Power Transmission Bottlenecks: A Deal-Breaker for a Renewable World?

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MIT Energy Initiative, 15th May 2023

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Motivation
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
Can electrolytic hydrogen and a hydrogen network help?

Can we substitute for power grid by producing electrolytic hydrogen (here or abroad) and transporting it through a new and/or re-purposed hydrogen pipeline network to demand?
For other potential hydrogen demand sectors, they need a hydrogen network if low cost H₂ is not locally available. But for each sector there are alternatives to transporting hydrogen.

<table>
<thead>
<tr>
<th>sector</th>
<th>alternatives if hydrogen not available</th>
</tr>
</thead>
<tbody>
<tr>
<td>backup power &amp; district heat</td>
<td>use derivative fuels (e-methane, e-methanol)</td>
</tr>
<tr>
<td>process heat</td>
<td>electrify/use derivative fuels</td>
</tr>
<tr>
<td>heavy duty trucks</td>
<td>use battery electric vehicles</td>
</tr>
<tr>
<td>iron direct reduction</td>
<td>industry relocates to cluster/abroad</td>
</tr>
<tr>
<td>ammonia</td>
<td>industry relocates to cluster/abroad</td>
</tr>
<tr>
<td>high value chemicals</td>
<td>transport derivative precursors instead</td>
</tr>
<tr>
<td>shipping</td>
<td>transport derivative fuels instead</td>
</tr>
<tr>
<td>aviation</td>
<td>transport derivative fuels instead</td>
</tr>
</tbody>
</table>

⇒ There is no strict need for a hydrogen network, but it may be easier/cost-optimal.
How do we capture, utilise, transport and sequester carbon?

- Hydrogen economy is also linked to carbon dioxide management
- Need CCS for process emissions, CCU for synfuels and basic chemicals, CDR for unabatable and negative emissions
- For synthetic hydrocarbons, do we transport hydrogen to carbon sources, or carbon to hydrogen sources?
- Can we avoid hydrogen grid altogether and transport only CO₂, CH₄ and MeOH?

Source: F. Neumann, C. Tries, F. Hofmann, 2023
Modelling challenges: spatial resolution and sectoral co-optimisation

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

**Challenge 2:** Need to co-optimise balancing solutions with generation.
⇒ Optimising separately is inefficient.

⇒ Need very large models, big data and methods for complexity management.
European Sector-Coupled Model
PyPSA-Eur-Sec
Python for Power System Analysis (PyPSA)

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

- Fills missing gap between **power 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). It is **used worldwide** by researchers, consultants, TSOs and NGOs.
Optimisation of annual system costs

Find the long-term cost-optimal energy system, including investments and short-term costs:

Minimise

\[
\text{Yearly system costs} = \sum_n \left( \text{Annualised capital costs} \right) + \sum_{n,t} \left( \text{Marginal costs} \right)
\]

subject to

- meeting **energy demand** at each node \( n \) (e.g. region) and time \( t \) (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** \( \forall n, t \)
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) \( \leq \) (**geographical potentials** for renewables)
- **CO}_2 \text{ constraint} (e.g. reduction compared to 1990)

In short: mostly-greenfield investment optimisation, multi-period with linear power flow.

Optimise transmission, generation and storage **jointly**, since they’re strongly interacting.
PyPSA is used worldwide by dozens of research institutes and companies (TU Delft, KIT, Shell, TSO TransnetBW, TSO APG, TERI, Agora Energiewende, RMI, Ember, Instrat, Fraunhofer ISE, Climate Analytics, CLIMACT, DLR, FZJ, RLI, Saudi Aramco, Edison Energy, spire, etc.).
German Transmission System Operator (TSO) TransnetBW used an open model (PyPSA-Eur-Sec) to model the European energy system in 2050. Why? Easier to build on an existing model than reinvent the wheel.
PyPSA example: 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 open framework PyPSA. Why? Easy to customize, lower cost than commercial alternatives like PLEXOS, good for building up skills and reproducible by other stakeholders.
NGO Ember used PyPSA to model a gas phase out in the UK by 2030, releasing all code on [github](https://github.com).

### The UK can phase out gas from power by 2030

Share of domestic electricity generation, by fuel type (%)

- **2021**
  - Coal
  - Other
  - Onshore wind
  - Offshore wind
  - Solar
  - Bioenergy & waste
  - Other renewables
  - Hydrogen
  - Nuclear
  - Gas
  - CCS
  - Gas

- **Ember (2030)**
  - Unabated gas to generate just 0.7% of UK power

Source: Ember PyPSA-UK model results, DUKES and ET statistics
See report for full modelling assumptions, input data and source code.

Source: Ember, 2022
The Rocky Mountain Institute (RMI) in Boulder, Colorado used PyPSA to model hydrogen production costs around the world, since PyPSA had a track record for such calculations.

Source: RMI, 2021
What is PyPSA-Eur-Sec?

Model for Europe with all energy flows... and bottlenecks in energy networks.

**Sources**
- Wind & Solar PV
- Hydroelectricity
- Biogas
- Fossil gas
- Other biomass
- Atmosphere
- Fossil oil

**Grids & Storage**
- Electricity
- Hydrogen
- Methane
- Carbon Dioxide
- Liquid hydrocarbons
- Electrolysis
- Fuel cell
- Methanation
- Steam reforming
- Direct air capture
- Carbon capture
- Fischer-Tropsch

**Demand**
- Electric devices
- Resistive heaters
- Heat pumps
- Gas boilers
- CHP
- Electric
- Fuel cell
- Internal combustion
- Industry

**Heating**
- HVAC 220 kV
- HVAC 300 kV
- HVAC 380 kV
- HVDC

**Transport**

Technische Universität Berlin
Data-driven energy modelling

Lots of different types of data and process knowledge come together for the modelling. **Full pipeline** of data processing from raw data to results is managed in an **open workflow**.

- **clustered network model**
- **power plants and technology assumptions**
- **renewable potentials and hourly time series for each region**
- **demand projections time series**
Final energy and non-energy demand for net-zero scenario

Source: Neumann et al, 2023
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

Source: Fraunhofer ISI
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, solid biomass, methane; 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>Methanol; ammonia and LH₂ also possible</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
Technology Choices: Exogenous Versus Endogenous

**Exogenous** assumptions (modeller chooses):

- energy services demand
- energy carrier for road transport (2050: BEV for light-duty, BEV or FCEV for heavy-duty)
- kerosene for aviation
- energy carrier for shipping (2050: MeOH)
- steel production 2050: DRI with hydrogen, then electric arc (could compete with BF+CCS)
- electrification & recycling in industry

**Endogenous** (model optimizes):

- electricity generation fleet
- electricity, gas, hydrogen and carbon networks
- space and water heating technologies (including insulation)
- all P2G/L/H/C
- supply of process heat for industry
- carbon management (CCUTS)
Modelling Results
Results for 181-node model of European energy system

- Couple all energy sectors (power, heat, transport, industry)
- Reduce net CO₂ emissions to zero
- Assume energy autarky
- Assume 181 smaller bidding zones
- Conservative technology assumptions (for 2030 from Danish Energy Agency)

Examine effects of:

- power grid expansion
- new hydrogen grid
- e-fuel imports
Daily average of hourly electricity balance

Demand (negative values) is higher in winter thanks to power-to-space-heat; complemented by winter wind; electrolysers have capacity factors in 40-60% range.

Source: Neumann et al, 2023
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)

Source: Brown et al., “Synergies of sector coupling,” 2018
Distribution of technologies: double today’s power grid volume

Electricity grid expansion of 413 TWkm...

- 20 bn€/a → 10 GW
- 10 bn€/a → 5 GW
- 5 bn€/a

Source: Neumann et al, 2023
Distribution of technologies: double today’s power grid volume

Electricity grid expansion of 413 TWkm...

- System cost: 20 bn€/a, grid expansion: 10 GW
- System cost: 10 bn€/a, grid expansion: 5 GW
- System cost: 5 bn€/a

...and new hydrogen grid of 204 TWkm.

- H2 Electrolysis
- H2 Fuel Cell
- H2 pipeline (total)
- H2 pipeline (repurposed)

Source: Neumann et al, 2023
Distribution of technologies: 50% more power grid volume

System cost:
- 20 bEUR/a
- 10 bEUR/a
- 5 bEUR/a

Added grid:
- 10 GW
- 5 GW

Technologies:
- DAC
- H2 storage
- Battery storage
- Electricity distribution grid
- Gas-to-power/heat
- Hot water storage
- Hydroelectricity
- Offshore wind
- Onshore wind
- Power-to-gas
- Power-to-heat
- Power-to-liquid
- Solar PV
- Solar rooftop
- HVAC line
- HVDC link

Source: Neumann et al, 2023
Distribution of technologies: 25% more power grid volume

- **System cost**: 20 bEUR/a, 10 bEUR/a, 5 bEUR/a
- **Added grid**: 10 GW, 5 GW

**Technologies**:
- H2 Electrolysis
- H2 Fuel Cell
- H2 pipeline (total)
- H2 pipeline (repurposed)

**Source**: Neumann et al, 2023
Distribution of technologies: no power grid expansion

No electricity grid expansion...

<table>
<thead>
<tr>
<th>System Cost</th>
<th>Grid Expansion</th>
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<tbody>
<tr>
<td>20 bn€/a</td>
<td>10 GW</td>
</tr>
<tr>
<td>10 bn€/a</td>
<td>5 GW</td>
</tr>
<tr>
<td>5 bn€/a</td>
<td>3 GW</td>
</tr>
</tbody>
</table>

...and new hydrogen grid of 307 TWkm.

Source: Neumann et al, 2023
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: \( \sim € 50 \) billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)
With and without hydrogen network

- **Cost** of hydrogen network: € 6-8 billion per year
- **Net benefit** is higher: € 12-26 billion per year (1.6-3.4% of total)
- Hydrogen network brings **robust benefit** if you assume energy autarky
- Benefit is strongest without power grid expansion
- Power grid expansion is better if you have to choose

Source: Neumann et al, 2023
Energy grid in different cases

- More hydrogen grid with less power grid
- Without power expansion, hydrogen transports more energy
- Hydrogen grid is not perfect substitute
- Two-thirds of hydrogen grid can re-use methane pipes

Source: Neumann et al, 2023
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 $\sim \text{€} 77$ billion per year as we **eliminate onshore wind** (with no grid expansion)
- Rise is only half if we **allow a quarter of technical potential** ($\sim 120$ GW for Germany)
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.
Synthetic fuels from outside Europe?

Green hydrogen with pipeline transport costs around \(~ 80 \text{ \euro}/\text{MWh}\) in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH\(_3\) form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.
Do the results change if we import e-fuels from outside Europe? Not really

Hydrogen network is still used to transport hydrogen to spatially-fixed demands in industry, heavy trucks, backup power and heat

Costs are similar, since need DAC for carbon outside of Europe; in Europe point sources of CO₂ suffice

Source: Neumann et al, 2023
With e-fuel, hydrogen and electricity imports instead of autarky

- Allowing imports of electricity, green hydrogen, e-fuels, changes infrastructure needs completely
- PtX out-sourced from Europe
- Electricity imported too, providing seasonal balancing

Source: Hampp, Brown, Neumann; 2022/3
E-fuel imports reduce costs, but not completely

Cost-optimal import volume of 3750 TWh, reducing costs by 7% versus autarky.

Source: Hampp, Brown, Neumann; 2022/3
There is a **large degeneracy** of different possible energy systems close to the optimum.
Pathway for European energy system from now until 2050

For a fixed CO₂ 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)
Appearance of technologies until 2050 depends on temperature target

Source: M. Victoria et al, 2021
- Carbon capture (left): from process emissions, but also from heat production in industry and for combined-heat-and-power (CHP) plants
- Sequestration limited to 200 MtCO₂/a (enough to cover today’s process emissions)
- Further carbon capture is used for Fischer-Tropsch fuels (kerosene and naphtha)
- The tighter the CO₂ budget, the more is captured, and at some point direct air capture (DAC) also plays a role
- If sequestration is relaxed to 1000 MtCO₂/a, then CDR compensates unabated emissions elsewhere

Source: M. Victoria et al, 2021
Pipeline network for liquid carbon dioxide can reduce costs, particularly for large sequestration.

Source: F. Neumann, C. Tries, F. Hofmann, 2023
Future work

- Allow **industry relocation**
- Explore **circular carbon economy**
- 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)
- Cost-benefit of **sufficiency**
- Improving **open access** to models
Offshore network topology, floating wind

- How meshed does the offshore network need to be?
- Can offshore hubs and islands reduce costs?
- How do wake effects impact production for dense configurations?
- Should hydrogen be produced offshore on at landing points?
- Do we need floating wind if onshore potentials are limited?

Source: Philipp Glaum, 2023
PyPSA-Eur-Sec is open source. You can run your it with your own assumptions in a simplified online version of the model: https://model.energy/scenarios/

Hydrogen network scenario explorer: https://h2-network.streamlit.app
Conclusions
Conclusions

- There are **many trade-offs** to be made between cost, unpopular infrastructure, speed of implementation and security; but also many **near-optimal** compromise solutions
- Can work around transmission bottlenecks, but **costly** and needs **tight coordination**
- **Hydrogen networks** reduce system costs, especially if imports and power grid expansion are limited; but can avoid both power grid expansion and H₂ network (for a cost)
- The more restricted we are, the more **policy intervention** is required for joint planning, enabling local price signals, responsive demand and robust carbon pricing
- Many more **tricky topics to come**: e-fuel/material imports, industry relocation, geopolitical risk spreading, carbon transport, use and sequestration
- Need to find solutions which are **robust to uncertainty** ⇒ calculate many scenarios
- **Openness and transparency** and critical to ensure **re-usability, customisability** and **swift policy response** by diverse actors
More information

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):

Example: 100% renewable electricity system for Europe

Within 10% of the optimum we can:

- Eliminate most grid expansion
- Exclude onshore or offshore wind or PV
- Exclude battery or most hydrogen storage

Robust conclusions: wind, some transmission, some storage, preferably hydrogen storage, required for a cost-effective solution.

This gives space to choose solutions with higher public acceptance.

Source: Neumann & Brown, 2020
Transport sector: Electrification of Transport

Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- Road and rail transport is fully electrified (vehicle costs are not considered)
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1100 TWh_{el}/a for Europe
- In model can replace Battery Electric Vehicles (BEVs) with Fuel Cell Electric Vehicles (FCEVs) consuming hydrogen. Advantage: hydrogen cheap to store. Disadvantage: efficiency of fuel cell only 60%, compared to 90% for battery discharging.
Transport sector: Battery Electric Vehicles

- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes in consumer behaviour assumed (e.g. car-sharing/pooling)
- BEVs are treated as exogenous (capital costs NOT included in calculation)

Availability (i.e. fraction of vehicles plugged in) of Battery Electric Vehicles (BEV).
Heating sector: Many Options with Thermal Energy Storage (TES)

- All space and water heating in the residential and services sectors is considered, with no additional efficiency measures (conservative) - total heating demand is $3585 \text{TWh}_{th}/a$.

- Heating demand can be met by heat pumps, resistive heaters, gas boilers, solar thermal, Combined-Heat-and-Power (CHP) units. No industrial waste heat.

- Thermal Energy Storage (TES) is available to the system as hot water tanks.

Heat demand profile from 2011 in each region using population-weighted average daily $T$ in each region, degree-day approx. and scaled to Eurostat total heating demand.
We model both fully decentralised heating and cases where up to 45% of heat demand is met with district heating in northern countries. Heating technology options for buildings:

**Decentral individual heating** can be supplied by:

- Air- or Ground-sourced heat pumps
- Resistive heaters
- Gas boilers
- Small solar thermal
- Water tanks with short time constant \( \tau = 3 \) days

**Central heating** can be supplied via district heating networks by:

- Air-sourced heat pumps
- Resistive heaters
- Gas boilers
- Large solar thermal
- Water tanks with long time constant \( \tau = 180 \) days
- CHPs

Building renovations can be co-optimised to reduce space heating demand.