46770 Integrated energy grids

Marta Victoria

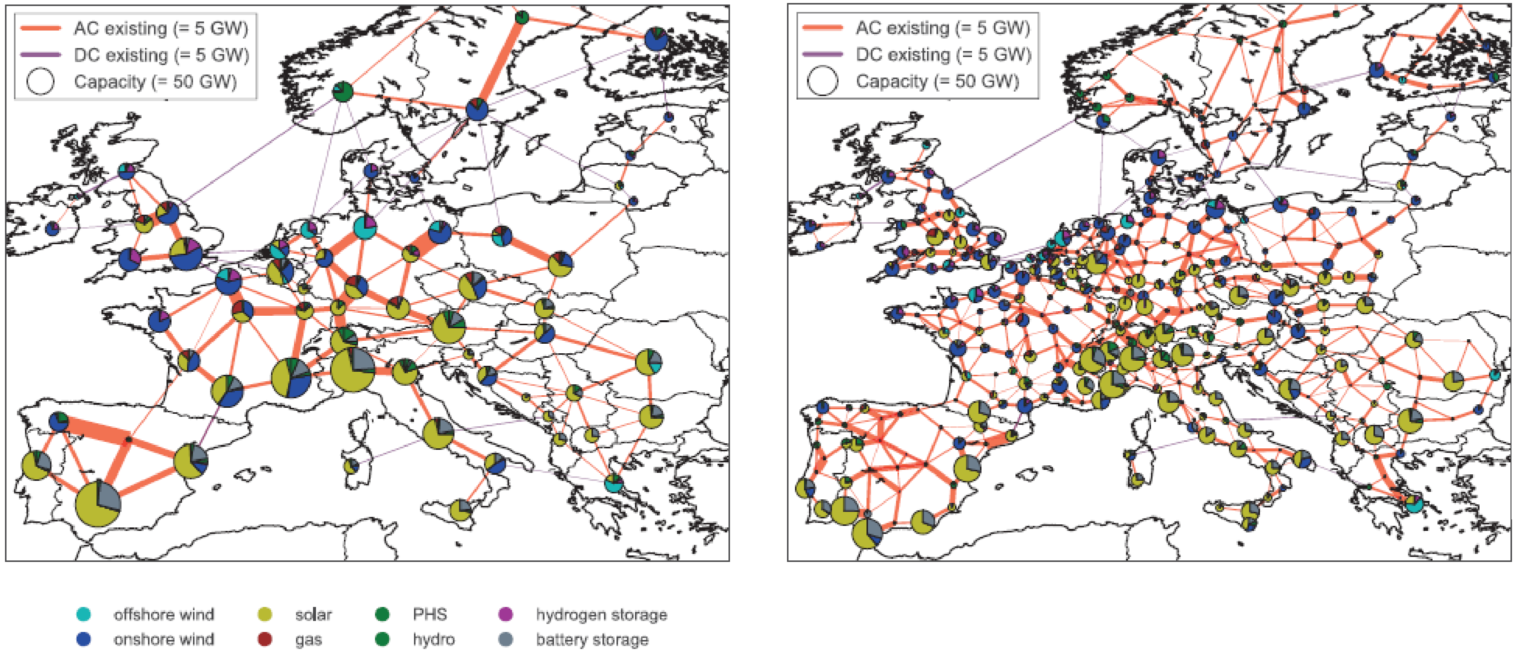
Lecture 12 – Multicarrier energy systems II (industry, aviation, shipping)

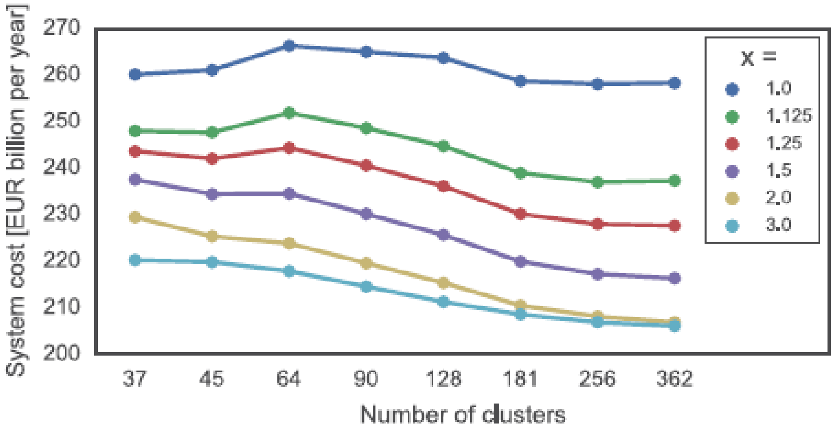
Which spatial and temporal resolution is good enough?

Which spatial resolution is good enough?

When increasing the number of nodes, the system cost remains roughly constant due to the counterbalancing of two effects:
(a) sites with high capacity factors for wind and solar are available for a more finely resolved network,

(b) but the emergence of bottlenecks inside countries prevents the use wind energy generated at exterior nodes



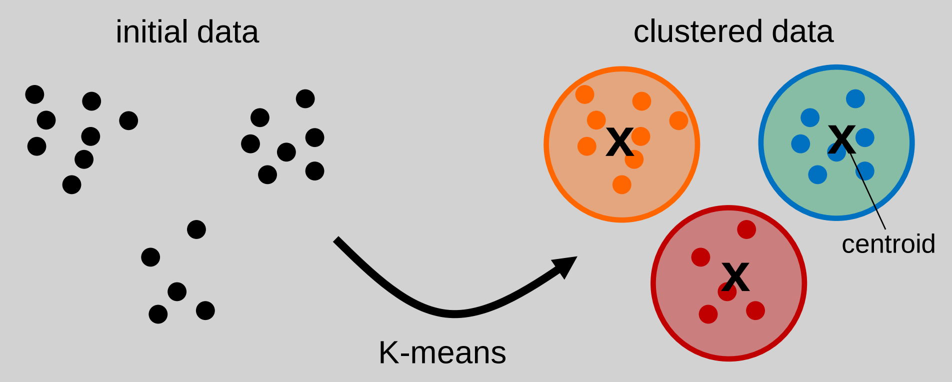


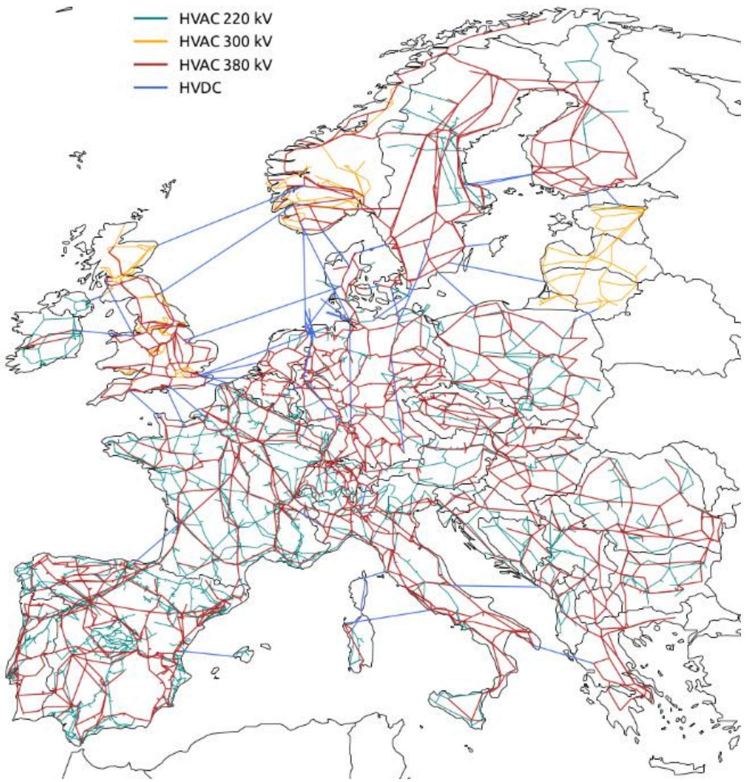
Hörsch and Brown, IEEE (2017)

Higher spatial resolution requires more computation capabilities and downscaling historical information that is typically provided at country level.

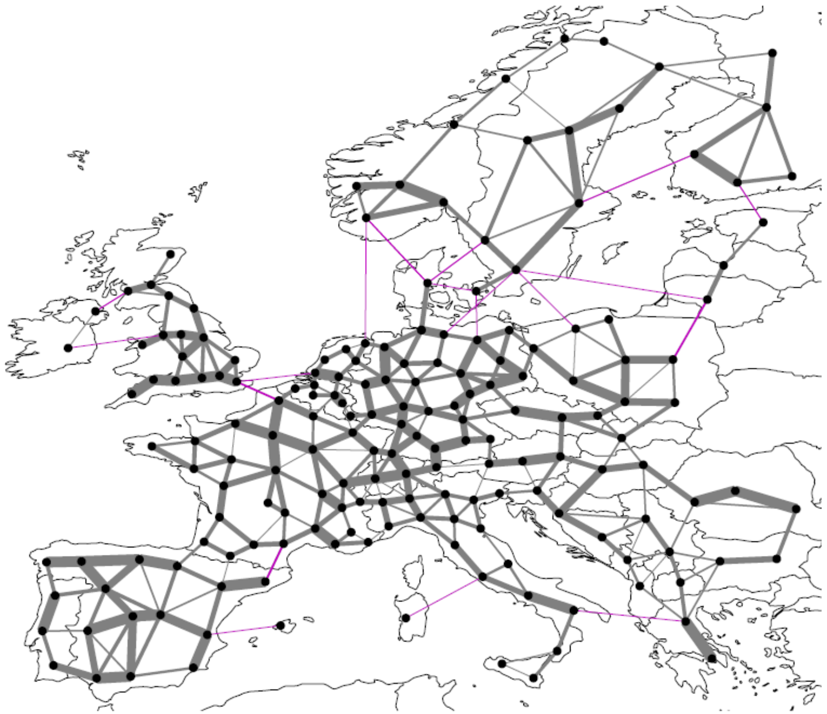
How can we cluster power networks?

We cluster the network using k-means algorithms.





Existing HVAC and HVDC network in Europe



Network clustered to 181 nodes

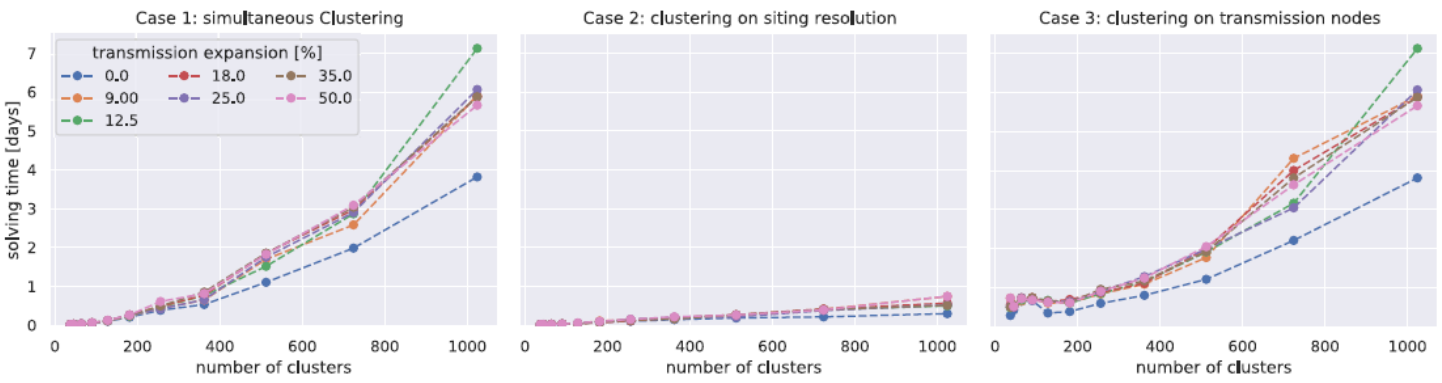
The area is split using Voronoi cells

(each point assigned to the closest node)

Source: wikipedia

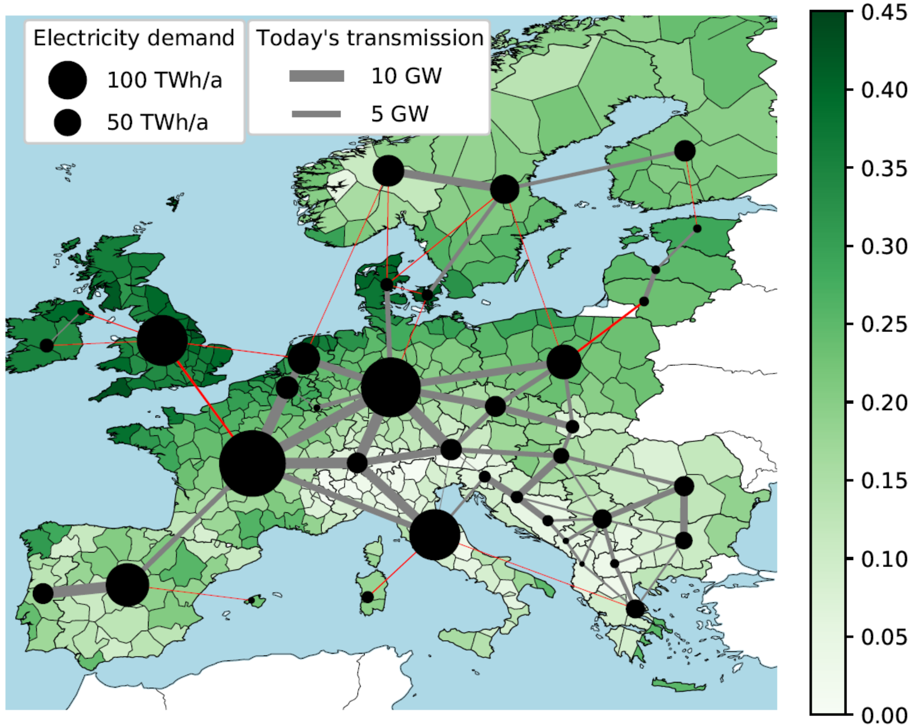
Which spatial resolution is good enough?

Attaining high resolution on transmission nodes increases solving time, but increasing (only) resolution on sites for renewable has negligible impact.



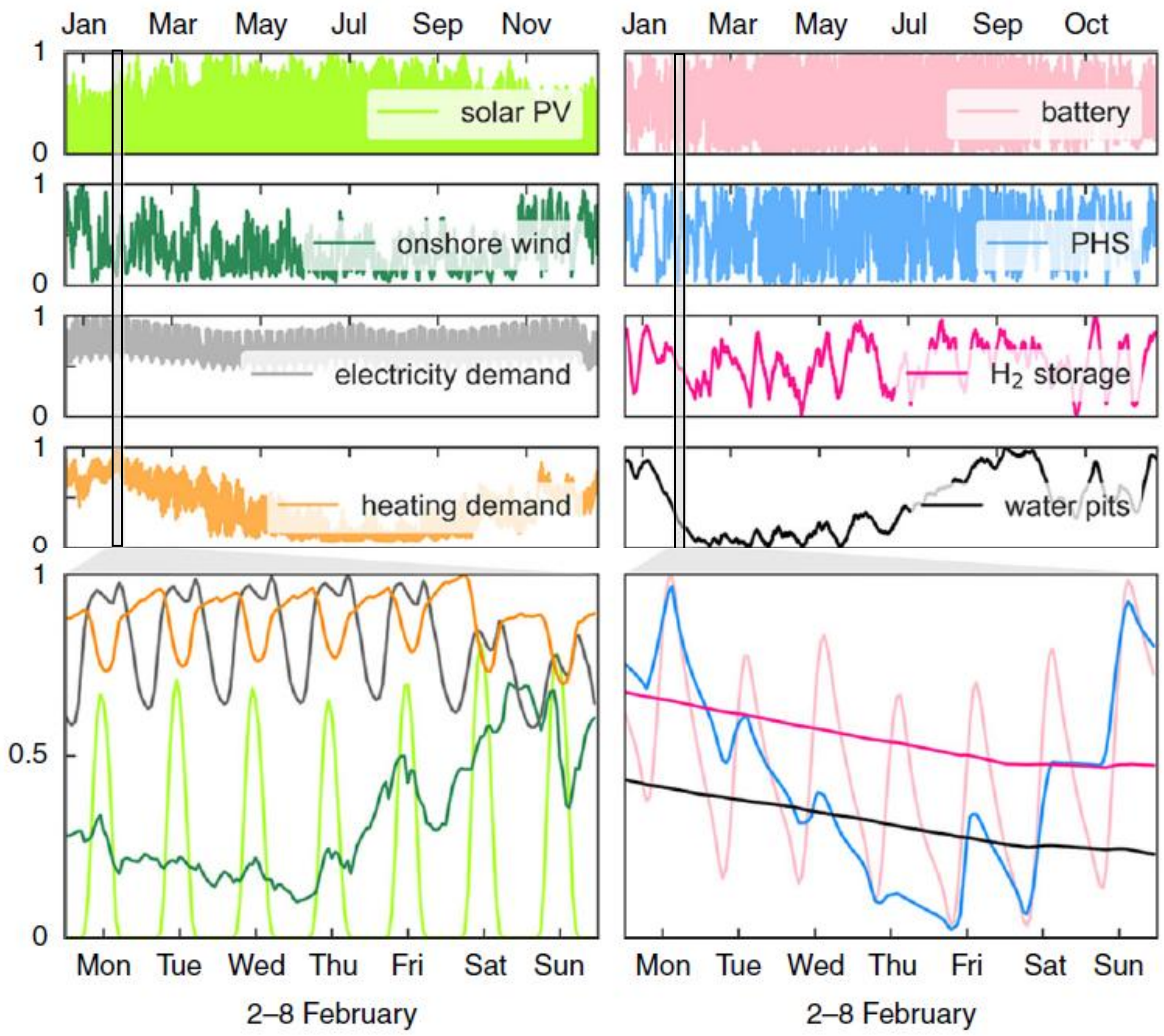
Frysztacki et al., Applied Energy (2021)

In our recent works, we keep a 37-node network and 370 nodes to resolve solar and wind resource.



Victoria et al., Joule (2022)

Which time resolution is good enough?



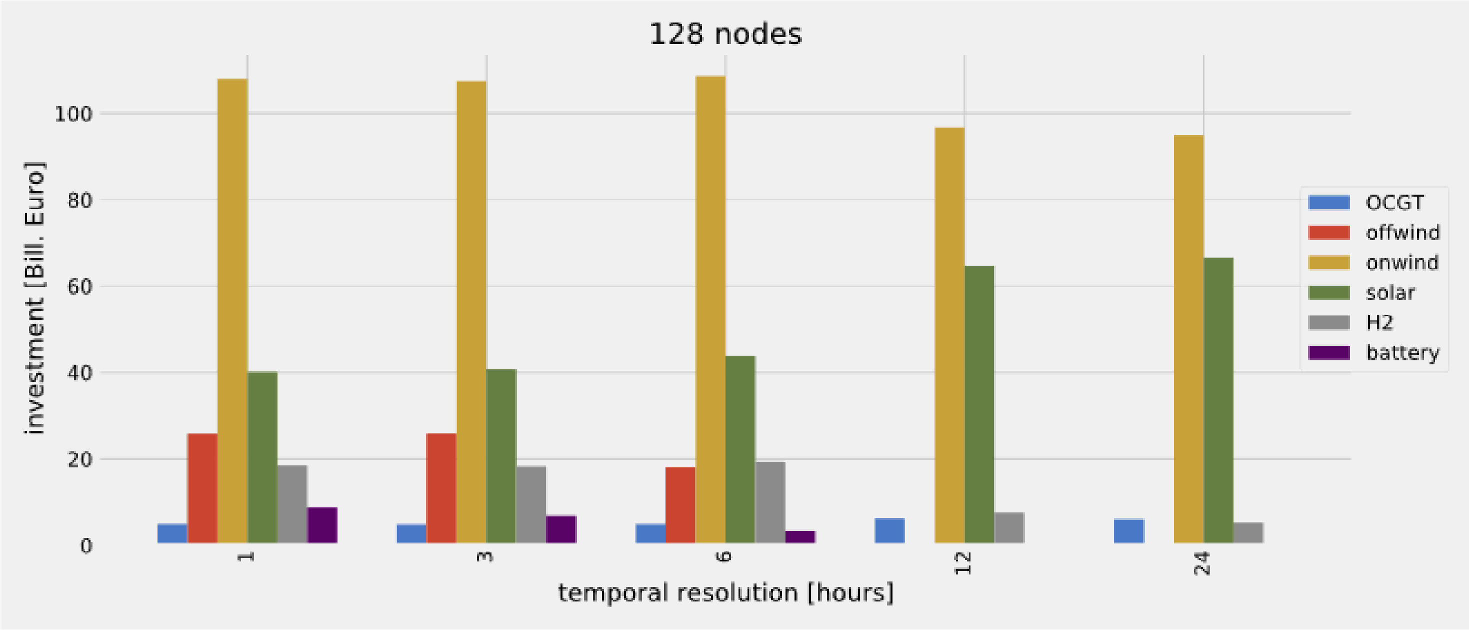
Victoria et al., Nature Commun. (2020)

We need **uninterrupted hourly time stepping for a full year** to capture the main fluctuations:

- solar and wind power generation smoothed by the grid and storage
- the role of long-term storage
- system operation during dark doldrums (i.e., periods with low wind and solar generation)

Which time resolution is good enough?

Resolution coarser than 3 hours get a solar balance “for free” and does not need batteries



Schyska et al., Joule. (2021)

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Lecture 12 – Multicarrier energy systems II (industry, aviation, shipping)

Learning goals

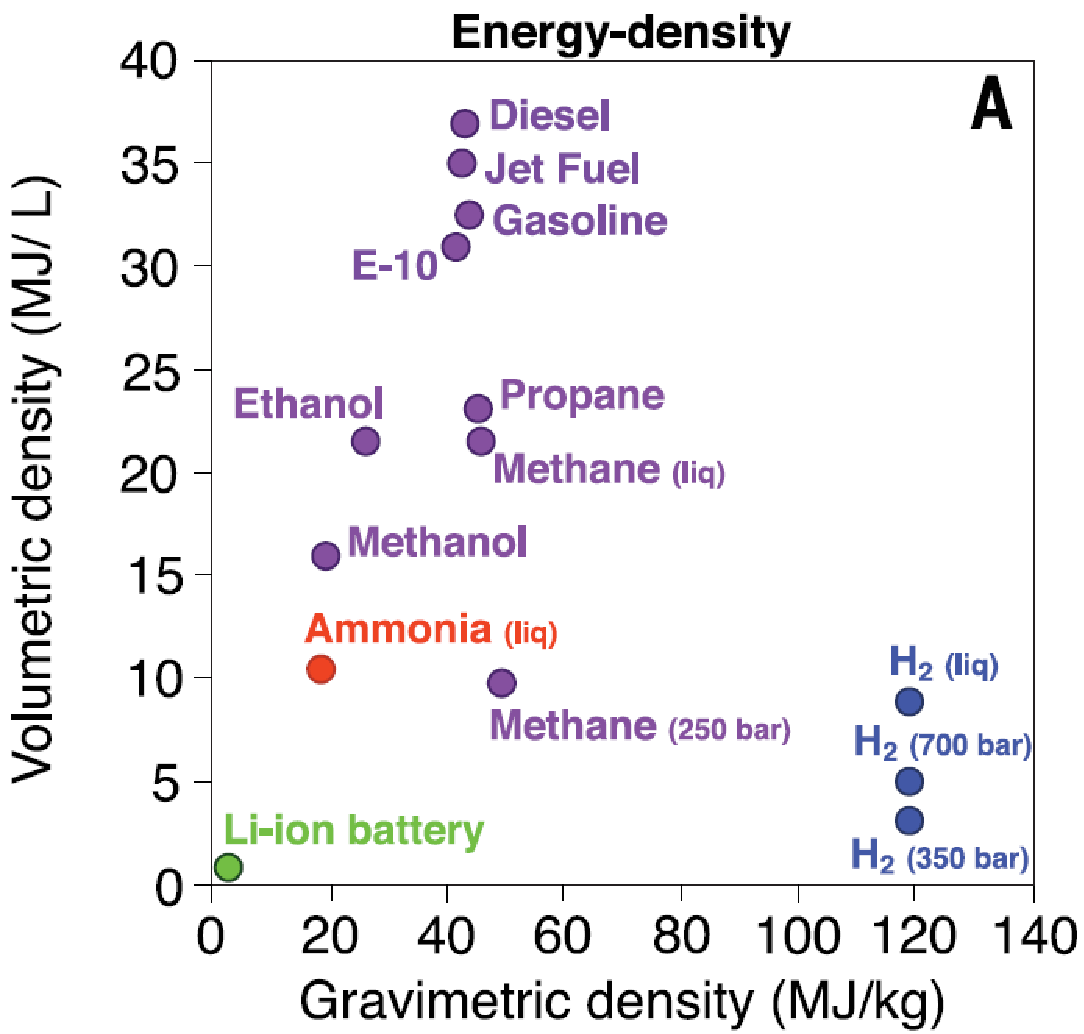
- Present the main challenges and opportunities introduced by muti-carrier energy systems comprising power-to-X technologies.
- Describe modelling approaches that can be used to represent shipping and aviation demand and strategies to decarbonize those sectors
- Describe modelling approaches that can be used to represent industry demand and technologies to decarbonize the different industrial sectors
- Describe modelling approaches that can be used to represent power-to-X technologies
- Formulate optimization problems comprising power, shipping, aviation and industry sectors in the computer

Modelling shipping/aviation demand and flexibility

Shipping and aviation

Challenge: shipping and aviation require fuels with good volumetric and gravimetric density

Opportunity: synthetic fuels (hydrogen, methanol, methane, oil) can be produced when there is an excess of renewables providing flexibility



Ref: Davis et al, Science (2018)

Shipping

Ammonia can be produced via Haber-Bosch process

$N_2 + 3\ H_2 \rightarrow 2\ NH_3$

Methanol can be produced in methanolisation units

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

Shipping

	Hydrogen (H_2)	Ammonia (NH_3)	Methanol (CH_3OH)
Fuel properties under ambient conditions	gas	gas	liquid
Fuel energy density	8.5 MJ/L for liquid 120 MJ/kg	11.6 MJ/L 22.5 MJ/kg	15.7 MJ/L 19.5 MJ/kg
Engine TRL	4	6	9
Toxicity	Non-toxic	Very high	Lower than oil
Key benefit	No efficiency losses for conversion into ammonia or methanol	Does not contain carbon (no need to previously capture CO_2)	Easy to convert a ship to use methanol (allow dual-fuel engine)

Aviation

Synthetic hydrocarbon can be produced by Fischer-Tropsch process

$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$

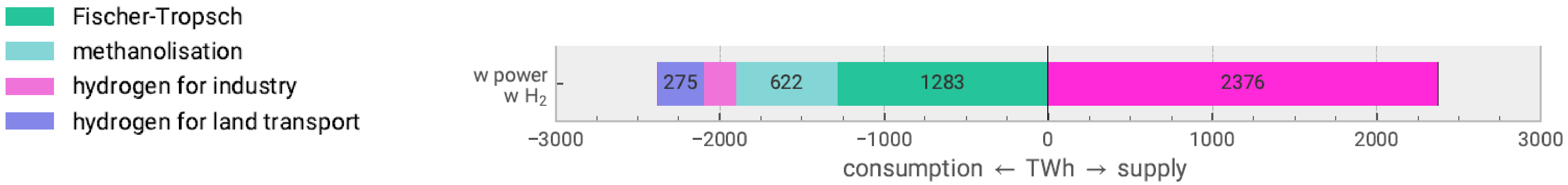
Energy expensive to produce.

Alternative strategies being discussed for this sector: biomass-based jetfuel, demand reduction, offset by negative emissions

Hydrogen demand, production, storge and transport

Hydrogen demand

Hydrogen is mostly needed to produce synthetic fuels



Neuman, Zeyen, Victoria, Brown, Joule, 2023

Up-to-date information: Johnson et al., 2025 Realistic roles for hydrogen in the future energy transition

Hydrogen production

Current situation:

H_2 produced from methane

$CH_4 + H_2O \rightarrow CO + 3H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

Possible alternative routes in the future:

Blue hydrogen: produced from methane while capturing the CO_2

(current capture rate around 90%)

Green hydrogen: produced using electricity

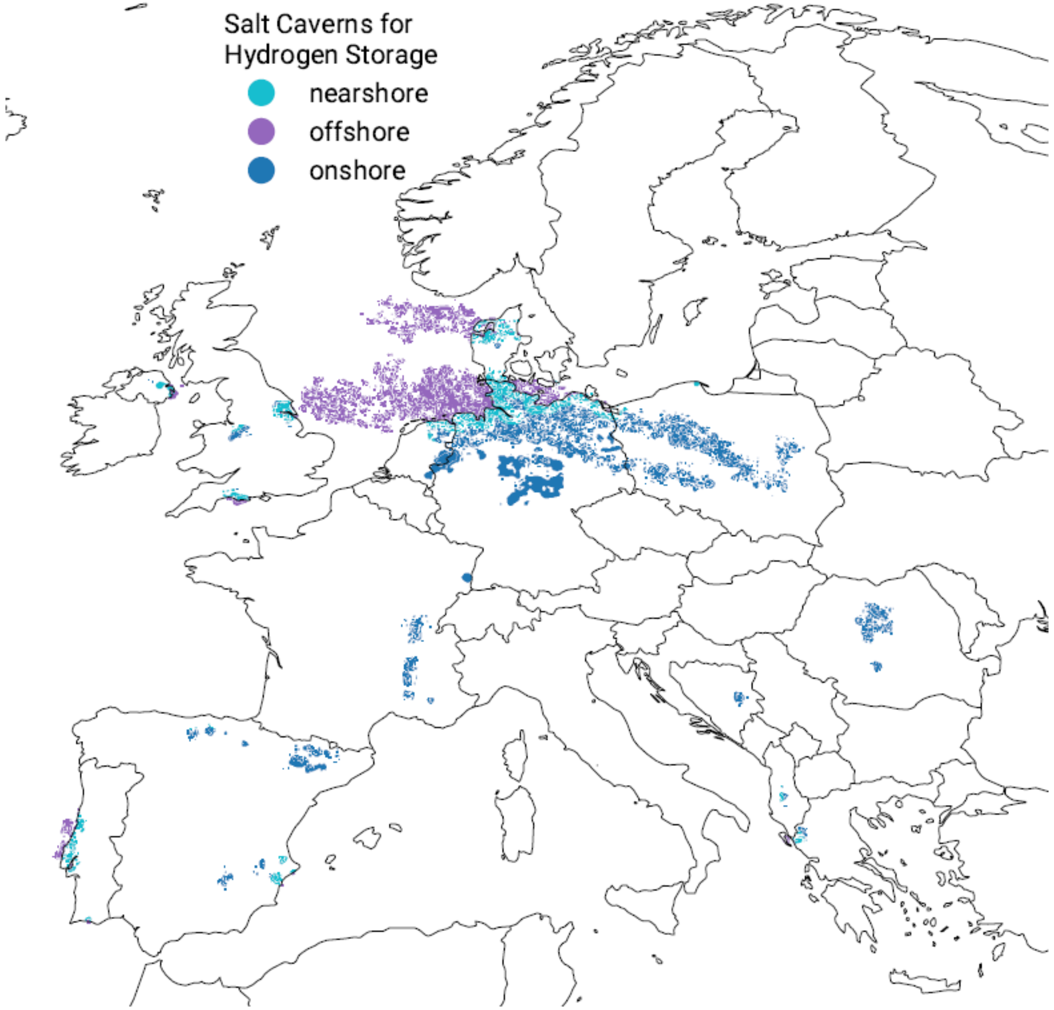
$H_2O \rightarrow H_2 + \frac{1}{2}O_2$

Which one has lower cost? Depends on electrolyzer cost, CO_2 price and capture rate

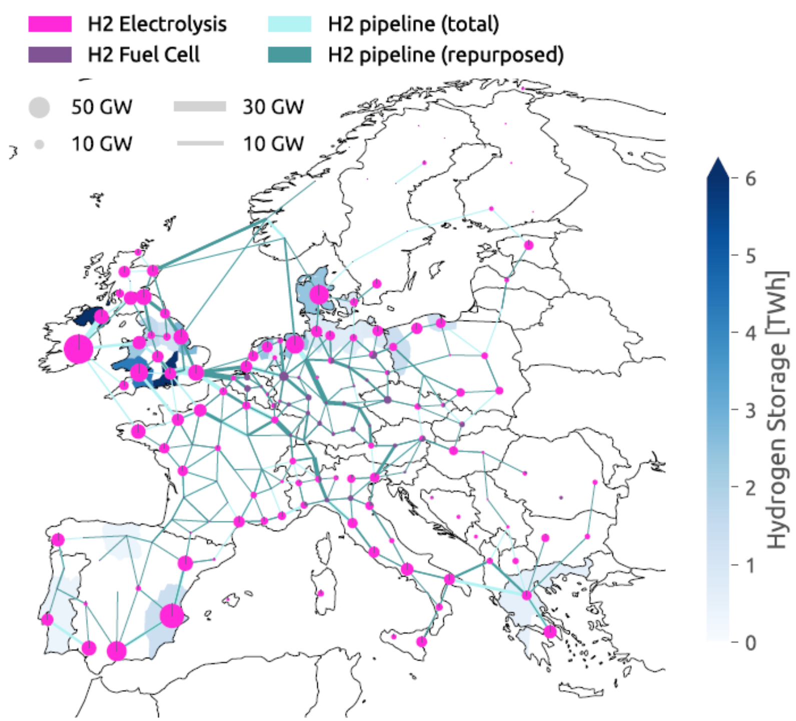
Hydrogen storage

Hydrogen can be easily stored in overground tanks

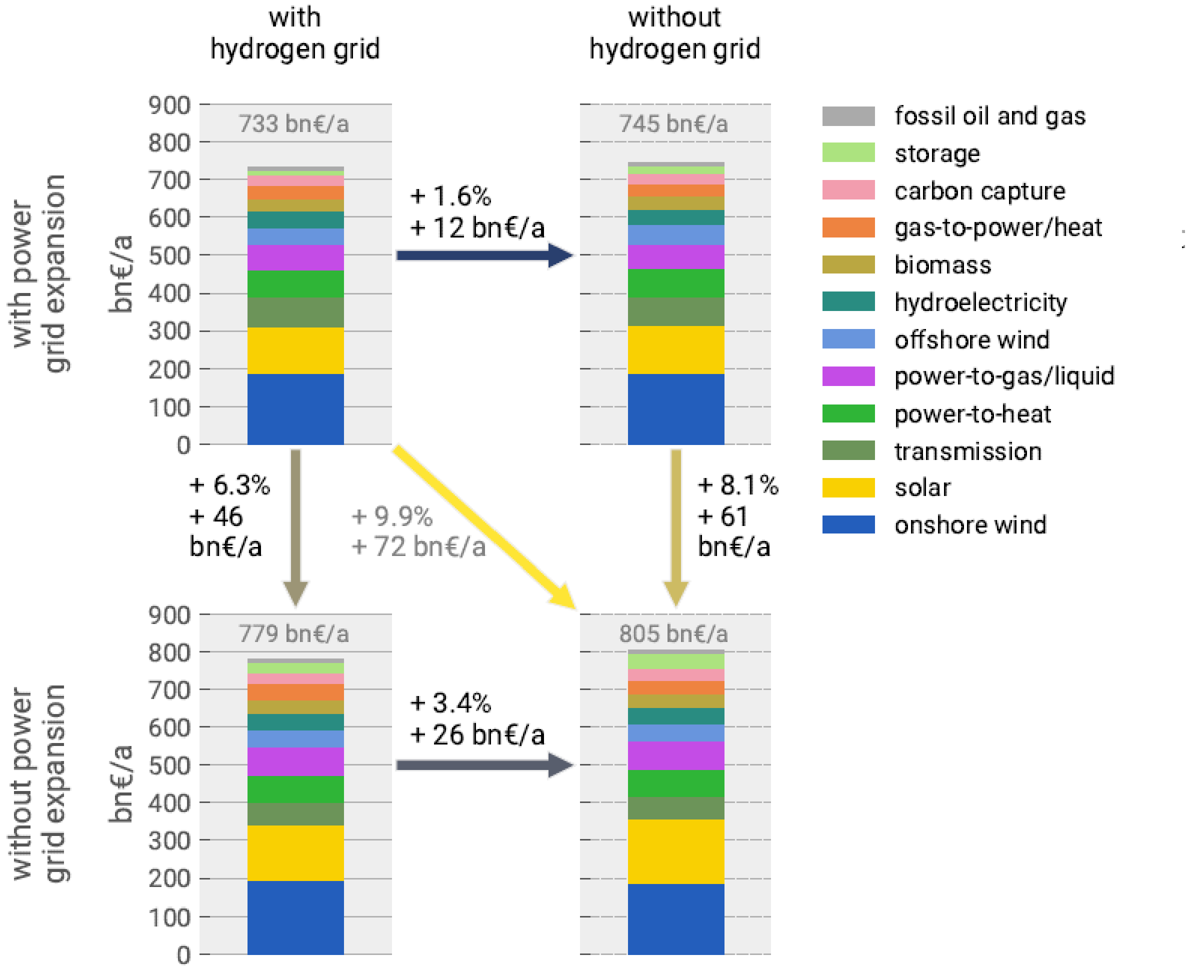
Hydrogen can also be stored in underground salt caverns



Is a H_2 grid cost-effective for Europe?



Neuman, Zeyen, Victoria, Brown, Joule, 2023

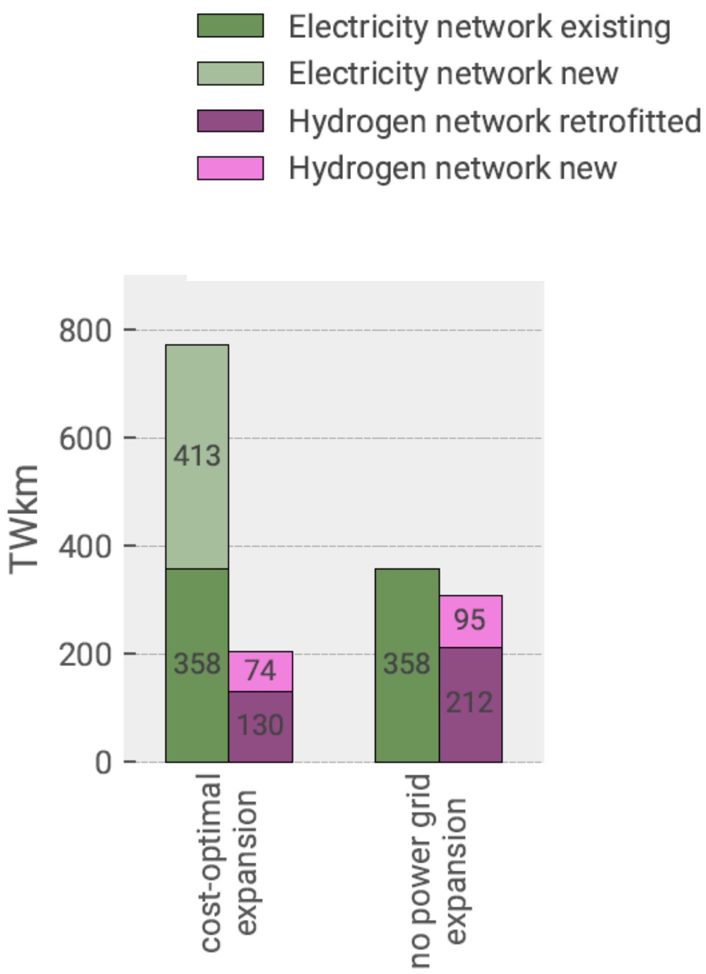


H_2 and electricity transmission grid play complementary roles but:

- Not building H_2 network increases system cost by 1.6%
- Not expanding electricity transmission grid increases cost by 6.3%

Is a H_2 grid cost-effective for Europe?

Electricity transmission grid duplicates its capacity, H_2 network mostly repurposed from gas network

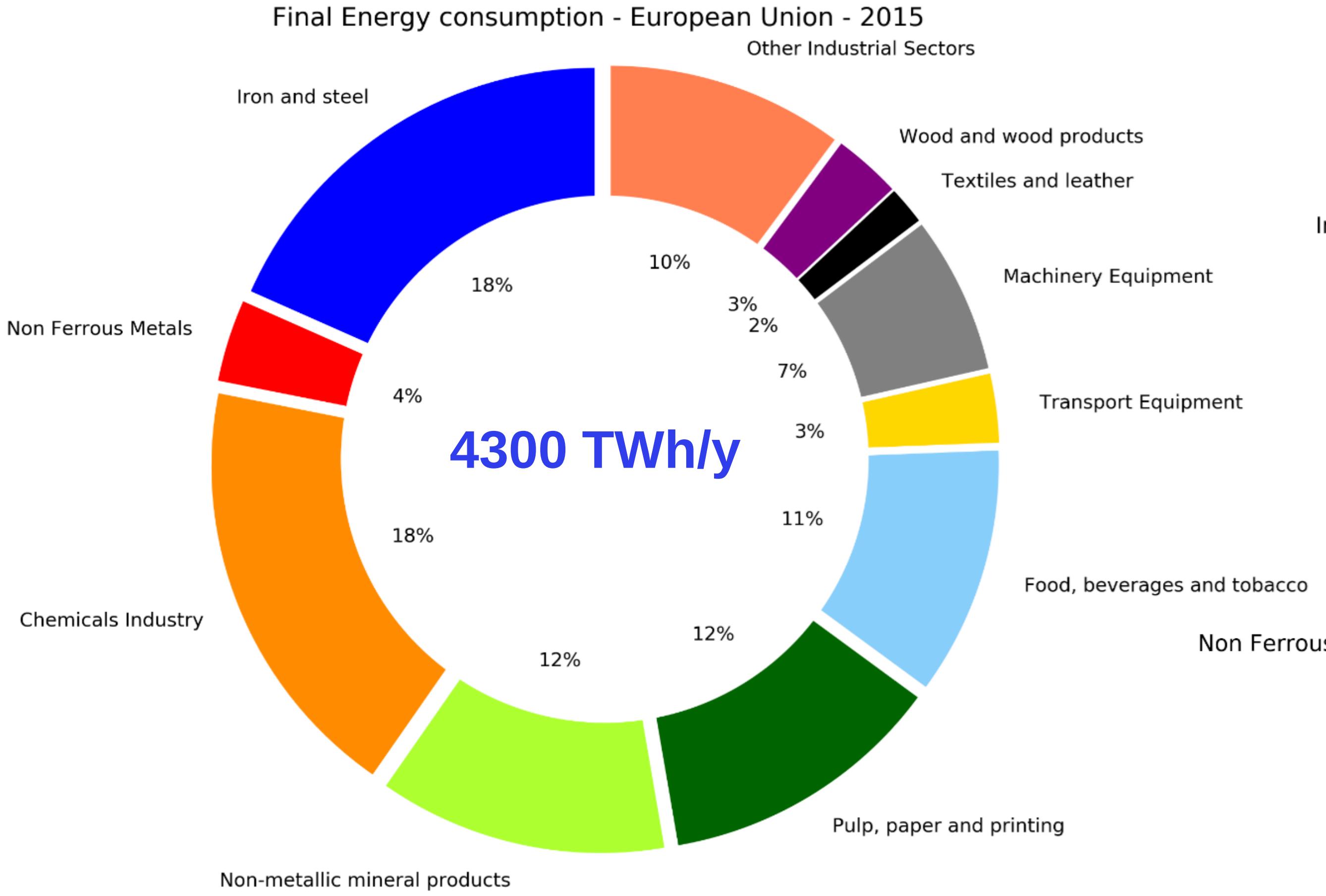


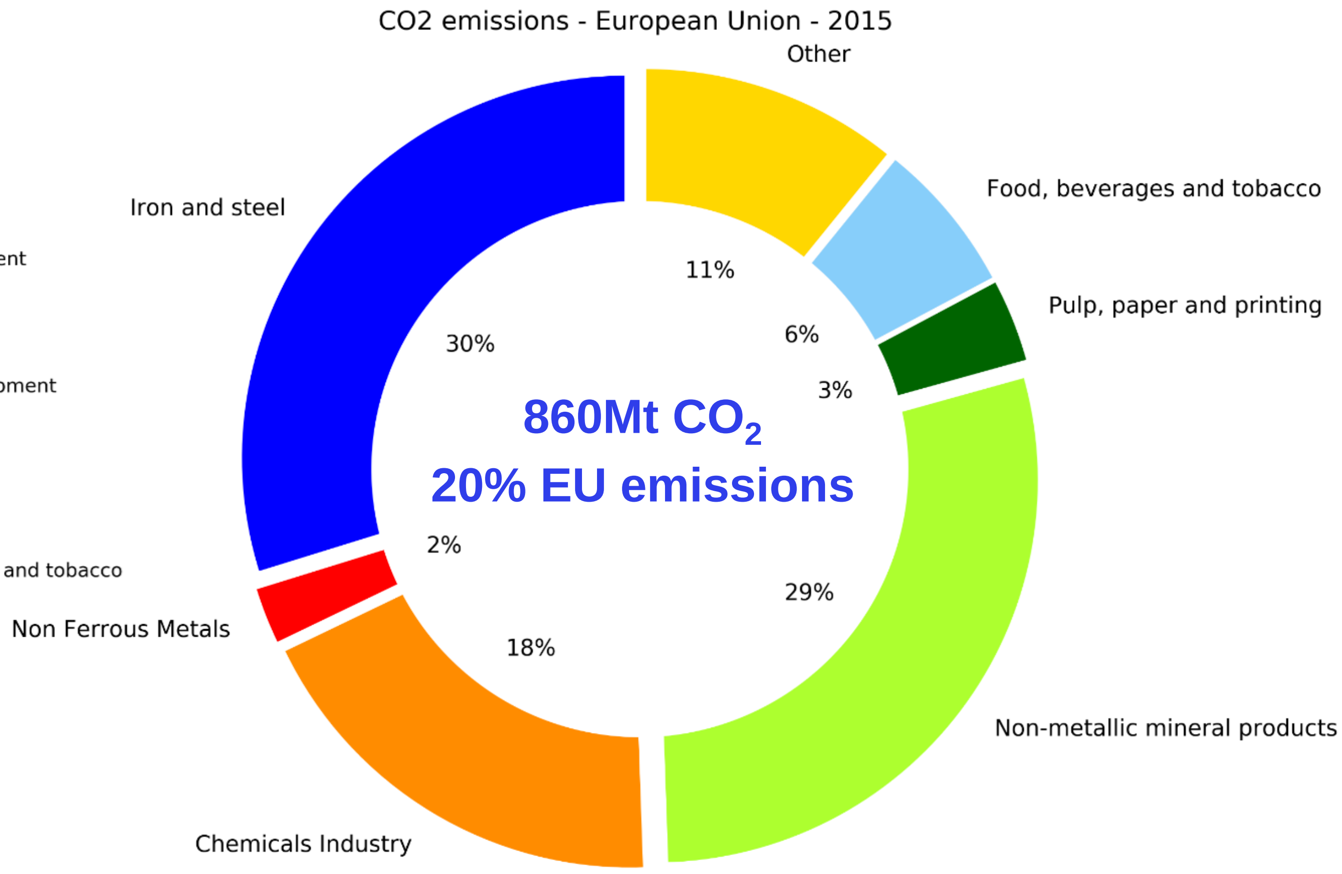
Neuman, Zeyen, Victoria, Brown, Joule, 2023

Modelling industry demand and flexibility

Current status

There are different industry sectors with different characteristics





L. Mantzos, *et al*., JRC-IDEES: Integrated Database of the European Energy Sectors

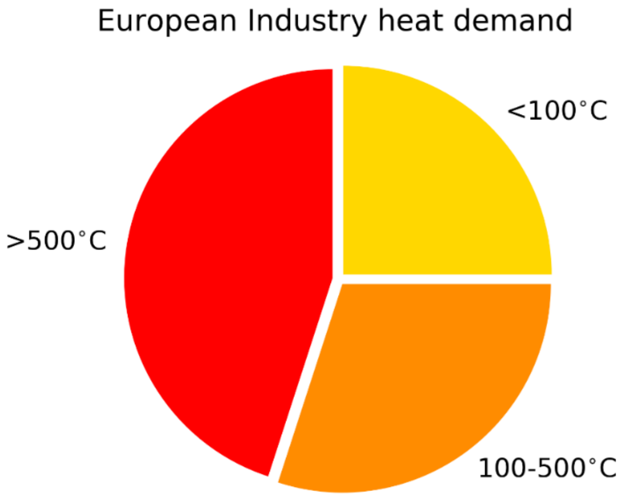
Industry demand

Challenges: supply of high-temperature heat and process emissions

Industry CO_2 emissions = Energy supply + Process emissions

Strategies to reduce emissions

Use low-carbon energy sources



M. Rehfeldt, et al. Energy Efficiency 11, 2018

Alternative manufacturing processes

Reduce required virgin materials by recycling and circular economy practices

Opportunities: flexible electricity demand, synthetic fuels (hydrogen, methanol, methane, oil) can be produced when there is an excess of renewables providing flexibility

Iron and Steel

Current situation:

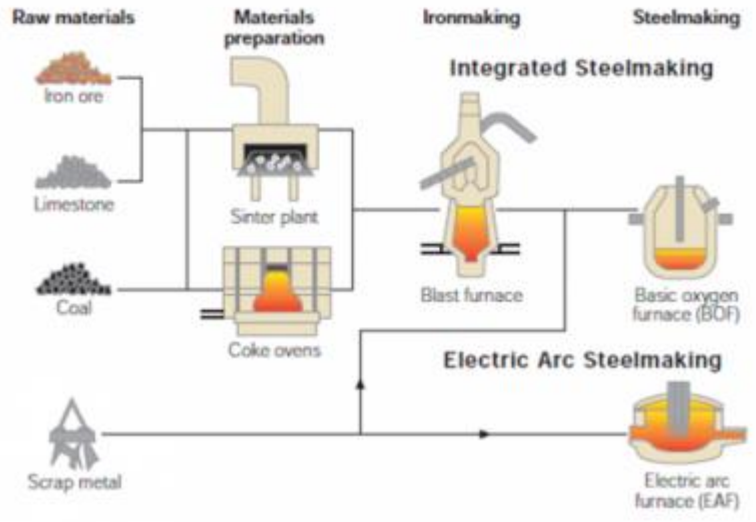
- 60% Primary route, integrated steelworks :

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ 0.22 tCO_2/t steel

Process emissions !

$FeO + CO \rightarrow Fe + CO_2$

$FeO + CO \rightarrow Fe + CO_2$

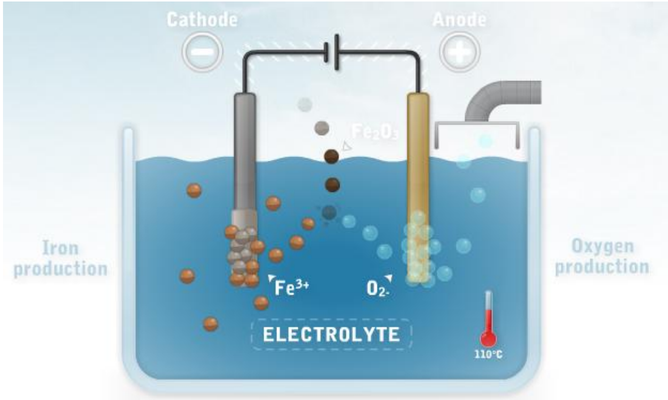


- 40% Secondary route, electric arc furnaces melt scrap metal 0.03 tCO_2/t steel

Possible alternative route in the future:

Direct Reduced Iron (DRI) : $Fe_2O_3 + 2H_2 \rightarrow 2FeO + 2H_2O$

$FeO + H_2 \rightarrow Fe + H_2O$



Hydrogen-based DRI is being explored in H2Future, HYBRIT, and SALCOS projects.

Smelting, furnaces, refining and rolling, and products finishing can be electrified.

Chemicals industry

This sector includes the production of basic organic (olefins, alcohols, aromatics) and inorganic compounds (ammonia, chlorine), polymers (plastics) and end-user products (cosmetics, pharmaceutics).

CO_2 emissions = energy supply + process emissions + carbon embedded in plastics

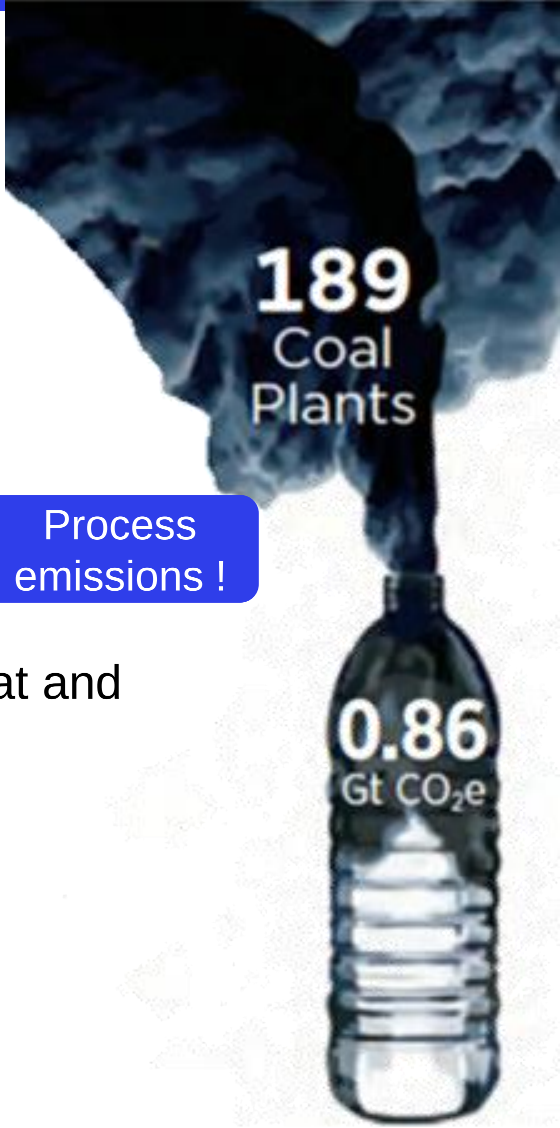
Process emissions !

Energy-related emissions can be reduced using biomass to supply high-temperature heat and electrification of other activities

Chemical industry consumes large amounts of fossil-fuel based products as feedstock

Synthetic hydrocarbon feedstock could be produced by Fischer-Tropsch process

$$(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$



2019 plastic emissions in USA, Plastic & Climate

Chemicals industry - Ammonia

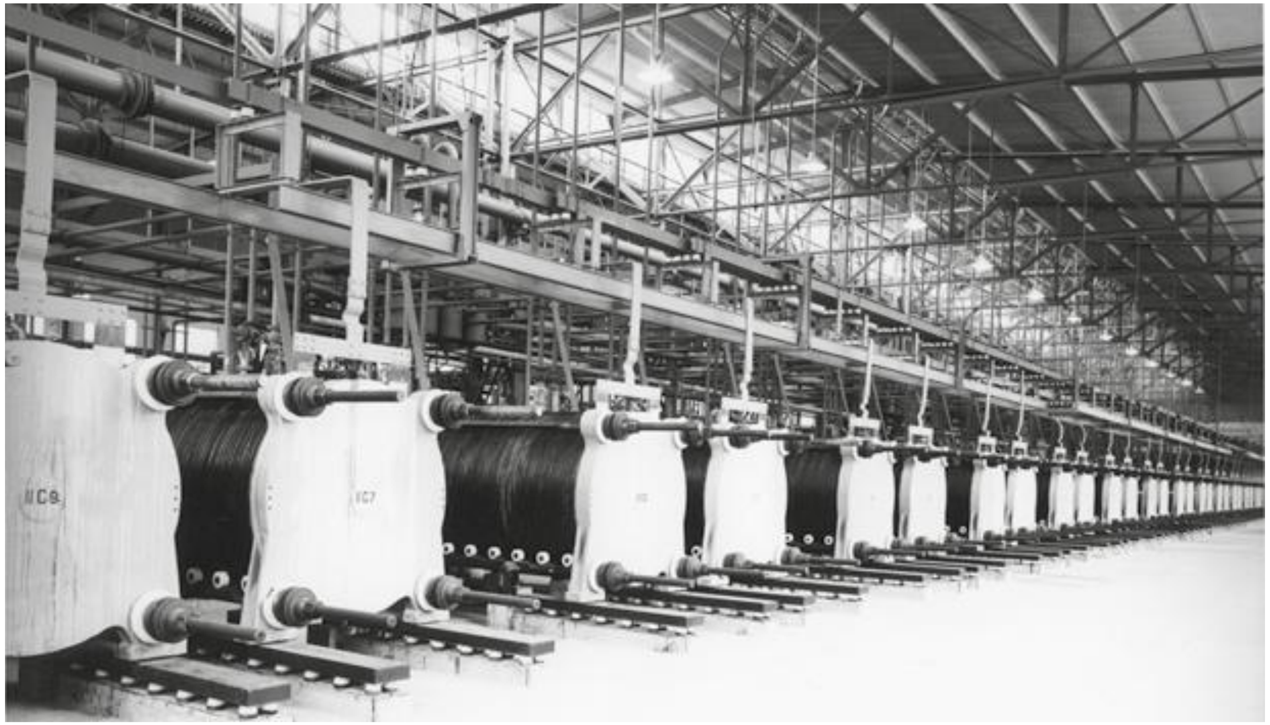
Current situation:

Today almost all the hydrogen is obtained by steam reforming of methane but electrolysers can be used

Possible alternative route in the future:

Ammonia can be produced via Haber-Bosch process

$N_2 + 3H_2 \rightarrow 2NH_3$



135 MW electrolysers for Ammonia production in Glomfjord, Norway (1953-1991), NEL

Cement, ceramics and glass

Current situation:

Calcination of limestone to lime: $CaCO_3 \rightarrow CaO + CO_2$ 0.54 tCO_2/t cement

Process emissions !

Possible alternative route in the future:

Alternatives at an early development stage: Carbon Capture and Storage (CCS), using new raw materials (wood constructions) or new cement alternatives

For cement, energy-related emissions can be reduced using biomass to supply high-temperature heat and electrification of other activities.

Ceramics and glass manufacturing could be electrified.

Aluminum and other non-ferrous metals

Current situation:

This sector includes the manufacturing of base metals (aluminium, copper, lead or zinc), precious metals (gold, silver), and technology metals (molybdenum, cobalt, silicon).

Aluminium (50% of this sector)

- 40% Primary route, bauxite (aluminium ore) → alumina → aluminium : $2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$

Process emissions !

- 60% Secondary route, scrap metal is re-melted

Possible alternative route in the future:

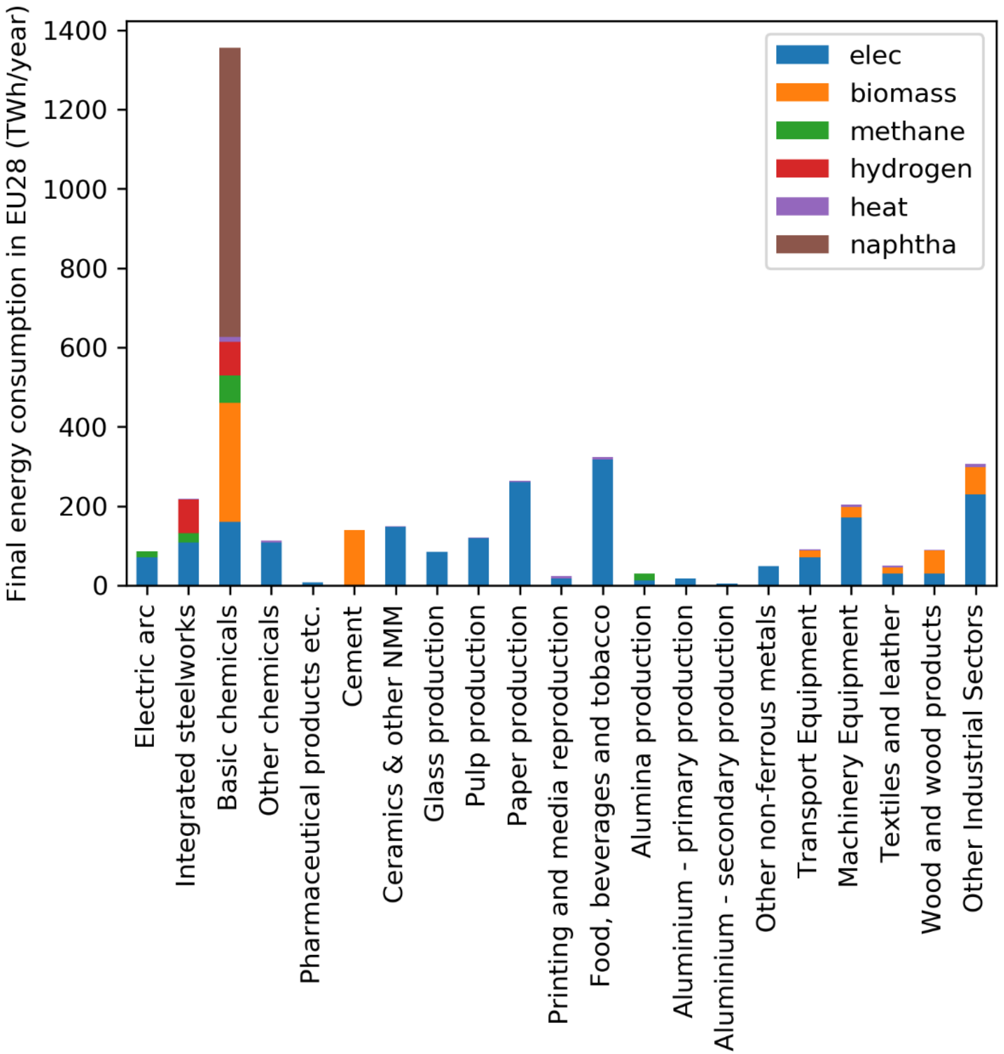
Energy-related emissions can be reduced using methane to supply high-temperature heat and electrification of other activities.

Other industrial sectors

- Pulp, paper and printing
- Food, beverages and tobacco
- Machinery equipment
- Transport equipment
- Wood and wood products
- Textiles and leather
- Other industrial sectors

Most of the activities can be electrified, biomass could also provide process heat

Future scenario: low-carbon industry consumption



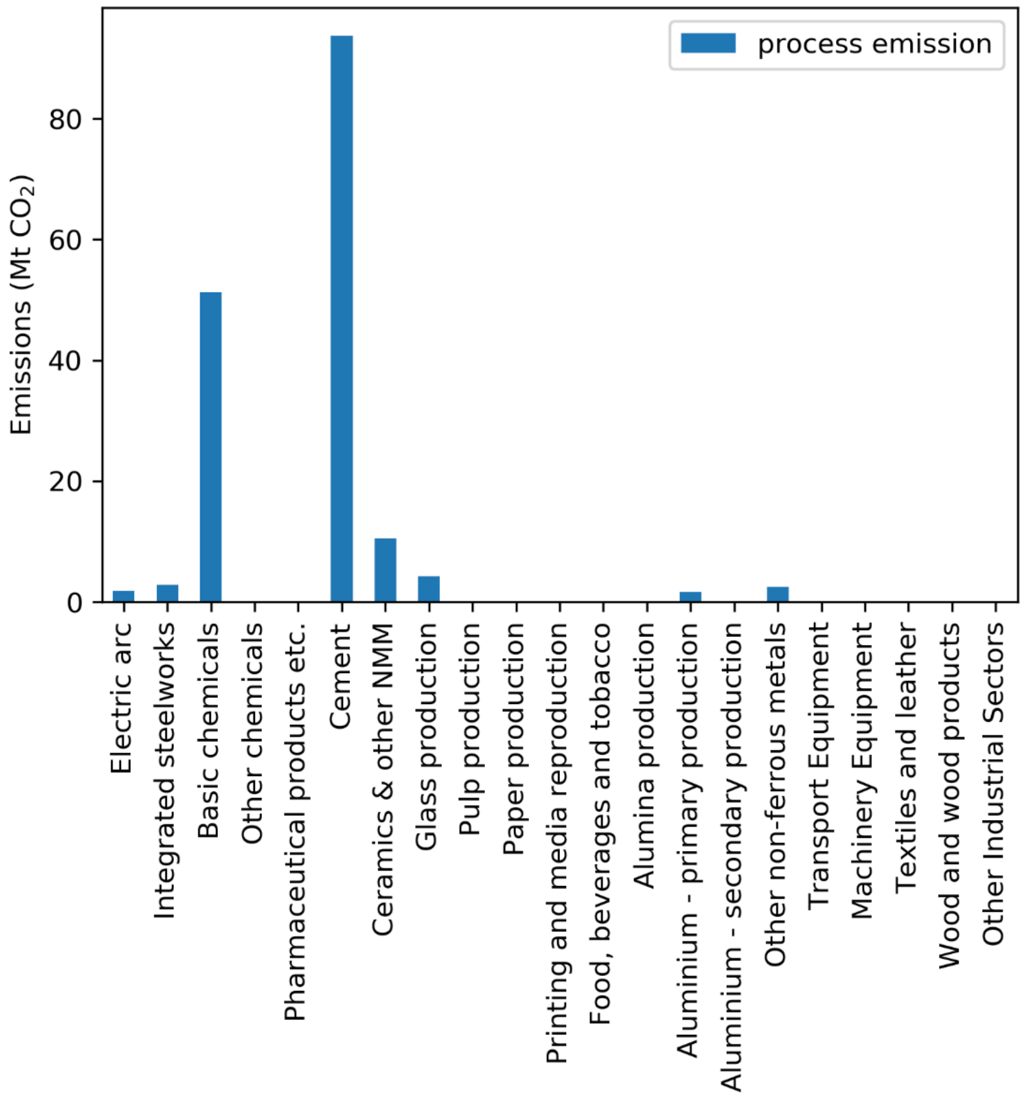
Victoria et al., Joule (2021)

European industry can be decarbonized by

- Electrifying most of the activities, increase electricity consumption by 1027 TWh/y (36% current EU electricity consumption)
- Biomass* (624 TWh/y) and methane (123 TWh/y) for high-temperature processes
- 58 TWh/y low-temperature heat
- 728 TWh/y naphtha-equivalent

* Solid biomass sustainable potential =1263 TWh/y (JRC Bioenergy potentials)

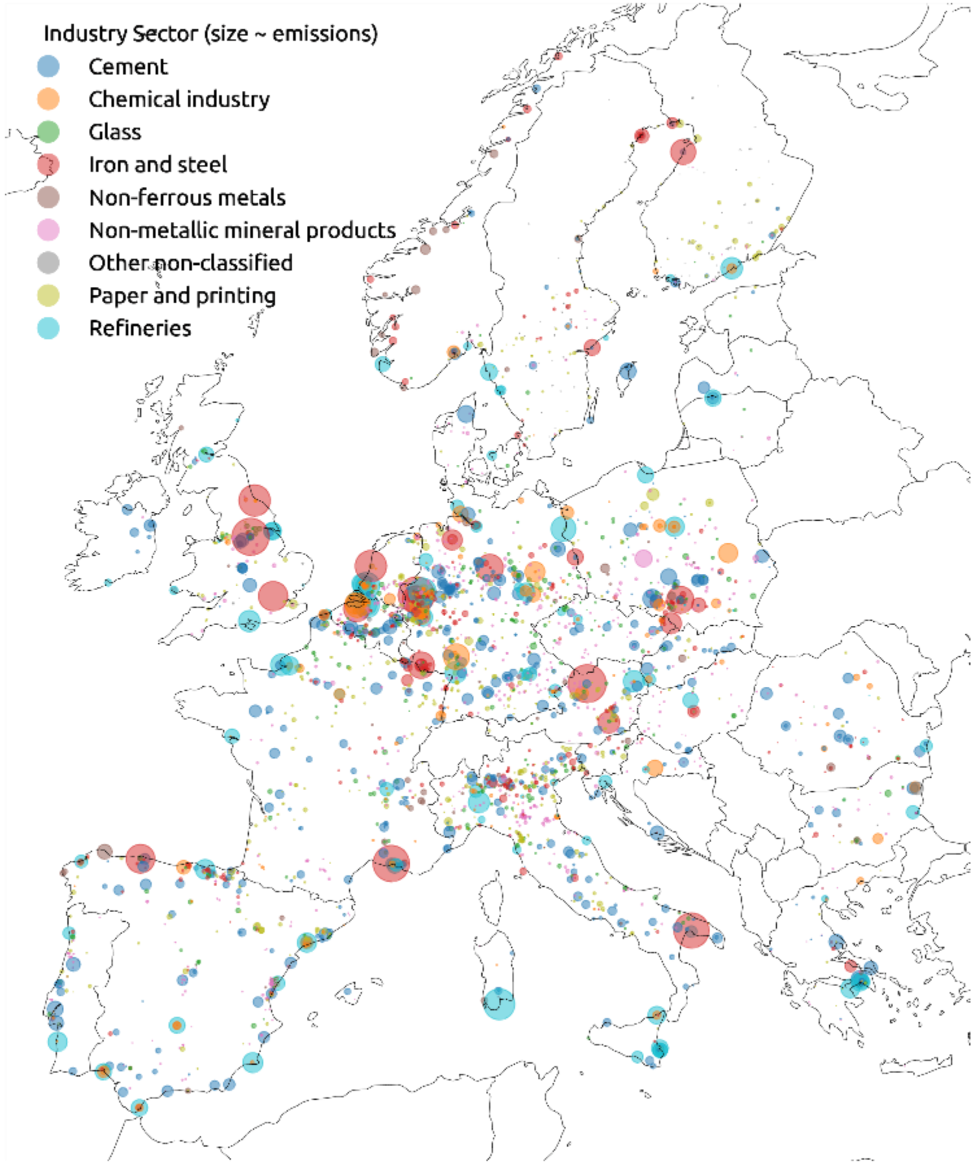
Future scenario: low-carbon industry consumption



Process emissions still represents 169 Mt CO_2 (20% of total CO_2 emissions from industry in 2015)

Future scenario: low-carbon industry consumption

The transformation of the industry will significantly change the demand for fuel and feedstock.

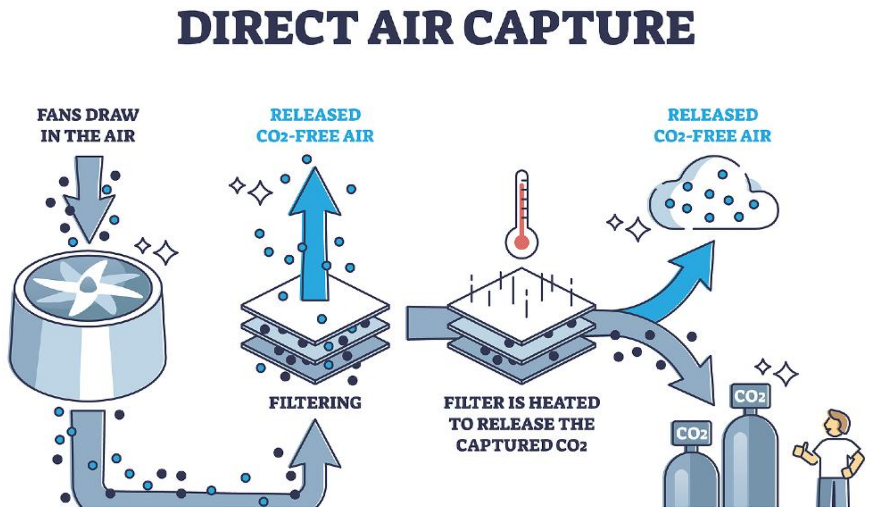


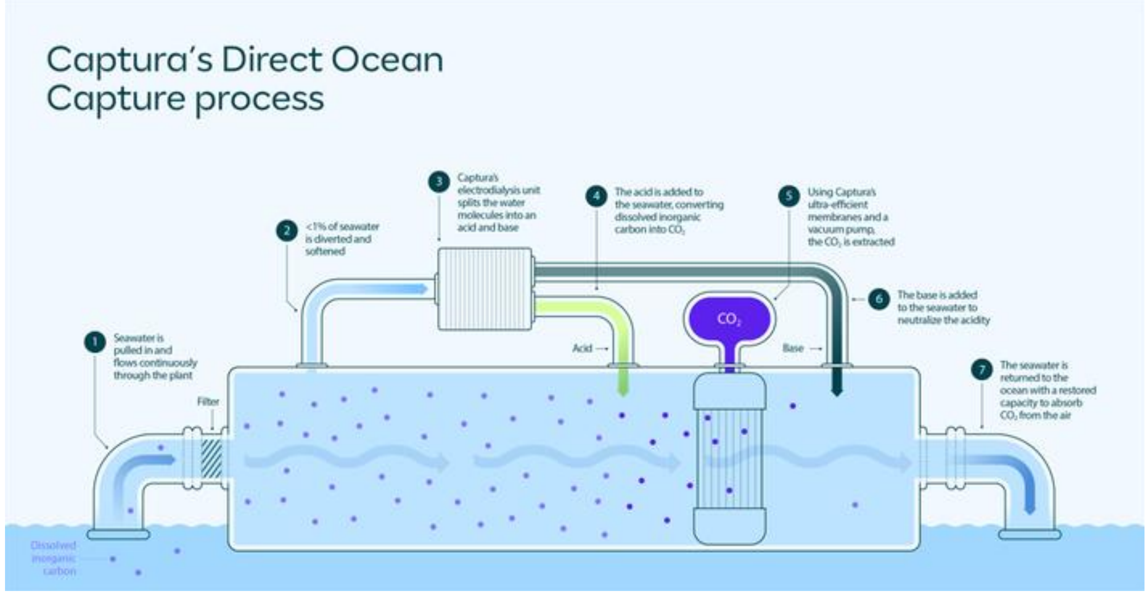
Carbon capture, conversion and storage

CO_2 capture

CO_2 can be sequestered from point-sources: Combined Heat and Power, or Power plants, Industry (e.g. Cement)

or diluted sources such as Direct Air Capture (DAC) or Direct Ocean Capture (DOC)



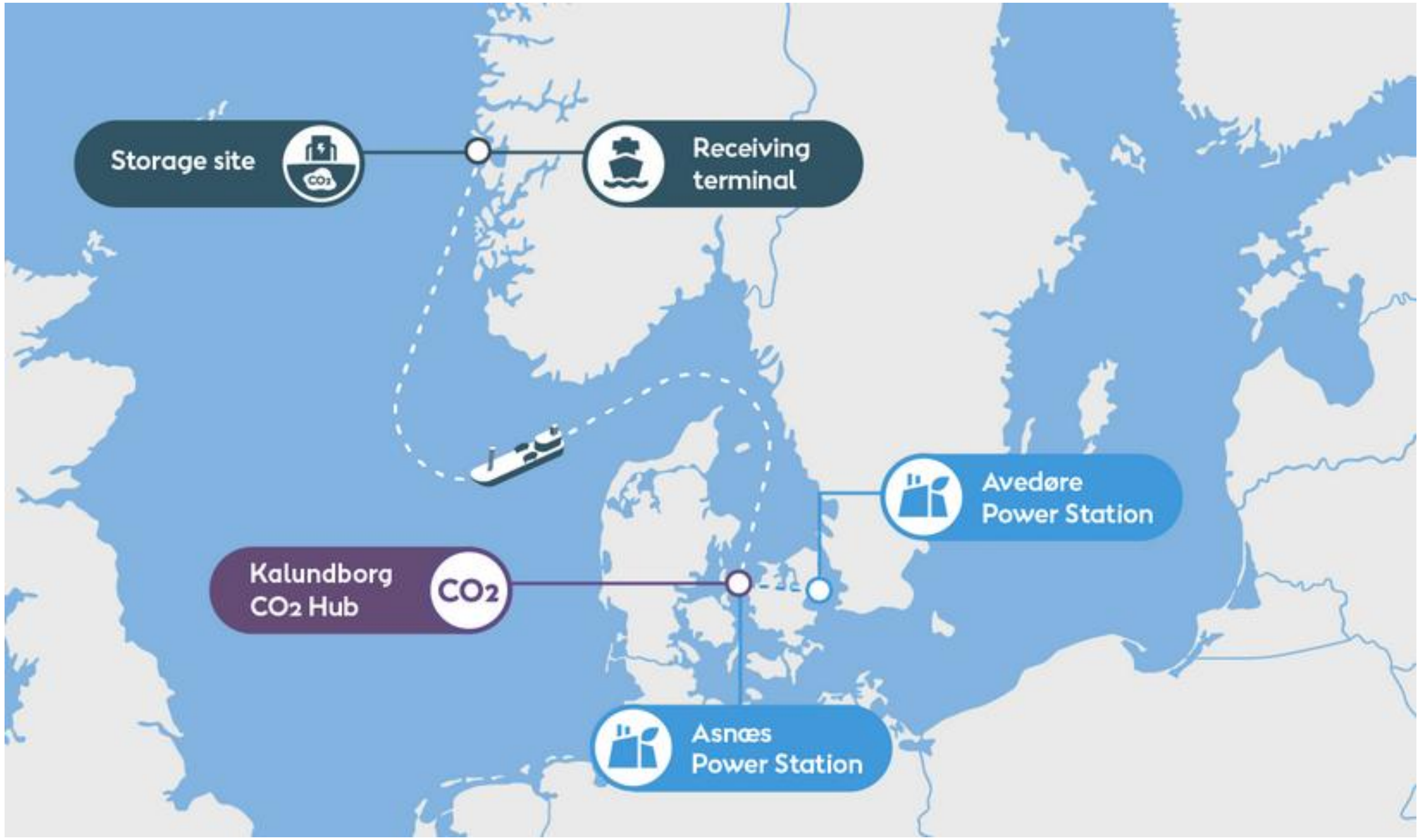


CO_2 conversion or sequestration

Captured CO_2 can be used to produced synthetic fuels (methane, methanol, oil)

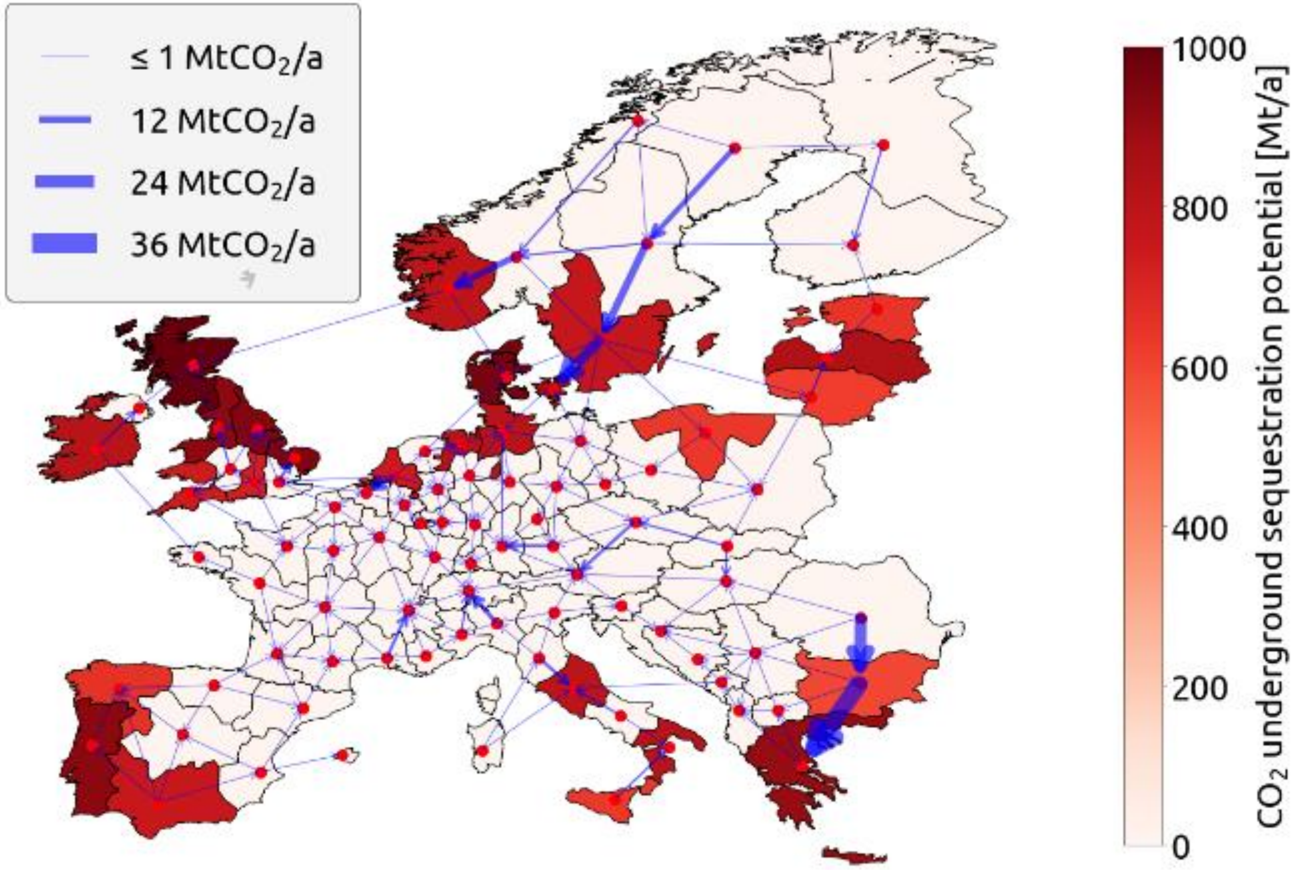
Or it can be sequestered underground

['Ørsted Kalundborg CO2 Hub']: From the beginning of 2026, 430,000 tonnes of CO2 will be captured from two heat and power plants and store it in the North Sea.



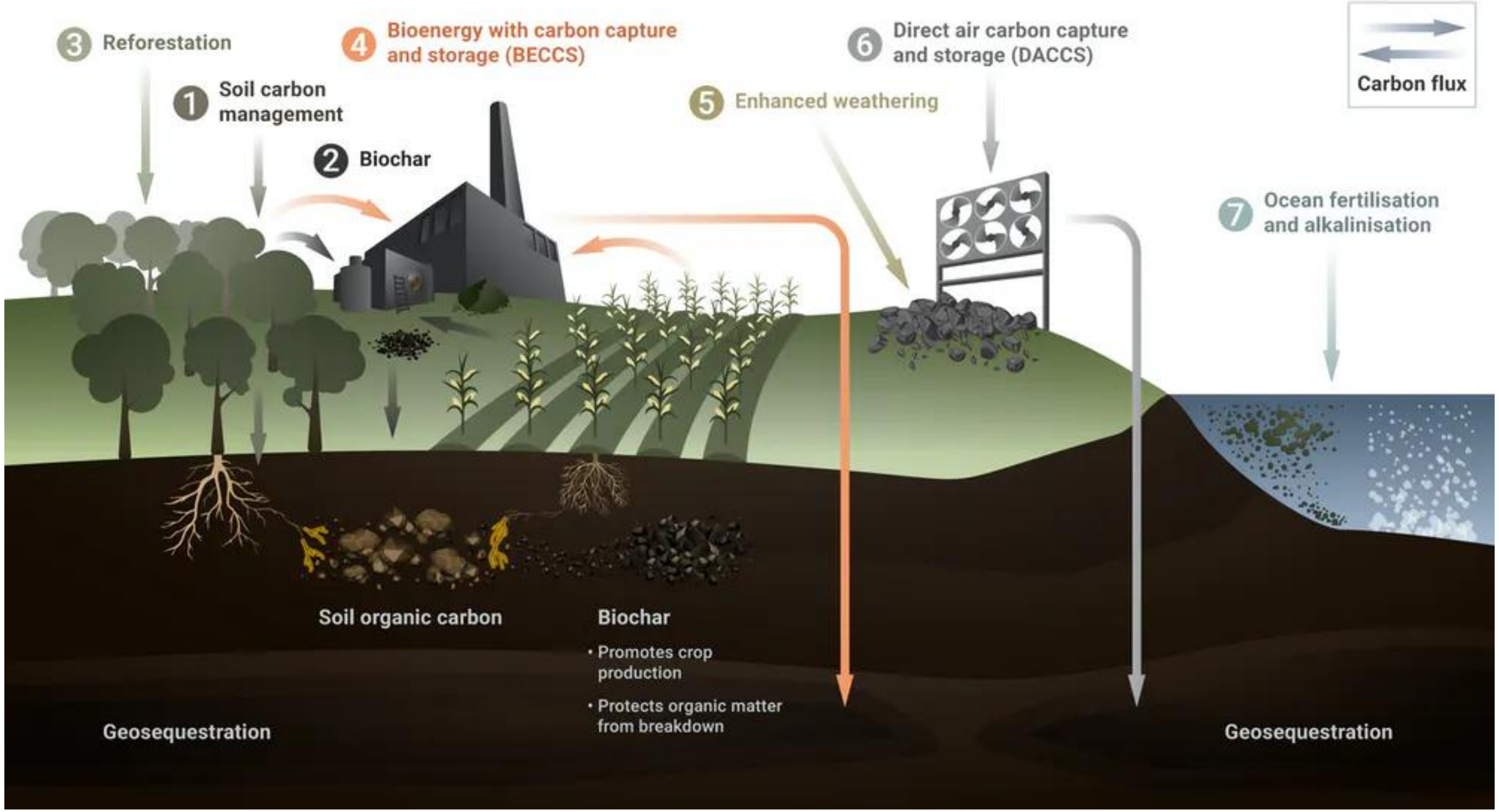
CO2 transport ?

We found that it can be cost-effective to transport CO2 using a network of pipelines build for that purpose.



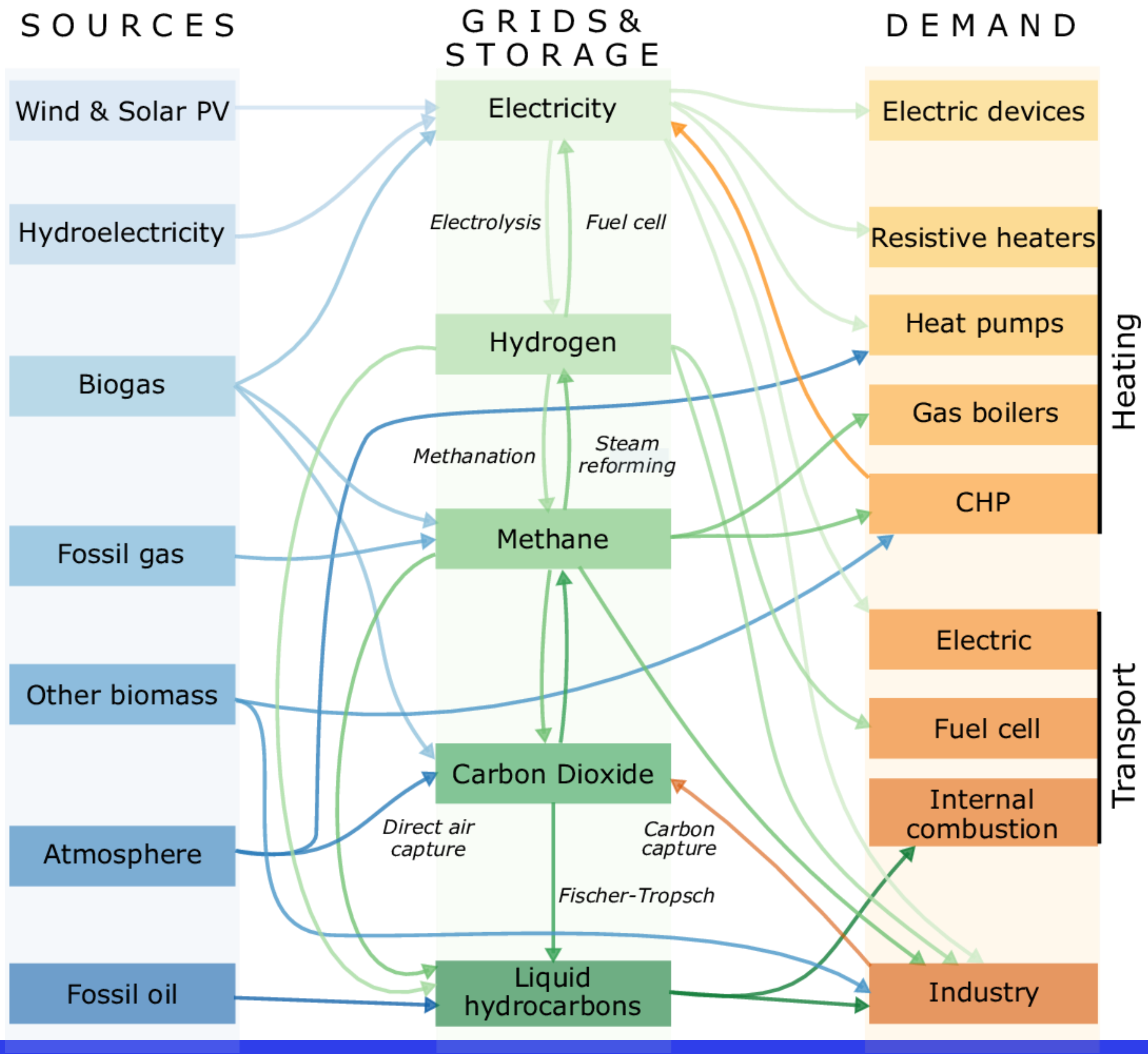
Fernandes et al (under review) ArXiv

Other CCU strategies outside the energy sector



Ref: The conversation

Energy and carbon balancing



Problems for this lecture

Problems 12.1 (**Group 23**)

Problems 12.2 (**Group 24**)

DTU