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

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ENERDAY 2023, Dresden, Germany

May 5, 2023

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.

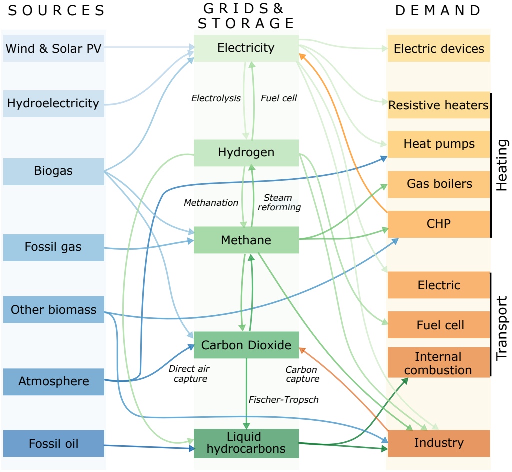
Trade-offs between full **self-sufficiency** and wide-ranging **energy imports** from outside Europe:

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

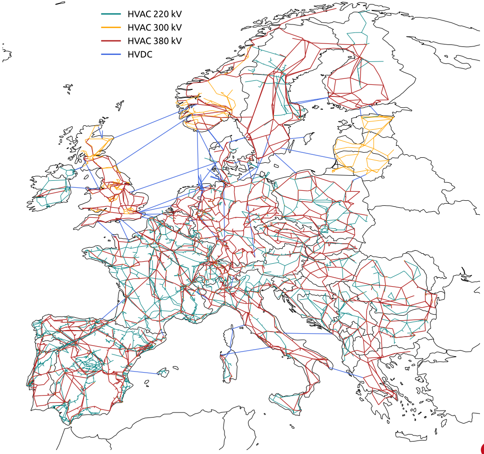
Coupling of a **global supply chain model** with open all-sector **European energy model**.

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

Model for Europe with all energy flows...



...and bottlenecks in energy networks...



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

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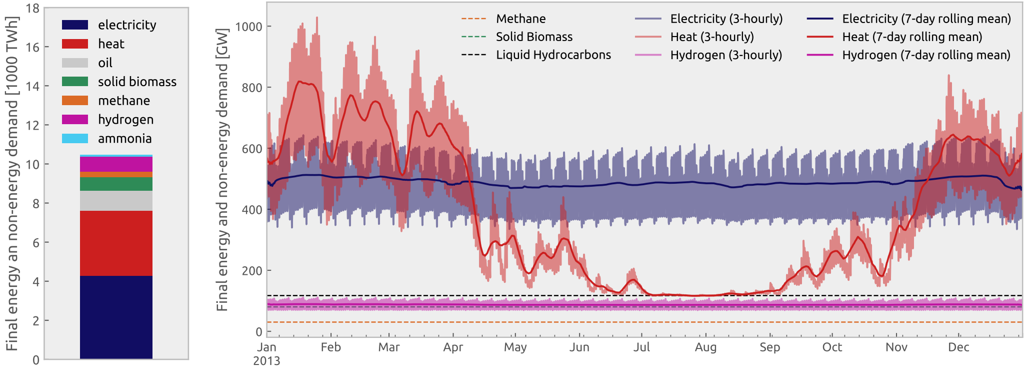
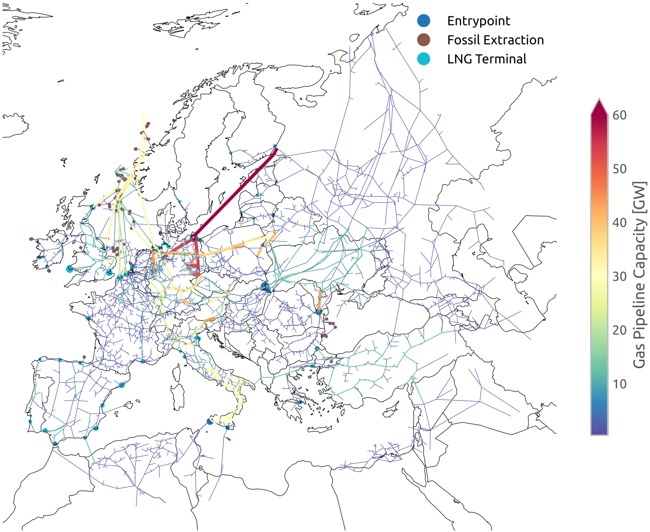
… and temporal variability in demand and supply.



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)

Gas transmission network with LNG terminals and pipeline entrypoints

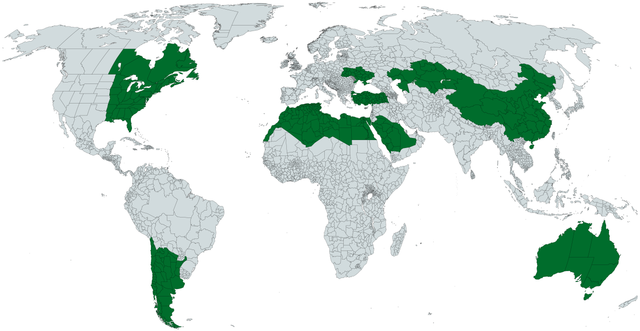


- incorporate open dataset of European gas transmission network from **SciGRID_gas** project into PyPSA-Eur
- supplement dataset with **existing and planned LNG terminals** from `www.gem.wiki`

Source: SciGRID_gas, `https://www.gas.scigrid.de/`

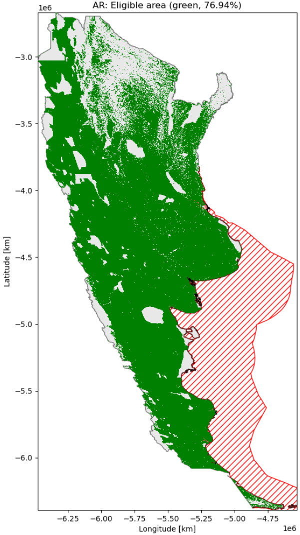
Model of global green energy supply chains – exporting regions

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

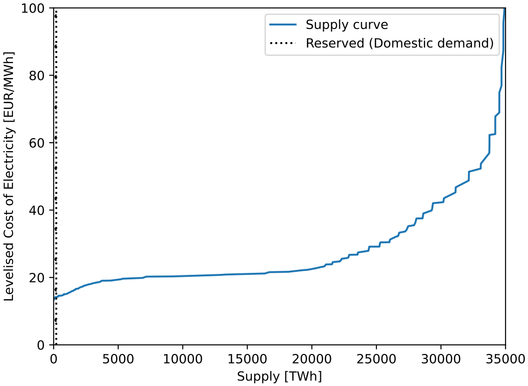


Source: https://github.com/euronion/trace, see also IRENA Global Hydrogen Trade Outlook

Model of global green energy supply chains – supply cost curves



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

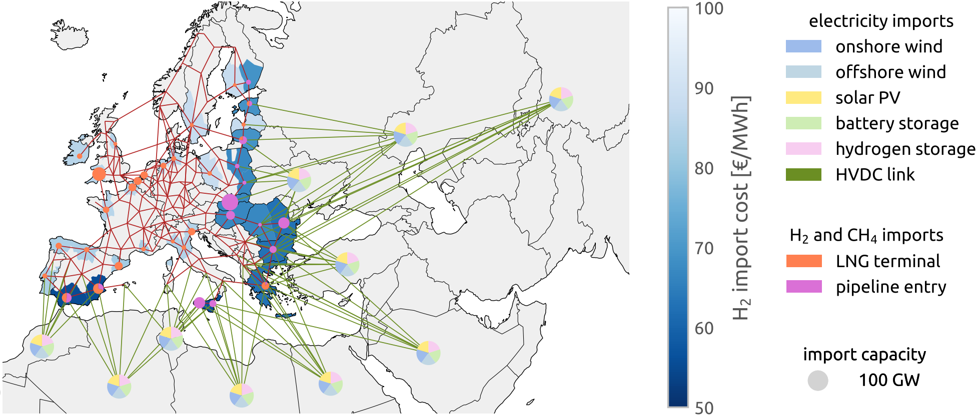


Source: https://github.com/euronion/trace, see also IRENA Global Hydrogen Trade Outlook

Locations and costs for imports vary by energy carrier

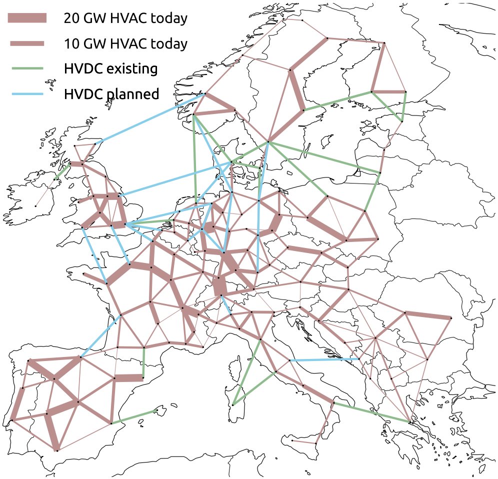
electricity imports endogenously optimised, **gaseous carrier imports** where LNG terminals and pipelines exist

NH_3	85 €/MWh	[AR]	**Fischer-Tropsch**	115 €/MWh	[AR]	← single EU node
CH_4 (LNG)	88-90 €/MWh	[AR]	**CH_4 (pipeline)**	100 €/MWh	[DZ]	← spatially resolved
Electricity	37-57 €/MWh		**H_2 (pipeline/ship))**	55-88 €/MWh		



Import scenarios for a European system with net-zero CO_2 emissions

- couple **all energy sectors** (power, heat, transport, industry, feedstocks, agriculture, international aviation & shipping)
- reduce net CO_2 emissions **to zero**
- cluster to **128** regions, **3**-hourly timesteps
- power (x2), gas and hydrogen **networks**
- technology assumptions for **2030** (DEA)
- CO_2 sequestration below **200 $MtCO_2/a$**
- vary **import volumes** and **carriers**



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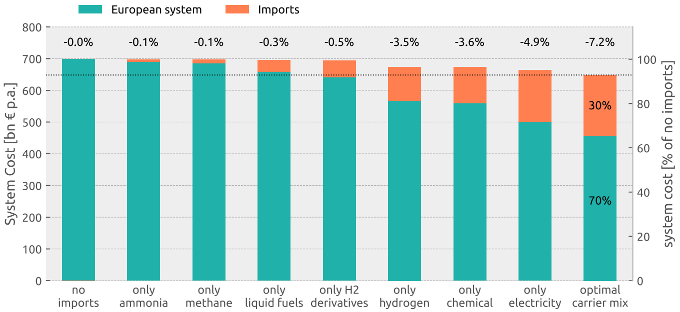
Preliminary: Cost reduction by imports depends on available options



- cost benefit of energy imports limited to **7%**
- half of the benefit can be achieved with **exclusive hydrogen imports**, but requires a lot of infrastructure (later)
- a cost reduction by 5% can be achieved with **exclusive electricity imports**
- up to **30%** of system cost is spent on energy imports

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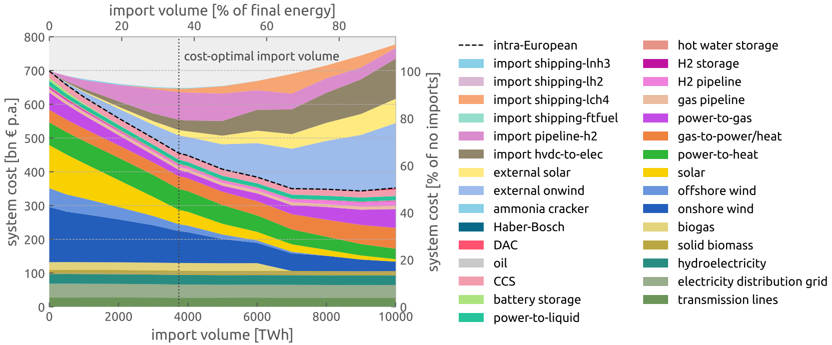
Preliminary: System cost configurations with increasing energy imports



→ 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**

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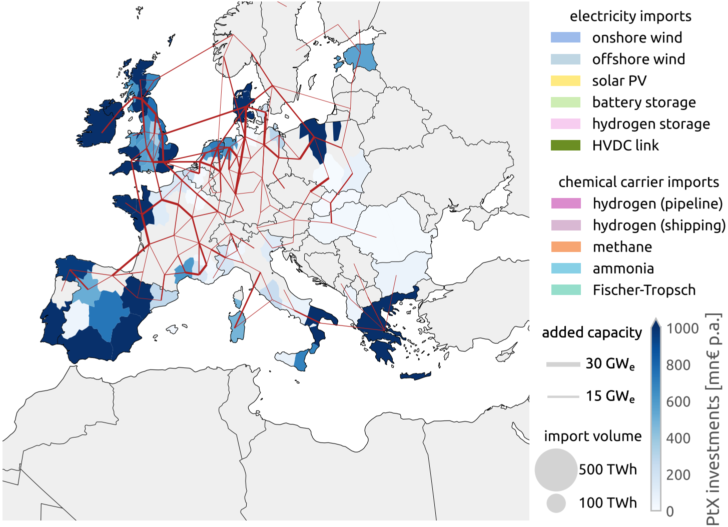
Preliminary: European **self-sufficient** energy supply without imports



- 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

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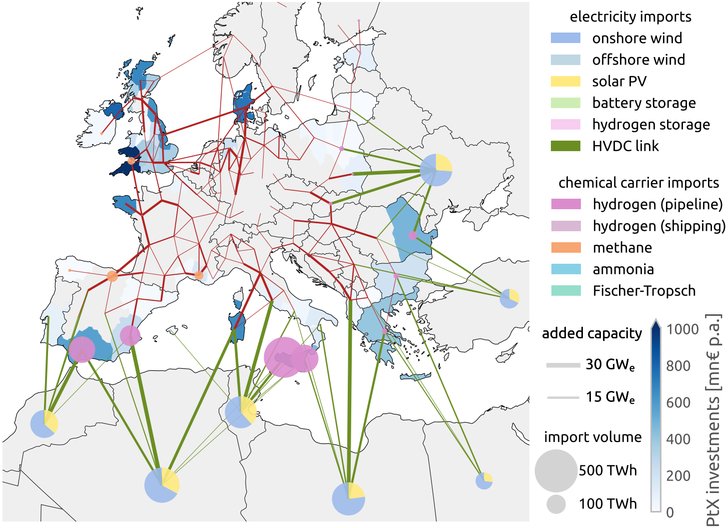
Preliminary: European energy supply with imports and **flexible** carrier

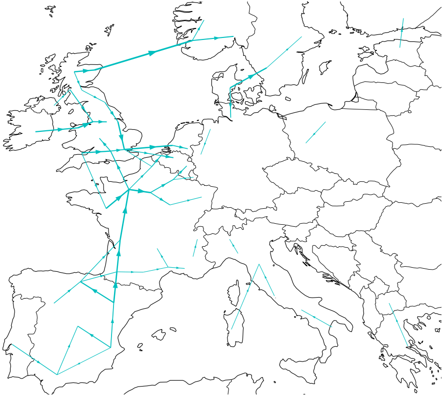


- much less **PtX production** owing to imported hydrogen
- some power grid expansion **diverted to South Europe** to absorb inbound power
- electricity imports **distribute evenly** across exporting countries to facilitate grid integration
- **both wind and solar** in exporting countries for seasonal balancing

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

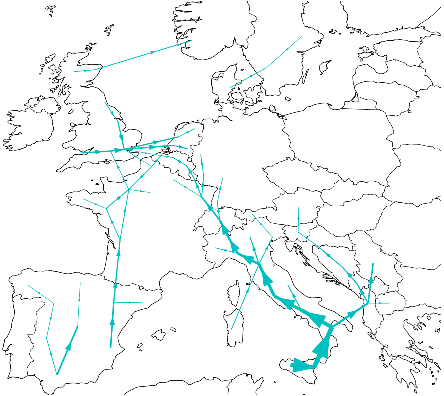
. . . from distributing hydrogen from **North Sea** to transporting imports **from North-Africa**

without imports



network capacity +30%

with imports

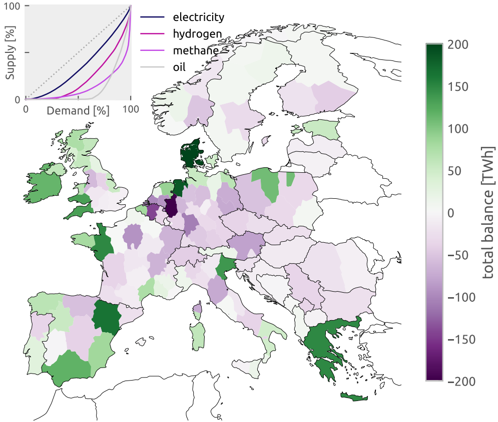


energy transported +70%

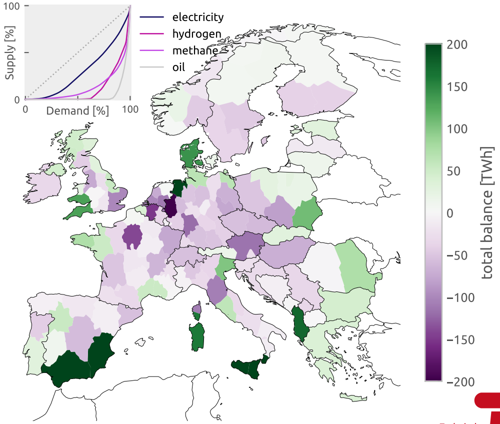
Regional energy imbalance reinforced by import options. . .

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

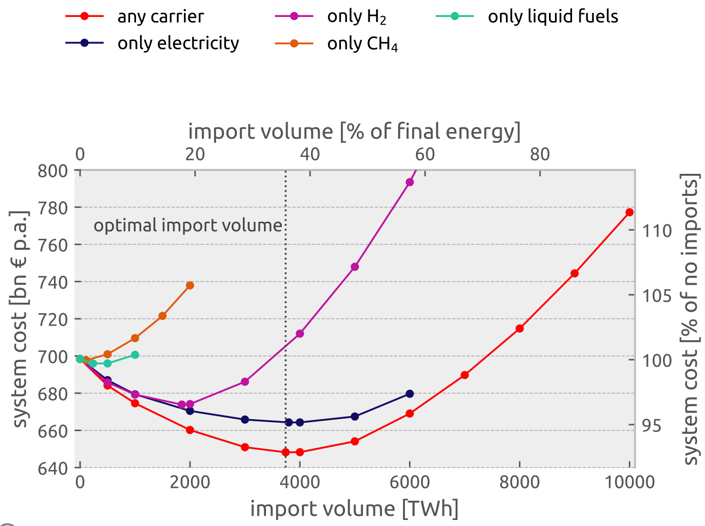
without imports



with imports



Cost sensitivity with restricted import carrier choices



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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**, diversification, and land usage.
- All results **depend strongly on assumptions**: more work on import cost sensitivities, losses in European energy networks, industry relocation, and material imports (like green steel or sponge iron).

Contact, License, Additional Resources

Find the slides:

https://neumann.fyi/files/enerday-import-benefits.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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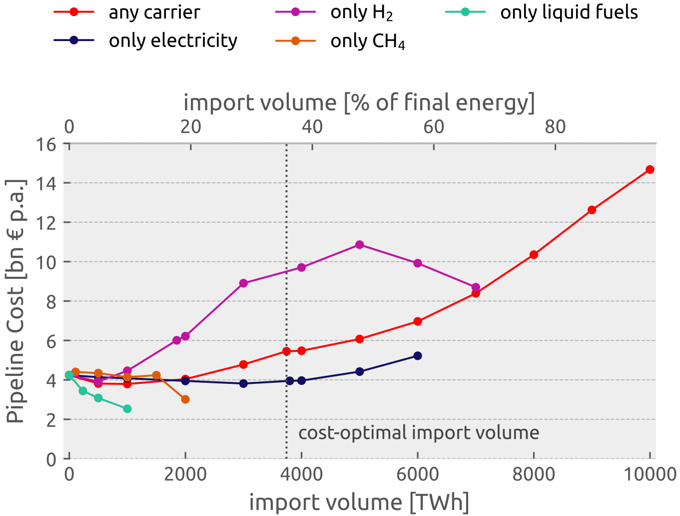
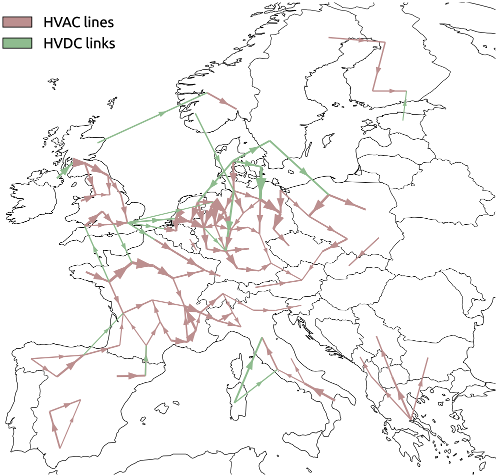
Spending on hydrogen pipelines depends on imported energy carriers



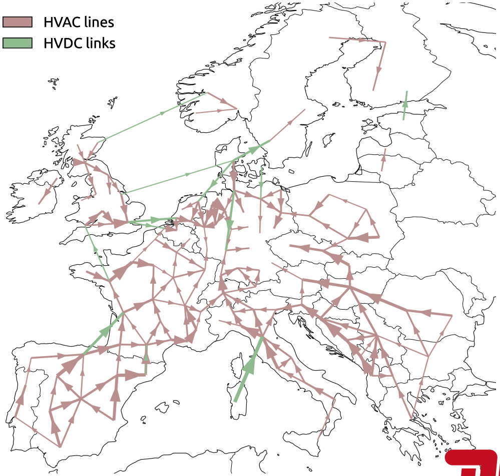
- demand for hydrogen network **decreases** when more H_2 derivatives are imported directly
- demand for hydrogen network **increases** when more H_2 is imported

Electricity imports lead to more South-North power transmission

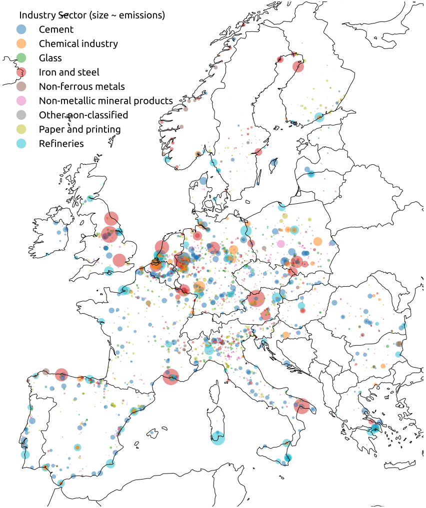
without imports



with imports



Industry: Process and Fuel Switching & Carbon Management

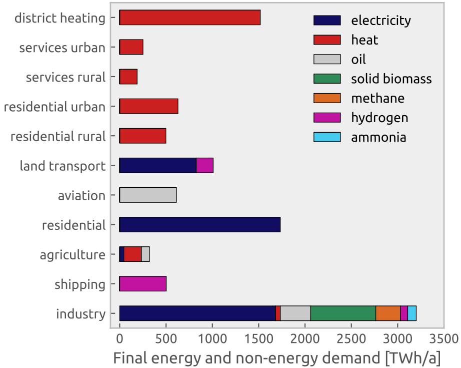


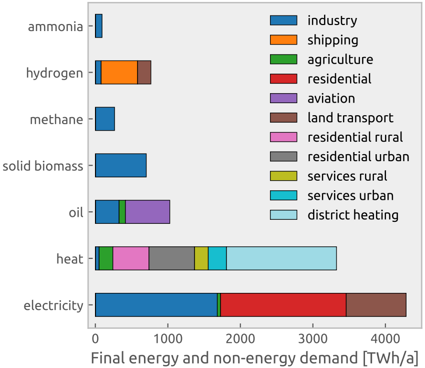
Iron & Steel	70% from scrap, rest from H_2-DRI + EAF
Aluminium	80% recycling; methane for high-enthalpy heat
Cement	Solid biomass; capture of CO_2 emissions
Ceramics	Electrification
Ammonia	Clean hydrogen
Plastics	55% recycling and synthetic naphtha
Other industry	Electrification; process heat from biomass
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 $MtCO_2/a$; carbon in plastics releases into atmosphere

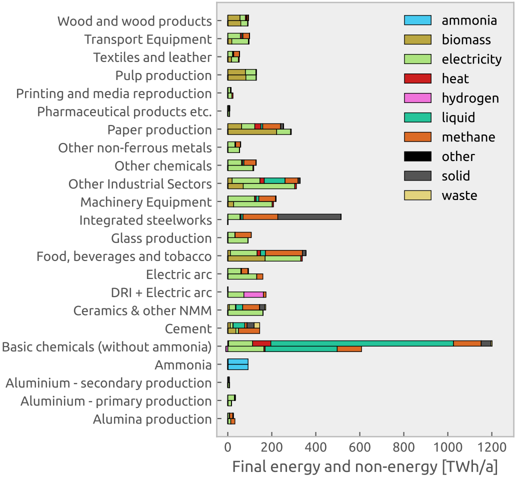
Source: Hotmaps Industrial Sites Database

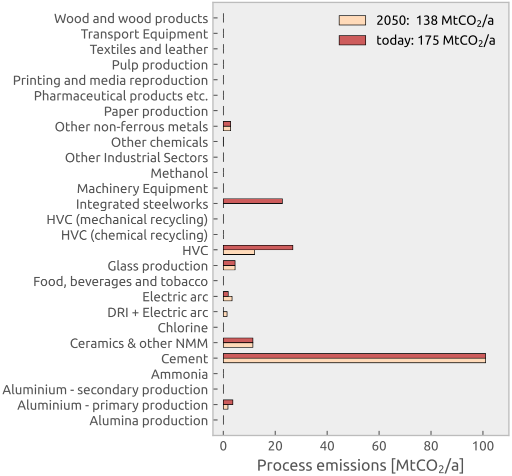
Final Energy Consumption by Carrier





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

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

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

subject to

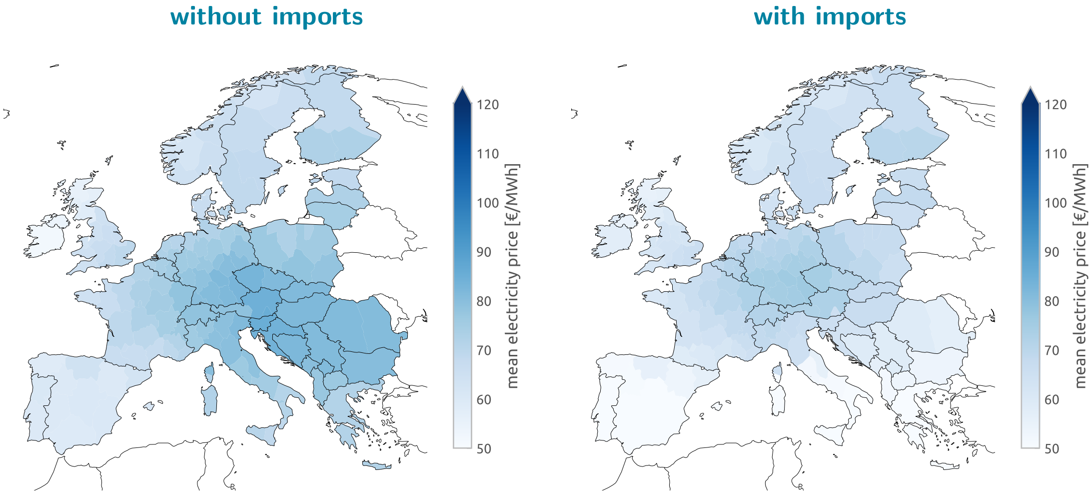
- meeting energy demand in each region r and time t for each carrier
- transmission constraints between regions and (linearised) power flow
- wind, solar, hydro availability time series $\forall\ r, t$
- geographical potentials for renewables
- emission reduction targets

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

Optimise transmission, generation, conversion and storage **jointly** $\rightarrow$ strongly interacting.

Source: See also https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html

Electricity imports lower prices as better resources become available



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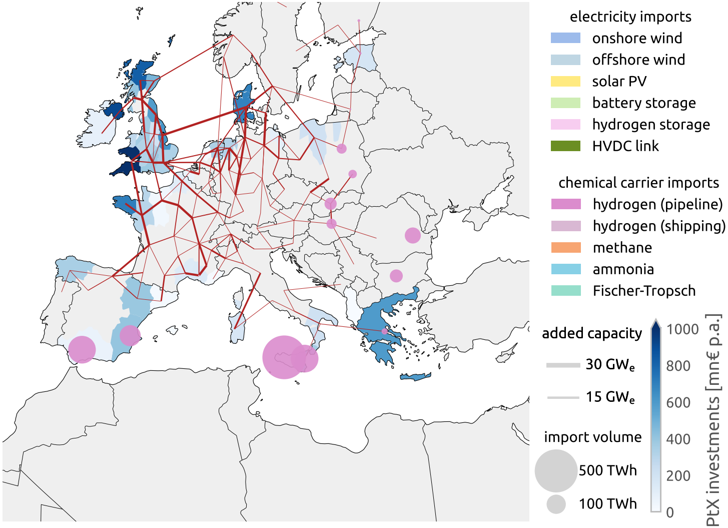
Preliminary: European energy supply with **exclusive hydrogen** imports



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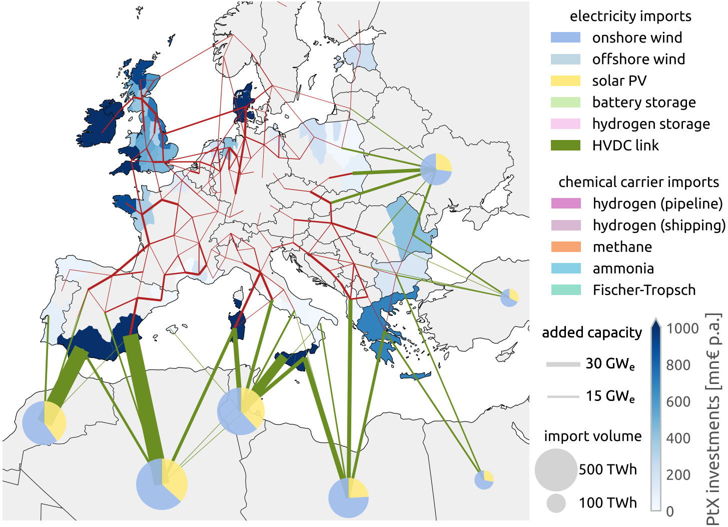
Preliminary: European energy supply with **exclusive electricity** imports



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

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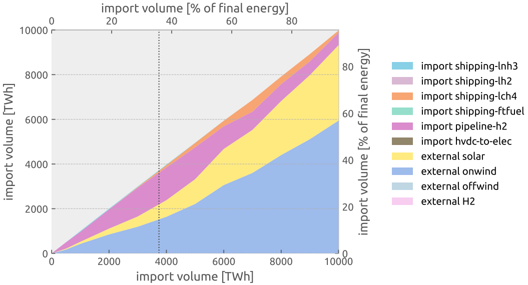
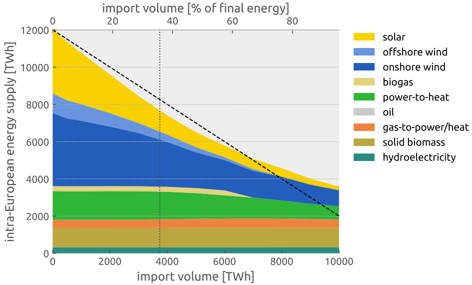
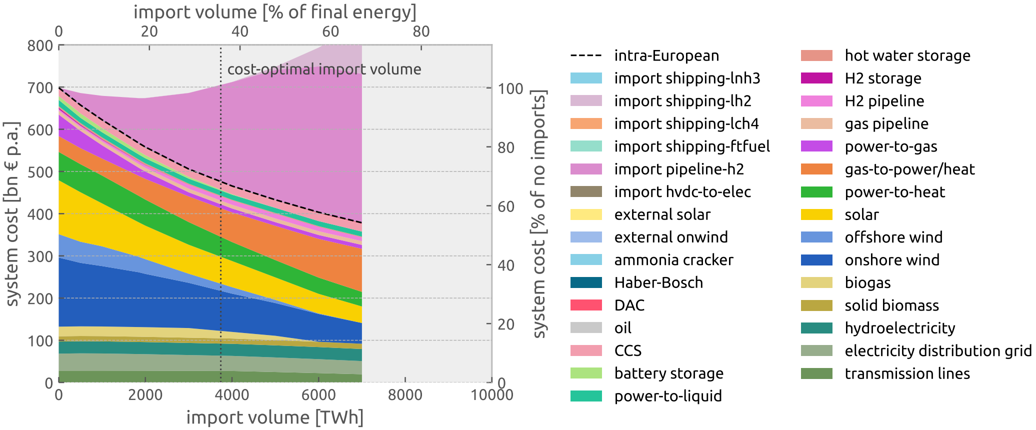
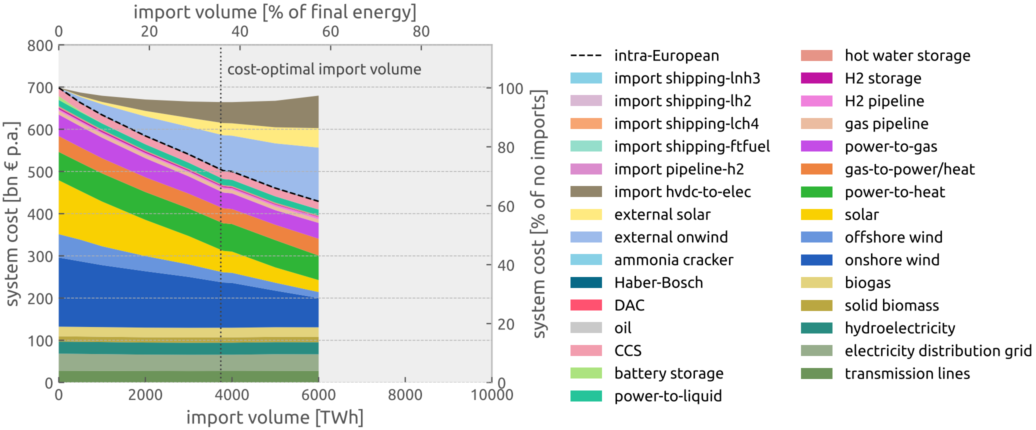

import volume [% of final energy]
import volume [TWh]
import volume [% of final energy]
import shipping-lnh3
import shipping-lh2
import shipping-lch4
import shipping-ftfuel
import pipeline-h2
import hvdc-to-elec
external solar
external onwind
external offwind
external H2


import volume [% of final energy]
intra-European energy supply [TWh]
import volume [TWh]
solar
offshore wind
onshore wind
biogas
power-to-heat
oil
gas-to-power/heat
solid biomass
hydroelectricity


import volume [% of final energy]
0
20
40
60
80
800
700
600
500
400
300
200
100
0
system cost [bn € p.a.]
cost-optimal import volume
100
80
60
40
20
0
system cost [% of no imports]
0
2000
4000
6000
8000
10000
import volume [TWh]
intra-European
import shipping-lnh3
import shipping-lh2
import shipping-lch4
import shipping-ftfuel
import pipeline-h2
import hvdc-to-elec
external solar
external onwind
ammonia cracker
Haber-Bosch
DAC
oil
CCS
battery storage
power-to-liquid
hot water storage
H2 storage
H2 pipeline
gas pipeline
power-to-gas
gas-to-power/heat
power-to-heat
solar
offshore wind
onshore wind
biogas
solid biomass
hydroelectricity
electricity distribution grid
transmission lines



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