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

Johannes Hampp, Tom Brown, **Fabian Neumann**

f.neumann@tu-berlin.de
Department of Digital Transformation in Energy Systems
Technical University of Berlin, Germany

ECEMP 2022, online

October 5, 2022

Technische Universität Berlin

CC BY

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?

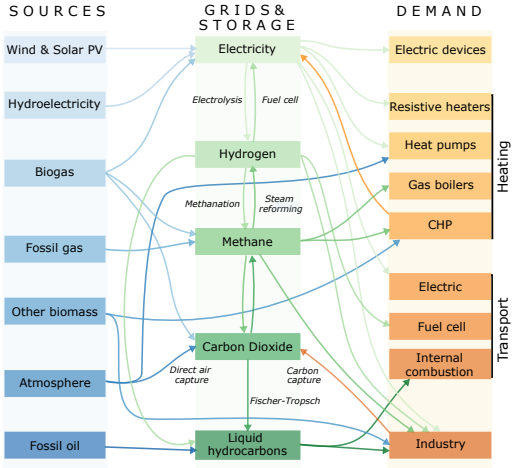
Coupling of a **global supply chain model** with open all-sector **European energy model**.

cc

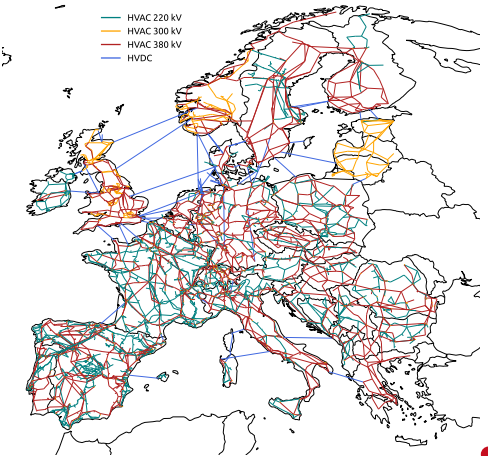
Technische Universität Berlin

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

Model for Europe with all energy flows...



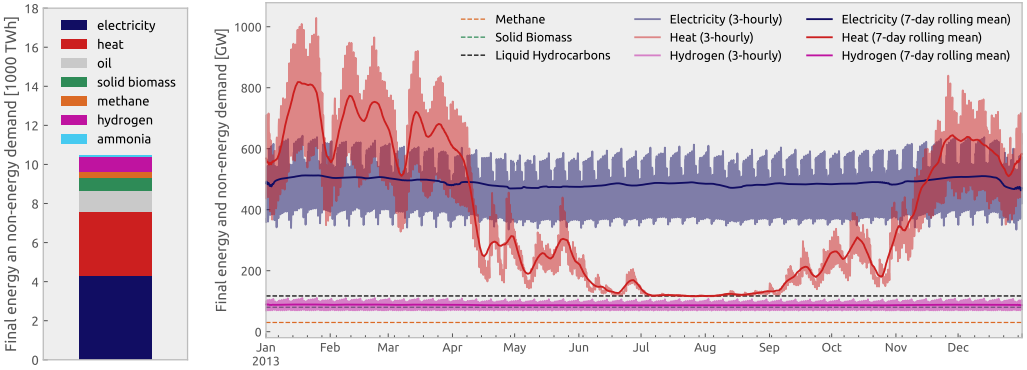
...and bottlenecks in energy networks...



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

CC BY
Technische Universität Berlin

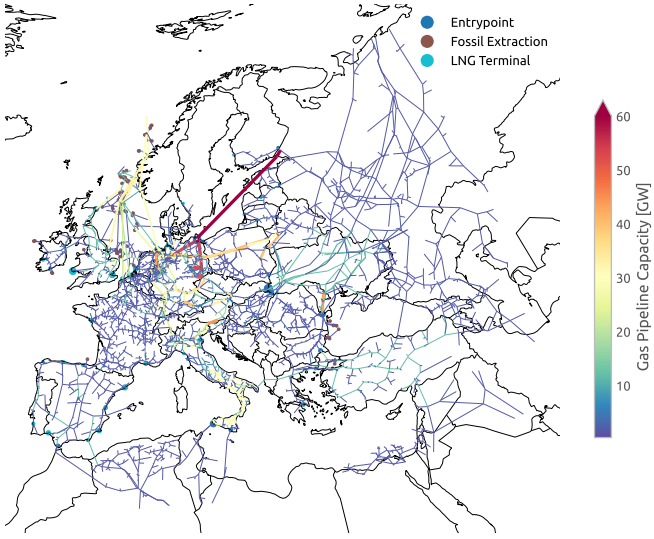
... and temporal variability in demand and supply.



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: For a 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`

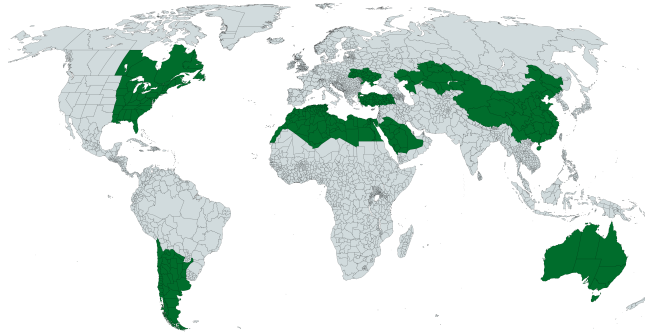
Source: SciGRID_gas

CC BY

Technische Universität Berlin

Model of global green energy supply chains

- **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)

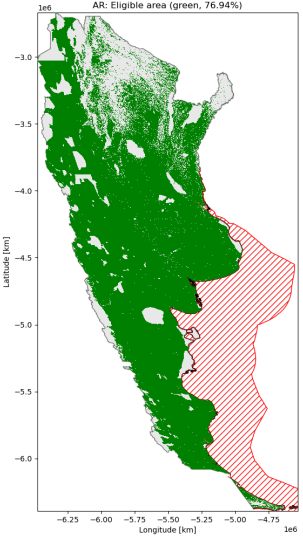


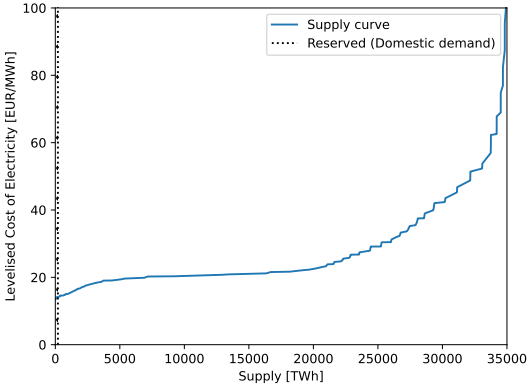
Source: https://github.com/euronion/trace

CC BY

Technische Universität Berlin

Model of global green energy supply chains





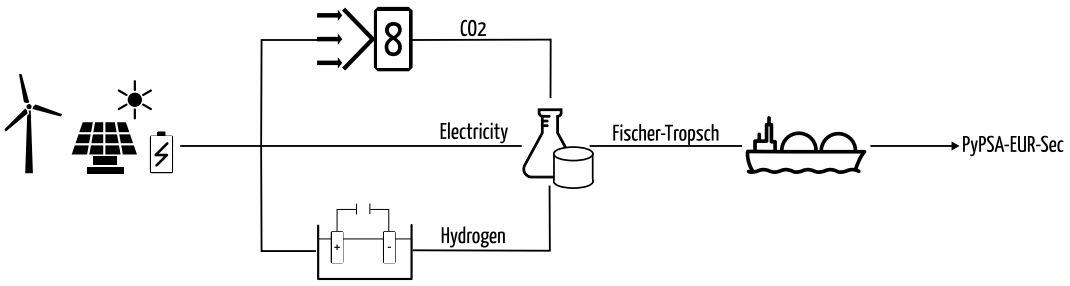
hourly PV, on-/offshore wind subject to eligible land grouped into classes for **regional supply curves** – domestic demand

Source: https://github.com/euronion/trace

CC BY

Model of global green energy supply chains

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



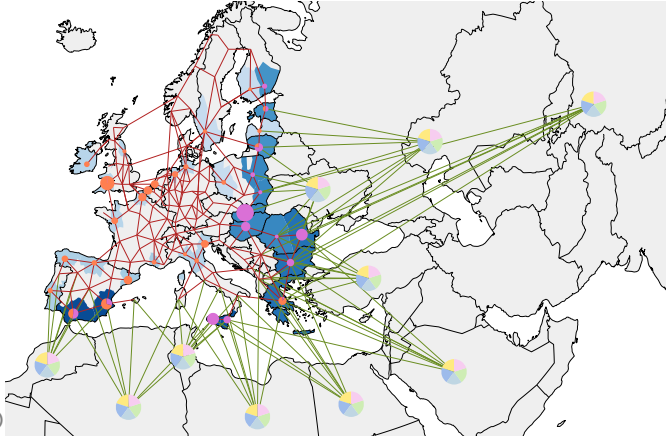
Source: https://github.com/euronion/trace

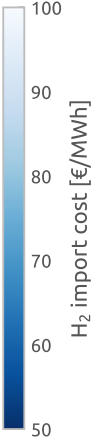
Technische Universität Berlin

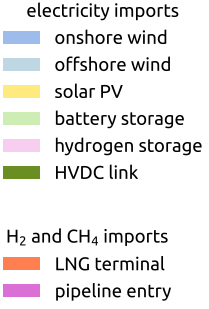
Import locations and costs for a variety of energy carriers

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

NH_3	85 €/MWh	[AR, CL]	**CH_4 (LNG)**	89 €/MWh	[AR, CL]
Fischer-Tropsch	115 €/MWh	[AR, CL]	**CH_4 (pipeline)**	100 €/MWh	[DZ]



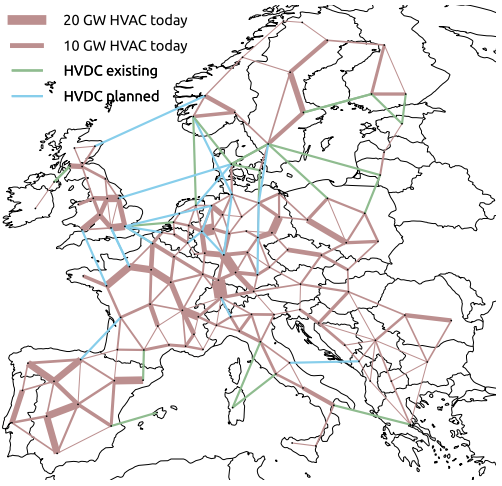




Technische Universität Berlin

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

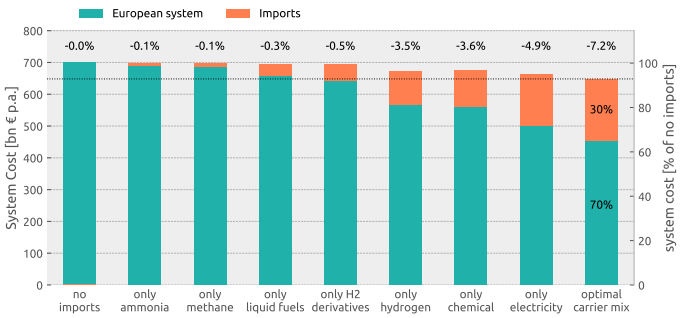
- Couple **all energy sectors** (power, heat, transport, industry, feedstocks, agriculture, international aviation & shipping)
- Reduce net CO_2 emissions **to zero**
- Cluster to **128** regions, **3**-hourly timesteps
- Power (x2), gas and hydrogen **networks**
- Technology assumptions for **2030**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



CC BY

Technische Universität Berlin

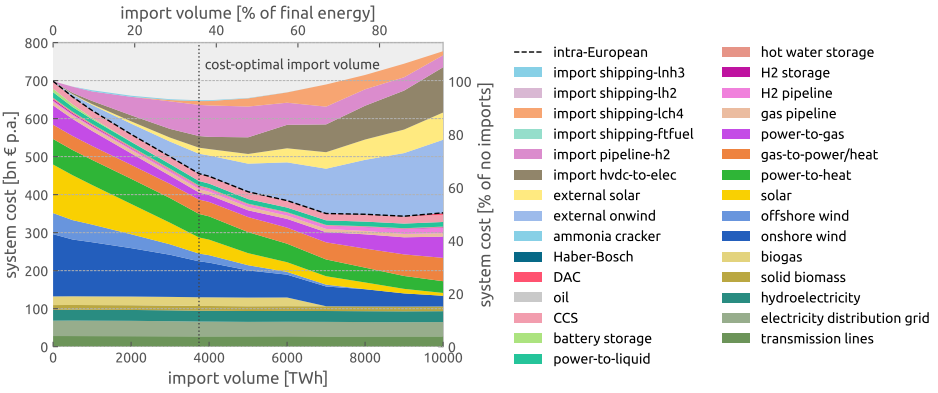
Preliminary: Cost reduction by energy imports depending on available options



- 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

CC BY

Preliminary: System cost configurations with increasing energy imports



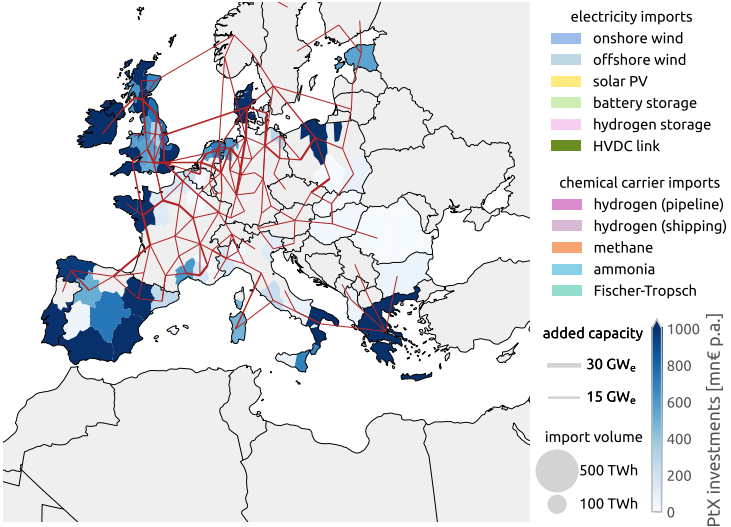
→ cost-optimal import volume **3750 TWh** (of which 59% electricity, 39% hydrogen)

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

CC BY

Technische Universität Berlin

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

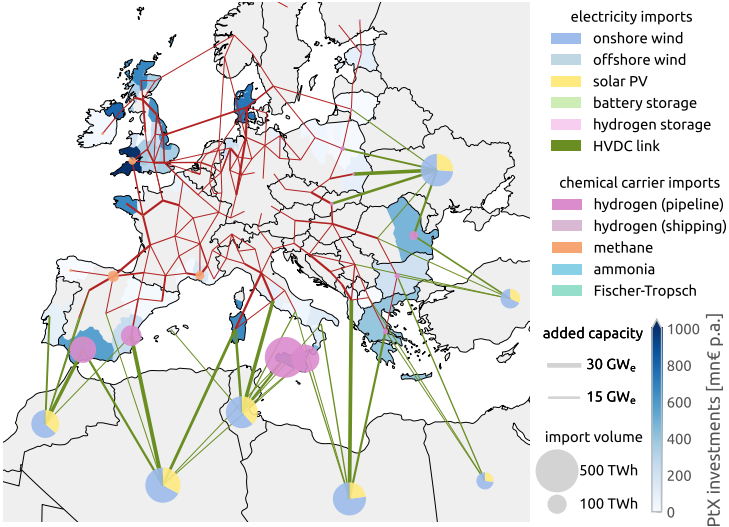


- large **PtX production** within Europe to cover demands for steel, plastics, kerosene etc.
- concentrated in Southern Europe and the British Isles
- **electricity grid reinforcements** focused mostly in northwest Europe

CC BY

Technische Universität Berlin

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

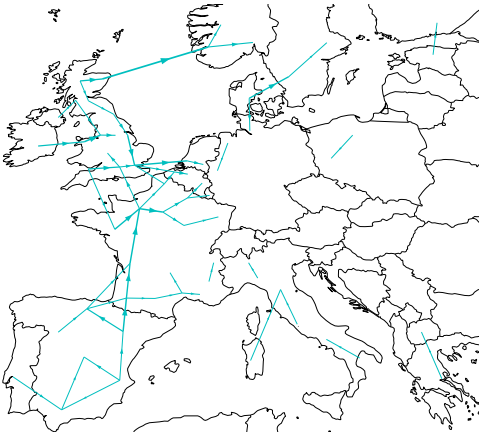
CC BY

Technische Universität Berlin

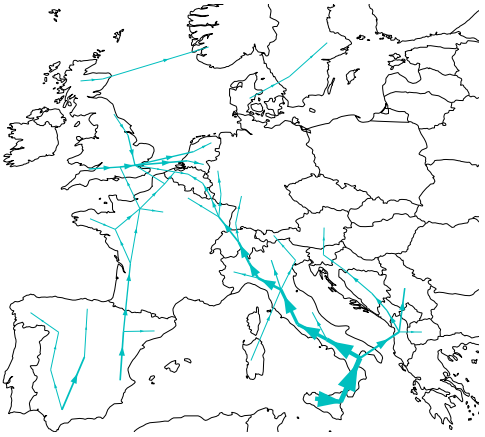
Increased energy imports change the role of hydrogen network. . .

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

without imports



with imports

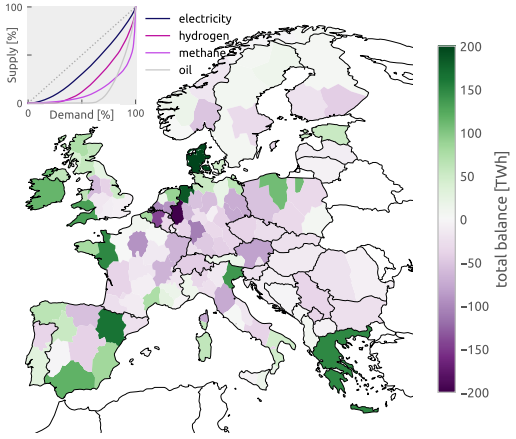


CC BY

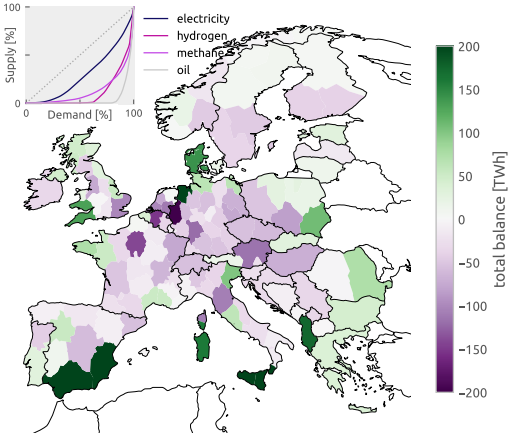
Technische Universität Berlin

Regional energy imbalance reinforced by import options

without imports



with imports



Preliminary Conclusions

- Imports of green e-fuels reduce cost of net-zero European energy system **by 7%**.
- **Hydrogen and electricity** appear as preferred import carriers with current setup.
- **European infrastructure requirements** depend on strategy taken on energy imports.
- Other factors than pure costs might drive import strategy: **geopolitical** consideration, building **simple & easy-to-implement** systems, **reuse** of existing infrastructure, **resilience** of supply chains, **technology risk**.
- All results **depend strongly on assumptions** - e.g. volume/carrier/costs for energy imports, industry relocation and material imports and consumption.

cc

Contact, License, Additional Resources

Unless otherwise stated, the graphics and text are Copyright ©F.N., J.H., T.B., 2022.

This work is licensed under a Creative Commons "Attribution 4.0 International" license.

Find the slides:
https://neumann.fyi/files/ecemp-import-benefits.pdf

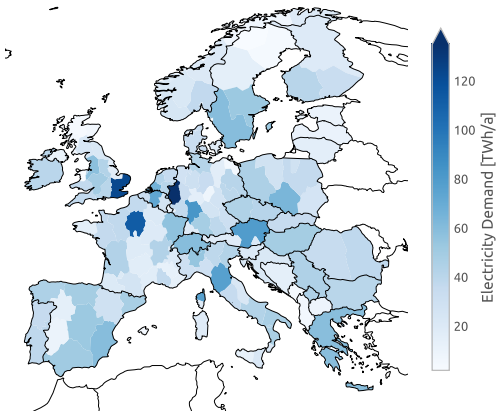
Find out more about PyPSA:
https://pypsa.org

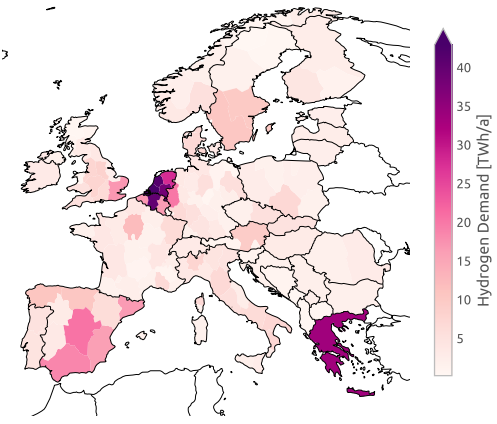
Find the open energy system model:
https://github.com/pypsa/pypsa-eur-sec

Send an email:
mailto:f.neumann@tu-berlin.de

Technische Universität Berlin

Demand Maps – Electricity and Hydrogen

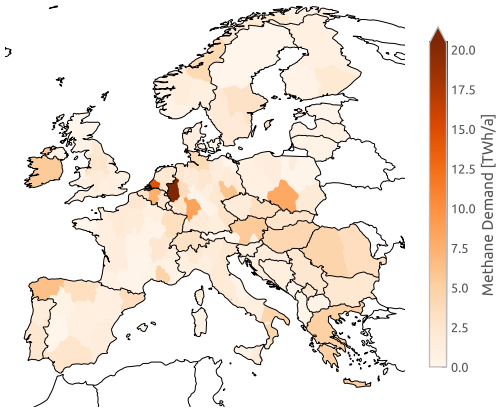


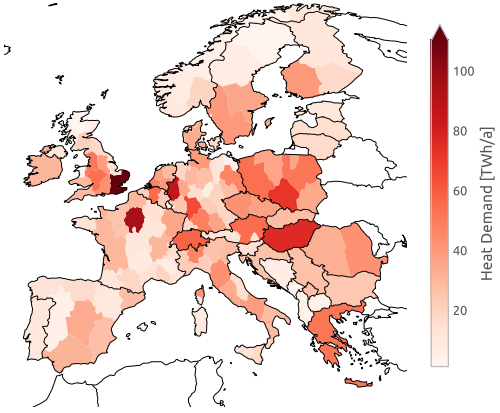


cc

Technische Universität Berlin

Demand Maps – Methane and Heat

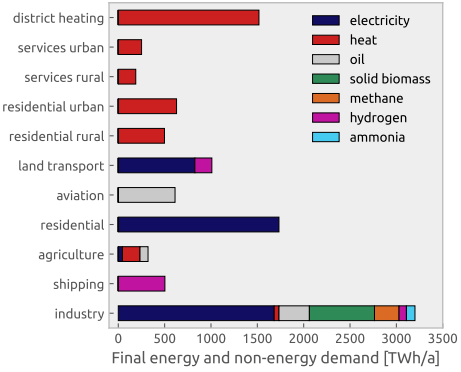


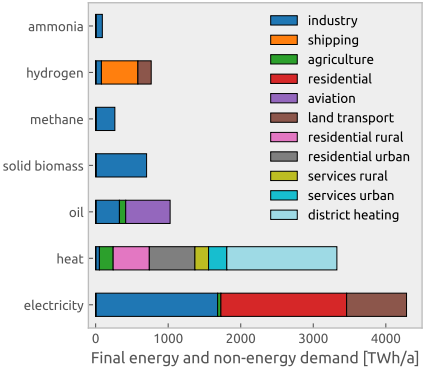


cc

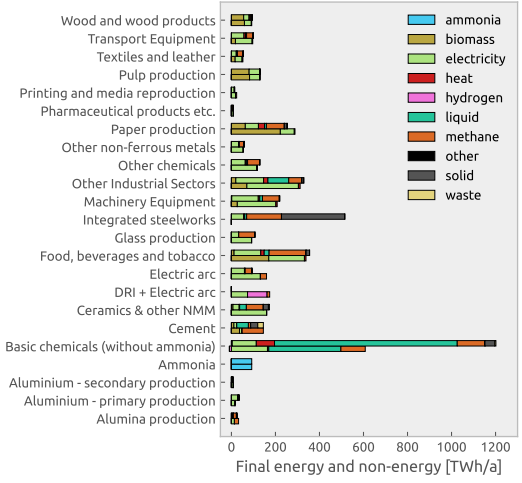
Technische Universität Berlin

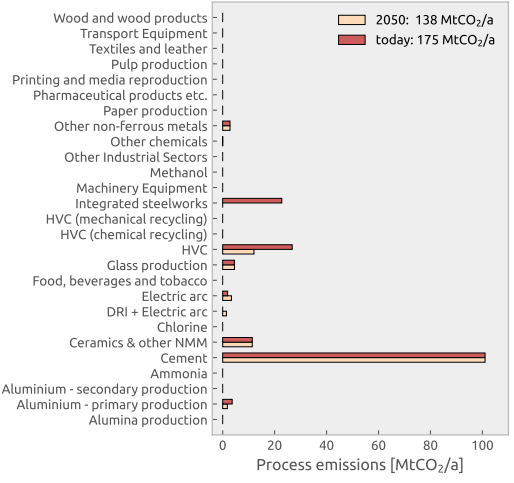
Final Energy Consumption by Carrier





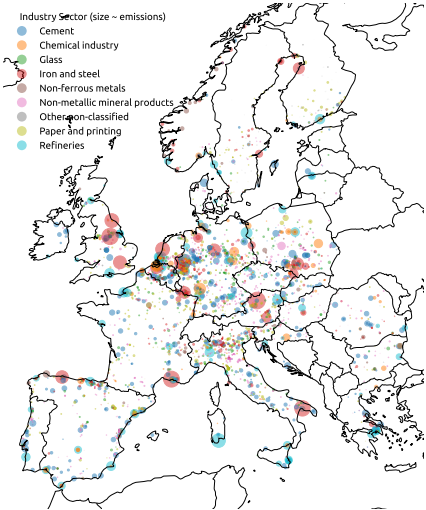
Industry Sector – Demand and Process Emissions





Technische Universität Berlin

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

Technische Universität Berlin

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

CC BY

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

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

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.

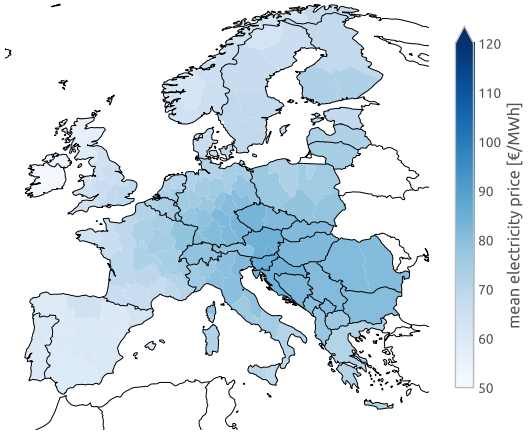
Source: See also https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html

cc

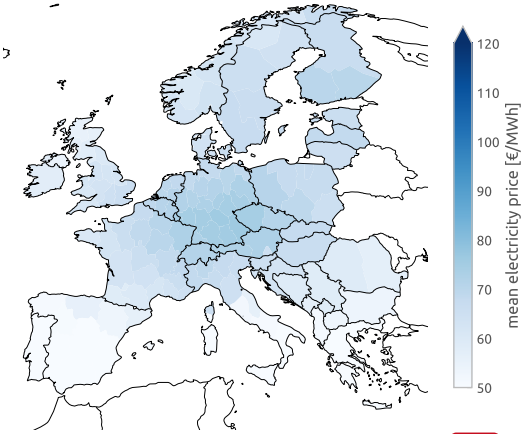
Technische Universität Berlin

Electricity imports lower prices as better resources become available

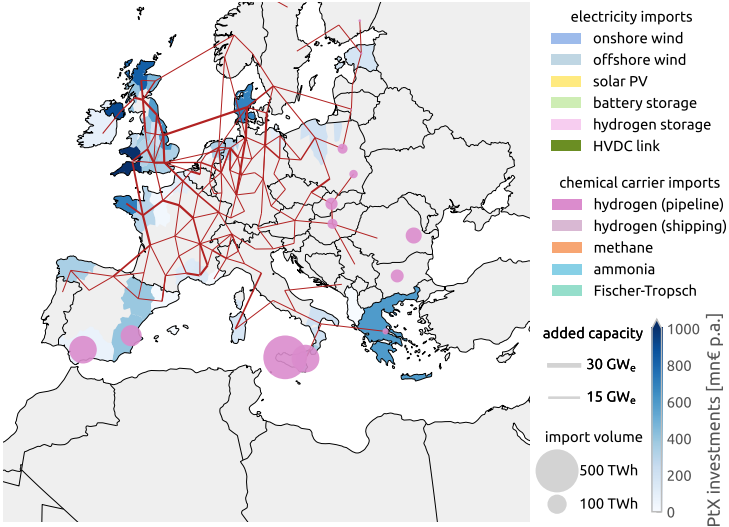
without imports



with imports



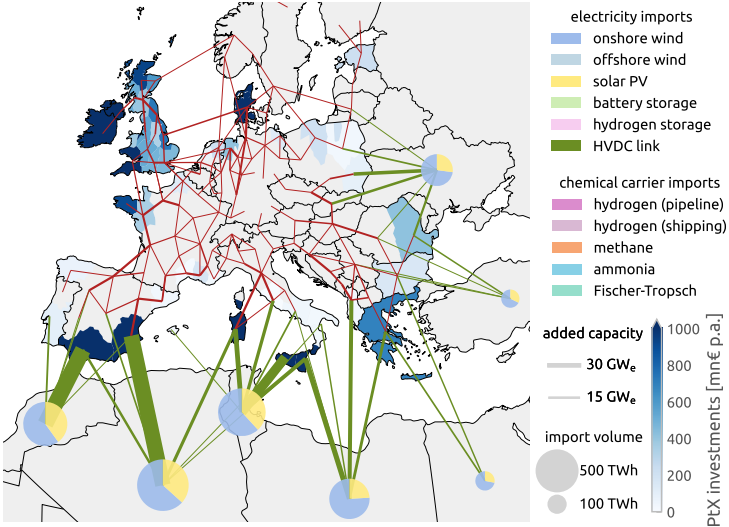
Preliminary: European energy supply with **exclusive hydrogen** imports



- item
- item
- item

Technische Universität Berlin

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



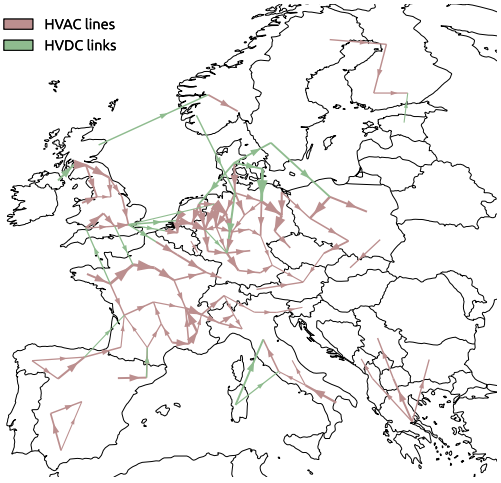
- exclusive electricity exports entail **massive (!) cross-continental HVDC** connections
- PtX production is **shifted to importing European nodes** as power grid capacity is limited

CC BY

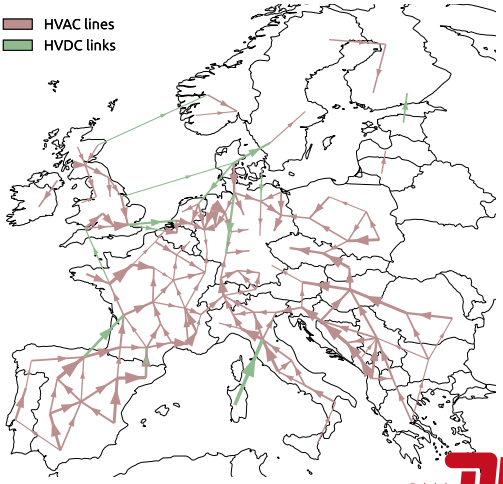
Technische Universität Berlin

Electricity imports lead to more South-North power transmission

without imports



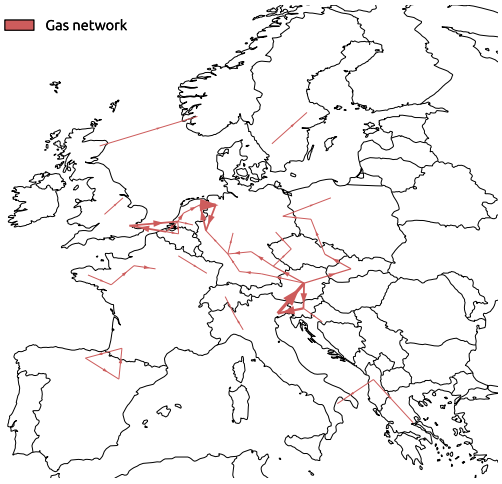
with imports



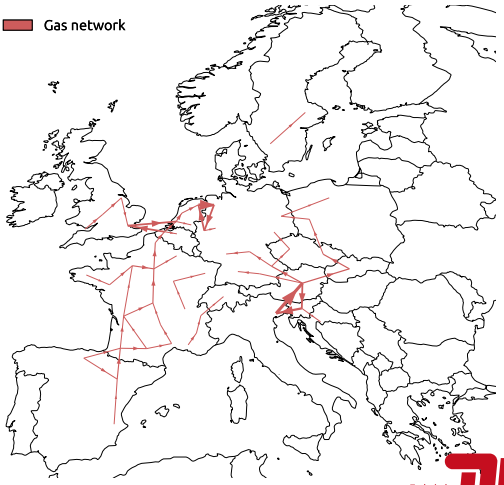
Technische Universität Berlin

Gas network flows only play a tangential role in both scenarios

without imports

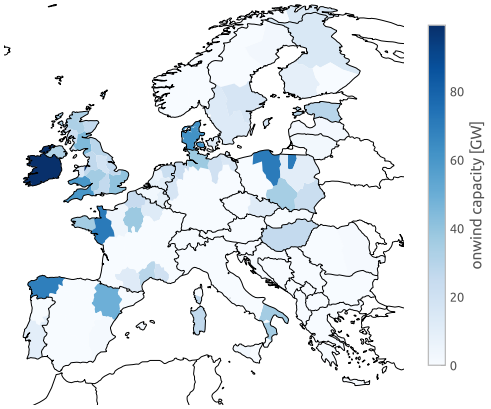


with imports

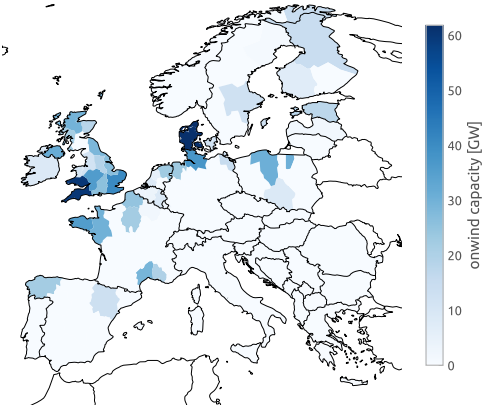


Capacities Built – Onshore Wind

without imports



with imports

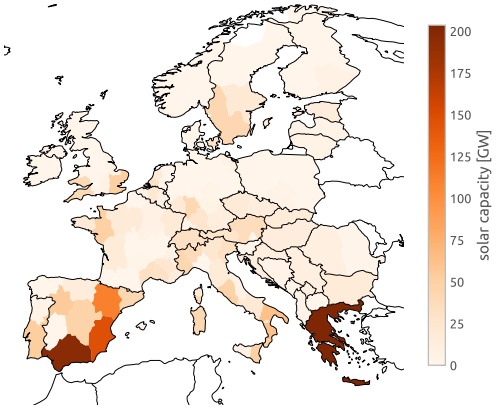


cc

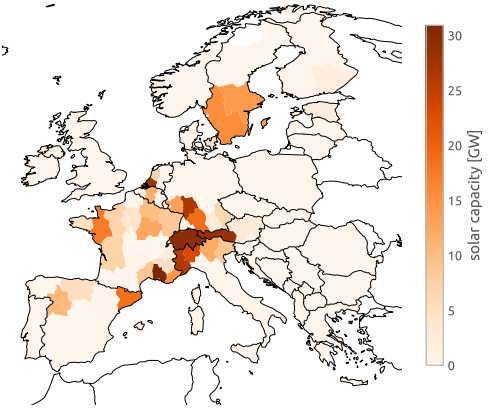
Technische Universität Berlin

Capacities Built – Solar

without imports



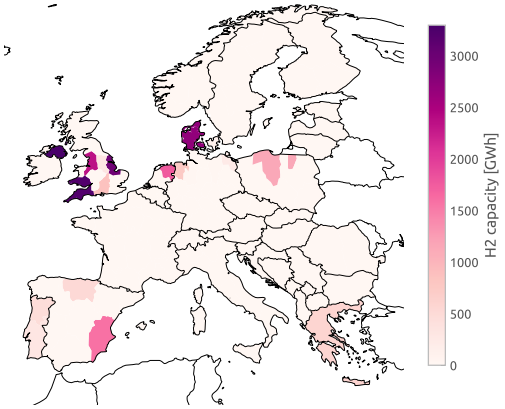
with imports



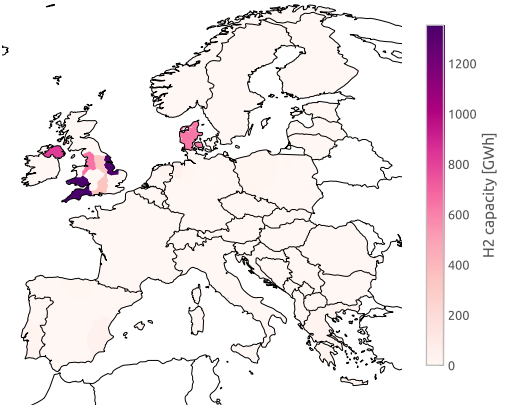
Technische Universität Berlin

Capacities Built – Hydrogen Storage

without imports



with imports

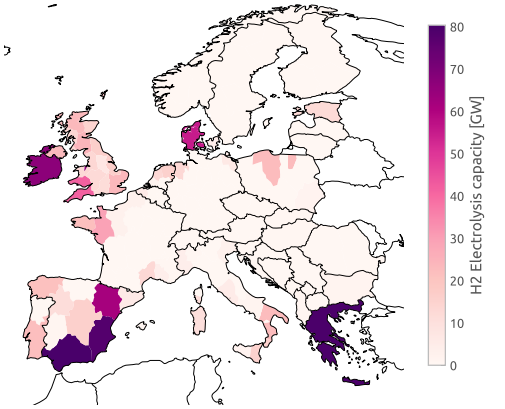


cc

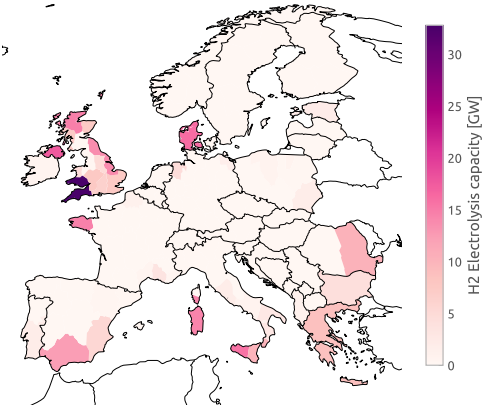
Technische Universität Berlin

Capacities Built – Electrolysis

without imports



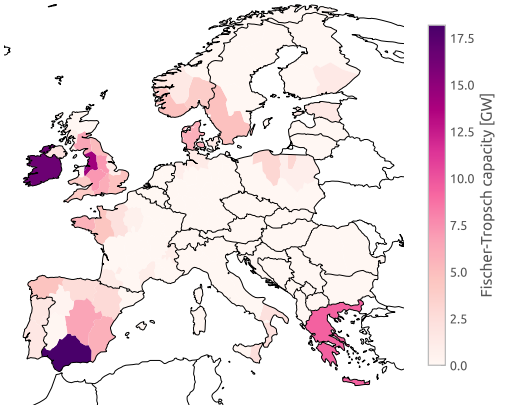
with imports



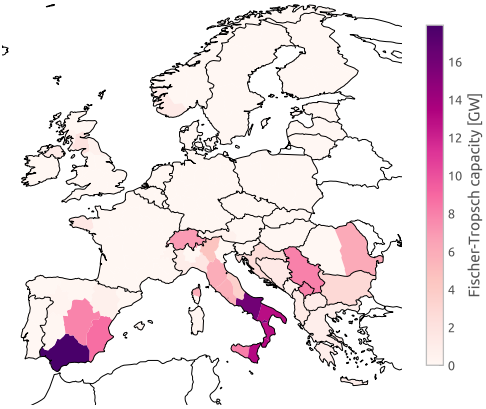
Technische Universität Berlin

Capacities Built – Fischer-Tropsch

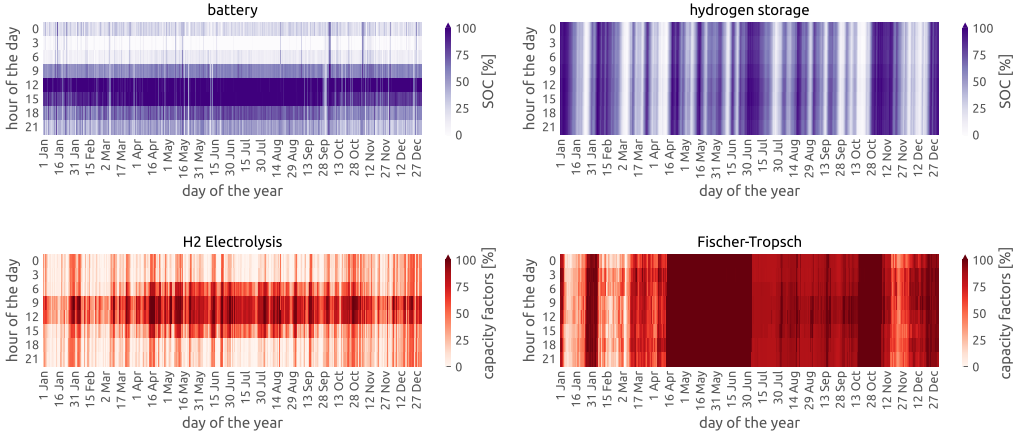
without imports



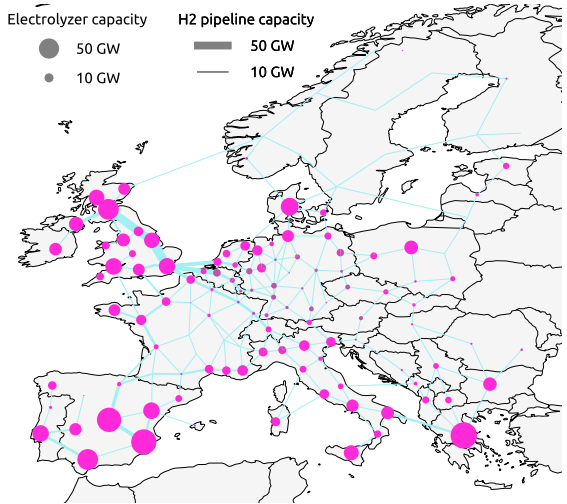
with imports



Utilisation Patterns (no imports)



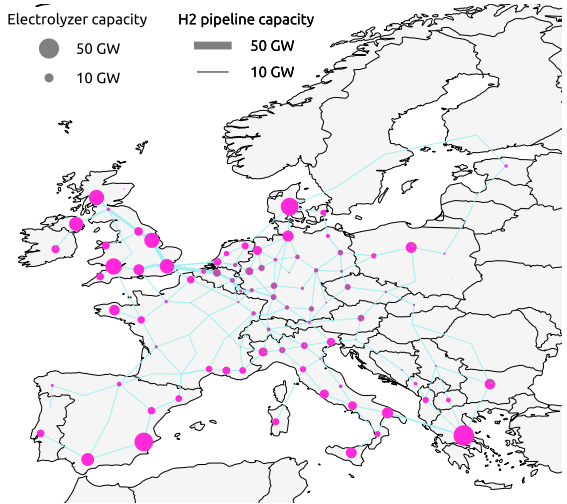
Imports of energy into Europe diminish hydrogen network benefit



- So far we looked at scenarios for **self-sufficient** energy supply
- But when H_2 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.

cc

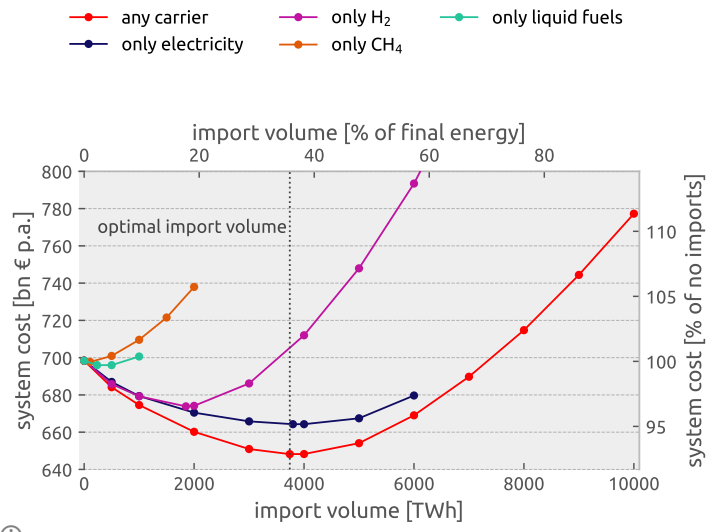
Imports of energy into Europe diminish hydrogen network benefit



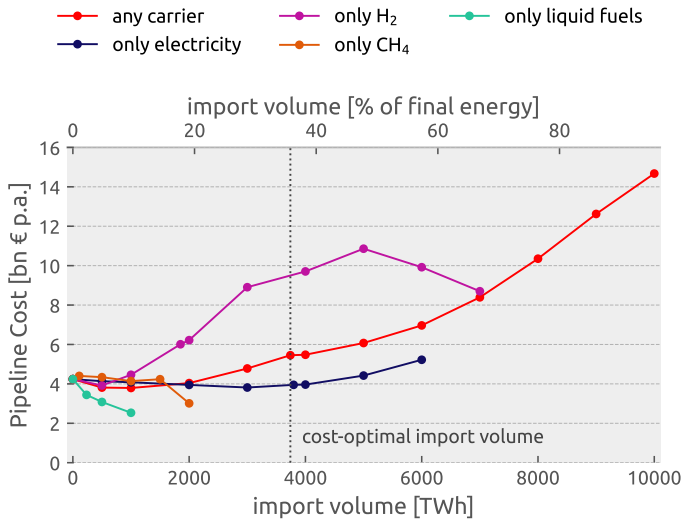
- So far we looked at scenarios for **self-sufficient** energy supply
- But when H_2 and derivatives are imported (shipping, aviation, industry, trucks), **hydrogen network benefit drops to 1%**.
- **Residual benefit** of €5 billion per year comes from transporting energy to **fuel cell CHPs** to renewable-poor and grid-poor inner-European nodes.

cc

Cost sensitivity with restricted import carrier choices



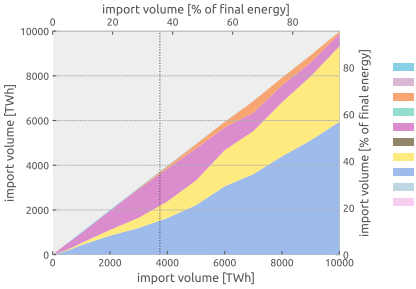
Spending on hydrogen pipelines depends on imported energy carriers

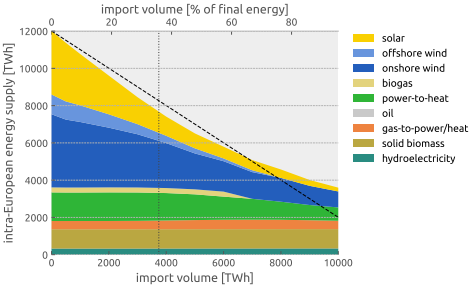


- demand for hydrogen network **decreases** when more H_2 derivatives are imported directly
- demand for hydrogen network **increases** when more H_2 is imported

cc

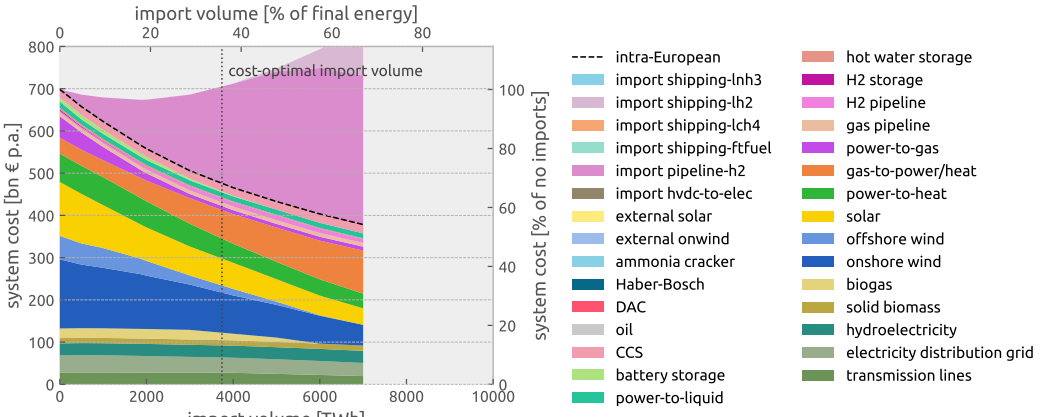
Technische Universität Berlin

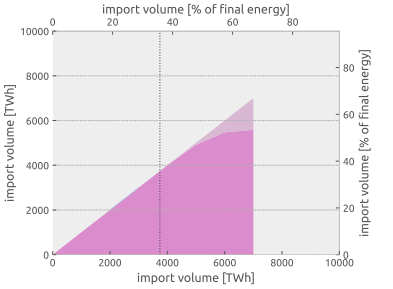


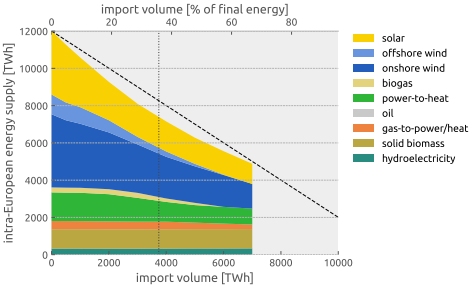


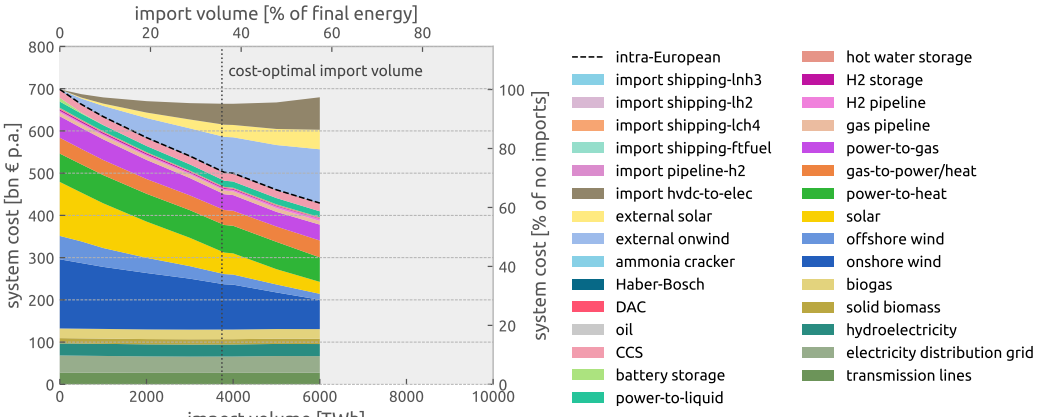
CC BY

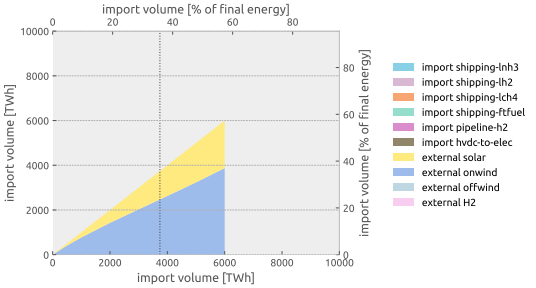
Technische Universität Berlin

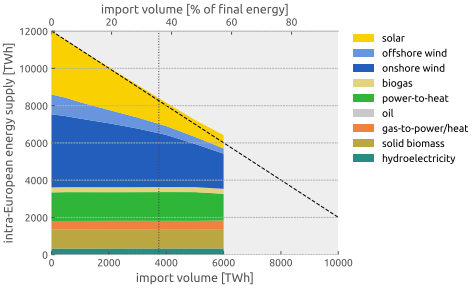

import volume [% of final energy]
0
20
40
60
80
cost-optimal import volume
system cost [bn € p.a.]
800
700
600
500
400
300
200
100
0
system cost [% of no imports]
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
import volume [TWh]
intra-European
import shipping-lnh3
import shipping-lh2
import shipping-lch4
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


import volume [% of final energy]
0
20
40
60
80
import volume [TWh]
0
2000
4000
6000
8000
10000
import volume [% of final energy]
0
20
40
60
80
import volume [TWh]
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]
0
20
40
60
80
intra-European energy supply [TWh]
0
2000
4000
6000
8000
10000
12000
import volume [TWh]
solar
offshore wind
onshore wind
biogas
power-to-heat
oil
gas-to-power/heat
solid biomass
hydroelectricity

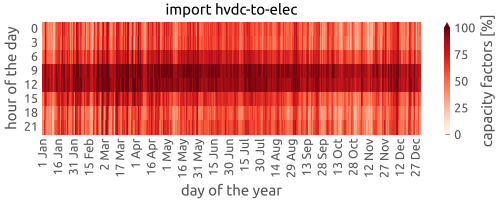

import volume [% of final energy]
0
20
40
60
80
cost-optimal import volume
system cost [bn € p.a.]
800
700
600
500
400
300
200
100
0
system cost [% of no imports]
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
import volume [TWh]
intra-European
import shipping-lnh3
import shipping-lh2
import shipping-lch4
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


import volume [% of final energy]
0
20
40
60
80
import volume [TWh]
0
2000
4000
6000
8000
10000
import volume [% of final energy]
0
20
40
60
80
import volume [TWh]
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

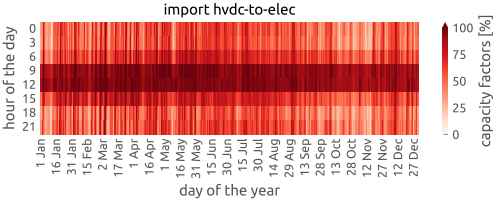

import volume [% of final energy]
0
20
40
60
80
intra-European energy supply [TWh]
0
2000
4000
6000
8000
10000
12000
import volume [TWh]
solar
offshore wind
onshore wind
biogas
power-to-heat
oil
gas-to-power/heat
solid biomass
hydroelectricity

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

any import carriers



only electricity imports



cc

Technische Universität Berlin