Hydrogen infrastructure planning in Europe: Networks, Imports, and Industry

Fabian Neumann with contributions by Tom Brown, Elisabeth Zeyen, Marta Victoria, Johannes Hampp, Fabian Hofmann, Christoph Tries

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Article

The potential role of a hydrogen network in Europe

Fabian Neumann,[1,4,*] Elisabeth Zeyen,[1] Marta Victoria,[2,3] and Tom Brown[1]

SUMMARY

Europe's electricity transmission expansion suffers many delays, despite its significance for integrating renewable electricity. A hydrogen network reusing the existing gas network could not only help to supply the demand for low-emission fuels but could also balance variations in wind and solar energies across the continent and thus avoid power grid expansion. Our investigation varies the allowed expansion of electricity and hydrogen grids in net-zero CO_2 scenarios for a sector-coupled European energy system, capturing transmission bottlenecks, renewable supply and demand variability, and pipeline retrofitting and geological storage potentials. We find that a hydrogen network connecting regions with low-cost and abundant renewable potentials to demand centers, electrofuel production, and cavern storage sites reduces system costs by up to 26 bn€/a (3.4%). Although expanding both networks together can achieve the largest cost reductions, by 9.9%, the expansion of neither is essential for a net-zero system as long as higher costs can be accepted and flexibility options allow managing transmission bottlenecks.

CONTEXT & SCALE

Many different combinations of infrastructure could make Europe carbon neutral by mid-century, but not all solutions meet the same level of acceptance. For example, power grid reinforcements have faced many delays, despite their value for integrating renewables. A hydrogen network reusing gas pipelines could substitute for moving cheap but remote renewables across the continent to where demand is.

We study trade-offs between new transmission lines and a hydrogen network in the European energy

Hydrogen Network – Why?

1. **Hydrogen demand** for industry (e.g. steelmaking and ammonia) located in areas with less attractive renewable potentials.
2. Best **wind and solar potentials** are located in the periphery of Europe.
3. **Bottlenecks** in the electricity network and limited acceptance for reinforcement.
4. Move hydrogen to where the geological conditions allow for cheap **underground storage**.

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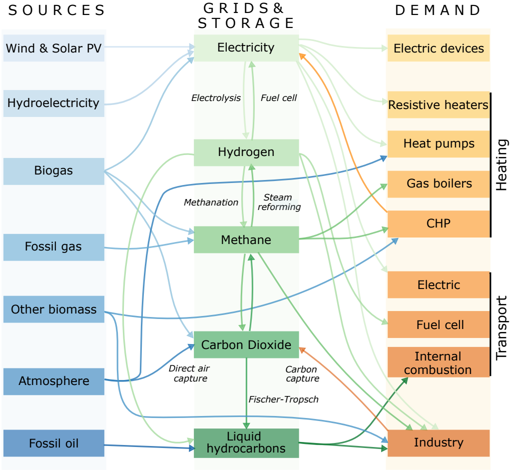
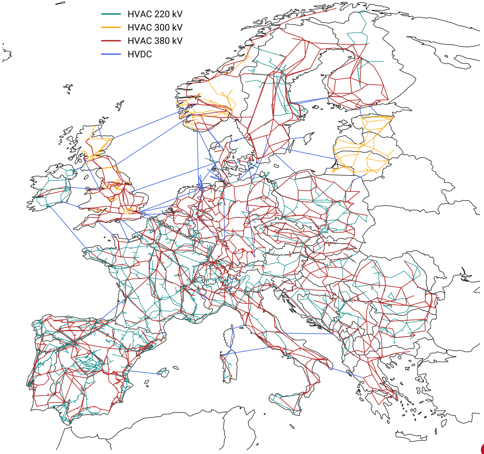
PyPSA-Eur - An open sector-coupled energy system model of Europe

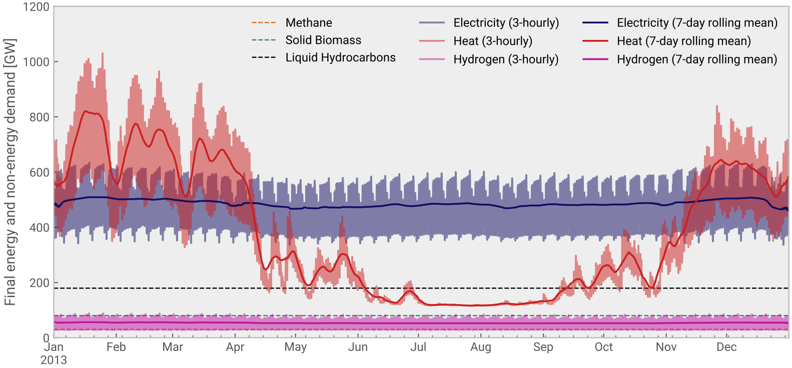
Europe with all energy and carbon flows,... … bottlenecks in energy networks...





Source: https://github.com/pypsa/pypsa-eur

… and temporal variability in demand and supply.



There are difficult periods in winter with **low** wind and solar, **high** space heating demand **low** air temperatures, which are bad for air-sourced heat pump performance

Source: https://github.com/pypsa/pypsa-eur; for similar graphic of another open energy system model based on calliope, see Pickering et al. (2022)

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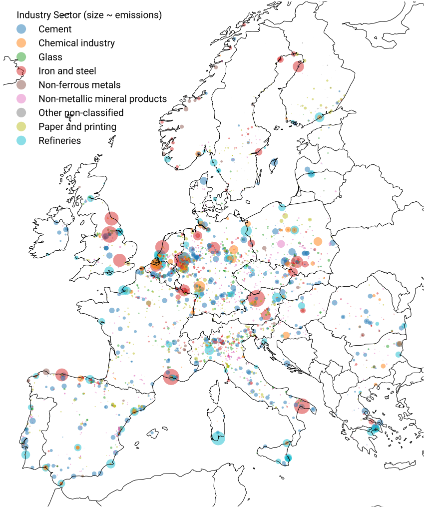
Industry: Process Switching, Carbon Management & Circular Economy



Iron & Steel	70% from scrap, rest from H_2-DRI + EAF
Aluminium	80% recycling; methane for high-enthalpy heat
Cement	Solid biomass; capture of CO_2 emissions
Ceramics	Electrification
Ammonia	Clean hydrogen
Plastics	55% recycling and synthetic naphtha
Other industry	Electrification; process heat from biomass
Shipping	Liquid hydrogen
Aviation	Kerosene from Fischer-Tropsch

Carbon is tracked through system: up to 90% of industrial emissions can be captured; biomass; direct air capture (DAC); sequestration limited to 200 $MtCO_2/a$; carbon in plastics releases into atmosphere

Source: Hotmaps Industrial Sites Database

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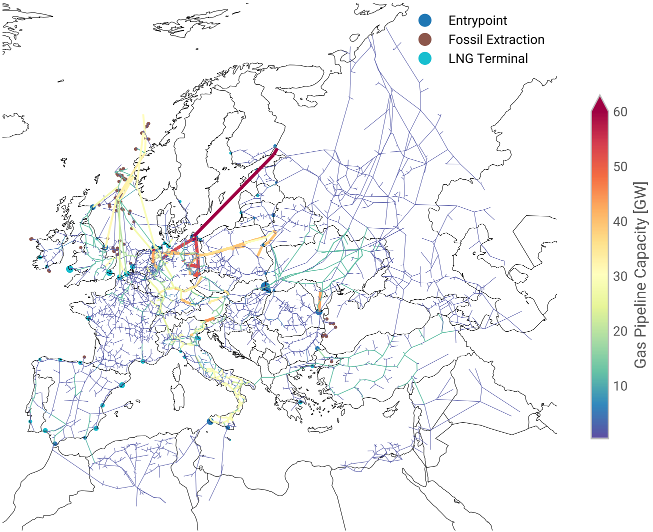
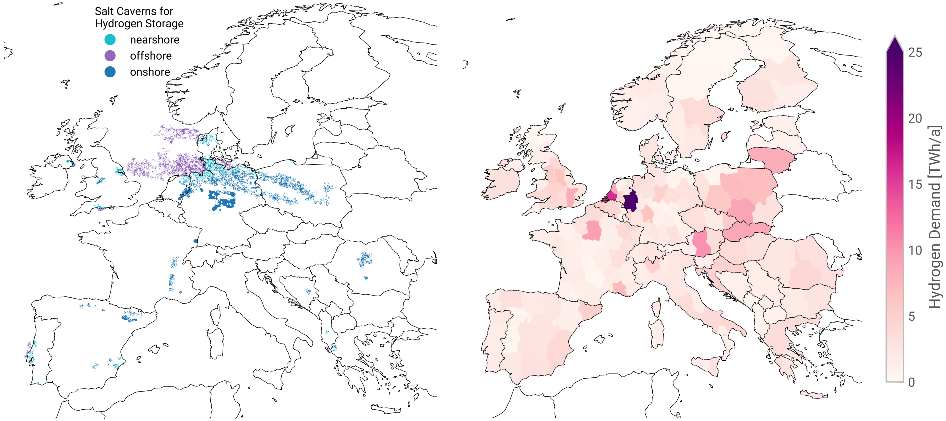
Gas transmission network with LNG terminals and retrofitting potentials



- open dataset of European gas transmission network from **SciGRID_gas**
- retrofitting potentials for **existing gas pipelines** to transport hydrogen
- for imports: supplement dataset with **existing and planned LNG terminals** from `www.gem.wiki`

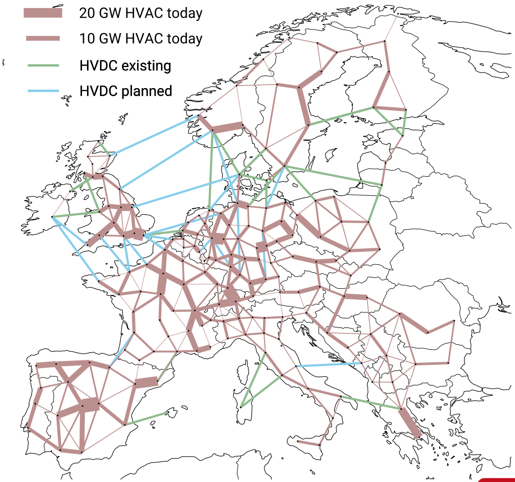
Source: SciGRID_gas, `https://www.gas.scigrid.de/`, Pluta et al. (2022)

Hydrogen cavern storage potentials in Europe



Scenarios for a European energy system with net-zero CO_2 emissions

- Couple **all energy sectors** (power, heat, transport, industry, feedstocks, agriculture, int. aviation & shipping)
- Cluster to 181 regions, 3-hourly time series
- Reduce net CO_2 emissions **to zero**
- **Technology assumptions** for 2030 (DEA)
- CO_2 sequestration limited to **200 Mt/a**
- Vary allowed electricity and hydrogen **network expansion**
- First: Europe energy **self-sufficient**
- Later: Vary **import volumes and carriers**



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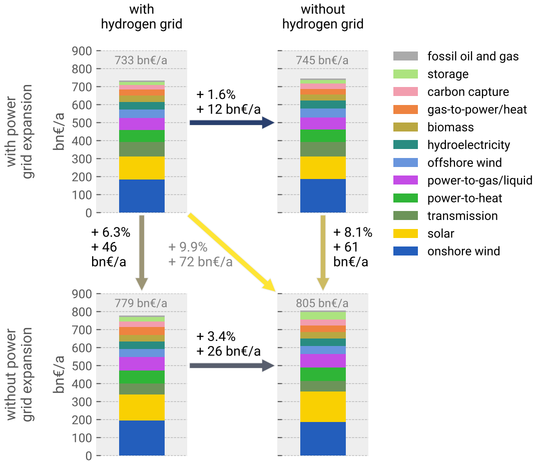
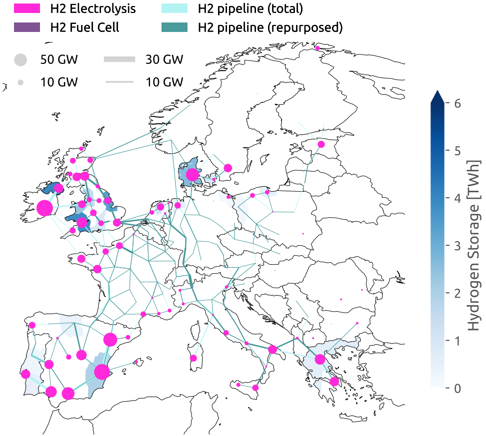
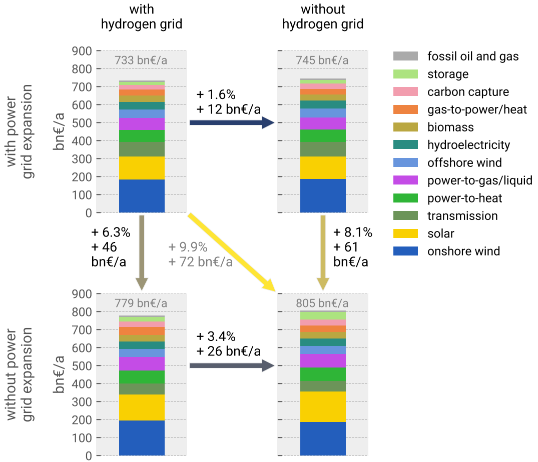
Comparison of power and hydrogen network infrastructure benefits

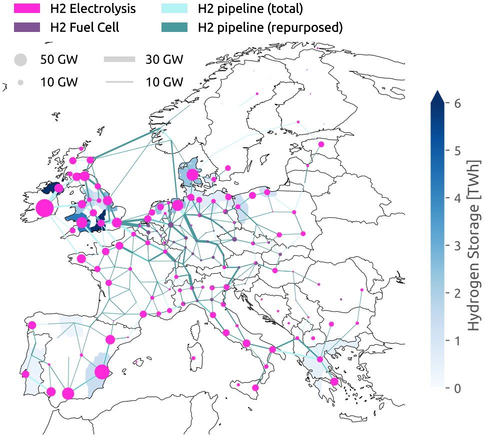




→ transmission expansion scenarios with **self-sufficient, net-zero CO_2 European supply**

Comparison of power and hydrogen network infrastructure benefits





→ transmission expansion scenarios with **self-sufficient, net-zero CO_2 European supply**

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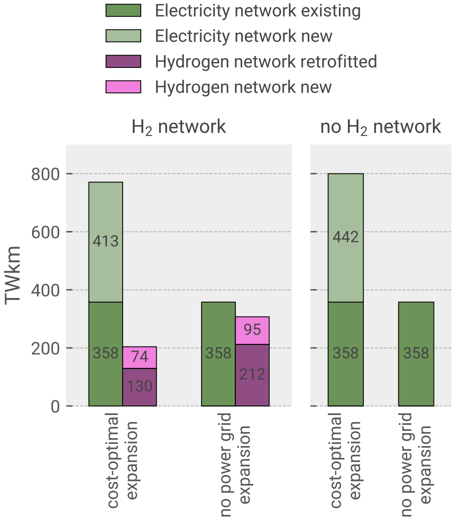
Electricity and hydrogen grid expansion and level of retrofitting



- **Up to 69%** of hydrogen backbone can repurpose existing gas network
- **Up to a third** of the gas transmisison network is retrofitted
- If grid expansion is disallowed, H_2 grid **transmits 2x more energy** than AC grid

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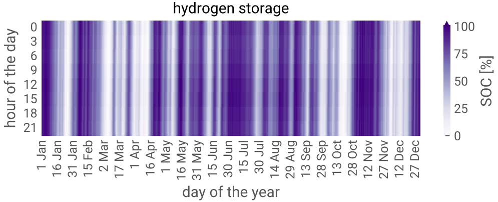
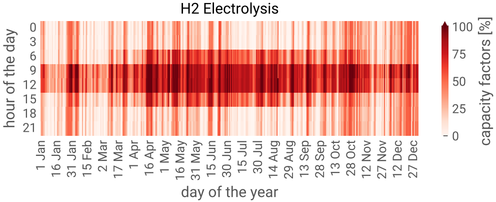
Two remarks on operational patterns of hydrogen technologies

Hydrogen acts mainly as **intermediary buffer** between
variable electricity feed-in and other more stable PtX processes.

Flexible electrolyser operation important,
but requires local and dynamic price signals to become reality.





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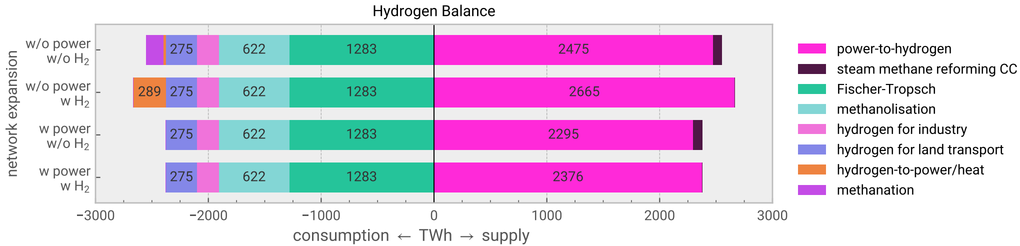
Hydrogen balance



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

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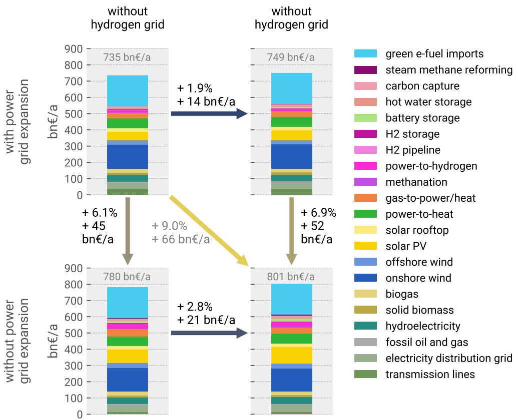
Which hydrogen demand sectors really need a hydrogen network?

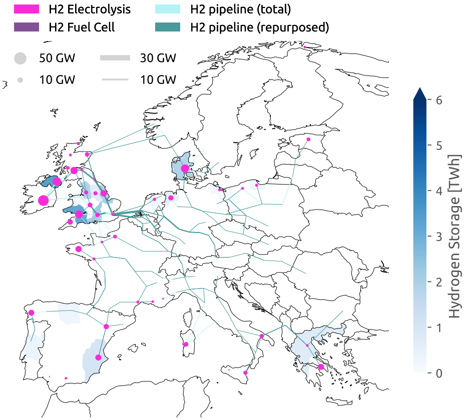
For potential hydrogen demand sectors, a hydrogen network can be attractive if low cost H_2 is not locally available. But for each sector there are **alternatives to transporting hydrogen**.

sector	alternative
backup power and district heat	use derivative fuels (e-methane, e-methanol)
process heat	electrify/use derivative fuels
heavy duty trucks	use battery electric vehicles
iron direct reduction	industry relocates to cluster/abroad
ammonia	industry relocates to cluster/abroad
high-value chemicals	transport/import derivative precursors instead
shipping	transport/import derivative fuels instead
aviation	transport/import derivative fuels instead

→ There is no strict need for a hydrogen network, but it may be easier and/or cheaper

Do results change with synthetic fuels from outside Europe?





→ with all liquid hydrocarbons imported, **infrastructure needs** for networks and PtX drop

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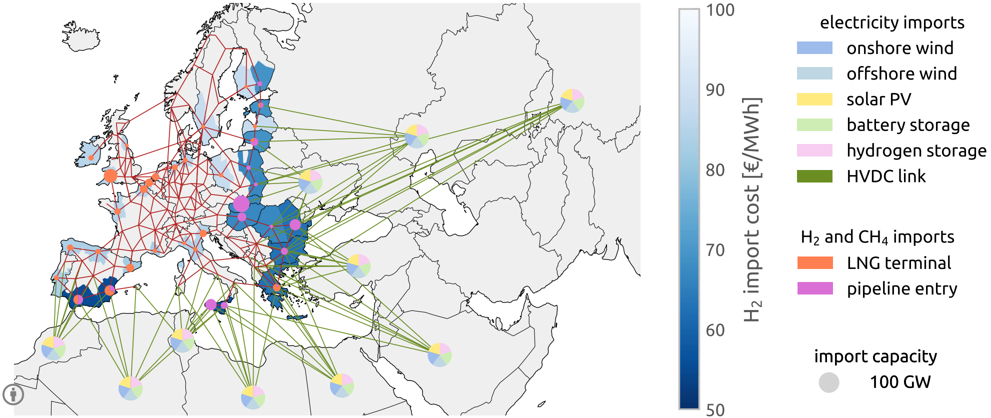
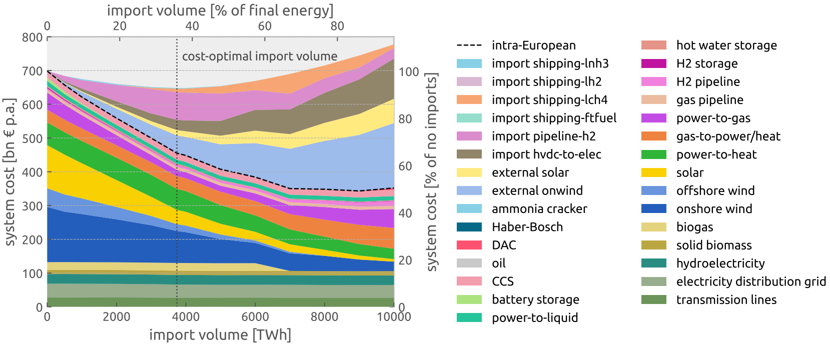
Locations and costs for imports vary by energy carrier

electricity imports endogenously optimised, **gaseous carrier imports** where LNG terminals and pipelines exist

electricity	37-57 €/MWh		**H_2 (pipeline/ship)**	55-88 €/MWh		← spatially resolved
CH_4 (LNG)	88-90 €/MWh	[AR]	**CH_4 (pipeline)**	100 €/MWh	[DZ]	← spatially resolved
NH_3	85 €/MWh	[AR]	**liquid hydrocarbons**	115 €/MWh	[AR]	← no spatial constraints



Effect of increasing energy imports on costs and European infrastructure

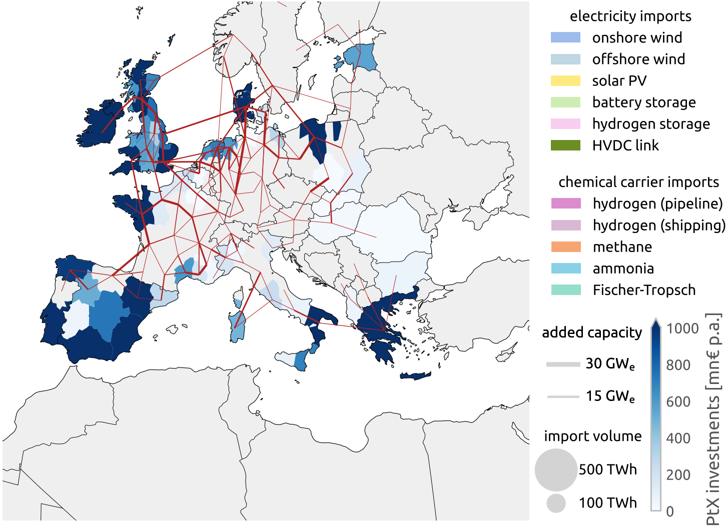


→ cost-optimal import volume **3750 TWh** (of which 60% electricity, 40% hydrogen)

→ half of the **7%** cost-benefit can be achieved with imports below **1000 TWh**

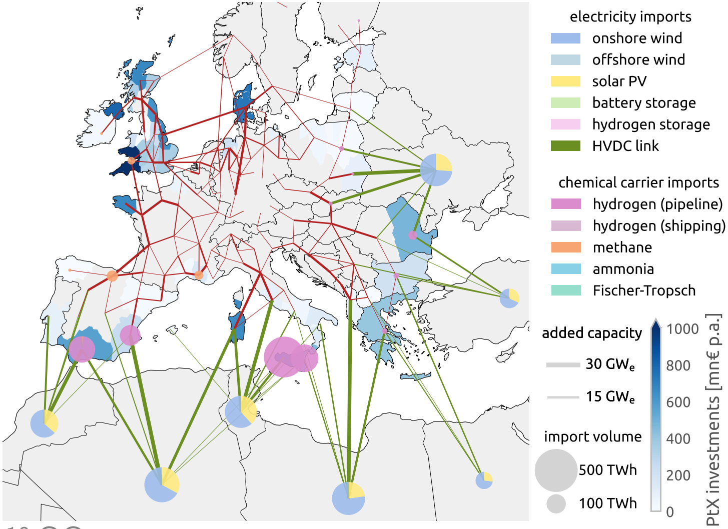
→ solution space is **very flat** in a wide range between **imports of 0 and 8000 TWh**

European **self-sufficient** energy supply infrastructure without imports



- large **PtX production** within Europe to cover demands for steel, plastics, e-chemicals, e-kerosene etc.
- concentrated in Southern Europe and the British Isles
- **electricity grid reinforcements** focused mostly in Northwest Europe

European energy supply infrastructure with imports and **flexible** carrier

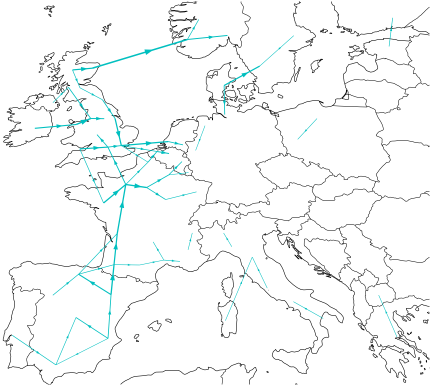


- much less **PtX production** owing to imported hydrogen
- some power grid expansion **diverted to South Europe** to absorb inbound power
- Why power and H_2 even though they require grid infrastructure unlike e-fuels?
- **Assumption 1:** waste heat of PtX for district heating
- **Assumption 2:** DAC for carbon outside of Europe, point sources inside of Europe

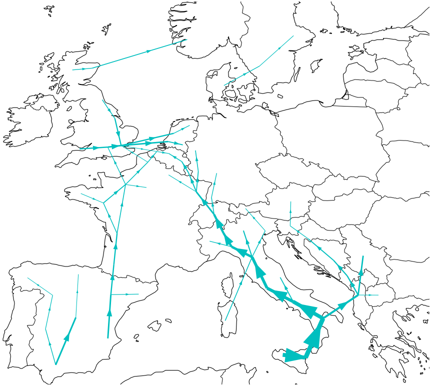
Increased energy imports change the role of the hydrogen network. . .

. . . from distributing hydrogen from **North Sea** to transporting imports **from North Africa**

without imports

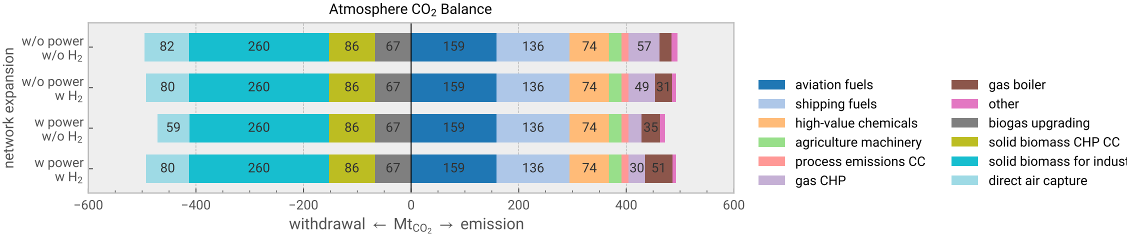


with imports



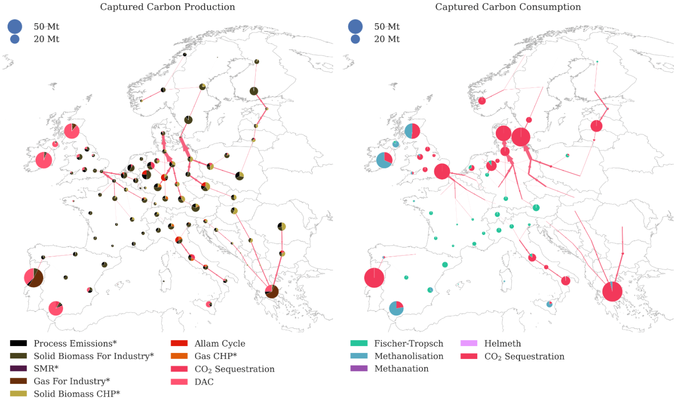
With imports, network capacity increases by 30% and energy transported by 70%.

Hydrogen economy is also linked to carbon management in net-zero.



- 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)

Transport hydrogen to carbon sources, or carbon to hydrogen sources?



Potential **spatial mismatch** between industrial point sources of CO_2, geological sequestration potential and availability of cheap hydrogen for derivative synthesis. **Pipeline network** for liquid CO_2 might reduce costs, esp. for large sequestration.

Source: Hofmann et al. (2023)

Wrap-Up

- Hydrogen network could **reduce system cost by up to 3.4%**, not as high as power grid
- Up to **69%** of hydrogen network uses **retrofitted gas network pipelines**
- No network expansion also feasible, but **at cost surcharge of 10%**
- Imports of green energy reduce cost of **net-zero European energy system by 7%**.
- Other factors than costs might rather drive import strategy: **geopolitical** considerations, building **simple & easy-to-implement** systems, **reuse** of existing infrastructure, **resilience** of supply chains, **technology risk**, diversification, and land usage.
- Results **depend strongly on assumptions**: more work on import cost sensitivities, industry relocation, material imports, circular carbon economy, fuel and process switching, endogenous technological learning etc.

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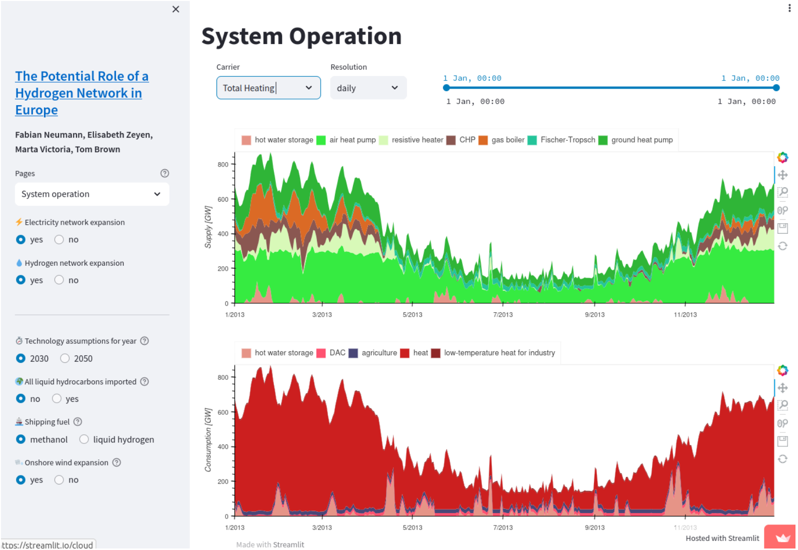
Interactive Dashboard: h2-network.streamlit.app



Contact, License, Additional Resources

Find the slides:

https://neumann.fyi/files/sustained-copenhagen.pdf

Find out more about PyPSA:

https://pypsa.org

Find the open energy system model:

https://github.com/pypsa/pypsa-eur

Send an email:

mailto:f.neumann@tu-berlin.de

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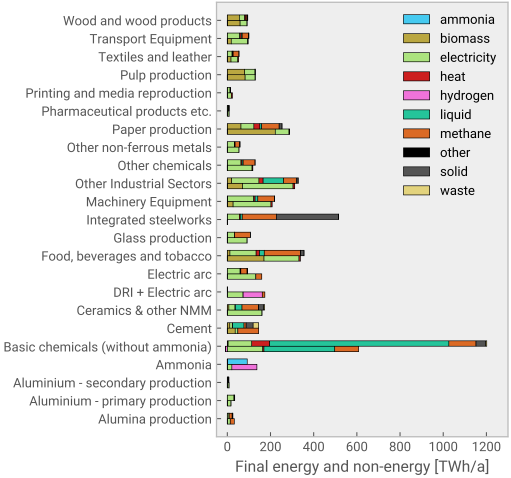
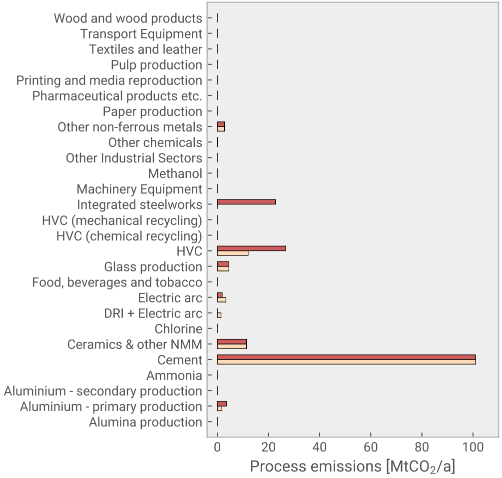
Industry Sector – Demand and Process Emissions





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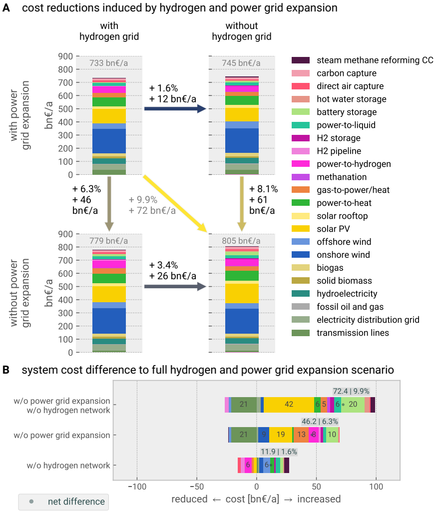
Technology Choices: Exogenous versus Endogenous

Exogenous assumptions (modeller chooses):

- energy services demand
- electricity for road transport
- kerosene for aviation
- hydrogen for shipping
- steel production in 2050: H_2-DRI + EAF
- electrification & recycling in industry
- district heating shares

Endogenous assumptions (model optimises):

- electricity generation fleet
- transmission reinforcement
- space and water heating technologies
- all P2X infrastructure
- V2G and other demand-side management
- supply of process heat for industry
- carbon capture



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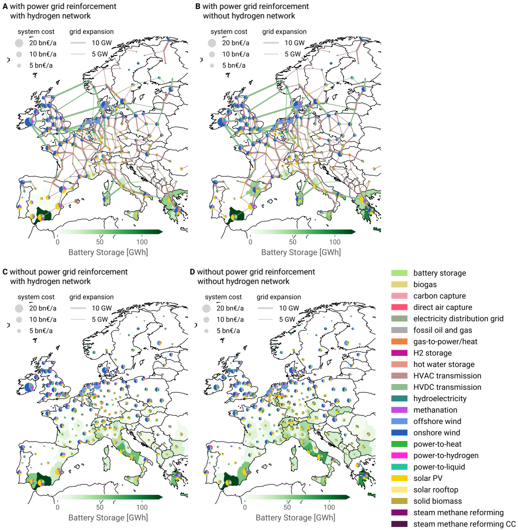
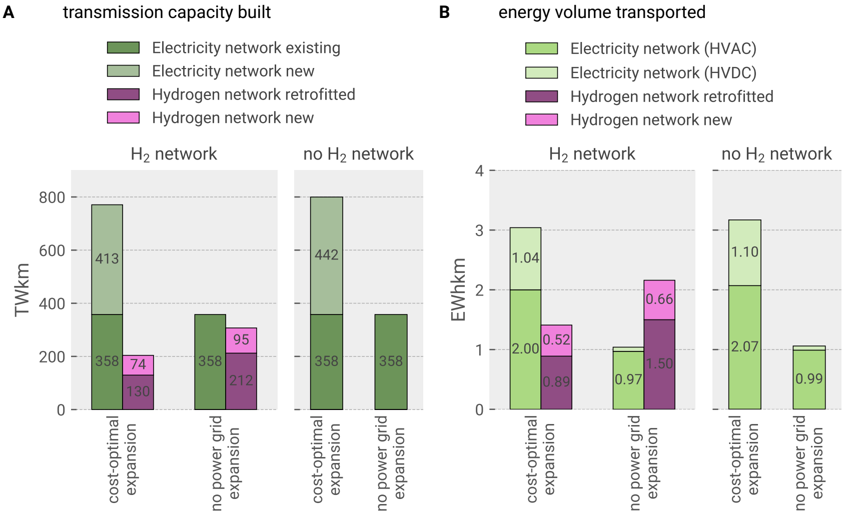
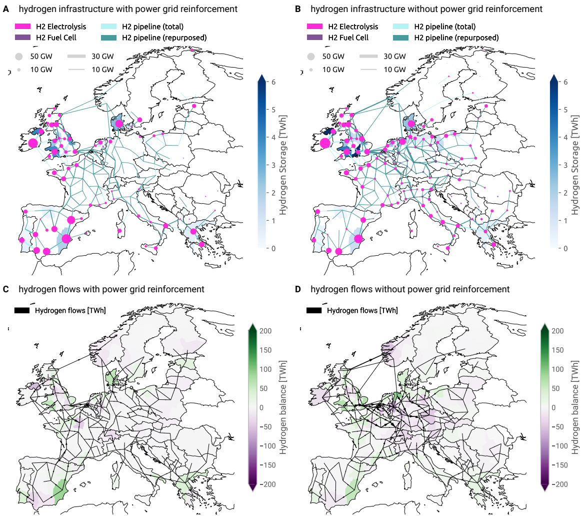

A with power grid reinforcement with hydrogen network
B with power grid reinforcement without hydrogen network
C without power grid reinforcement with hydrogen network
D without power grid reinforcement without hydrogen network
system cost
20 bn€/a
10 bn€/a
5 bn€/a
grid expansion
10 GW
5 GW
0
50
100
Battery Storage [GWh]
battery storage
biogas
carbon capture
direct air capture
electricity distribution grid
fossil oil and gas
gas-to-power/heat
H2 storage
hot water storage
HVAC transmission
HVDC transmission
hydroelectricity
methanation
offshore wind
onshore wind
power-to-heat
power-to-hydrogen
power-to-liquid
solar PV
solar rooftop
solid biomass
steam methane reforming
steam methane reforming CC


A
transmission capacity built
Electricity network existing
Electricity network new
Hydrogen network retrofitted
Hydrogen network new
H_2 network
no H_2 network
TWkm
800
600
400
200
0
413
358
74
130
358
95
212
442
358
358
cost-optimal expansion
no power grid expansion
B
energy volume transported
Electricity network (HVAC)
Electricity network (HVDC)
Hydrogen network retrofitted
Hydrogen network new
H_2 network
no H_2 network
EWhkm
4
3
2
1
0
1.04
2.00
0.52
0.89
0.97
0.66
1.50
1.10
2.07
0.99
cost-optimal expansion
no power grid expansion



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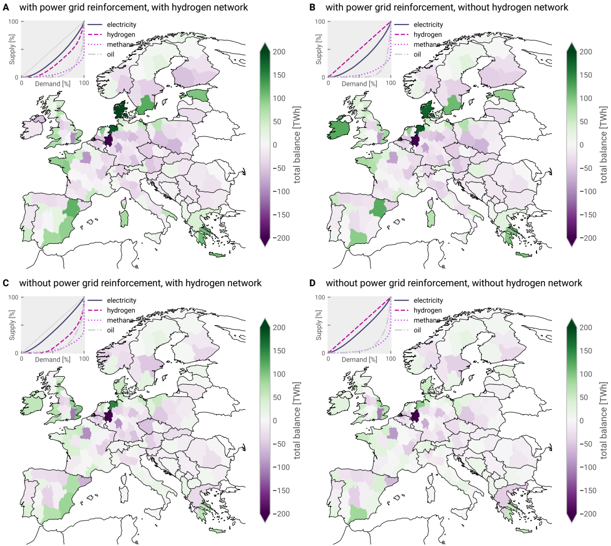
A with power grid reinforcement, with hydrogen network
B with power grid reinforcement, without hydrogen network
C without power grid reinforcement, with hydrogen network
D without power grid reinforcement, without hydrogen network
Supply [%]
Demand [%]
0
100
electricity
hydrogen
methane
oil
total balance [TWh]
200
150
100
50
0
−50
−100
−150
−200