

Energy Imports and Infrastructure in a Climate-Neutral European Energy System

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Introduction

Energy infrastructure to achieve net-zero does not always meet high levels of acceptance.

Other parts of the world have **cheap and abundant renewables** to offer in global markets.

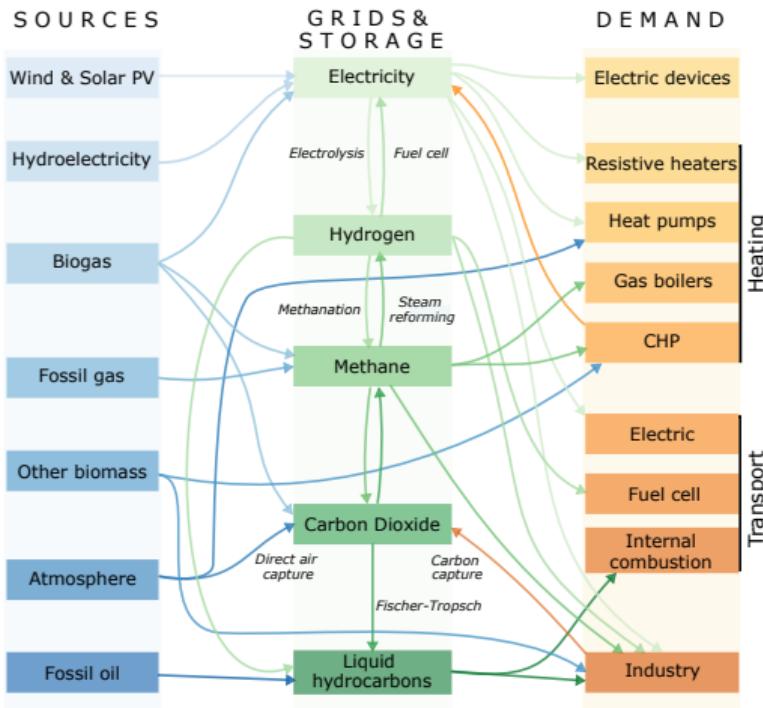
Trade-offs between full **self-sufficiency** and wide-ranging **energy imports** from outside Europe:

- cost reductions through energy imports?
 - from where to import?
 - to where to import?
- infrastructure needs inside Europe?

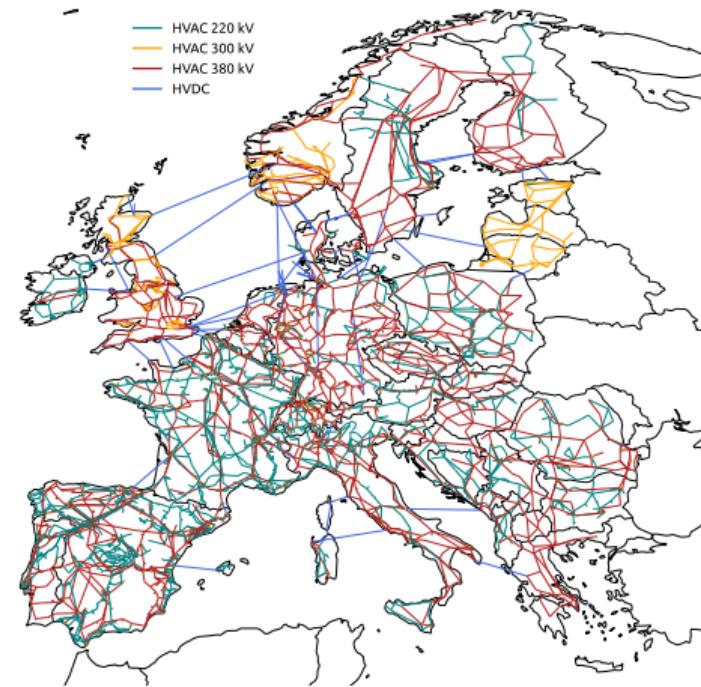
Coupling of a **global supply chain model** with open all-sector **European energy model**.

PyPSA-Eur-Sec - An open sector-coupled model of Europe

Model for Europe with all energy flows...

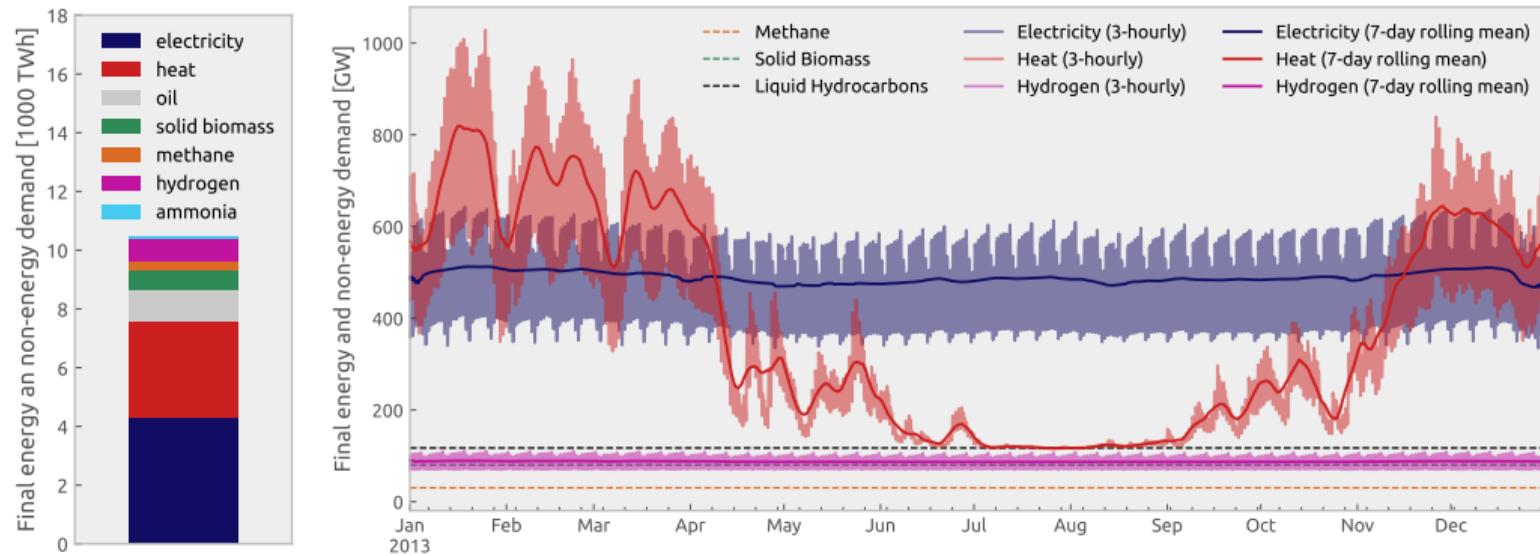


...and bottlenecks in energy networks...



Source: <https://github.com/pypsa/pypsa-eur-sec>

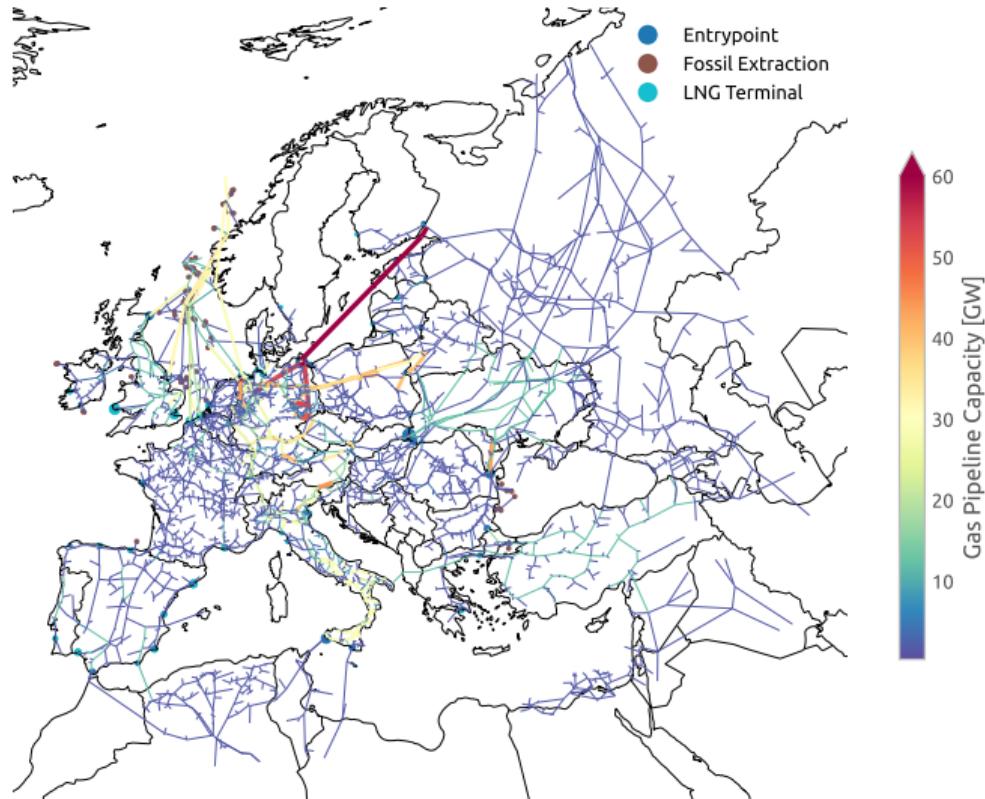
... and temporal variability in demand and supply.



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-sec>; for similar graphic of another open energy system model based on calliope, see Pickering et al. (2022)

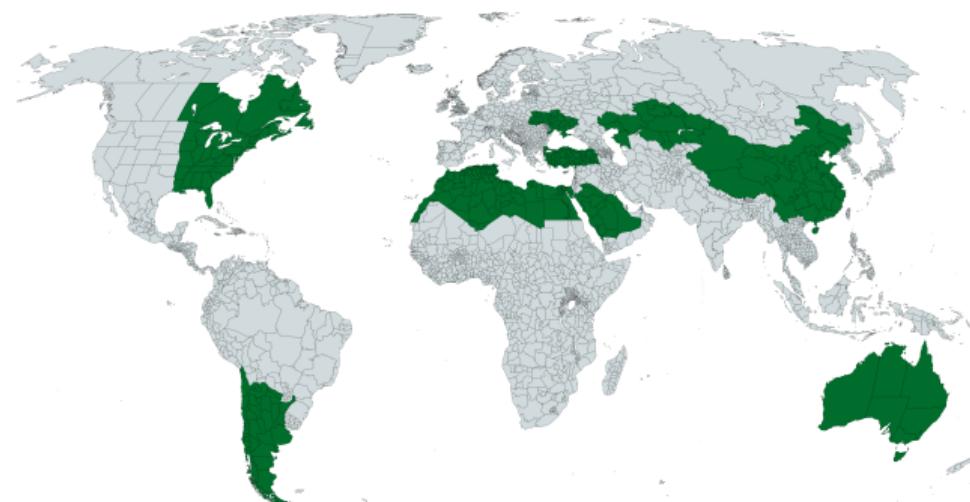
Gas transmission network with LNG terminals and pipeline entrypoints



- incorporate open dataset of European gas transmission network from **SciGRID_gas** project into PyPSA-Eur-Sec
- supplement dataset with **existing and planned LNG terminals** from www.gem.wiki

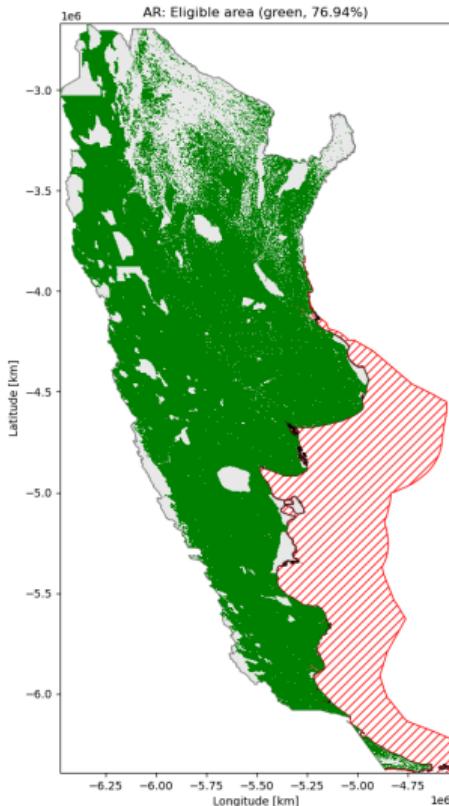
Model of global green energy supply chains – exporting regions

- **16 exporting regions**
- **Potential export carriers**
 - hydrogen (pipeline, ship)
 - methane (pipeline, ship)
 - ammonia (ship)
 - Fischer-Tropsch fuels (ship)
 - electricity (HVDC)
- **Import corridors into Europe**
 - **7 sea routes** (Atlantic, North Sea, Baltic Sea, Mediterranean)
 - **6 pipeline/HVDC routes** (Southern/Eastern Europe)

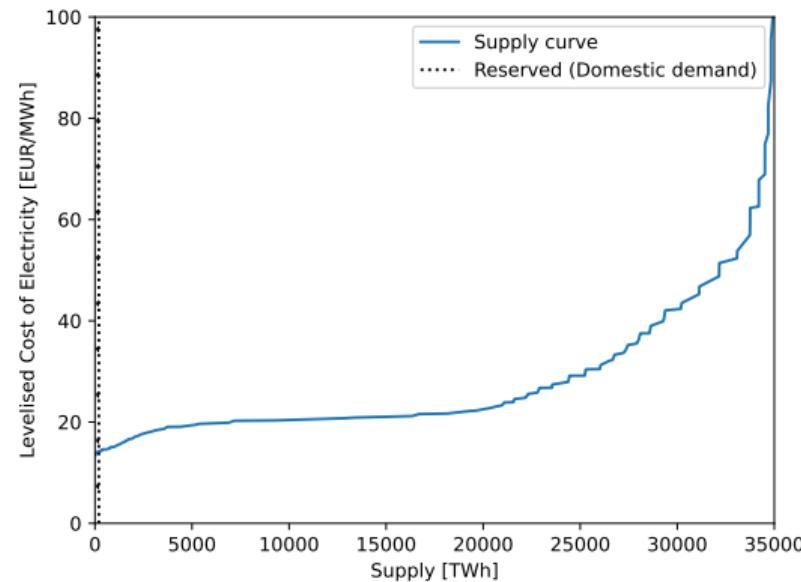


Source: <https://github.com/euronunion/trace>, see also
IRENA Global Hydrogen Trade Outlook

Model of global green energy supply chains – renewable electricity



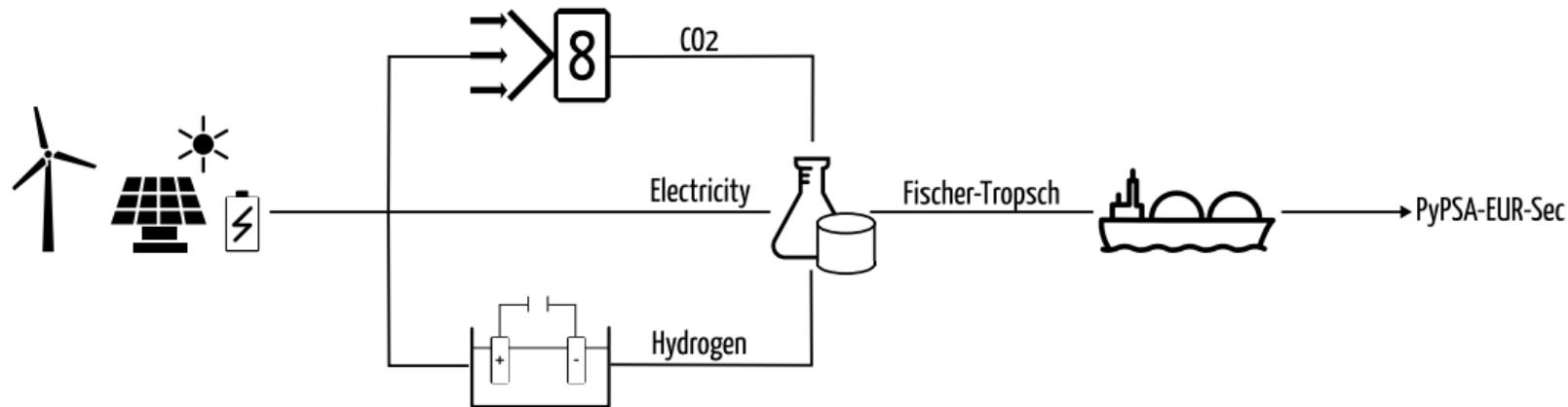
hourly solar PV, on-/offshore wind subject to eligible land grouped into classes for **regional supply curves** – domestic demand



Source: <https://github.com/euronunion/trace>, see also
IRENA Global Hydrogen Trade Outlook

Model of global green energy supply chains – import costs

- **Optimised investment** in supply chain components
- **Result:** supply curve for levelised cost of energy (€/MWh), ...
- **Example** for Fischer-Tropsch energy supply chain:

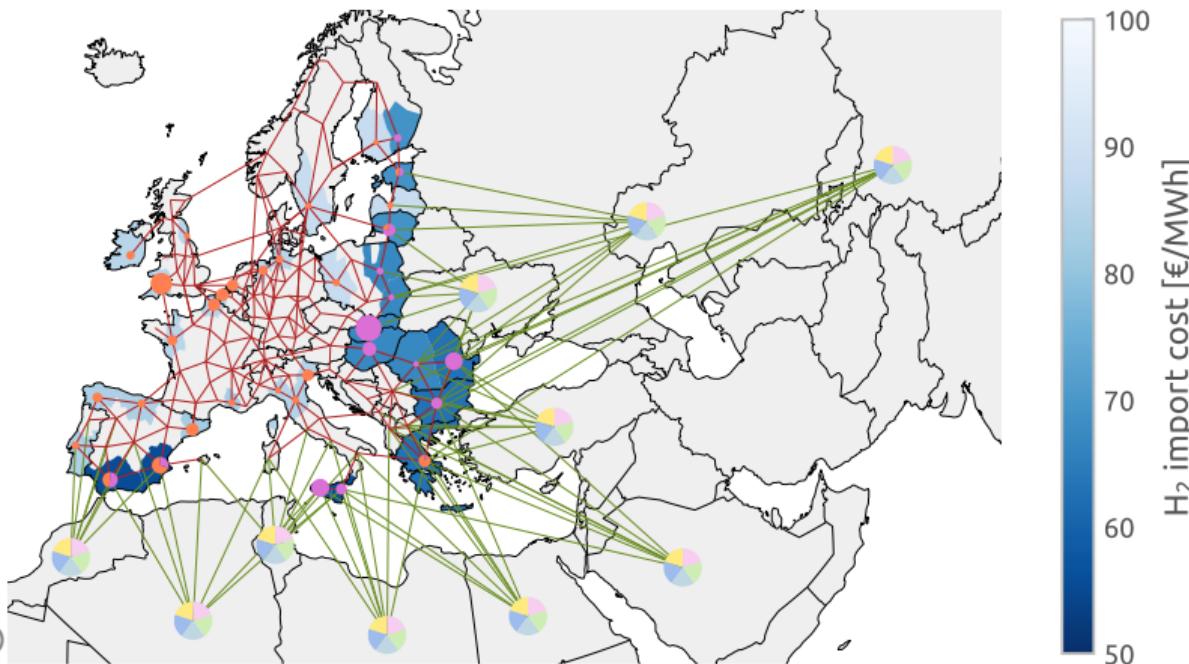


Source: <https://github.com/euronunion/trace>, see also
IRENA Global Hydrogen Trade Outlook

Locations and costs for imports vary by energy carrier

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

NH₃	85 €/MWh	[AR, CL]	Fischer-Tropsch	115 €/MWh	[AR, CL]	← single EU node
CH₄ (LNG)	89 €/MWh	[AR, CL]	CH₄ (pipeline)	100 €/MWh	[DZ]	← spatially resolved



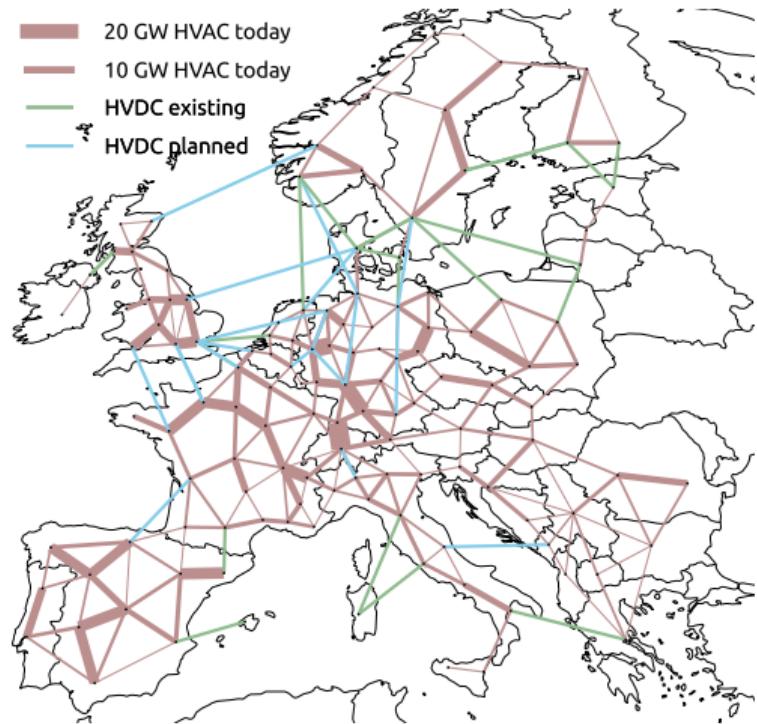
- electricity imports
- onshore wind
- offshore wind
- solar PV
- battery storage
- hydrogen storage
- HVDC link

- H₂ and CH₄ imports
- LNG terminal
- pipeline entry

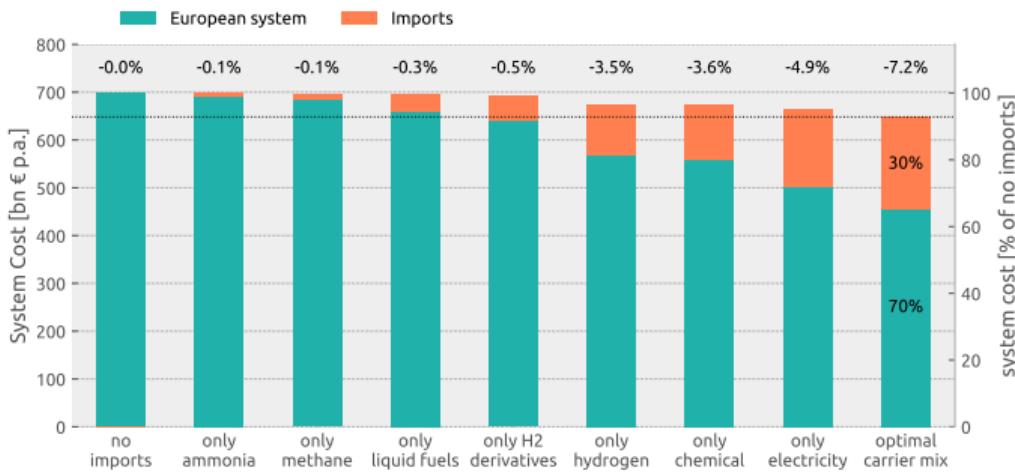
import capacity
100 GW

Import scenarios for a European system with net-zero CO₂ emissions

- couple **all energy sectors** (power, heat, transport, industry, feedstocks, agriculture, international aviation & shipping)
- reduce net CO₂ emissions **to zero**
- cluster to **128** regions, **3-hourly timesteps**
- power (x2), gas and hydrogen **networks**
- technology assumptions for **2030** (DEA)
- CO₂ sequestration below **200 MtCO₂/a**
- vary **import volumes** and **carriers**

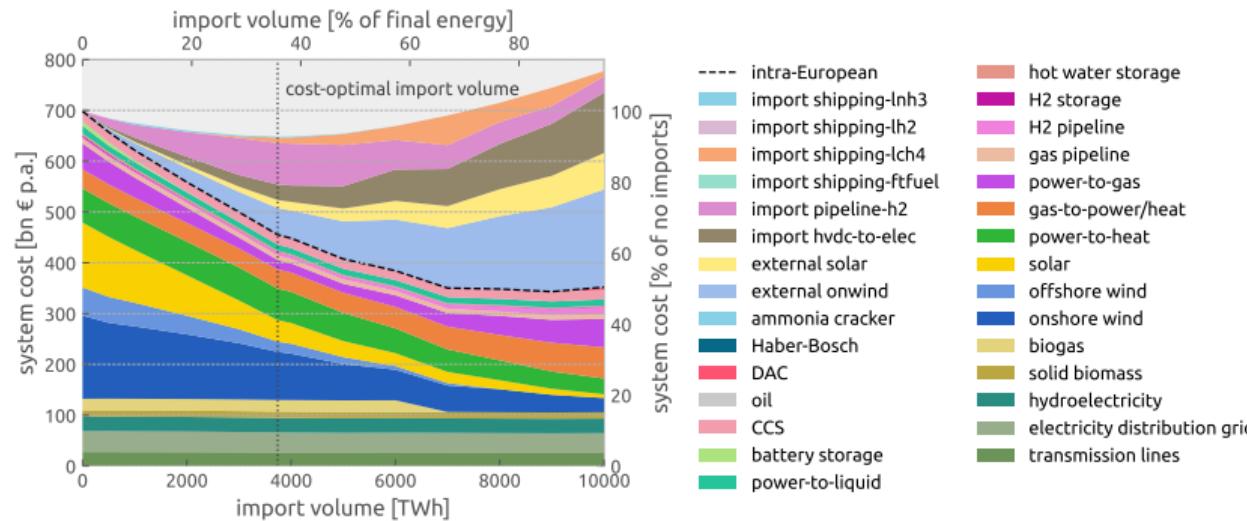


Preliminary: Cost reduction by imports depends on available options



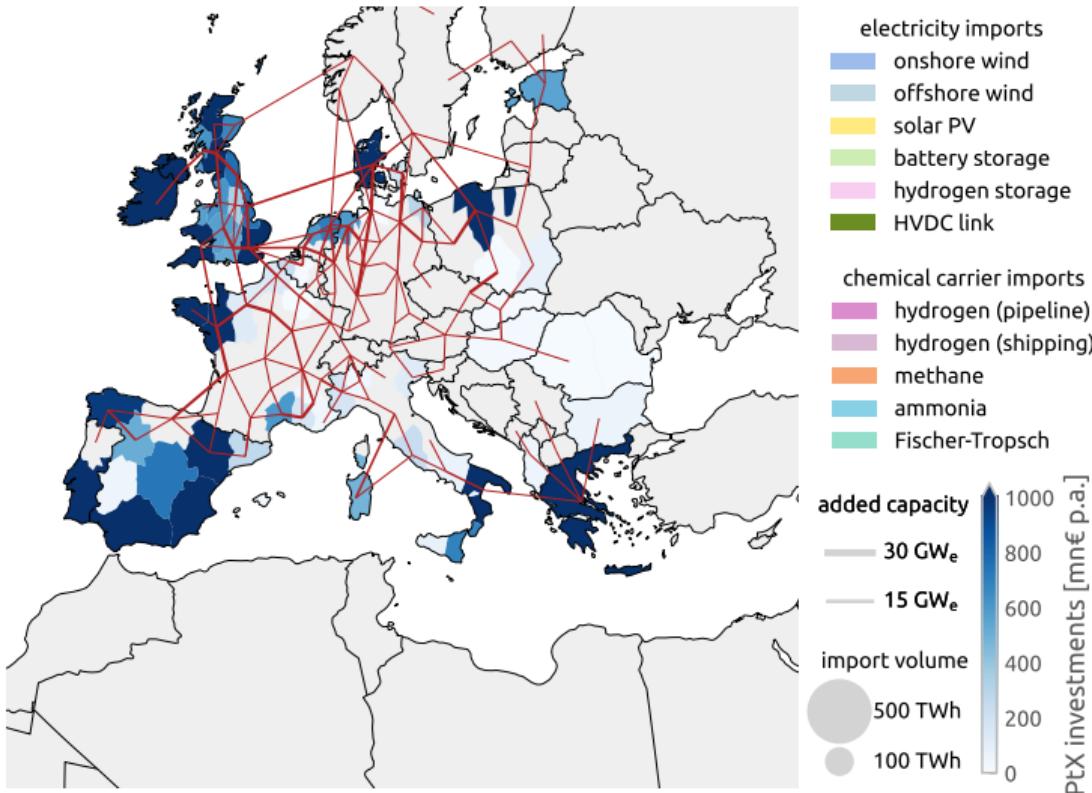
- cost benefit of energy imports limited to **7%**
- half of the benefit can be achieved with **exclusive hydrogen imports**
- a cost reduction by 5% can be achieved with **exclusive electricity imports**
- up to **30%** of system cost is spent on energy imports

Preliminary: System cost configurations with increasing energy imports



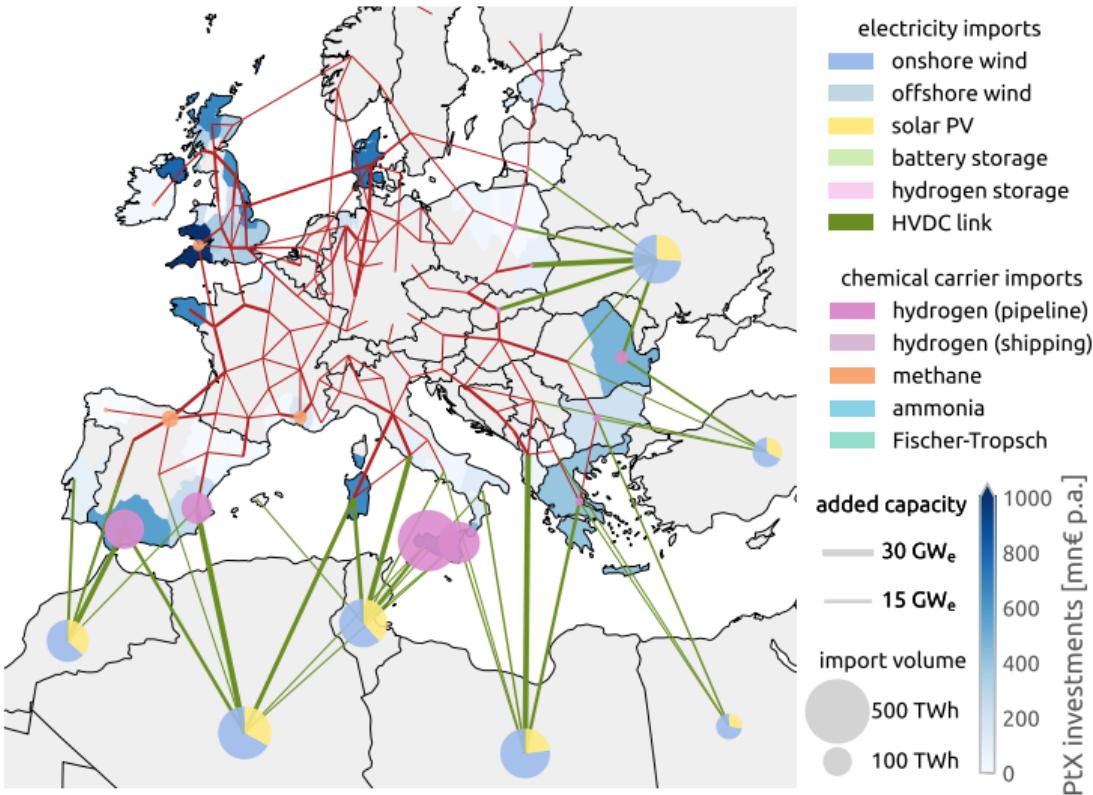
- cost-optimal import volume **3750 TWh** (of which 59% electricity, 39% hydrogen)
- half of the **7%** cost-benefit can be achieved with imports below **1000 TWh**
- solution space is **very flat** in a wide range between **imports of 0 and 8000 TWh**

Preliminary: European self-sufficient energy supply without imports



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

Preliminary: European energy supply 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
- electricity imports **distribute evenly** across exporting countries to facilitate grid integration
- **both wind and solar** in exporting countries for seasonal balancing

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

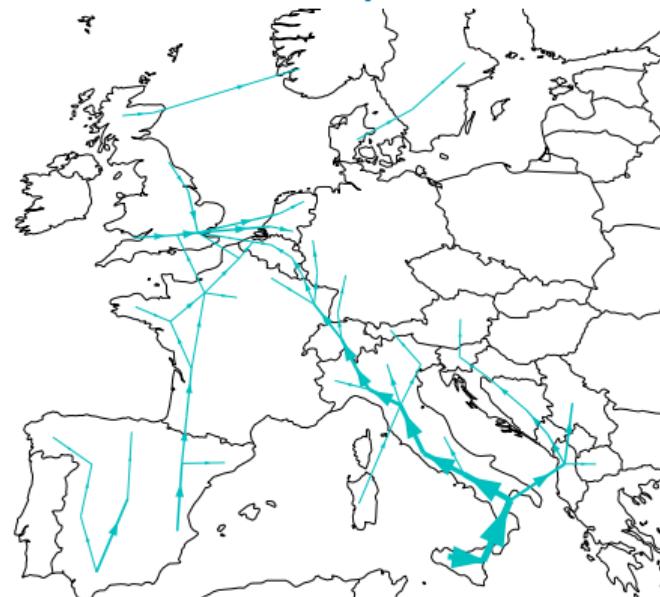
... from distributing hydrogen from **North Sea** to transporting imports **from North-Africa**

without imports



network capacity +30%

with imports

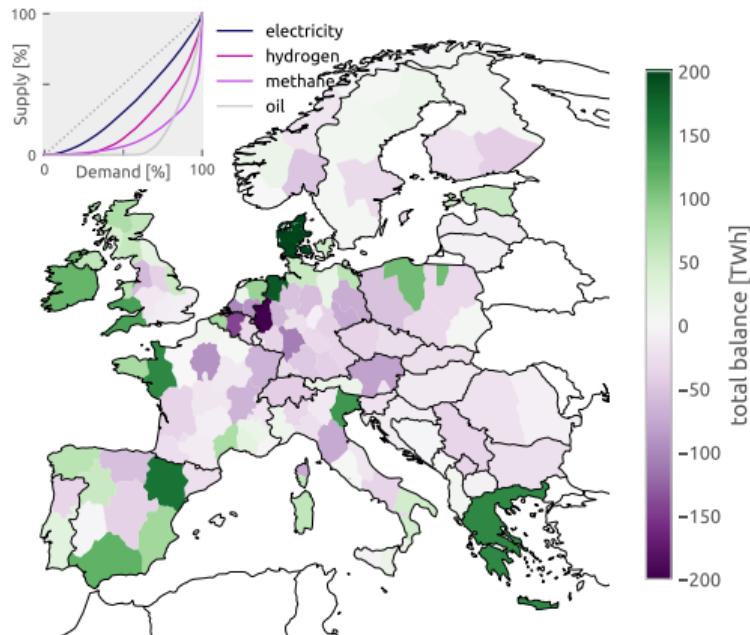


energy transported +70%

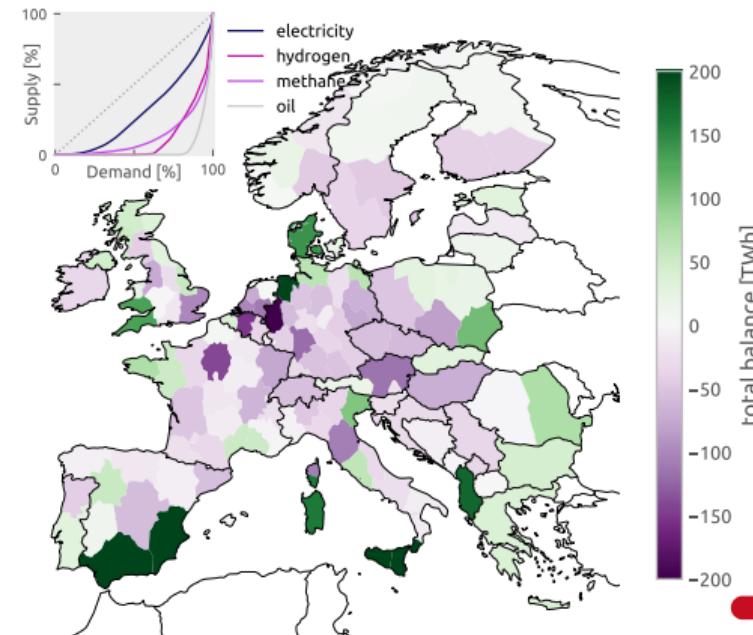
Regional energy imbalance reinforced by import options...

... but overall less energy infrastructure (wind, solar, grids) inside Europe.

without imports



with imports



Preliminary Conclusions

- Imports of green energy reduce cost of **net-zero European energy system by 7%**.
- **European infrastructure requirements** depend on strategy taken on energy imports.
- Other factors than pure costs might rather drive import strategy: **geopolitical** considerations, building **simple & easy-to-implement** systems, **reuse** of existing infrastructure, **resilience** of supply chains, **technology risk**.
- All results **depend strongly on assumptions**: more work on import cost sensitivities, losses in European energy networks, industry relocation, and material imports.

Contact, License, Additional Resources

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Find the slides:

<https://neumann.fyi/files/ecemp-import-benefits.pdf>

Find out more about PyPSA:

<https://pypsa.org>

Find the open energy system model:

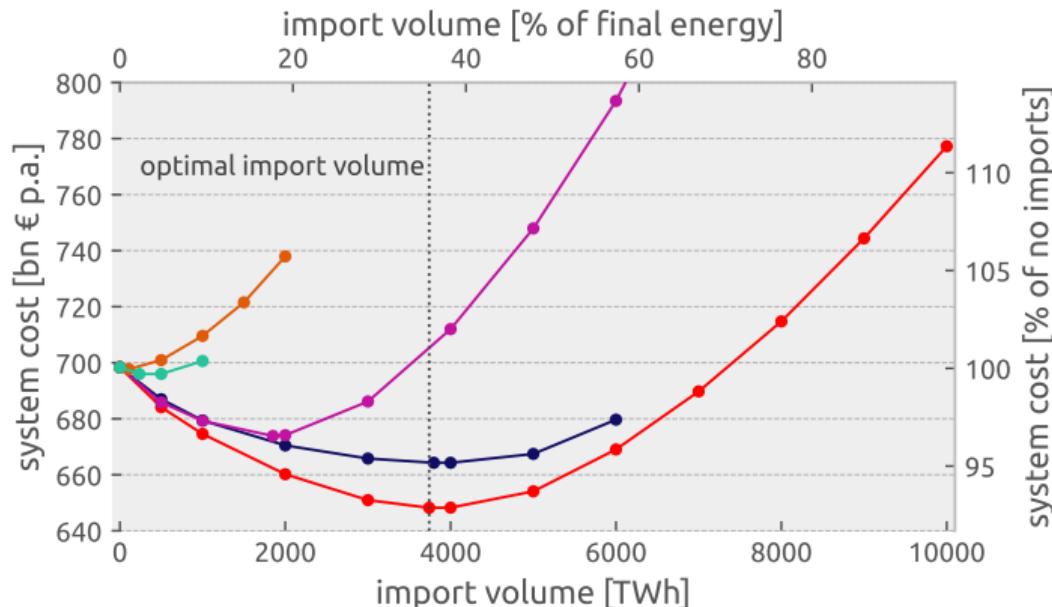
<https://github.com/pypsa/pypsa-eur-sec>

Send an email:

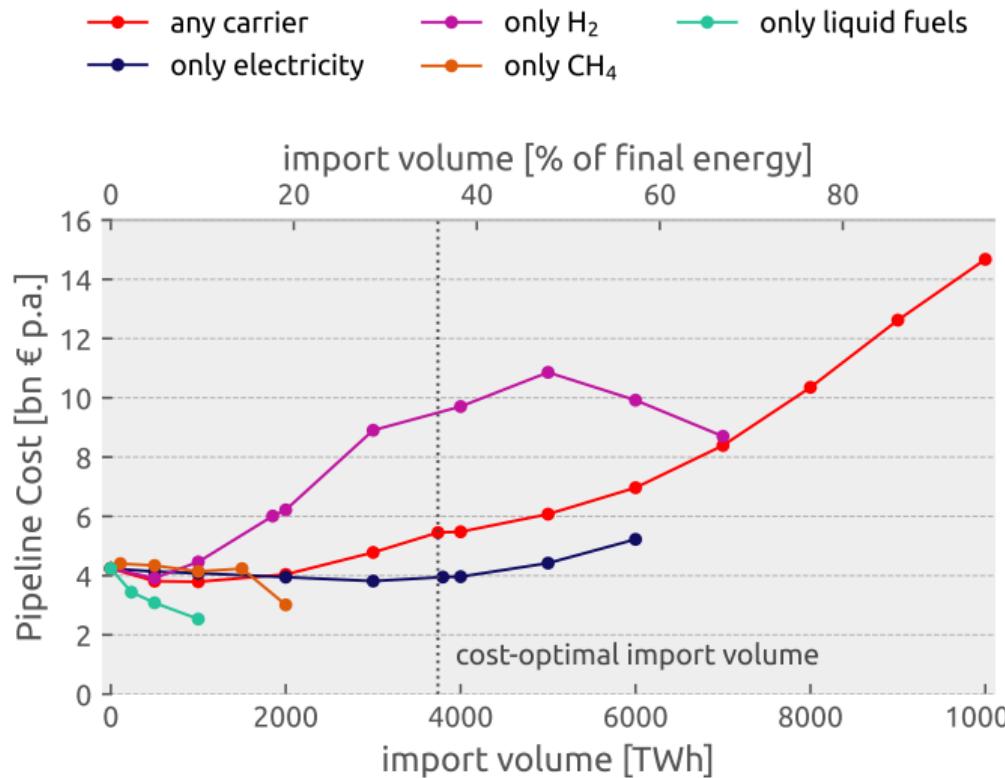
<mailto:f.neumann@tu-berlin.de>

Cost sensitivity with restricted import carrier choices

- any carrier
- only H₂
- only liquid fuels
- only electricity
- only CH₄



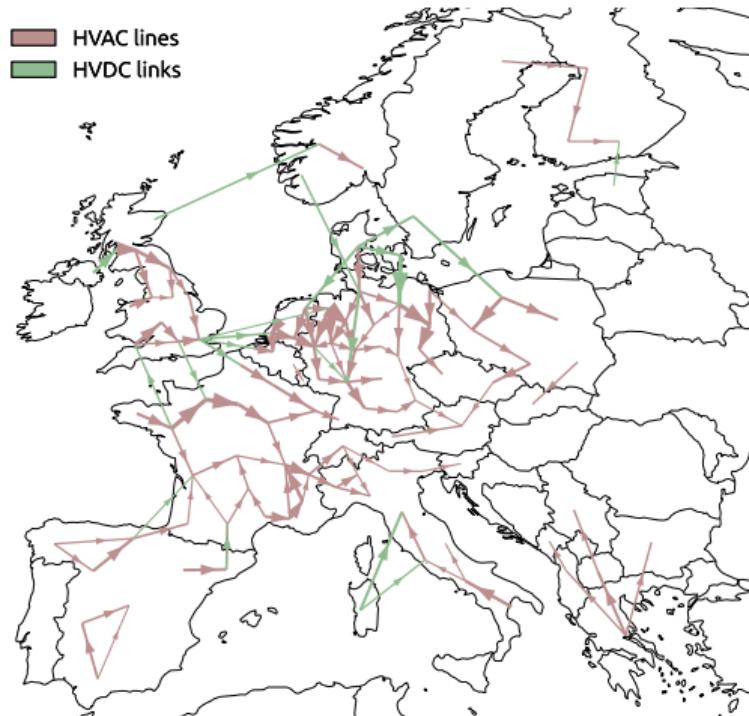
Spending on hydrogen pipelines depends on imported energy carriers



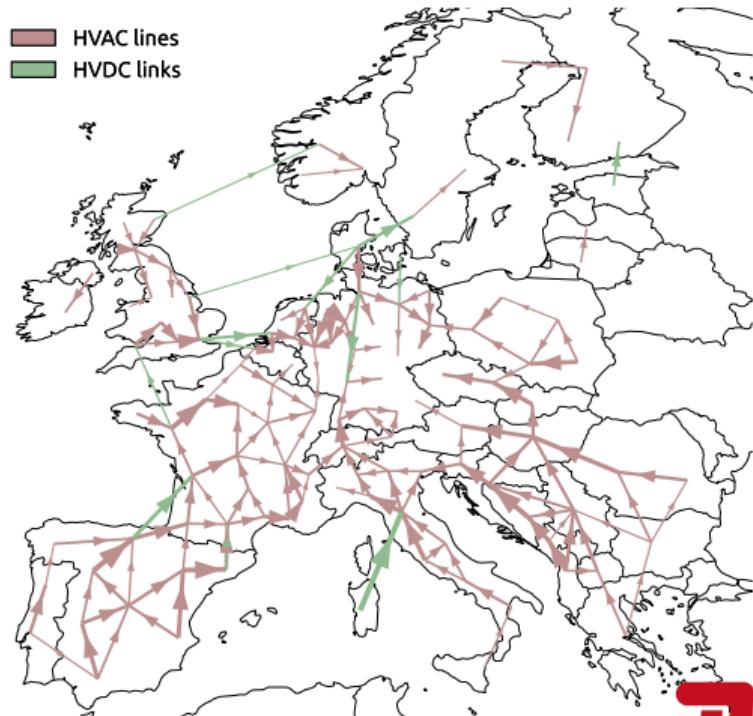
- demand for hydrogen network **decreases** when more H₂ derivatives are imported directly
- demand for hydrogen network **increases** when more H₂ is imported

Electricity imports lead to more South-North power transmission

without imports

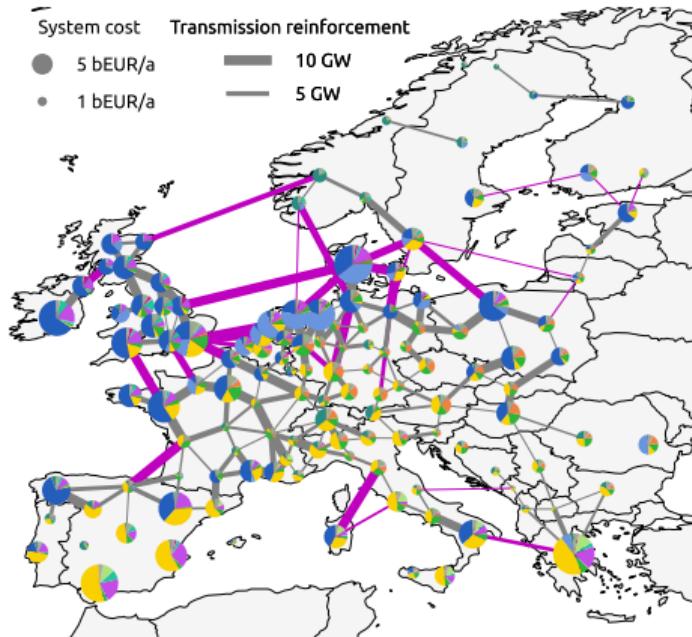


with imports

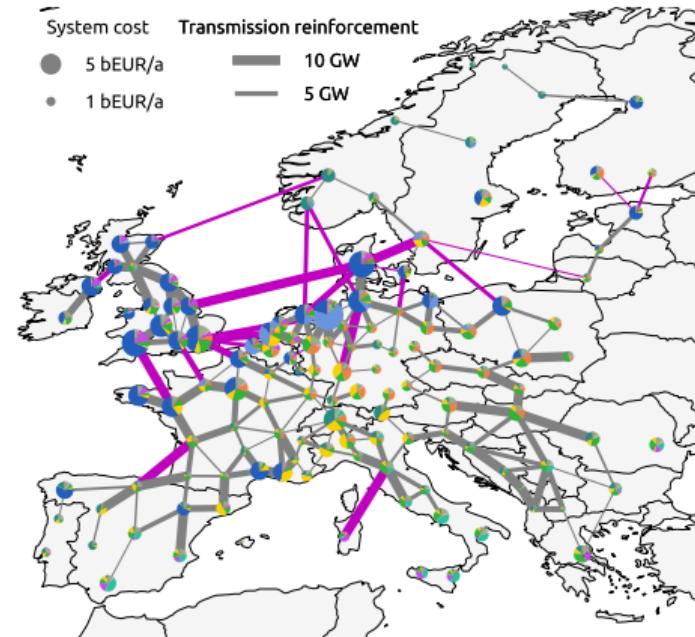


Costs

without imports

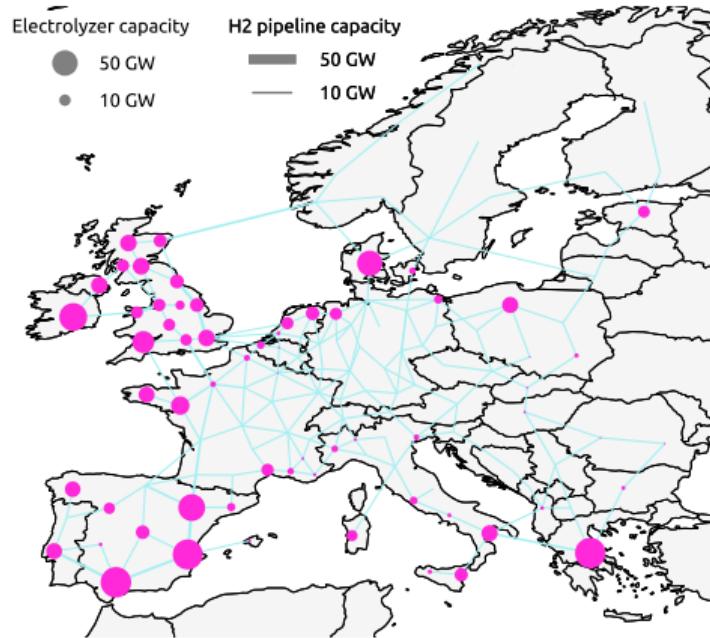


with imports

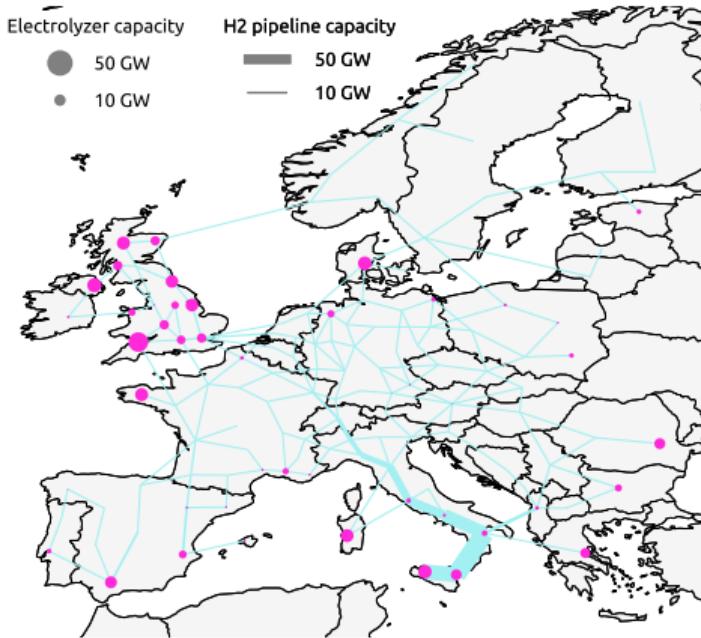


Hydrogen Infrastructure

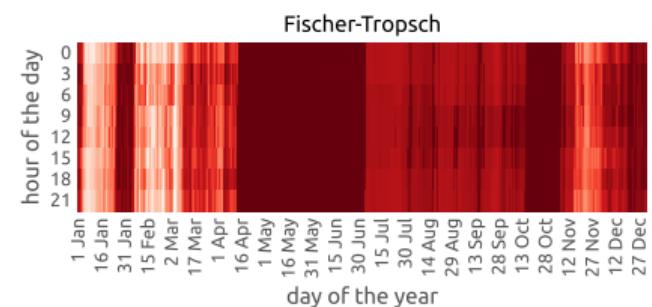
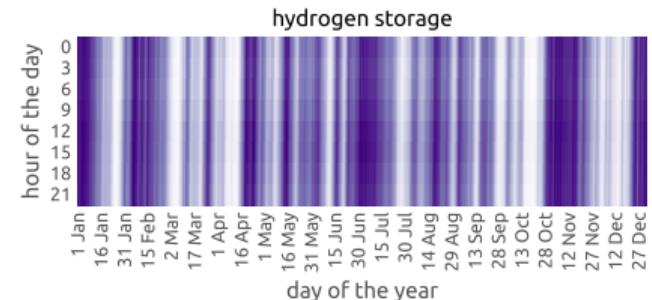
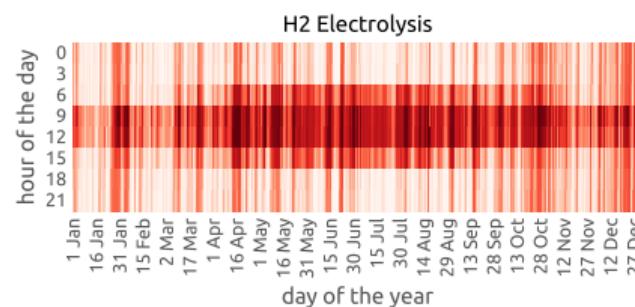
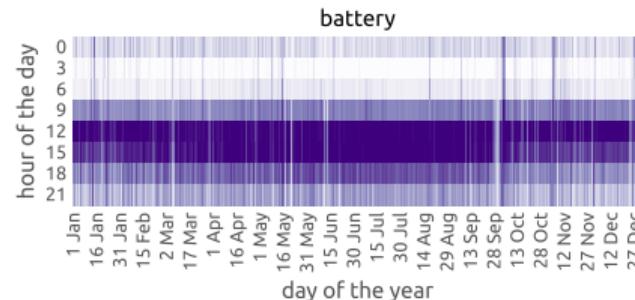
without imports



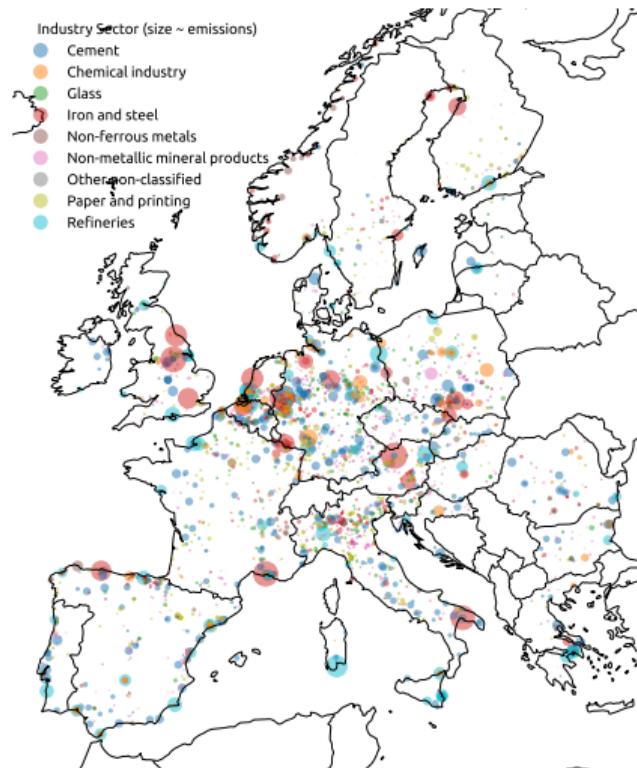
with imports



Utilisation Patterns (no imports)



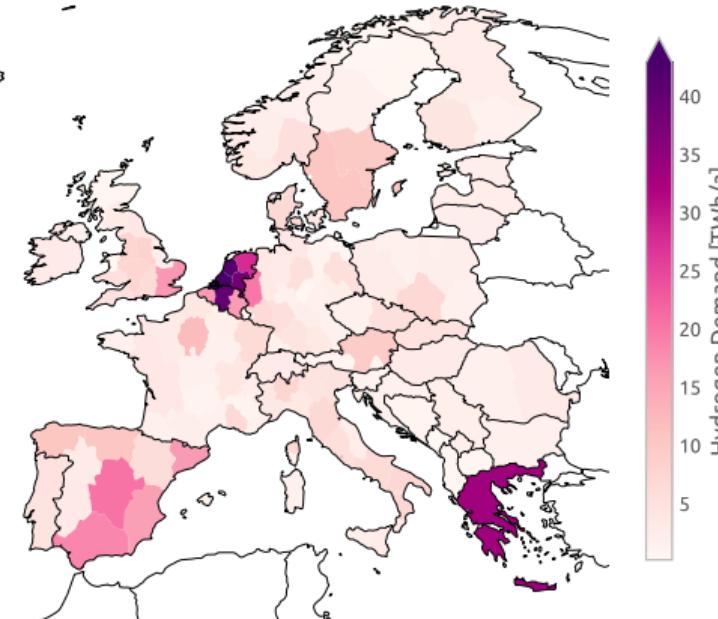
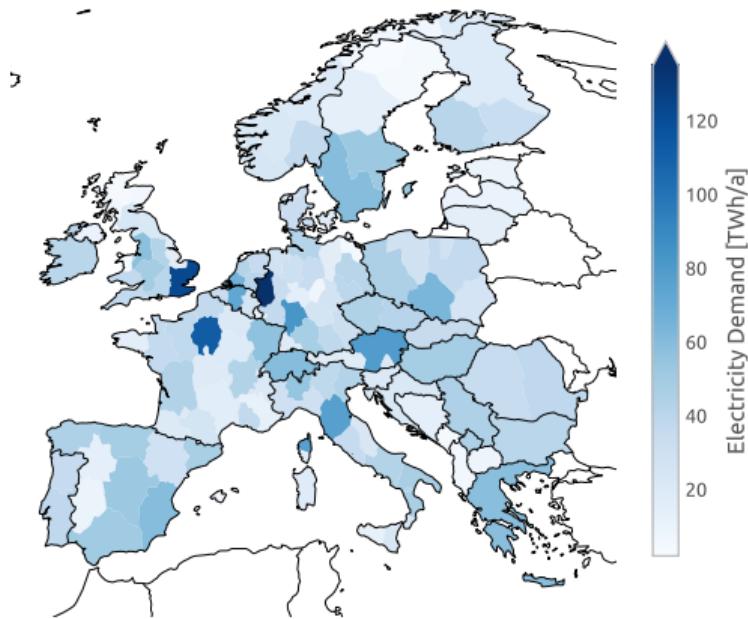
Industry: Process and Fuel Switching & Carbon Management



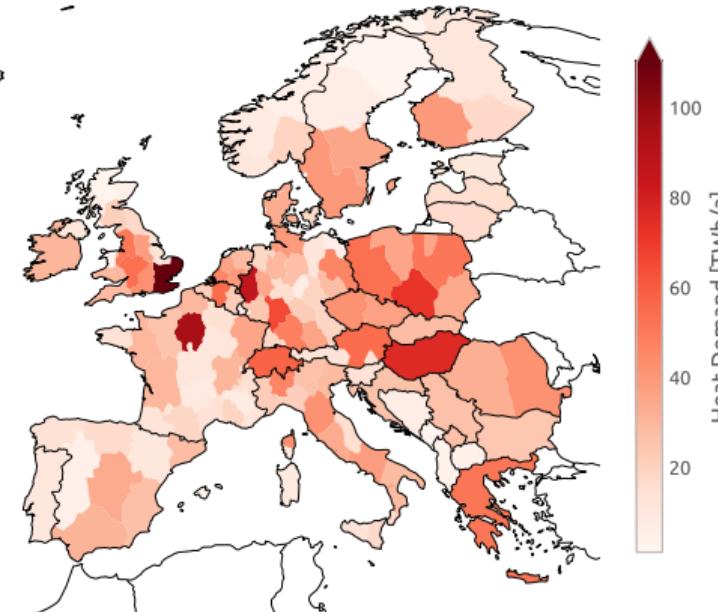
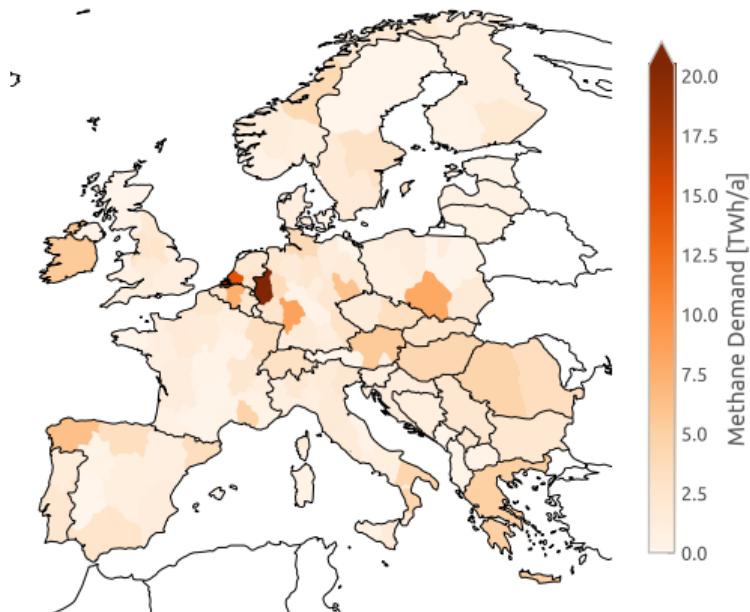
Iron & Steel	70% from scrap, rest from H ₂ -DRI + EAF
Aluminium	80% recycling; methane for high-enthalpy heat
Cement	Solid biomass; capture of CO ₂ emissions
Ceramics	Electrification
Ammonia	Clean hydrogen
Plastics	55% recycling and synthetic naphtha
Other industry	Electrification; process heat from 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 MtCO₂/a; carbon in plastics releases into atmosphere

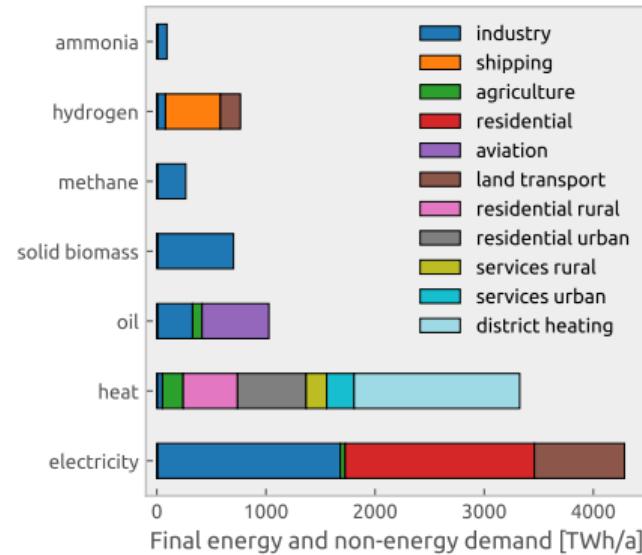
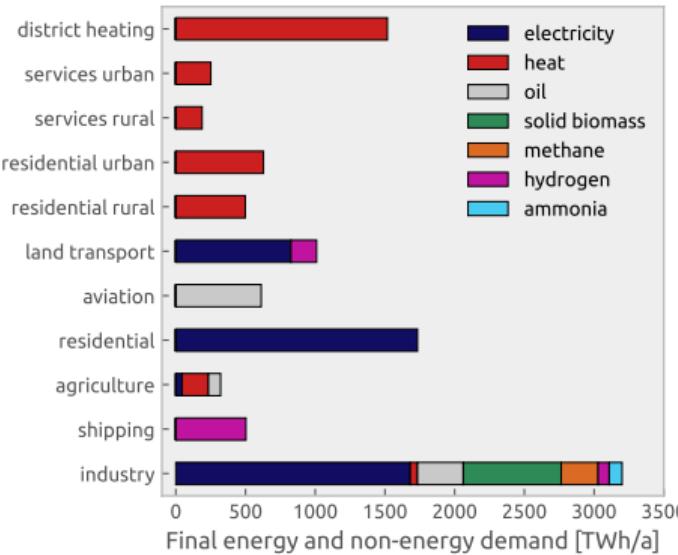
Demand Maps – Electricity and Hydrogen



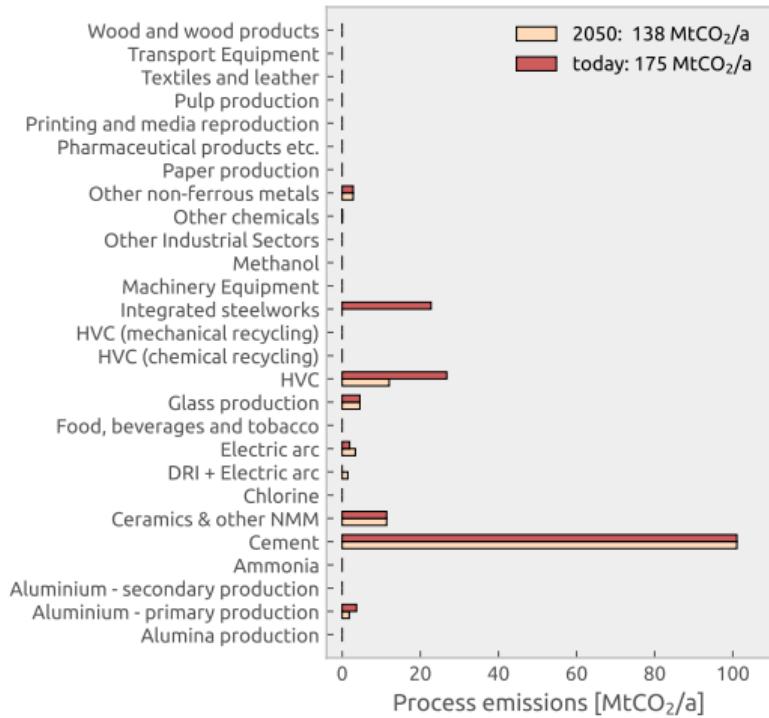
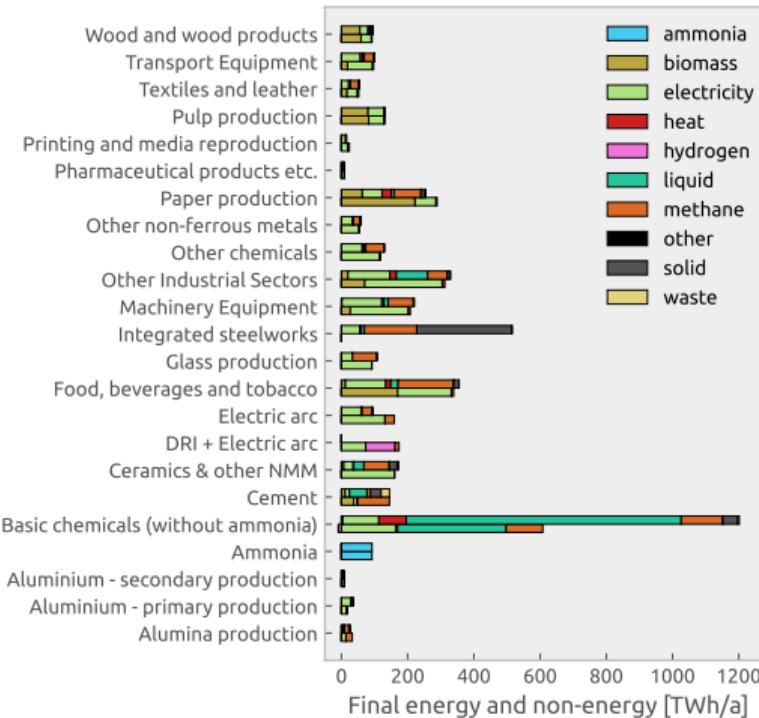
Demand Maps – Methane and Heat



Final Energy Consumption by Carrier



Industry Sector – Demand and Process Emissions



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: H₂-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

Find **most cost-effective** combination of generation, conversion, storage and transmission:

$$\text{Min} \left[\begin{array}{c} \text{Yearly} \\ \text{system costs} \end{array} \right] = \text{Min} \left[\sum_r \left(\begin{array}{c} \text{Annualised} \\ \text{capital costs} \end{array} \right) + \sum_{r,t} \left(\begin{array}{c} \text{Operating} \\ \text{costs} \end{array} \right) \right]$$

subject to

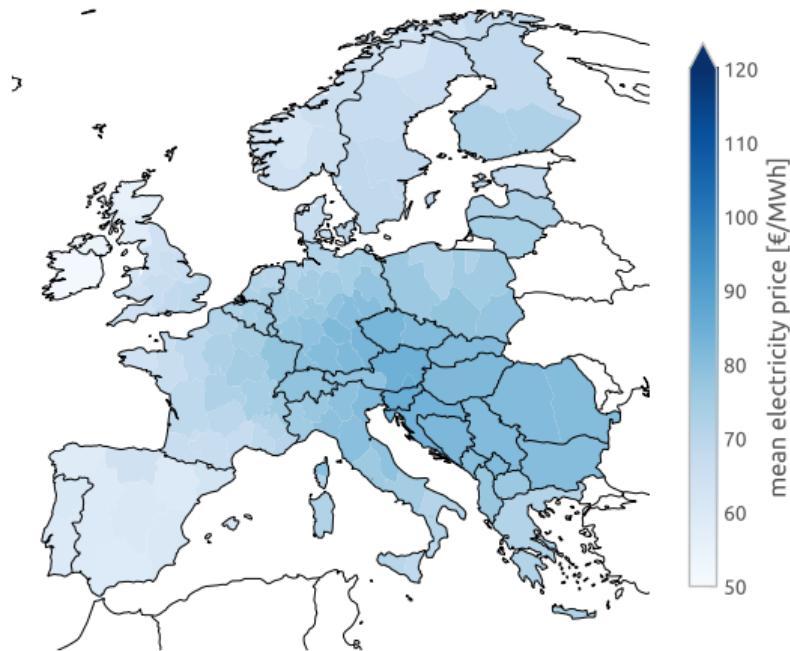
- meeting **energy demand** in each region r and time t for each carrier
- transmission constraints between regions and (linearised) power flow
- wind, solar, hydro **availability time series** $\forall r, t$
- geographical potentials for renewables
- emission reduction targets

In short: **mostly-greenfield** investment optimisation, multi-period (storage) with LPF.

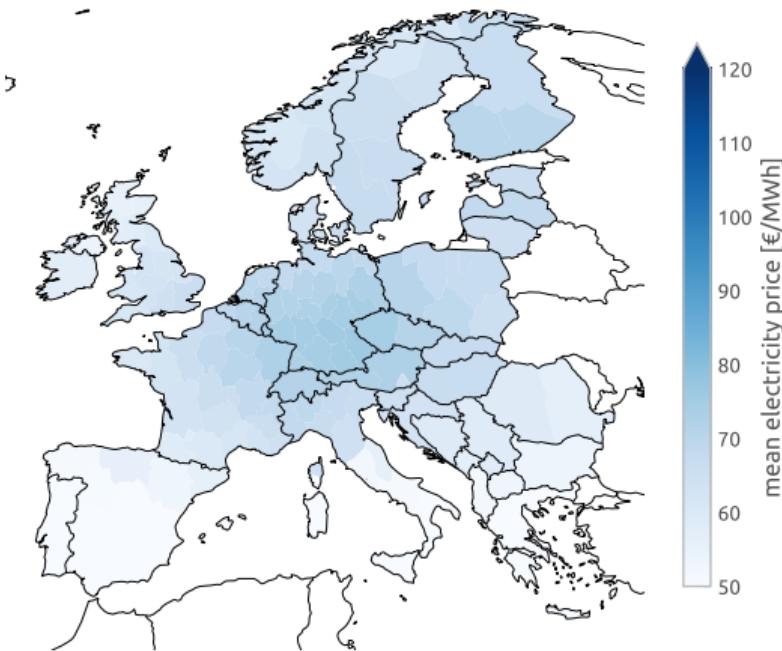
Optimise transmission, generation, conversion and storage **jointly** → strongly interacting.

Electricity imports lower prices as better resources become available

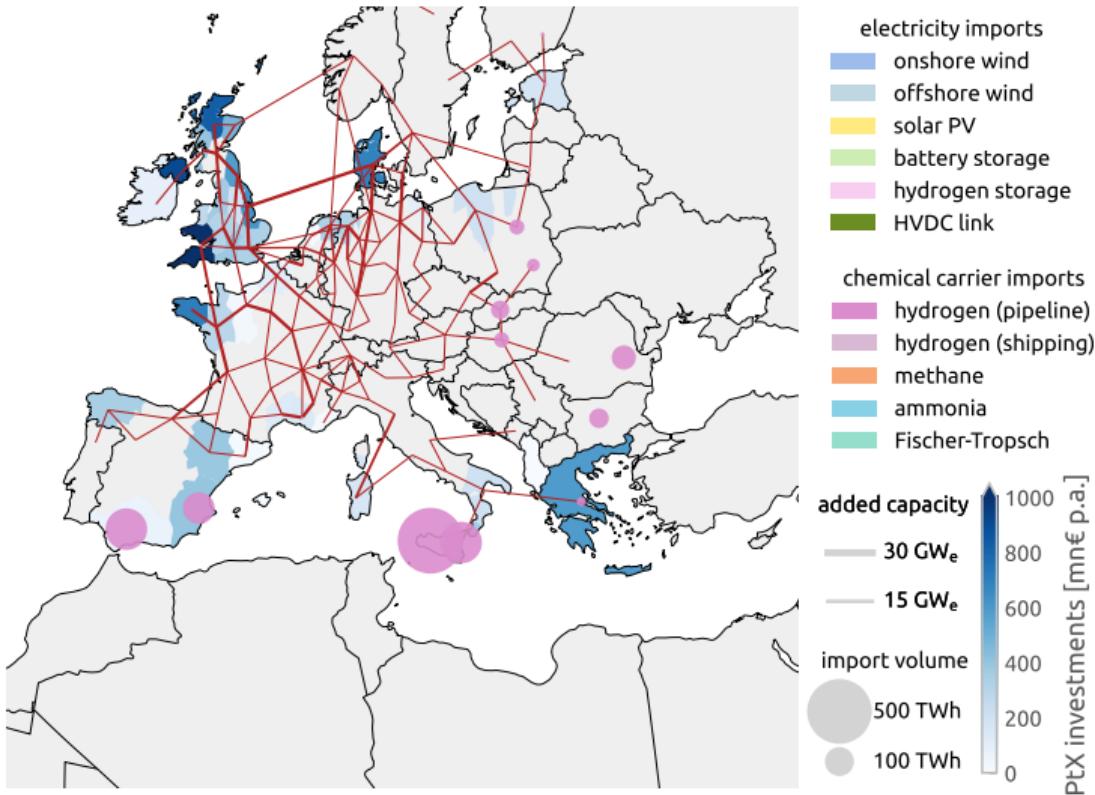
without imports



with imports

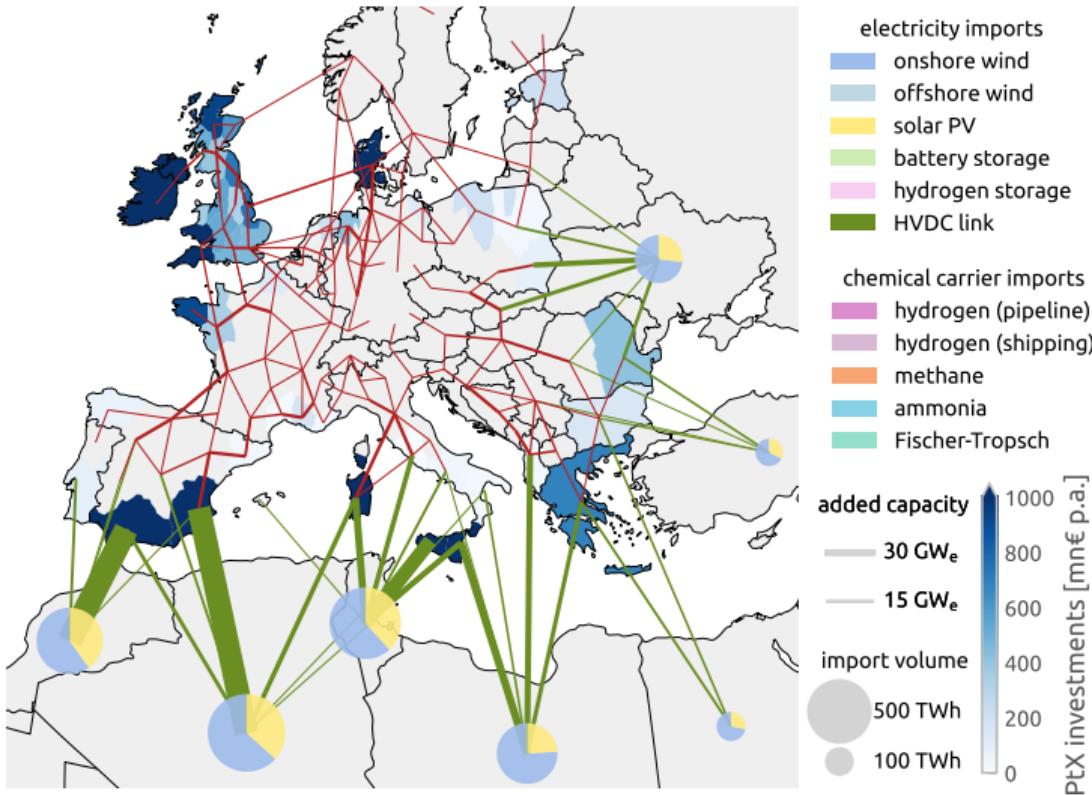


Preliminary: European energy supply with **exclusive hydrogen imports**



- item
- item
- item

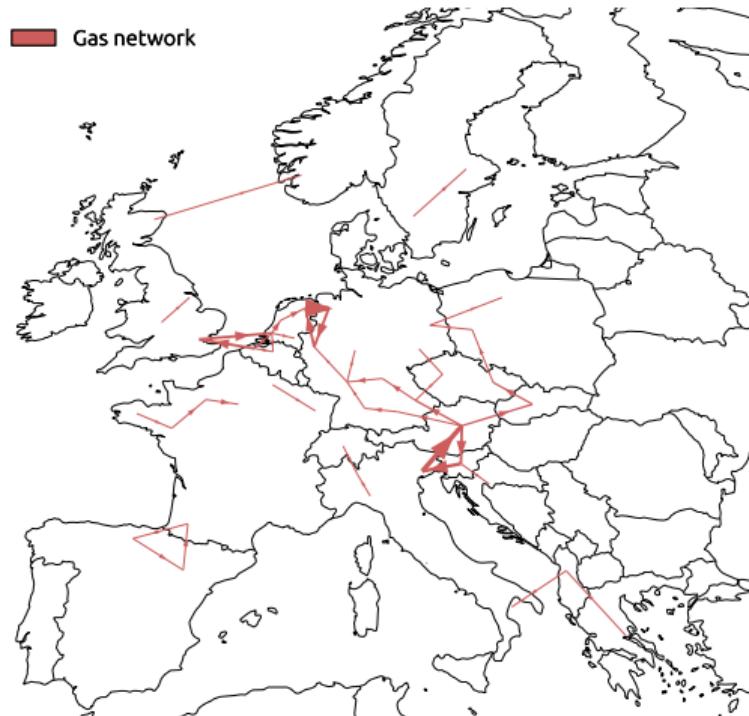
Preliminary: European energy supply with **exclusive electricity imports**



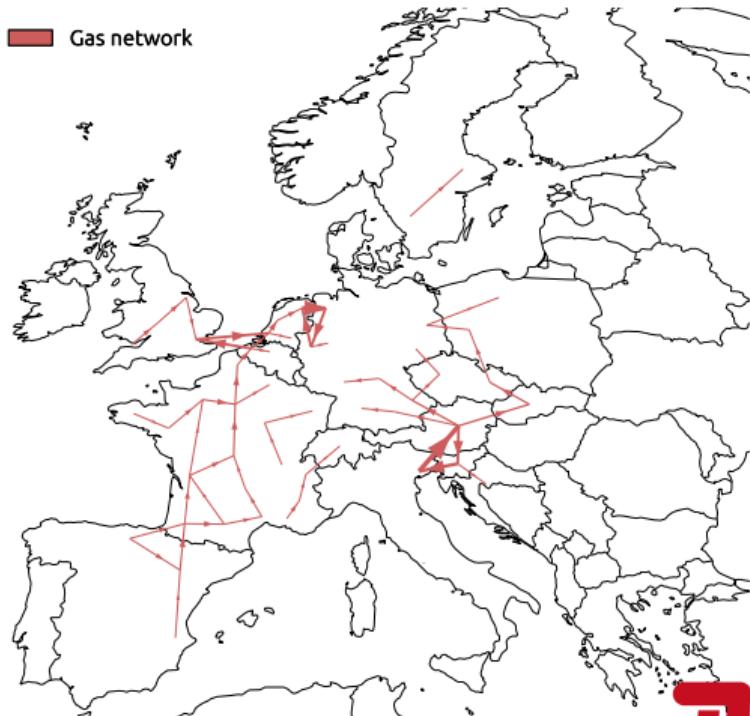
- exclusive electricity exports entail **massive (!) cross-continental HVDC connections**
- PtX production is **shifted to importing European nodes** as power grid capacity is limited

Gas network flows only play a tangential role in both scenarios

without imports

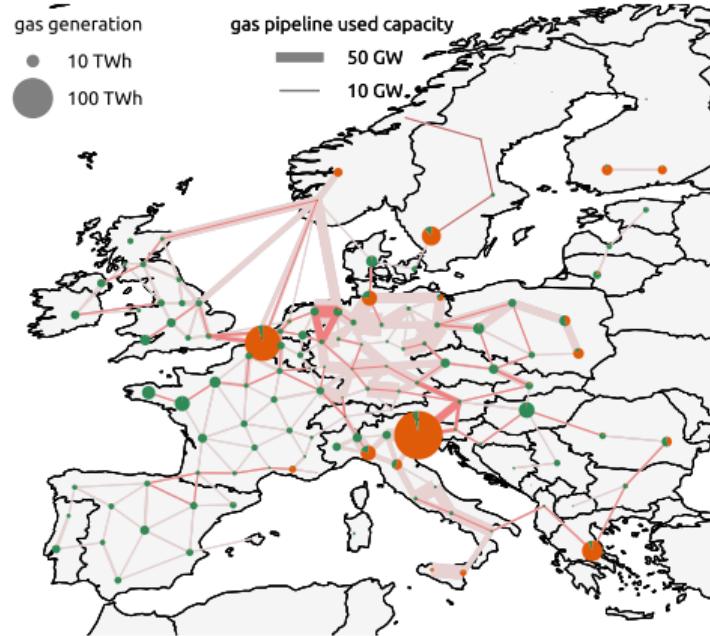


with imports

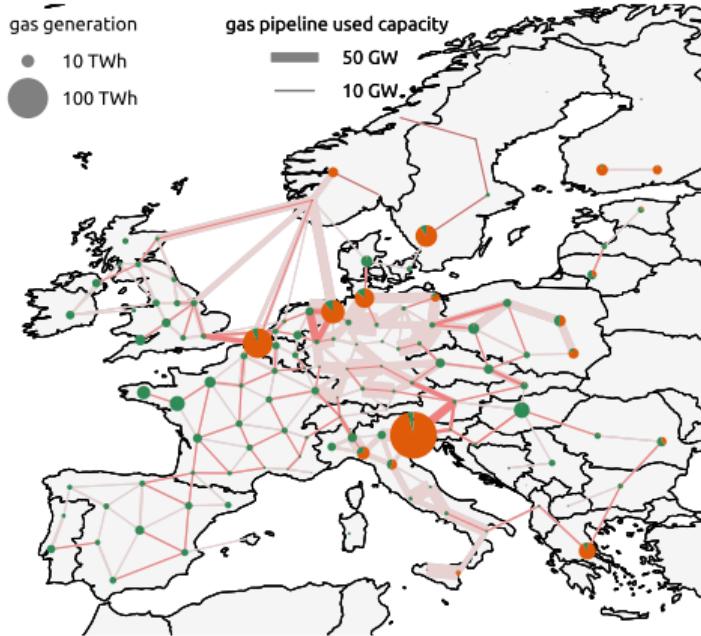


Gas Infrastructure

without imports

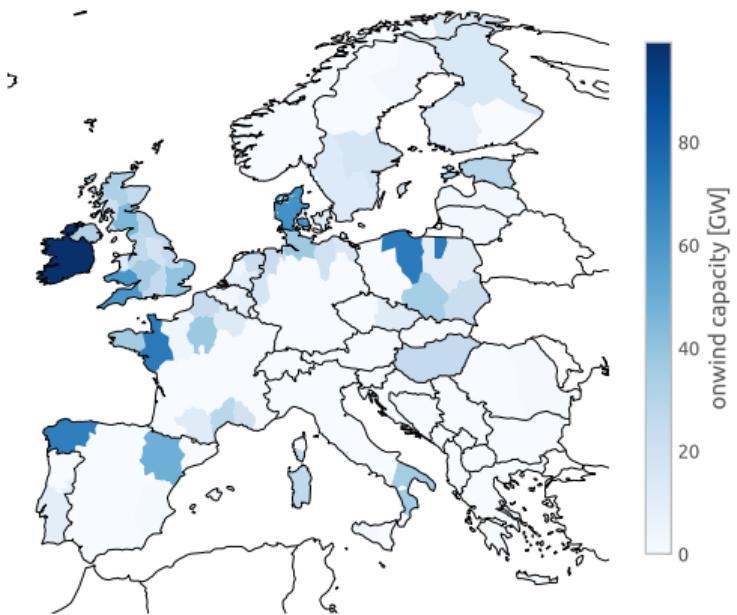


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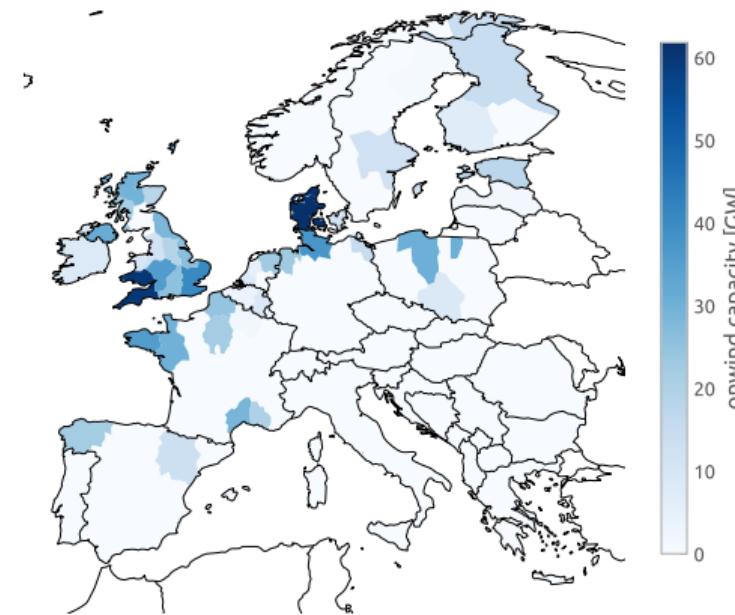


Capacities Built – Onshore Wind

without imports

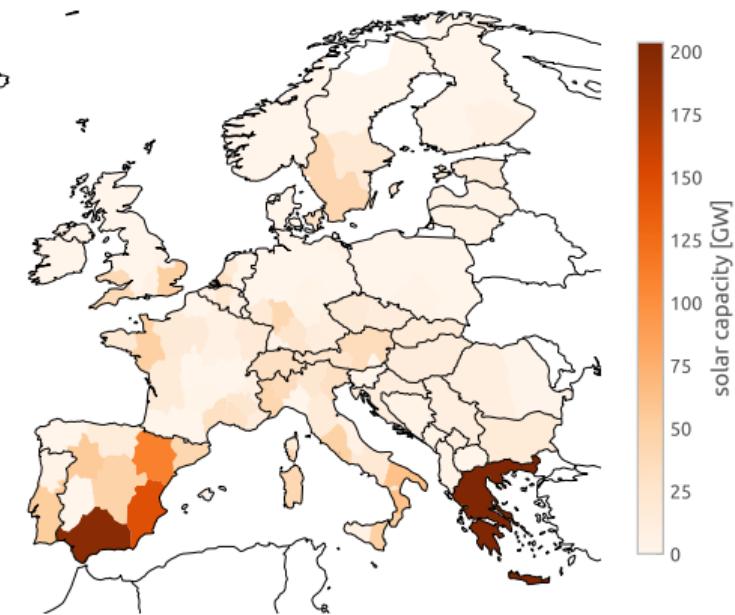


with imports

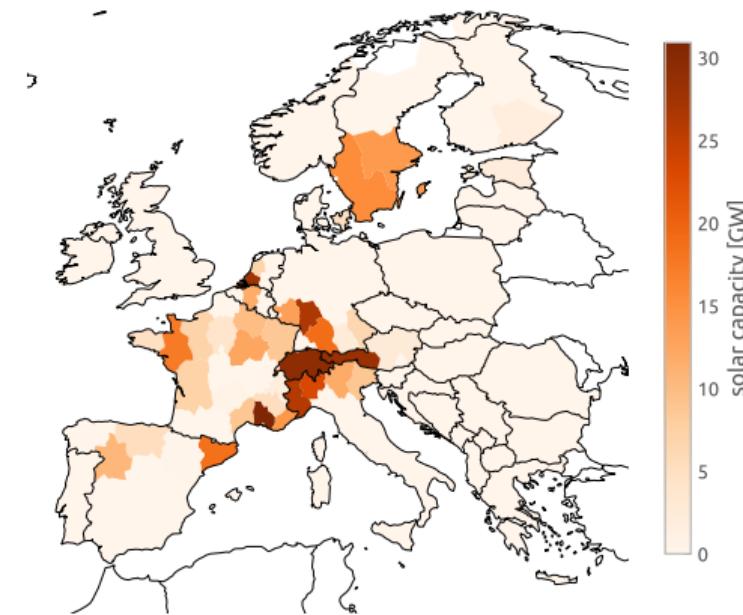


Capacities Built – Solar

without imports

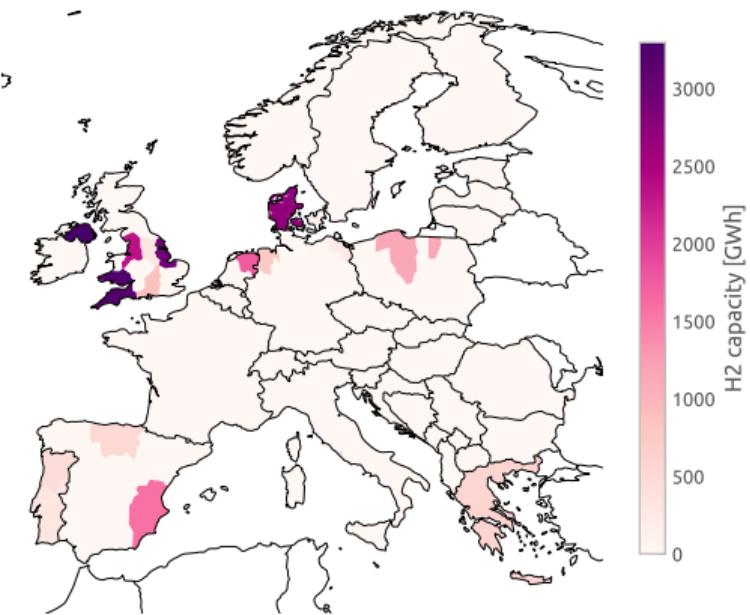


with imports

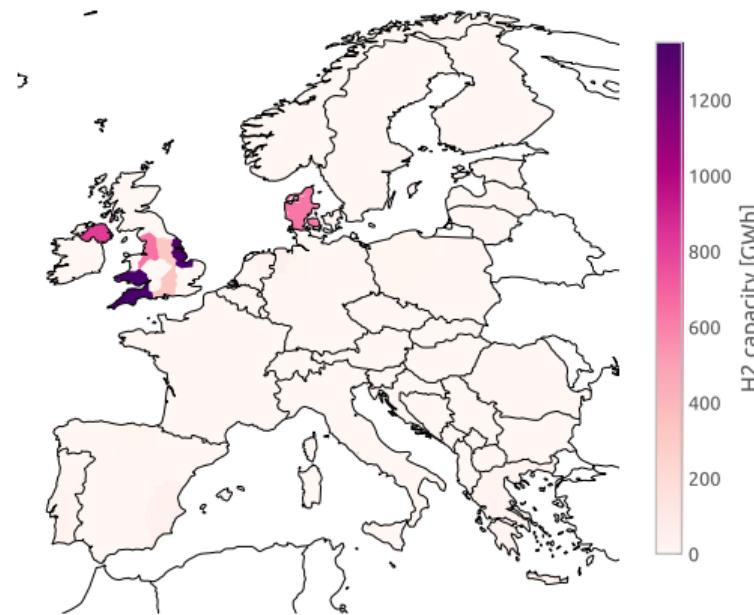


Capacities Built – Hydrogen Storage

without imports

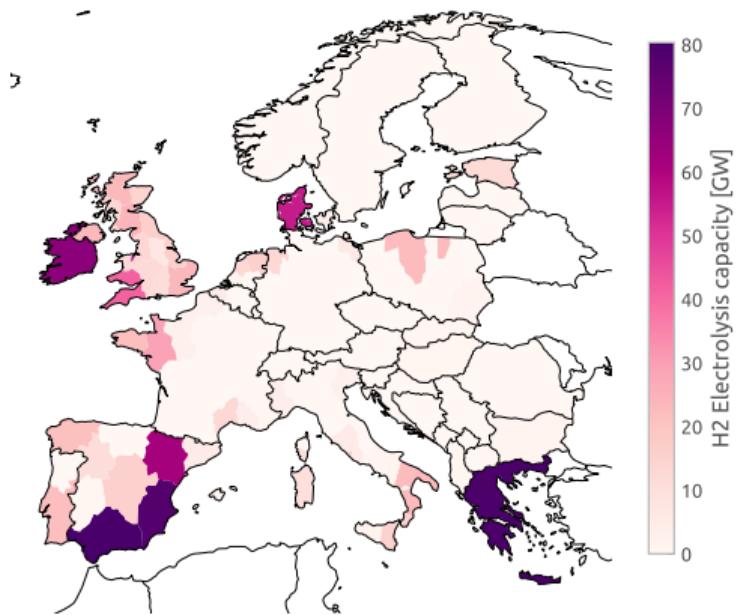


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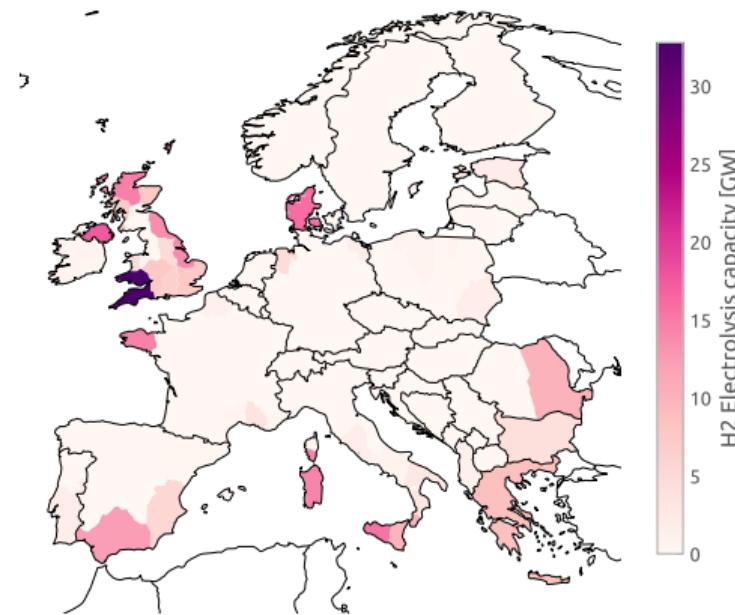


Capacities Built – Electrolysis

without imports

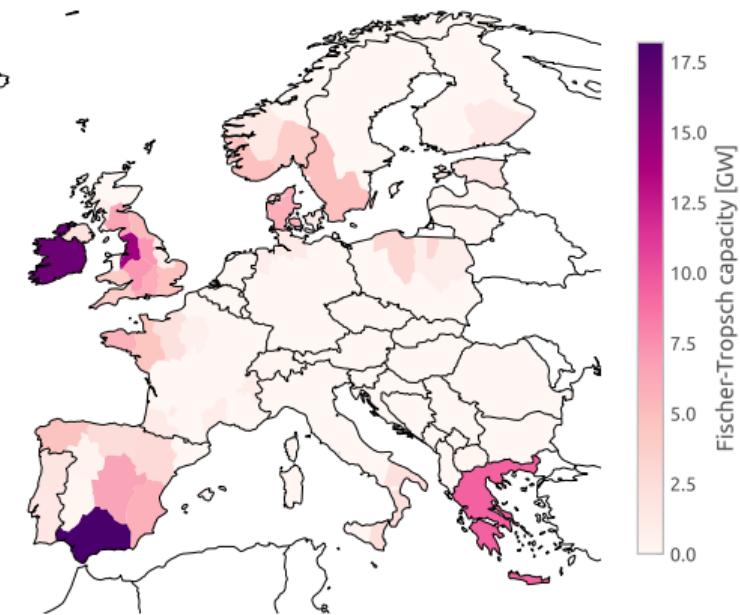


with imports

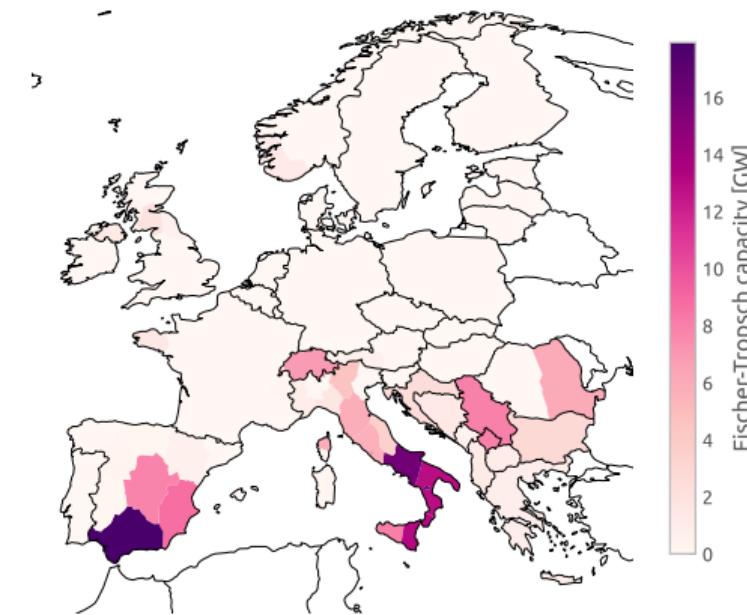


Capacities Built – Fischer-Tropsch

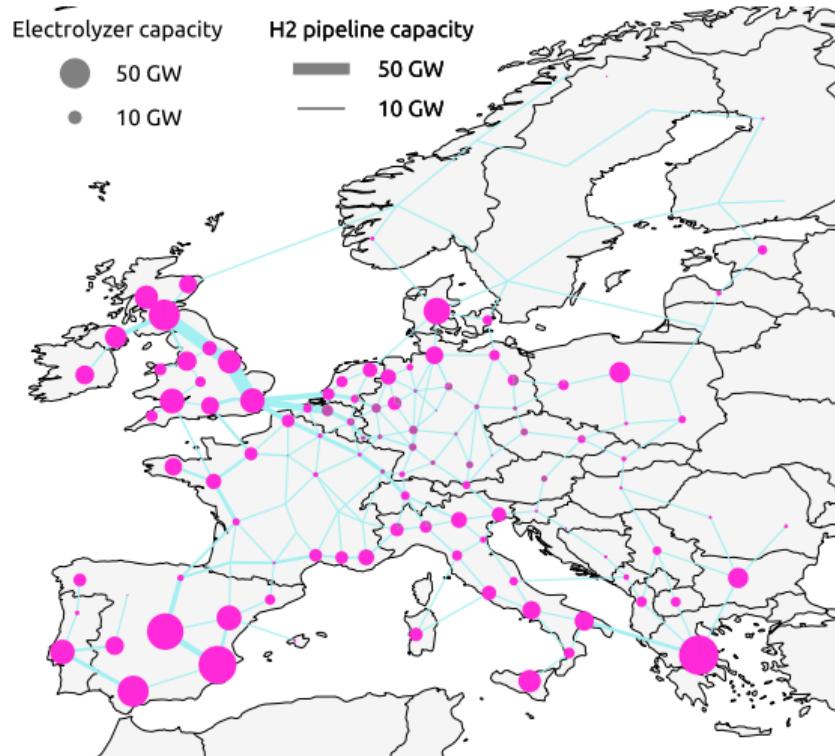
without imports



with imports

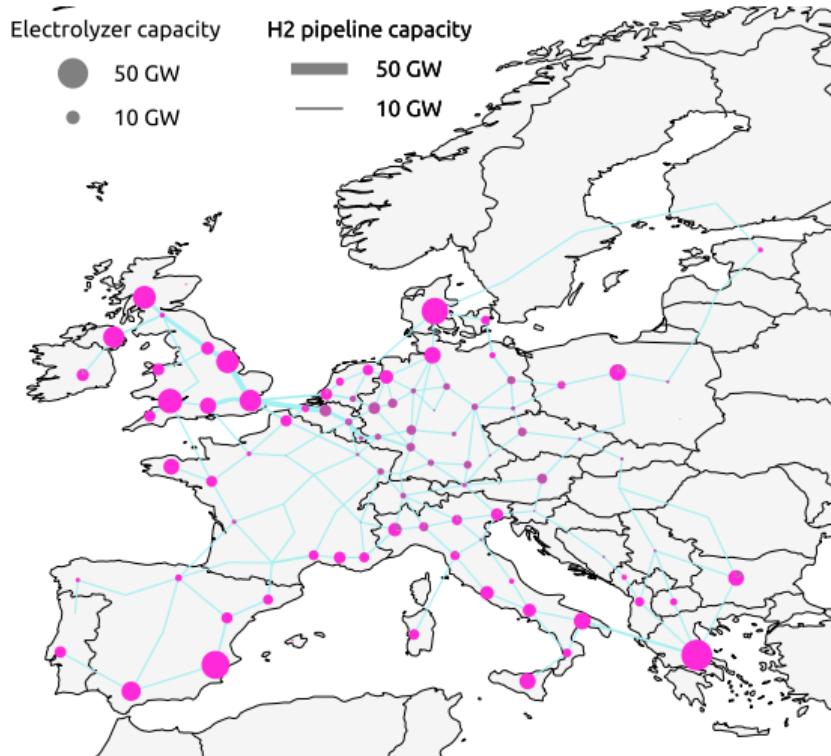


Imports of energy into Europe diminish hydrogen network benefit

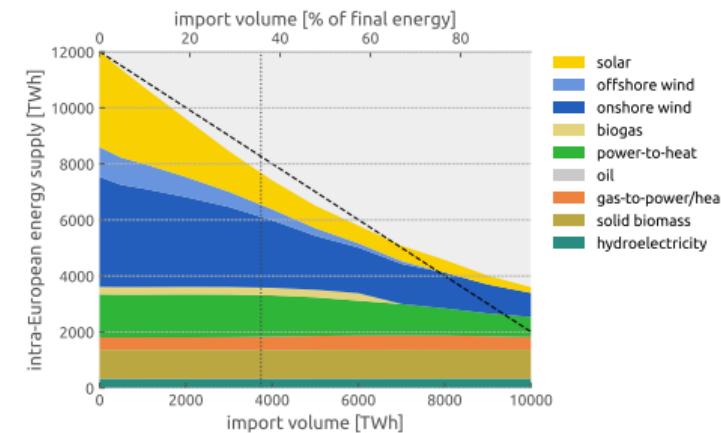
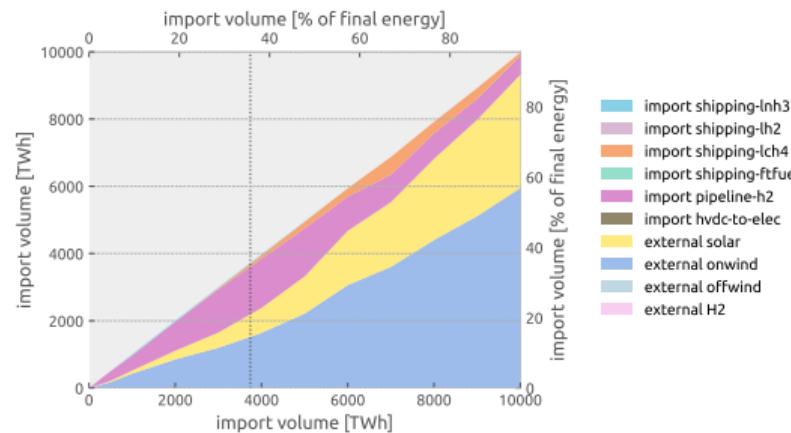


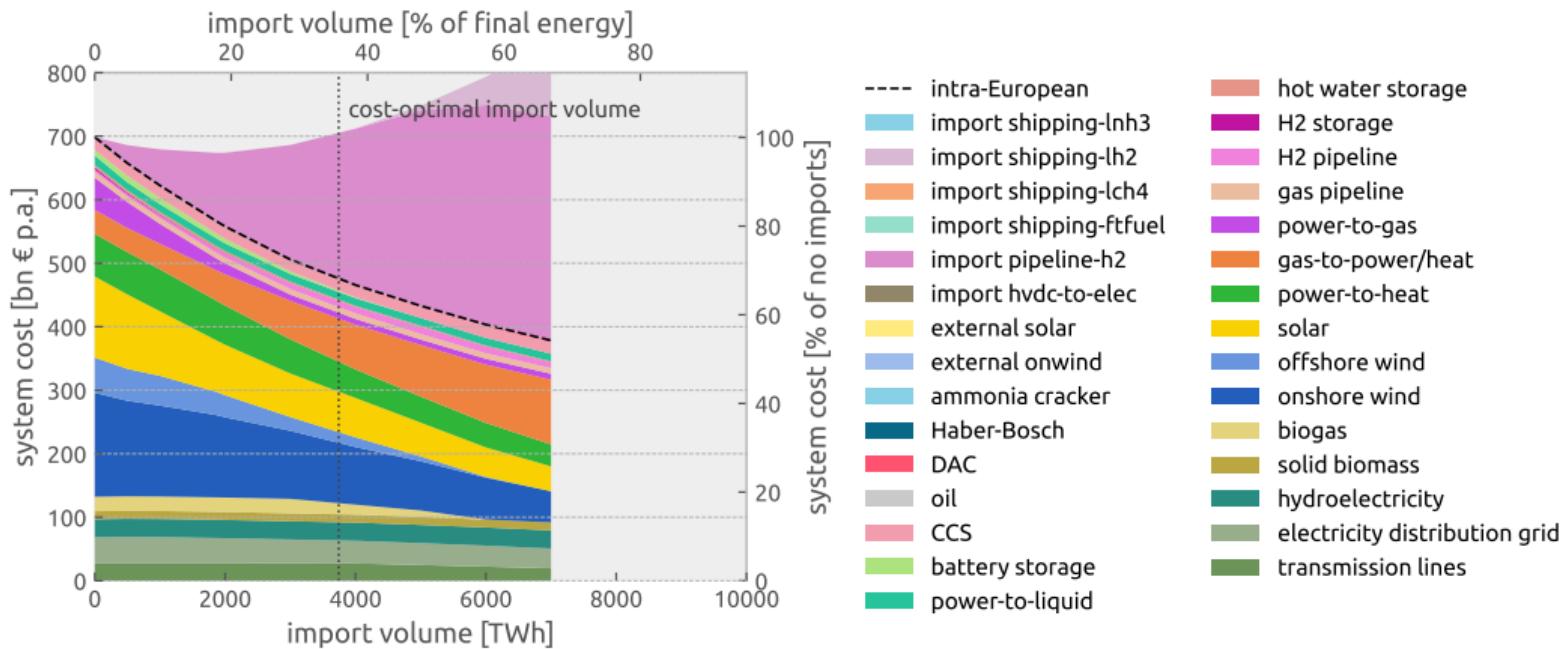
- So far we looked at scenarios for **self-sufficient** energy supply
- But when H₂ and derivatives are imported (shipping, aviation, industry, trucks), **hydrogen network benefit drops to 1%**.
- **Residual benefit** of €5 billion per year comes from transporting energy to **fuel cell CHPs** to renewable-poor and grid-poor inner-European nodes.

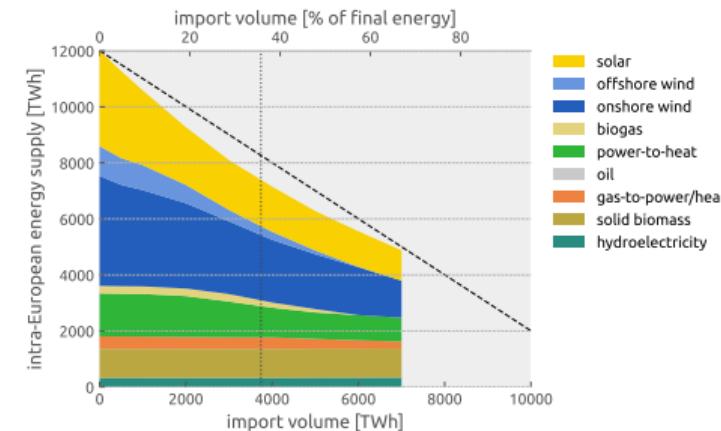
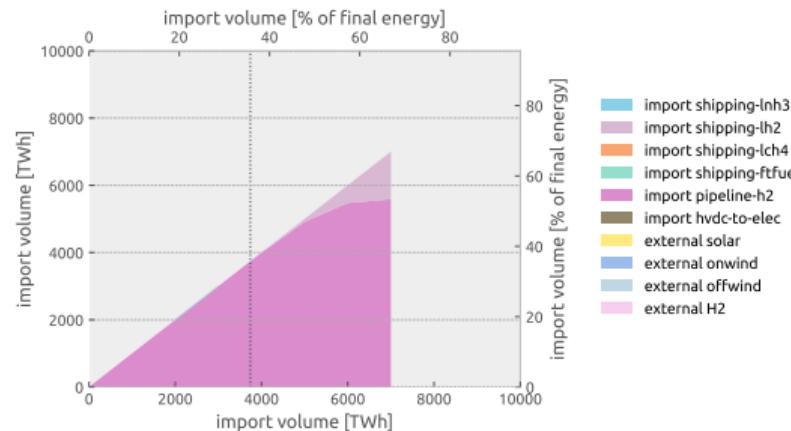
Imports of energy into Europe diminish hydrogen network benefit

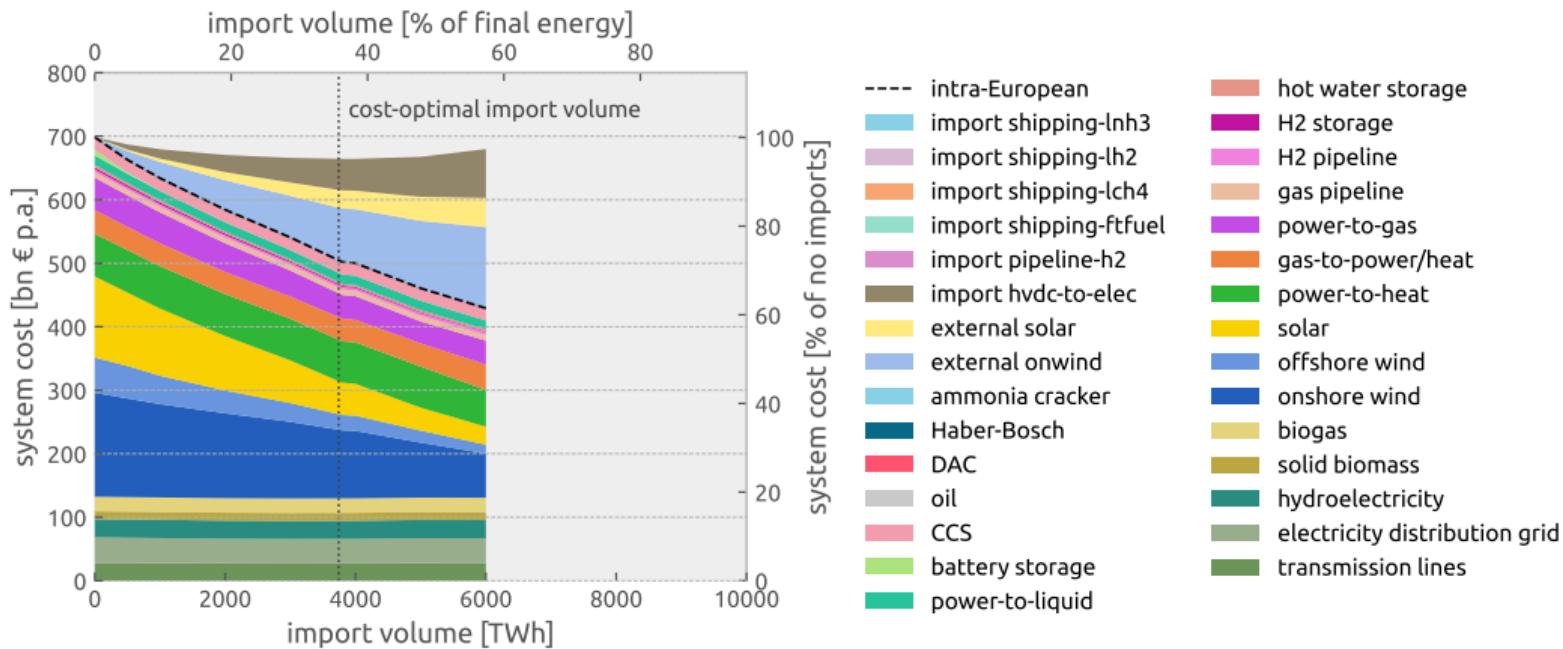


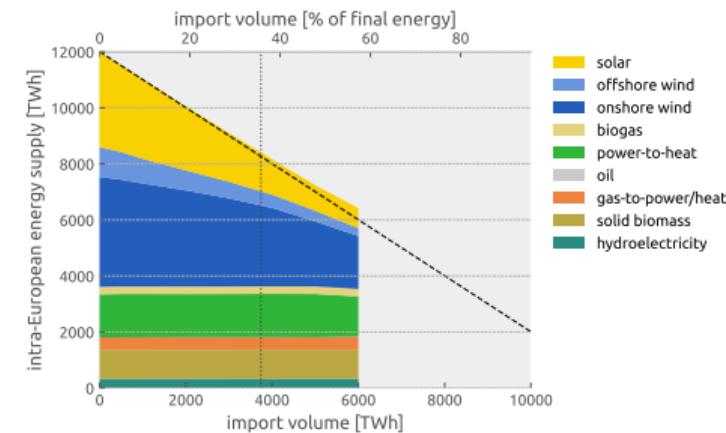
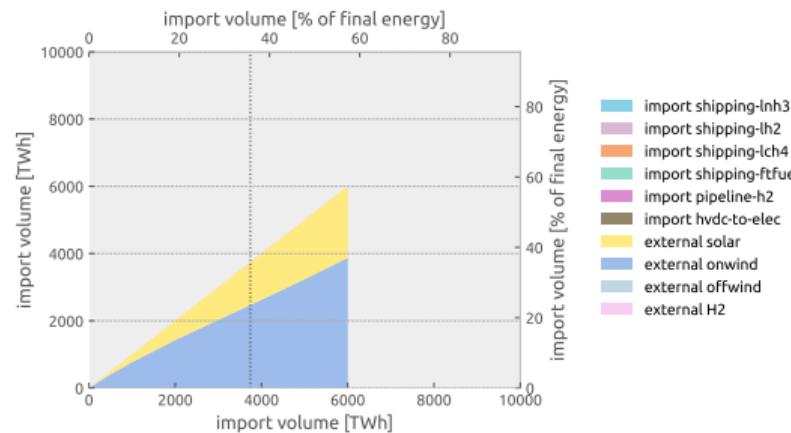
- So far we looked at scenarios for **self-sufficient** energy supply
- But when H₂ and derivatives are imported (shipping, aviation, industry, trucks), **hydrogen network benefit drops to 1%**.
- **Residual benefit** of €5 billion per year comes from transporting energy to **fuel cell CHPs** to renewable-poor and grid-poor inner-European nodes.











HVDC Import Link Utilisation Rates $\approx 55 - 66\%$

