Ultra-long-duration energy storage anywhere: methanol with carbon cycling

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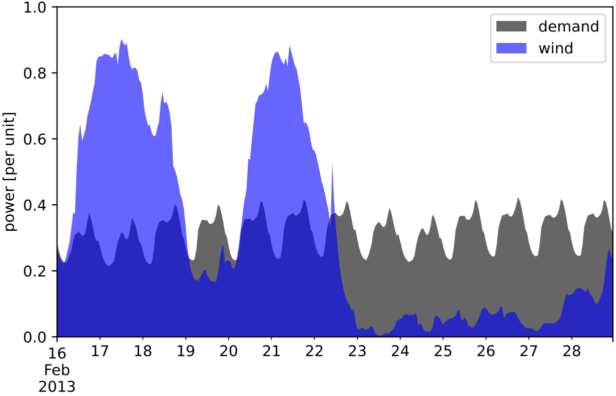
The Challenge

With only wind and solar, need long-duration storage



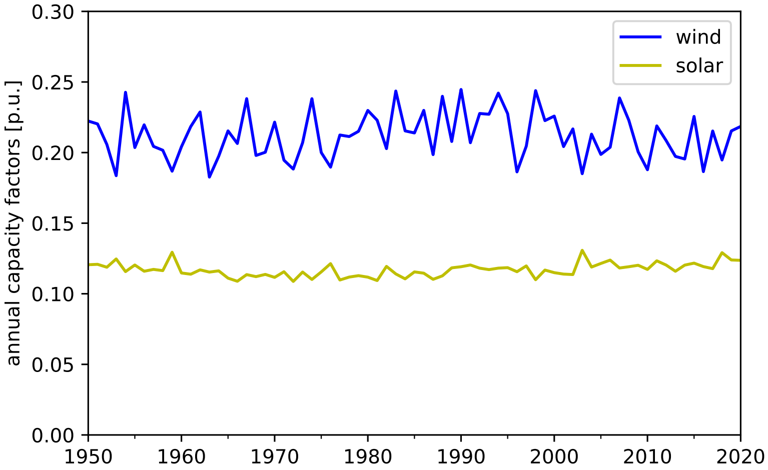
- Variability of wind and solar requires storage for **multiple days**
- Batteries cost 150-250 €/kWh, only suitable for a few hours
- Hydrogen pressure vessels cost 15-50 €/kWh, still too expensive
- **Underground salt caverns** for hydrogen cost 0.1-0.5 €/kWh, suitable for long-duration storage, **dominant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

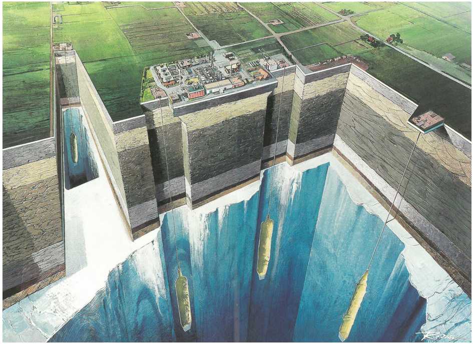
$\Rightarrow$ Need **ultra-long-duration energy storage** (ULDES), i.e. $>$ 100 hours.



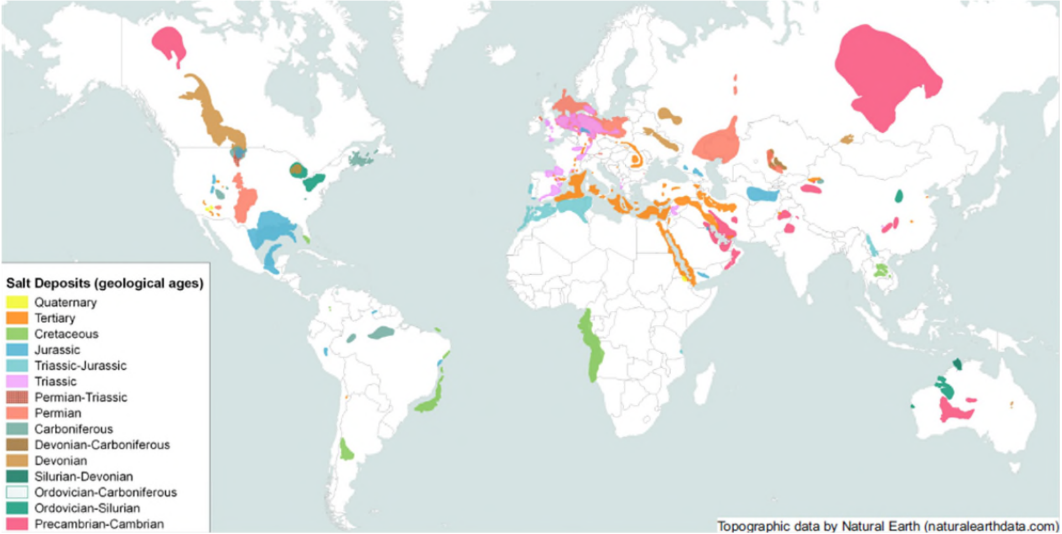
Source: Example of Germany

Establised idea: store hydrogen in salt caverns, transport by pipeline

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

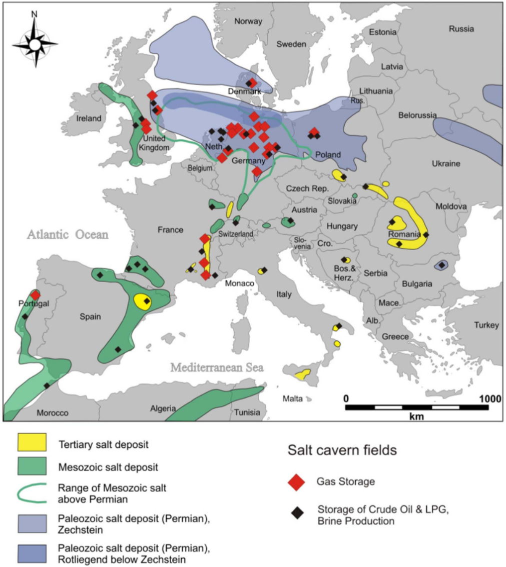


Problem: salt deposits for hydrogen caverns are highly localised



Source: Solution Mining Research Institute

Zoom on salt deposits in Europe and US



Hydrogen versus its derivatives

Storing hydrogen in underground salt caverns has several potential issues:

- Salt deposits may be **lacking**
- Or may require **GW-scale** power transmission or hydrogen pipeline to access salt locations
- Hydrogen can **leak** with global warming impacts
- Caverns and transport infrastructure can be subject to **local pushback**

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But looking to wider **hydrogen derivatives** we know we need

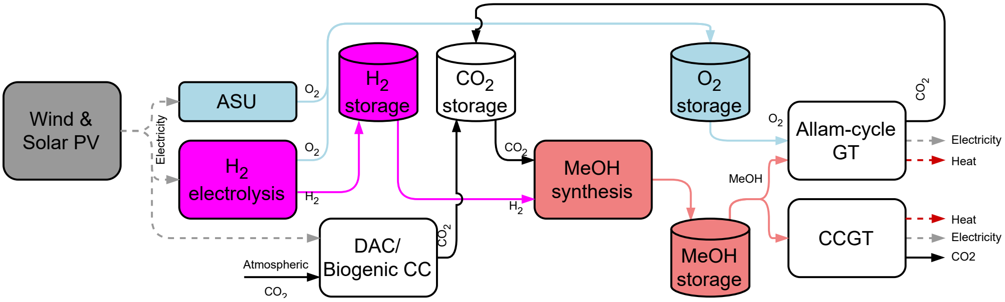
- **Ammonia** for fertiliser, perhaps shipping
- **Carbonaceous fuels** for aviation, shipping and chemical feedstocks

Why not use these for storage instead?

A Solution: Methanol Storage with Carbon Cycling

Solution: store e-methanol, now only liquids stored above ground

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



Source: Brown & Hampp 2023

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]()

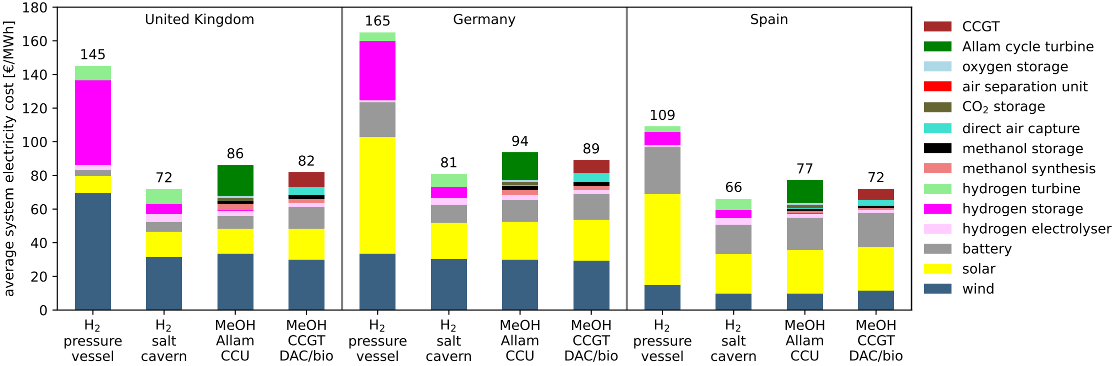
Study design

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

- **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

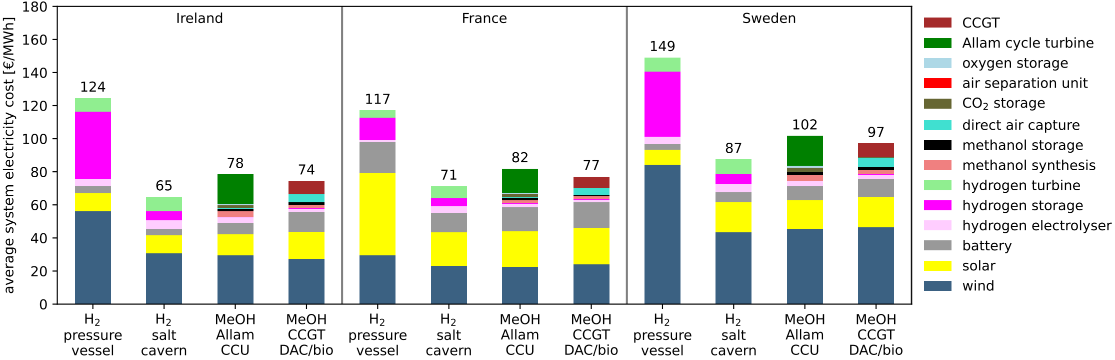
Methanol system **much cheaper** than H_2 pressure vessels where caverns not available; still 16-20% more expensive than salt caverns, but if Allam cycle costs reduce, only 6-7% more.



Source: Brown & Hampp 2023

Average electricity costs: Ireland, France, Sweden

Similar results in Ireland, France and Sweden.



Source: **Brown & Hampp 2023**

Filling levels of storage in days of electricity demand

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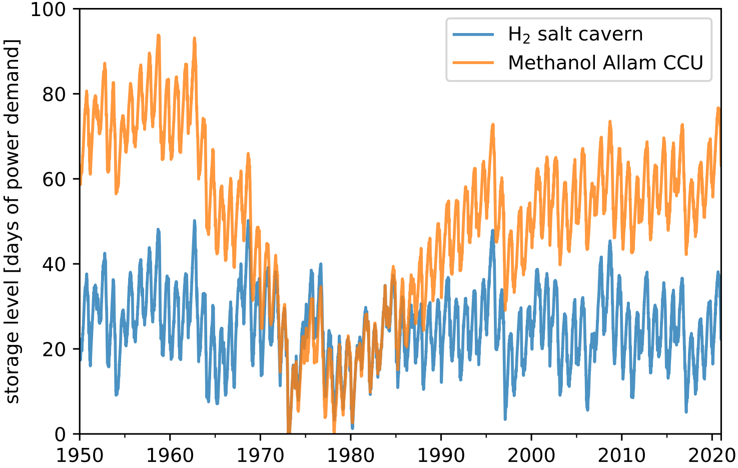
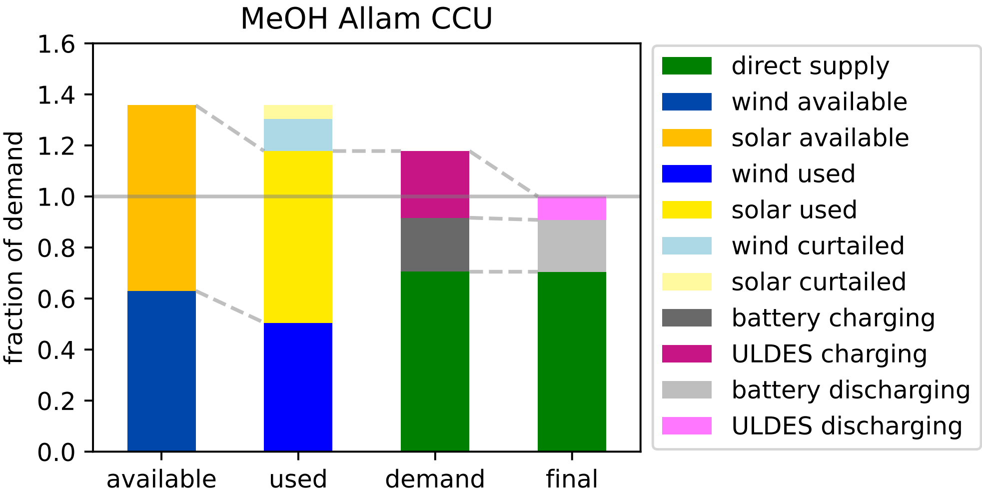
Methanol stored over many years for **multi-year reductions in wind output**. Storage large enough to cover **92 days** of electricity demand.



Source: **Brown & Hampp 2023**

Less than 10% of electricity provided by stored e-fuel

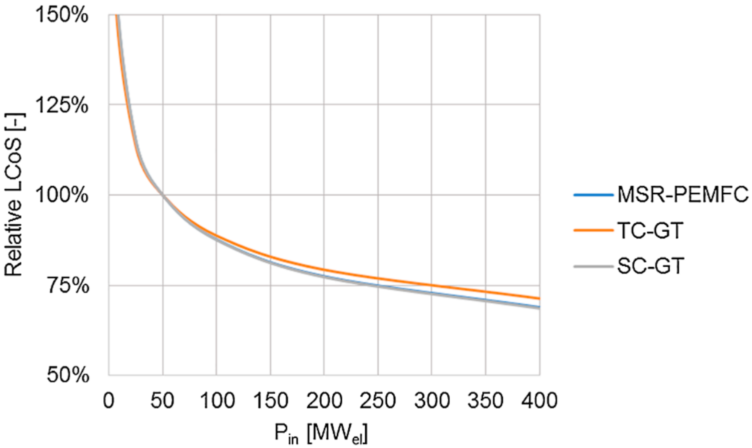
13% of available wind and solar is curtailed, a further 13% lost in storage conversion.



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**.



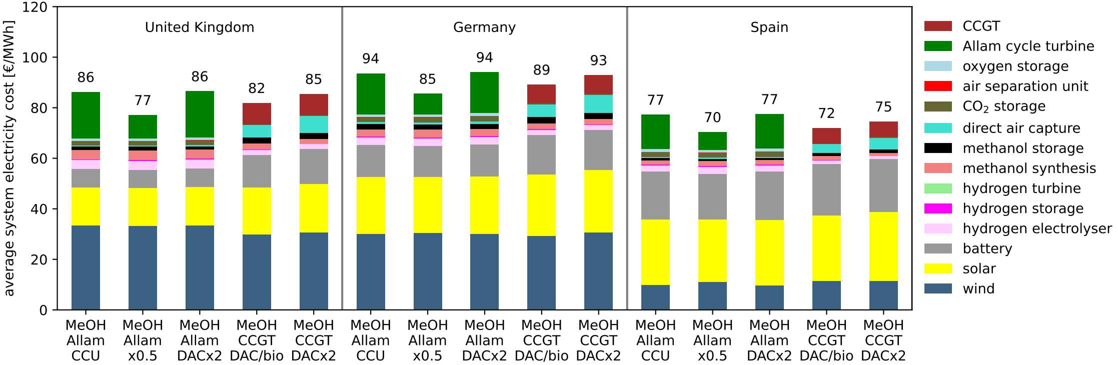
Source: [Baak et al, 2018]

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

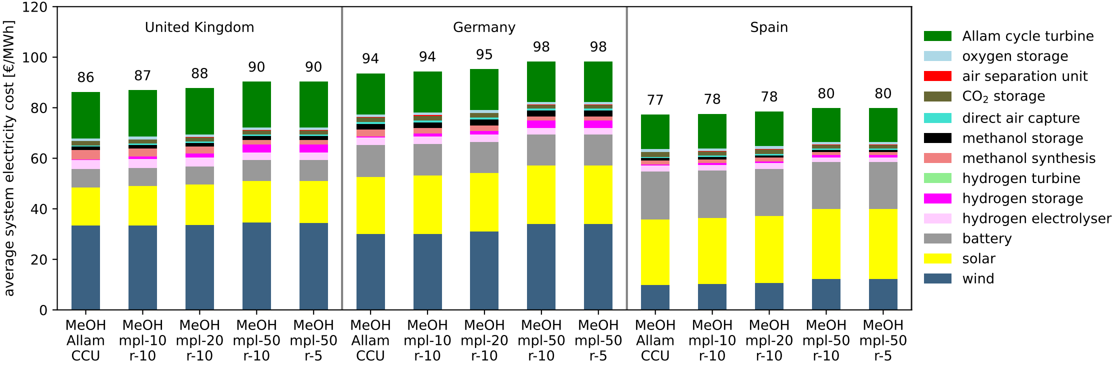
Effects of halving Allam cycle investment cost (from 1832 €/kW to 916 €/kW), doubling DAC investment cost (raises CO_2 cost in Germany from 202 €/tCO_2 to 316 €/tCO_2).



Source: Brown & Hampp 2023

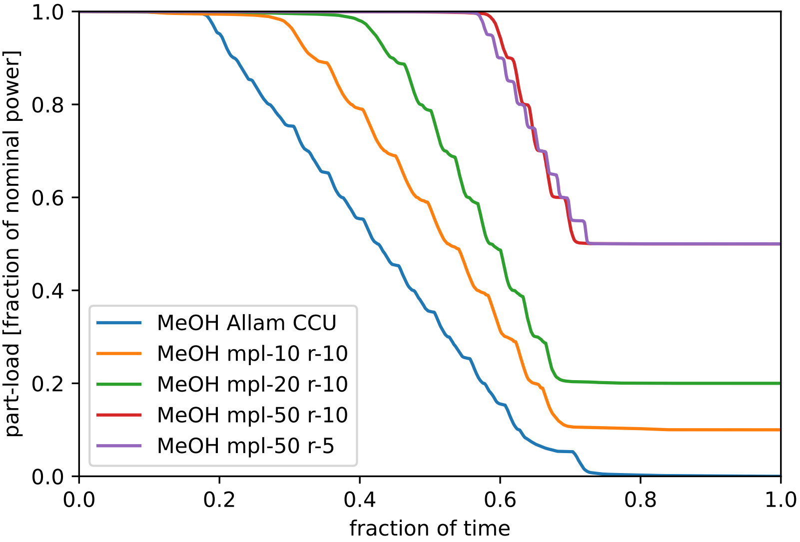
Sensitivity to flexibility assumptions

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

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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 and industry ⇒ **better to cycle if possible**.

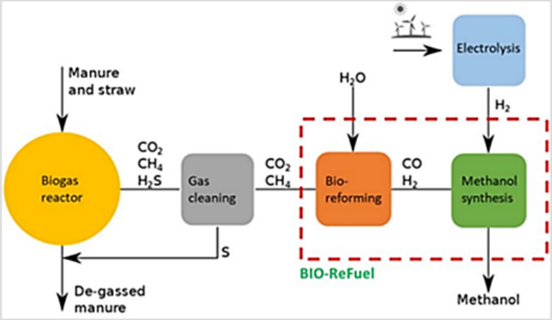


Figure 4: The process flow of bio-methanol production
Source: Lemvig Biogas

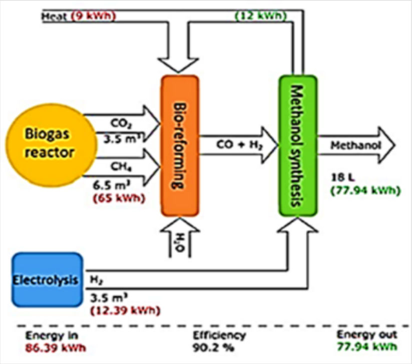


Figure 5: Energy balance
Source: Lemvig Biogas

Source: **IEA Bioenergy**

Plug for Open Modelling

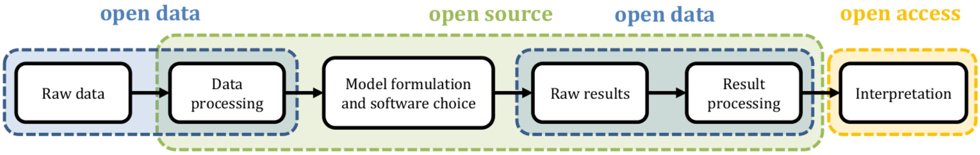
What is open modelling?

Open energy modelling means modelling with open software, open data and open publishing.

Open means that anybody is free to download the software/data/publications, inspect it, machine process it, share it with others, modify it, and redistribute the changes.

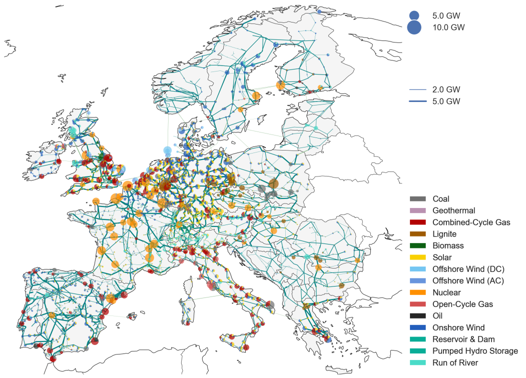
This is typically done by uploading the model to an online platform with an **open licence** telling users what their reuse rights are.

The **whole pipeline** should be open:



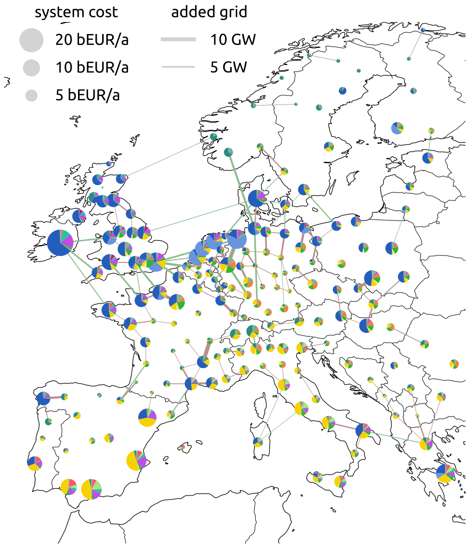
Python for Power System Analysis (PyPSA)

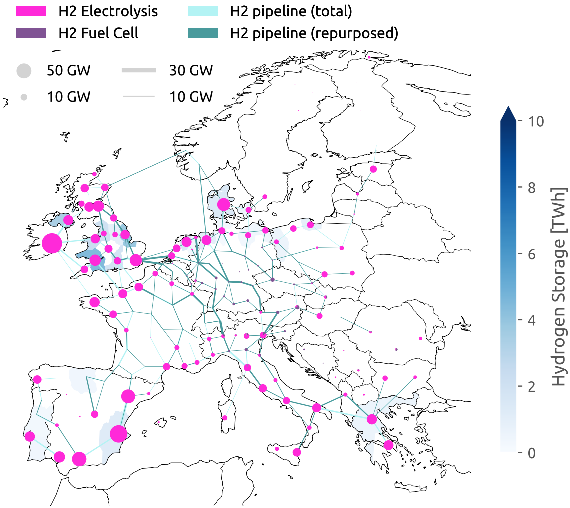
- **Open source** tool for modelling energy systems at **high resolution**.
- Fills missing gap between **power flow software** (e.g. PowerFactory, MATPOWER) and **energy system simulation software** (e.g. PLEXOS, TIMES, OSeMOSYS).
- Good grid modelling is increasingly important, for integration of **renewables** and **electrification** of transport, heating and industry.



PyPSA is available on [GitHub](). It is [used worldwide]() by researchers, consultants, TSOs and NGOs.

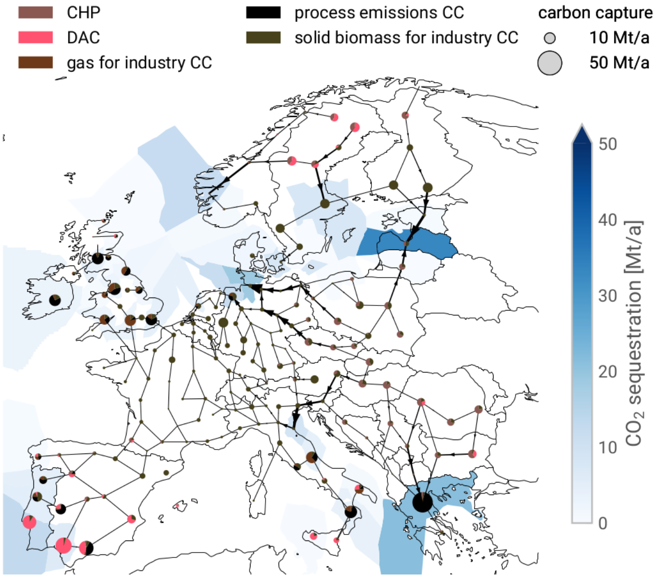
Integrated capacity expansion for electricity (left) and hydrogen (right)





Source: **Neumann et al, 2023**

How do we capture, utilise, transport and sequester carbon?



- Hydrogen economy is also linked to **carbon dioxide management**
- Need CCS for process emissions, CCU for synfuels and basic chemicals, CDR for unabatable and negative emissions
- For synthetic hydrocarbons, do we transport hydrogen to carbon sources, or carbon to hydrogen sources?
- Can we avoid hydrogen grid altogether and transport only CO_2, CH_4 and MeOH?

Source: F. Neumann, C. Tries, F. Hofmann, 2023

Conclusions

Conclusions

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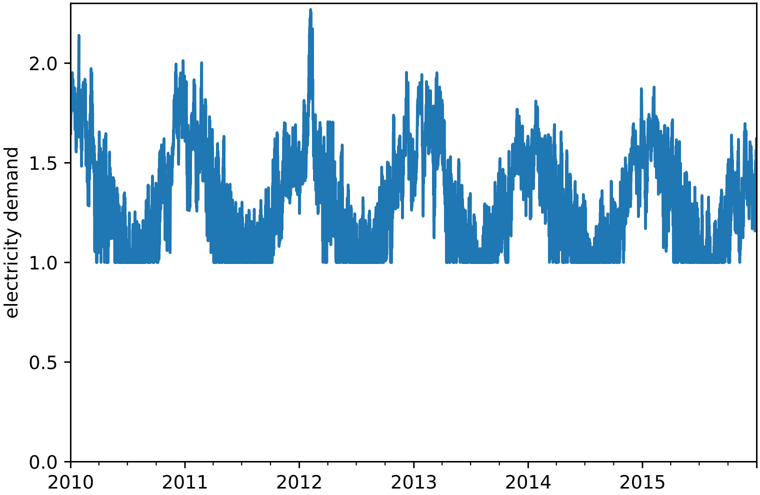
- Systems built on wind and solar will need **long-duration** storage both for variability and **resilience** against rare extreme events
- Where salt deposits are not available, **methanol storage** provides an attractive alternative, whereby carbon is **captured and cycled back** to synthesis
- System 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

Sensitivity to seasonal demand

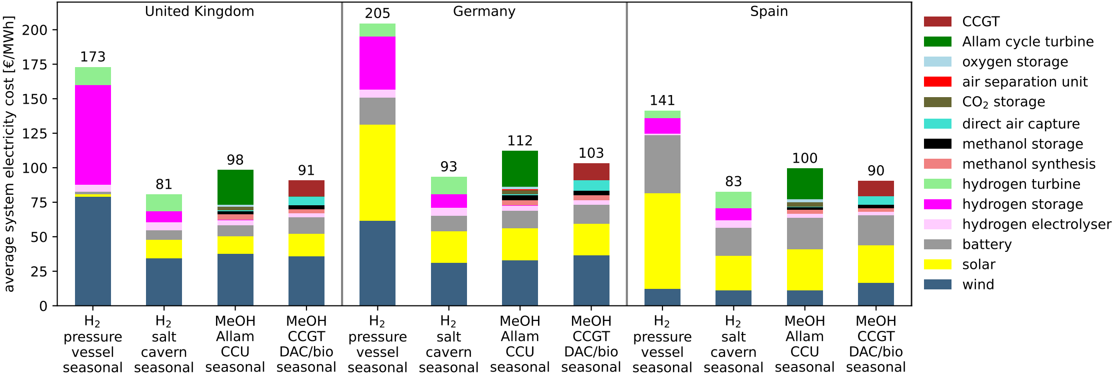
Suppose a third of demand comes from space heat pumps with **seasonal demand**.



Source: Example of Germany

Sensitivity to seasonal demand

Costs rise in all scenarios with 33% seasonal demand coming from heat pumps.



Sensitivity to CCS

Having both methanol and salt caverns; allowing CCS in Allam with fossil gas at 30 and 50 €/MWh_{th}.