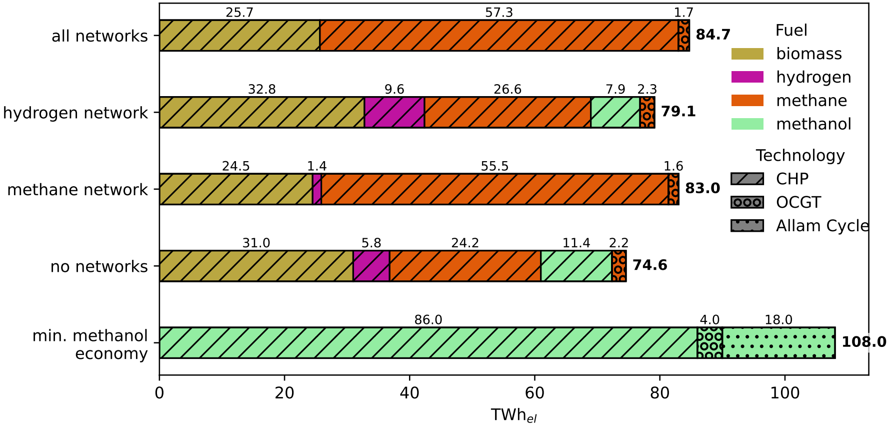
Reference: Glaum et al., 2025 (arxiv:2505.09277)

Conclusions

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

Dispatchable generation

Switch from a mix of biomass and methane to methanol-based generation.



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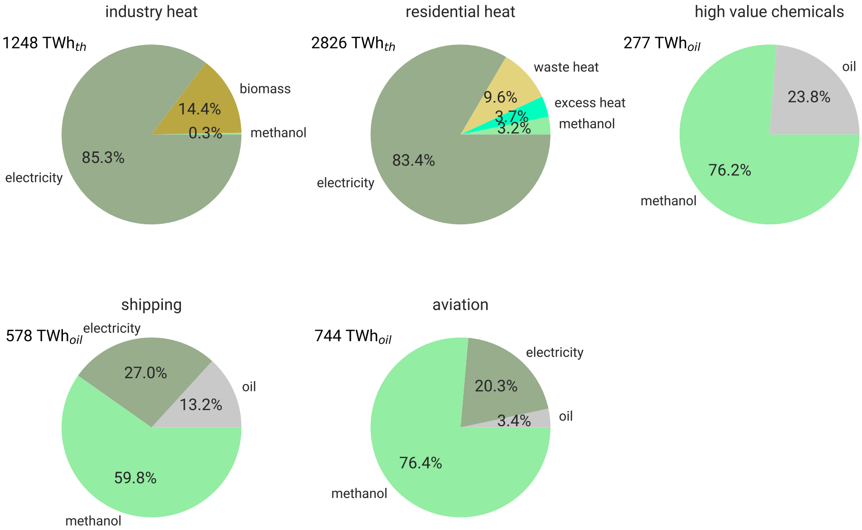
Final energy supply dominated by electricity and methanol



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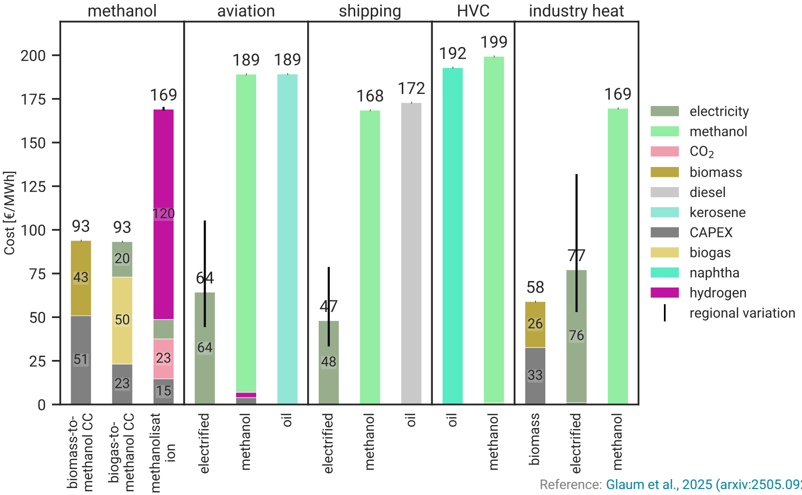
Production costs for different end use sectors

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



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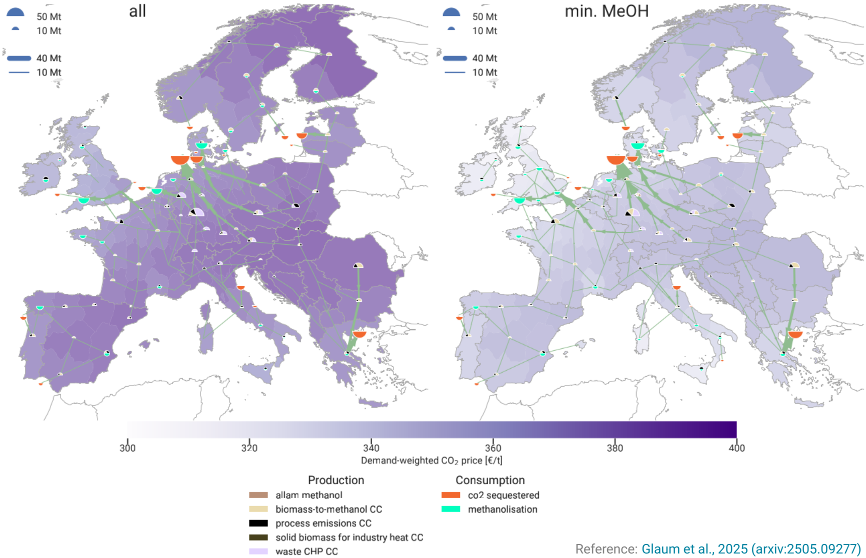
Underlying CO_2 network



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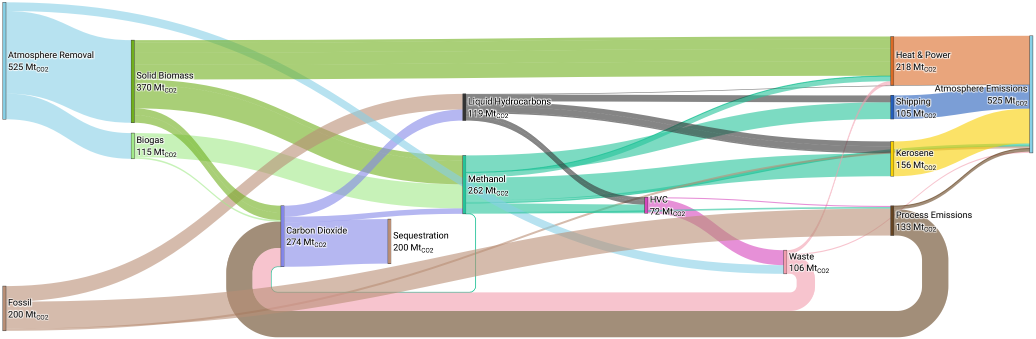
Carbon Management: CO_2 flows in Sankey diagram

For **Minimal Methanol Economy** scenario:



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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

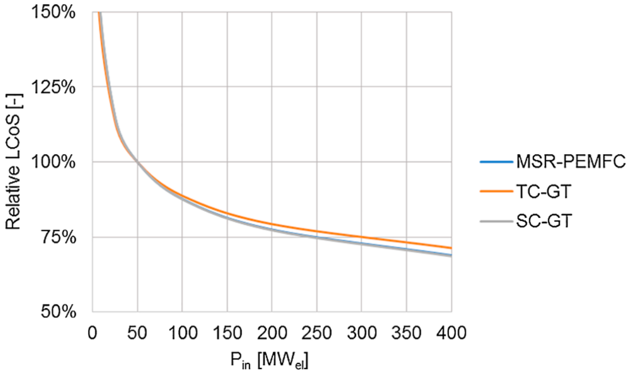
Reference: Wikipedia

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**.



Reference: Baak et al., 2018

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