Can a Hydrogen Network Replace Electricity Transmission Network Expansion in a Climate-Neutral Scenario for Europe?

Tom Brown, Marta Victoria (Aarhus), Fabian Neumann, Lisa Zeyen (TUB), Martha Frysztacki (KIT)
t.brown@tu-berlin.de, Department of Digital Transformation in Energy Systems TU Berlin
EMP-E, 27th October 2021
2050 scenarios for EU: power demand doubles, mostly met by VRE

Source: JRC, 2020
Problem: collides with low acceptance for power grid expansion...
...and low acceptance for onshore wind
Offshore wind can certainly help, but you still need to get the electricity to loads inland.
Can electrolytic hydrogen and a hydrogen network help?

Can we substitute for the electricity grid by producing **electrolytic hydrogen** and transporting it through a new and/or re-purposed **hydrogen pipeline network**?
Modelling challenges: spatial resolution and sectoral co-optimisation

**Challenge 1**: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs. One node per country or continent won’t work.
Modelling challenges: spatial resolution and sectoral co-optimisation

**Challenge 1**: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs. One node per country or continent won’t work.

**Challenge 2**: Need to co-optimise balancing solutions with generation. Optimising separately won’t work.

⇒ Need very large models, big data and methods for complexity management
What is PyPSA-Eur-Sec?

Represents all energy flows...

and bottlenecks in energy networks.
Data-driven energy modelling

Lots of different types of data and process knowledge come together for the modelling.

- Clustered network model
- Power plants and technology assumptions
- Renewable potentials and hourly time series for each region
- Demand projections time series
HotMaps open database of industry from Fraunhofer ISI

- Includes cement, basic chemicals, glass, iron & steel, non-ferrous metals, non-metallic minerals, paper, refineries
- Enables regional analyses, calculation of site-specific energy demand, waste heat potentials, emissions, market shares, process-specific evaluations
Process- and fuel-switching in industry, aviation, shipping

<table>
<thead>
<tr>
<th>Industry</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron &amp; Steel</td>
<td>70% from scrap, rest from direct reduction with 1.7 MWhH₂/tSteel + electric arc (process emissions 0.03 tCO₂/tSteel)</td>
</tr>
<tr>
<td>Aluminium</td>
<td>80% recycling, for rest: methane for high-enthalpy heat (bauxite to alumina) followed by electrolysis (process emissions 1.5 tCO₂/tAl)</td>
</tr>
<tr>
<td>Cement</td>
<td>Waste and solid biomass; capture of CO₂ emissions</td>
</tr>
<tr>
<td>Ceramics &amp; other NMM</td>
<td>Electrification</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Clean hydrogen</td>
</tr>
<tr>
<td>Plastics</td>
<td>Recycling and synthetic naphtha for primary production</td>
</tr>
<tr>
<td>Other industry</td>
<td>Electrification; process heat from biomass</td>
</tr>
<tr>
<td>Shipping</td>
<td>Liquid hydrogen, ammonia &amp; methanol</td>
</tr>
<tr>
<td>Aviation</td>
<td>Kerosene from Fischer-Tropsch</td>
</tr>
</tbody>
</table>

Carbon is tracked through system: up to 90% of industrial emissions can be captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration 20 €/tCO₂; yearly sequestration limited to 200 MtCO₂/a
# Decarbonisation of industry: process and fuel switching

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy Demand [TWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina production</td>
<td>110</td>
</tr>
<tr>
<td>Aluminium - primary production</td>
<td>90</td>
</tr>
<tr>
<td>Aluminium - secondary production</td>
<td>50</td>
</tr>
<tr>
<td>Ammonia</td>
<td>400</td>
</tr>
<tr>
<td>Cement</td>
<td>300</td>
</tr>
<tr>
<td>Ceramics &amp; other NMM</td>
<td>200</td>
</tr>
<tr>
<td>DRI + Electric arc</td>
<td>200</td>
</tr>
<tr>
<td>Electric arc</td>
<td>200</td>
</tr>
<tr>
<td>Food, beverages and tobacco</td>
<td>200</td>
</tr>
<tr>
<td>Glass production</td>
<td>200</td>
</tr>
<tr>
<td>Integrated steelworks</td>
<td>200</td>
</tr>
<tr>
<td>Machinery Equipment</td>
<td>200</td>
</tr>
<tr>
<td>Other Industrial Sectors</td>
<td>200</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>200</td>
</tr>
<tr>
<td>Other non-ferrous metals</td>
<td>200</td>
</tr>
<tr>
<td>Paper production</td>
<td>200</td>
</tr>
<tr>
<td>Pharmaceutical products etc.</td>
<td>200</td>
</tr>
<tr>
<td>Printing and media reproduction</td>
<td>200</td>
</tr>
<tr>
<td>Pulp production</td>
<td>200</td>
</tr>
<tr>
<td>Textiles and leather</td>
<td>200</td>
</tr>
<tr>
<td>Transport Equipment</td>
<td>200</td>
</tr>
<tr>
<td>Wood and wood products</td>
<td>200</td>
</tr>
</tbody>
</table>

- **Biomass**: Green
- **Electricity**: Light green
- **Heat**: Pink
- **Hydrogen**: Light purple
- **Liquid**: Dark purple
- **Methane**: Black
- **Other**: Grey
- **Solid**: Dark grey
Preliminary results: 181-node model of European energy system

Model set-up:

- Couple all energy sectors (power, heat, transport, industry)
- Reduce net CO₂ emissions to zero
- Assume 181 smaller bidding zones and widespread dynamic pricing
- Conservative technology assumptions (for 2030 from Danish Energy Agency)
Preliminary results: 181-node model of European energy system

Examine effect of:

- Limiting power grid expansion
- Limiting onshore wind potentials
- Removing hydrogen grid
Example problem with balancing: Cold week in winter

There are difficult periods in winter with:

- **Low** wind and solar (⇒ high prices)
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

Less-smart solution: backup gas boilers burning either natural gas, or synthetic methane.

Smart solution: building retrofitting, long-term thermal energy storage in district heating networks and efficient combined-heat-and-power plants.
Cold week in winter: inflexible (left); smart (right)

Electricity generation in DE for scenario Heating

Electricity generator power [GW]

Electricity generation in DE for scenario Central-TES

Electricity generator power [GW]

High-density heat supply in DE for scenario Heating

High-density heat supply [GW]

Source: Brown et al, “Synergies of sector coupling,” 2018
Distribution of technologies: 50% more power grid volume

Electricity grid expansion of 162 TWkm...

- System cost: 5 bEUR/a and 1 bEUR/a
- Transmission reinforcement: 10 GW and 5 GW

Electrolyzer capacity: 50 GW and 10 GW
H2 pipeline capacity: 50 GW and 10 GW
Distribution of technologies: 50% more power grid volume

Electricity grid expansion of 162 TWkm...

...and new hydrogen grid of 260 TWkm.
Distribution of technologies: 25% more power grid volume

Electricity grid expansion of 81 TWkm...

...and new hydrogen grid of 282 TWkm.

System cost
- 5 bEUR/a
- 1 bEUR/a

Transmission reinforcement
- 10 GW
- 5 GW

Electrolyzer capacity
- 50 GW
- 10 GW

H2 pipeline capacity
- 50 GW
- 10 GW
Distribution of technologies: no power grid expansion

No electricity grid expansion...

...and new hydrogen grid of 308 TWkm.
Benefit of power grid expansion for sector-coupled system

- Direct system costs **bit higher than today’s system** (€ 700 billion per year with same assumptions)
- Systems **without grid expansion** are feasible, but more costly
- As grid is expanded, **costs reduce** from solar, power-to-gas and H₂ network; more offshore wind
- Total cost benefit of extra grid: ∼ € 47 billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)
What about restricting onshore wind potentials?

**With onshore:** 1900 GW onshore, 220 GW offshore, 2700 GW utility PV, 320 GW rooftop.

**Without onshore:** 820 GW offshore, 5600 GW utility PV, 450 GW rooftop.
Without onshore: solar rooftop and offshore potentials maxxed out

If all sectors included and Europe self-sufficient, effect of **installable potentials** is critical.
Effect of onshore wind potentials on hydrogen network

**With onshore**: British Isles and North Sea dominate hydrogen production.

**Without onshore**: Southern Europe becomes much larger exporter of hydrogen.

![Map of Europe with hydrogen network](image)
Benefit of full onshore wind potentials

### Technical potentials for onshore wind respect land usage

### However, they do not represent the socially-acceptable potentials

### Technical potential of $\sim 480$ GW in Germany is unlikely to be built

### Costs rise by $\sim € 122$ billion per year as we eliminate onshore wind (with no grid expansion)

### Rise is only $\sim € 45$ billion per year if we allow a quarter of technical potential ($\sim 120$ GW for Germany)
Finally: with and without hydrogen network

- **Cost** of hydrogen network: € 6-8 billion per year (depending on scenario)
- **Net benefit** is much higher: € 21-48 billion per year (2.7-4.8% of total)
- Hydrogen network is **robustly beneficial infrastructure**
- Benefit is strongest when there is no power grid expansion
Transmission grid expansion versus hydrogen network

Compare power grid expansion and no H₂ grid (left) versus no power grid expansion and H₂ grid (right). Conclusion: both are important for costs; grid expansion brings more cost benefit; hydrogen network can partially substitute transmission expansion, but at higher system cost.

![Graph showing costs and components]
Compare power grid expansion and no H₂ grid (left) versus no power grid expansion and H₂ grid (right). Conclusion: both are important for costs; grid expansion brings more cost benefit; hydrogen network can partially substitute transmission expansion, but at higher system cost.
Summary of effect of increasing restrictions

Electrolyser capacity rises 1100 GW, 1300 GW, 1700 GW, 1800 GW.
Future work

- Consider **pathway** of investments 2020-2050
- Compare local production with import of **synfuels from outside Europe**
- Extend offshore wind potentials by including **floating wind** for depths > 50 m
- Examine benefits of offshore **hub-and-spoke grid topology**
- Proper consideration of **wake effects** (currently 11% linear reduction of CF)
- Benefits of **repurposing fossil gas grid** versus greenfield H₂ pipelines
- Cost-benefit of **sufficiency**
Pathway for European energy system from now until 2050

For a fixed CO\textsubscript{2} budget, it’s more cost-effective to **cut emissions early** than wait.

NB: These results only include electricity, heating in buildings and land-based transport.

Source: M. Victoria et al, Nature Communications (2020)
Green hydrogen with pipeline transport costs around \( \sim 80 \, \text{€/MWh} \) in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or \( \text{NH}_3 \) form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.

Source: Hampp et al, 2021
All the code and data behind PyPSA-Eur-Sec is **open source**. You can run your own scenarios with your own assumptions in a simplified **online version** of the model:

https://model.energy/scenarios/
Conclusions

- **Cross-sectoral** approaches are important to reduce CO2 emissions and for flexibility.
- There are many **trade-offs** between unpopular infrastructure and system cost.
- In our model, limiting power grid expansion costs $\sim \text{€}40-50$ billion per year more.
- If onshore wind expansion is restricted too, costs rise by further $\sim \text{€}120$ billion per year.
- If all sectors included and Europe self-sufficient, effect of **installable potentials** is critical.
- BUT: many **near-optimal compromise** energy systems with lower costs and higher public acceptance (see talk later by Dr. Fabian Neumann).
- **Hydrogen networks** can partially substitute for power grid expansion, but system costs are 3-5% higher; can also get away with neither power grid expansion nor H$_2$ network.
- All results depend strongly on assumptions and modelling approach - therefore **openness and transparency are critical**, guaranteed by open licences for data and code.
All input data and code for PyPSA-Eur-Sec is open and free to download:

2. https://github.com/pypsa/pypsa-eur: The power system model for Europe

Publications (selection):

What is open modelling?

Open energy modelling means modelling with open software, open data and open publishing.

Open means that anybody is free to download the software/data/publications, inspect it, machine process it, share it with others, modify it, and redistribute the changes.

This is typically done by uploading the model to an online platform with an open licence telling users what their reuse rights are.

The whole pipeline should be open:
Python for Power System Analysis (PyPSA)

- **Open source** tool for modelling energy systems at **high resolution**.

- Fills missing gap between **load flow software** (e.g. PowerFactory, MATPOWER) and **energy system simulation software** (e.g. PLEXOS, TIMES, OSeMOSYS).

- Good grid modelling is increasingly important, for integration of **renewables** and **electrification** of transport, heating and industry.

PyPSA is available on [GitHub](https://github.com).
PyPSA is used worldwide by dozens of research institutes and companies (TU Delft, Shell, TransnetBW, Fraunhofer ISE, DLR Oldenburg, FZJ, TU Berlin, RLI, TERI, Saudi Aramco, Edison Energy, spire and many others). Visitors to the website:
Example User of PyPSA: TERI in India

For a government-backed study of India’s power system in 2030, The Energy and Resources Institute (TERI) in New Delhi used PyPSA. Why? Easy to customize, lower cost than commercial alternatives, good for building up skills and reproducible by other stakeholders.
Example User of PyPSA-Eur-Sec: TransnetBW in Germany

German Transmission System Operator (TSO) TransnetBW for South-West Germany used an open model (PyPSA-Eur-Sec) to model the energy system in 2050, because it was better and easier than building their own model from scratch.

Source: https://www.transnetbw.de/de/stromnetz2050/
Online Visualisations and Interactive ‘Live’ Models

Online animated simulation results:
[pypsa.org/animations/](http://pypsa.org/animations/)

Live user-driven energy optimisation:
[model.energy](#)

![Diagram showing energy distribution and optimization models](image_url)