Managing Uncertainty in Sector-Coupled Scenarios for Climate Neutrality

Tom Brown, Fabian Neumann
t.brown@tu-berlin.de, Department of Digital Transformation in Energy Systems, TU Berlin

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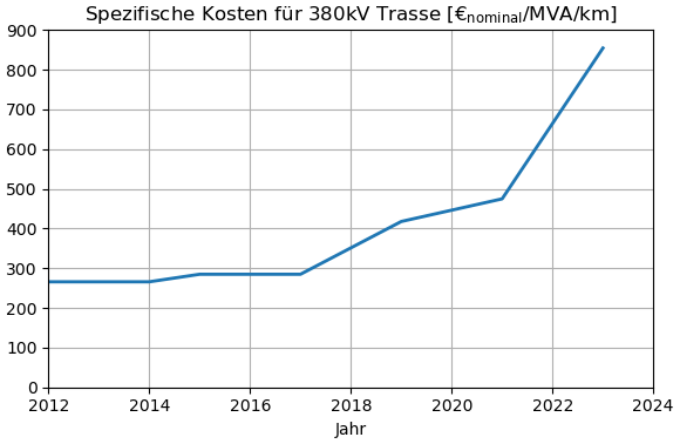
3 Thoughts on Managing Uncertainty in a Fragmenting World

- **Global restructuring is a source of uncertainty in system planning** (examples of energy-intensive value chains, supply-chain bottlenecks for grid and gas turbines)
- **Need agile solutions to manage infrastructure uncertainty** (example of near-optimal use of methanol for backup)
- **VRE and electrification magnify need for resilience and risk-averse planning** (example of black-start capable regions)

Major uncertainties for supply chains affect planning

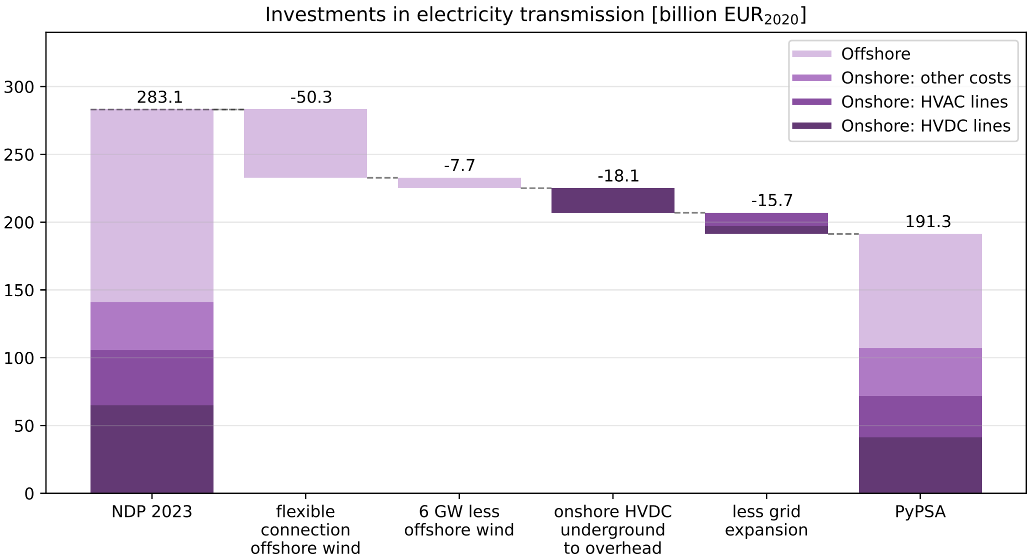
Supply chain bottlenecks causing a reassessment of planning

Demand for transmission lines and transformers (due to VRE, electrification) and gas turbines (due to data centres) has led to **supply bottlenecks**, costs growing 3-5x. German transmission expansion costs escalated from 2023 to 2025 from 320 bn€ to 440 bn€. Need to reassess!



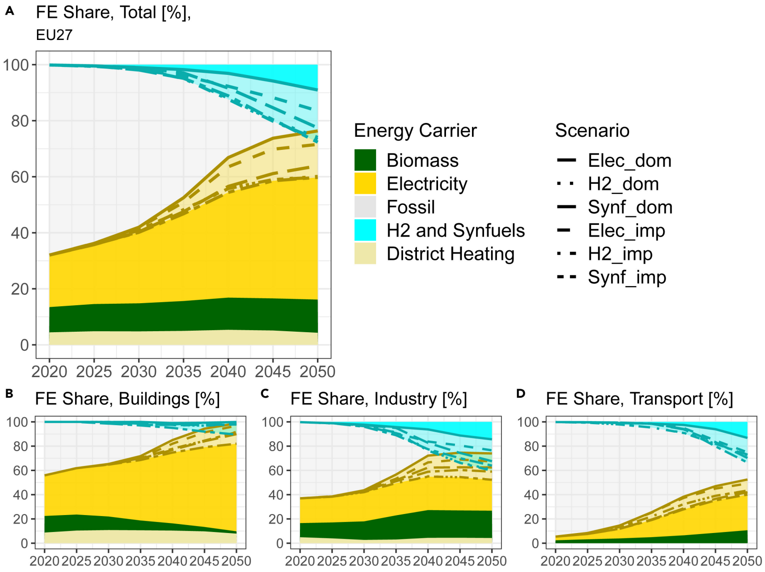
Source: Schreyer et al, 2024

Electricity transmission savings from Ariadne Scenario Report



Source: Ariadne, 2025

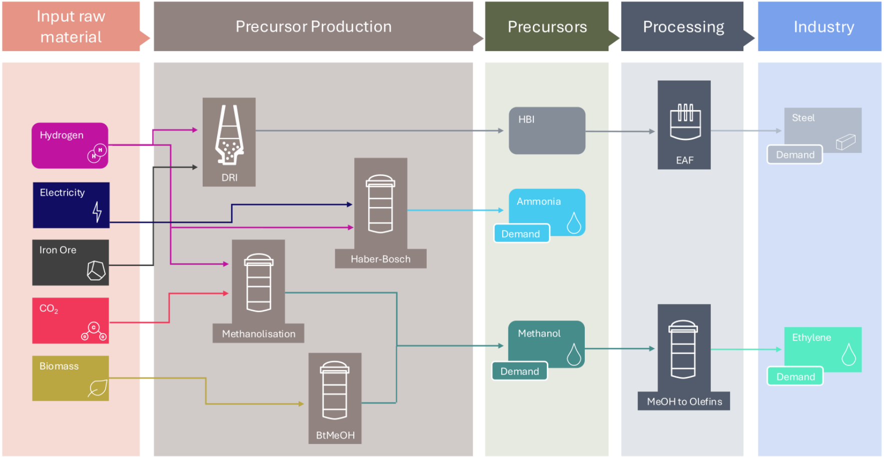
Scenarios show increase in electrification, hydrogen for some of rest



Source: Schreyer et al, 2024

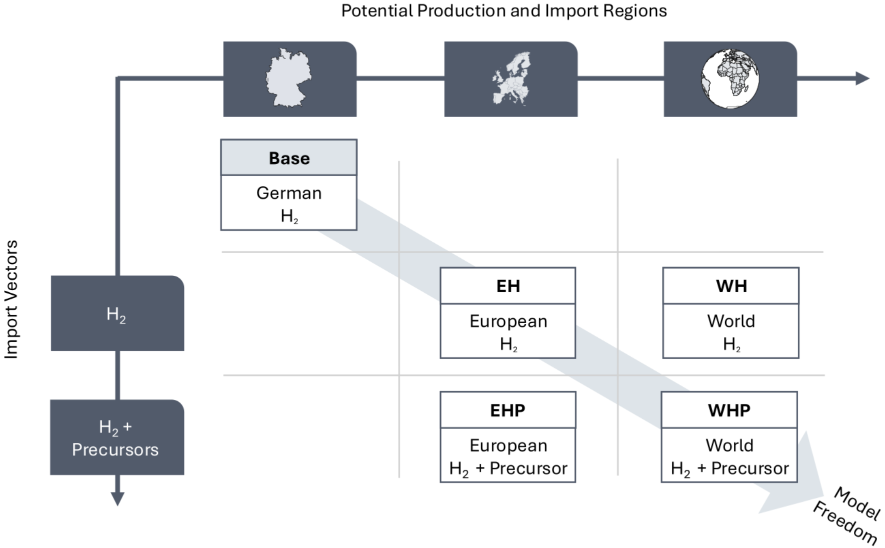
Transport derivates, not hydrogen

Most of hydrogen is used to produce **derivatives** like ammonia, direct-reduced iron (DRI) and methanol, precursors for energy-intensive industry and fuels for transport.



Source: Seibold et al, 2025

Germany could import hydrogen or precursors from Europe, World



Source: Seibold et al, 2025

Importing from World saves most costs, from Europe 48% of that

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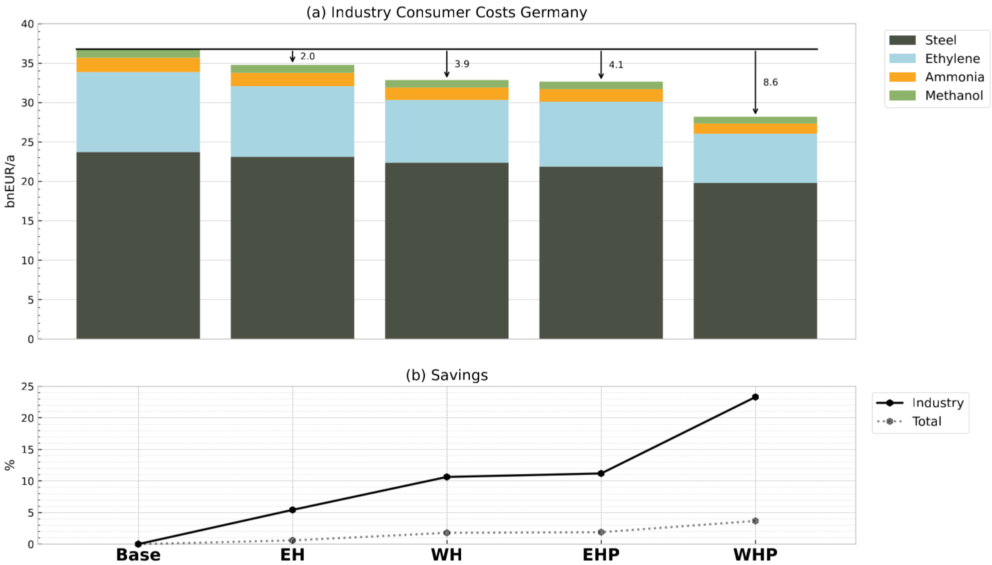
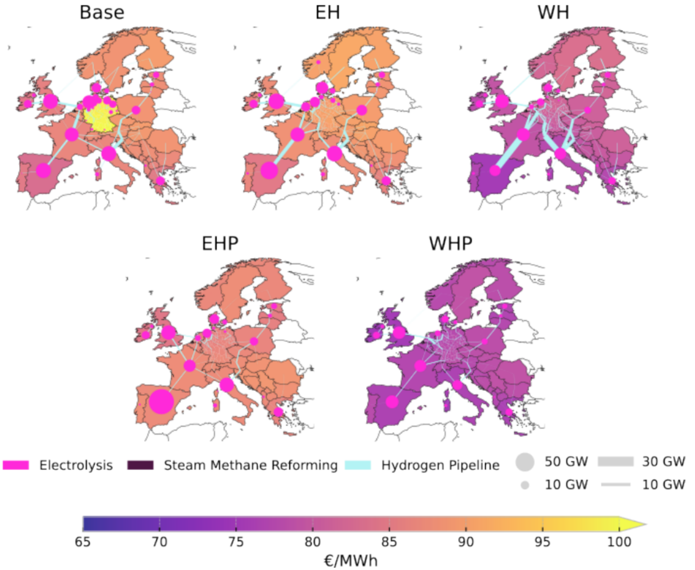


Source: Seibold et al, 2025

Precursor import reduces prices & infrastructure for hydrogen



Source: Seibold et al, 2025

Near-optimal solutions for agility: methanol

But which hydrogen demand sectors really need actual hydrogen?

All potential hydrogen demand sectors can be served by **electrification** or by **hydrogen derivatives** (e-fuels like ammonia, methanol, etc.) that are easier to transport and store.

sector	alternatives if hydrogen not available
heavy duty trucks	electrify
iron direct reduction	do reduction close to ore / in cluster
ammonia	synthesise close to hydrogen source
high value chemicals	methanol or naphtha
process heat	electrify/use e-fuels
shipping	methanol or ammonia
aviation	kerosene from methanol or Fischer-Tropsch
backup power & district heat	use derivative fuels (methane, methanol)

$\Rightarrow$ There is **no strict need** for hydrogen outside of industry clusters.

Challenges with hydrogen economy

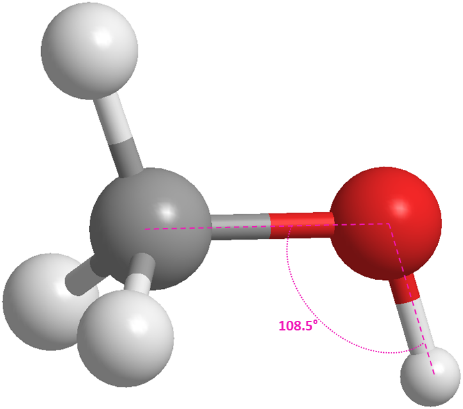
A hydrogen economy comes with **several challenges**:

- The molecule **size is small**, making it easy to leak and e.g. embrittle steel
- The **volumetric density** is low, making storage and transport difficult
- Salt deposits necessary easy underground storage in caverns are **not widely available**
- Vehicular transport is **costly**, pipeline network is necessary
- Hydrogen is an **indirect greenhouse gas** with GWP100 of 11.6 ± 2.8
- The widespread usage of a new gas requires a **coordinated scale-up** of lumpy **GW-scale** pipelines, storage, supply and demand

Introducing methanol

Methanol, the simplest alcohol CH_3OH can fit the bill for many non-electric sectors.

Advantages: liquid, easy to store/transport, widely traded, burns cleanly. Don't drink it!

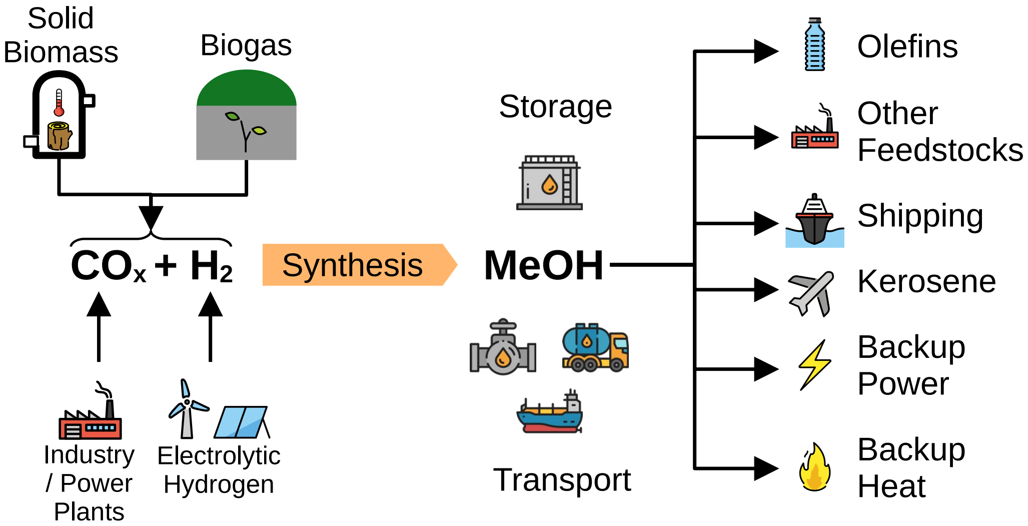


Source: Wikipedia; Yves Meur

Idea: ‘Electrification plus minimal methanol economy’

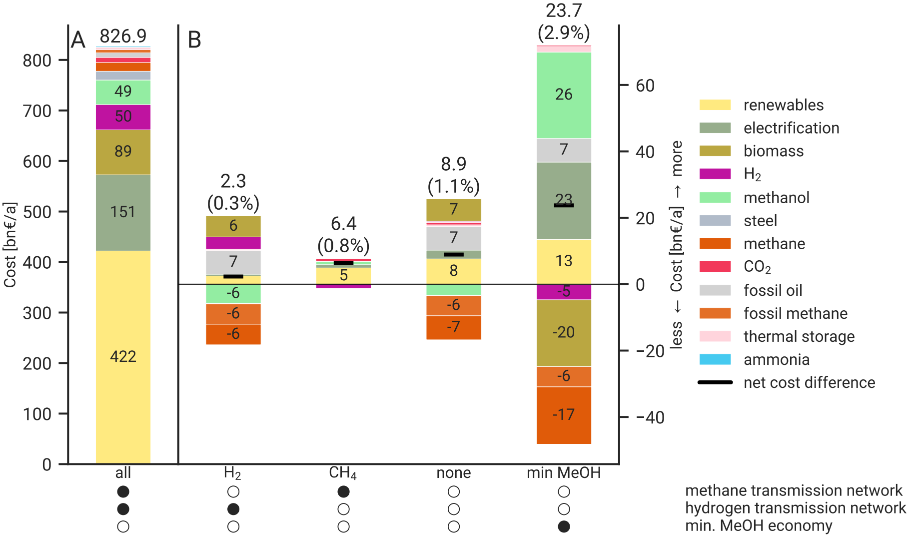
- **Electrify** as much as possible
- Use hydrogen in clusters for **sectors where really needed** (ammonia, iron ore reduction)
- Use **methanol as a gap-filler** for the rest (backup power & heat, shipping, aviation, chemical industry)
- Methanol is more easily **storeable and transportable** than hydrogen (liquid at RTP)
- Methanol **scales down** to MW-scale use cases without lumpiness of big infrastructure (frictions and non-linearities not seen by models)
- (E-)biomethanol can absorb sustainable carbon from **decentral biomass and wastes**, then be used directly in industry or dense fuels (carbon management)

Methanol as platform for hard-to-electrify



Source: [Glaum et al, 2025]

Methanol instead of gas/hydrogen grid only 3% more expensive



Source: **Glaum et al, 2025**

Resilience: Network Restoration After a Blackout

Designing a resilient system

- Electrified building heating and transport make **resilient system design** paramount
- Can each region black-start and run for two weeks during **system restoration** after a full blackout? During a cold wind lull?
- Are we sure gas or hydrogen networks would function during a blackout? Electronics in compressor stations are vulnerable, cf. Texas in Feb 2021 for unexpected issues.

Source: netztransparenz.de,2024

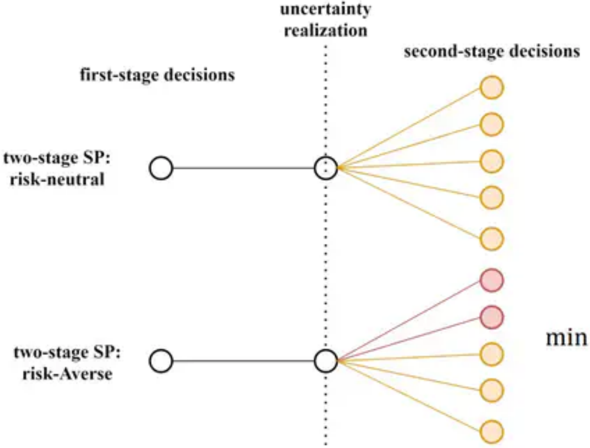
Simple, robust solution: peaker capacity with methanol tanks

- Put turbines or motors to cover **winter peak** in each region, next to a giant **methanol tank**
- Can also run as **synchronous condenser** to provide reactive power, fault current, inertia
- Methanol tanks cost just 0.01-0.05 €/kWh
- Single 200,000 m^3 tank can store **880 GWh**
- Can be built **anywhere**, take up little space
- Can be dimensioned to provide **resilience** against low wind years, volcanos, infrastructure outages, sabotage, blackouts

Source: Wikipedia

PyPSA v1.0: stochastic and risk-averse optimisation

Two-stage stochastic optimisation (first investments, then uncertainty on e.g. gas price or hydrogen volume) allows for Conditional Value-at-Risk (CVaR) formulation of risk-aversion.



$$\min \mathrm{IC} + \sum_{s=1}^{S} p_s \cdot \mathrm{OC}_s$$

$$\min \mathrm{IC} + (1-\omega) \sum_{s=1}^{S} p_s \cdot \mathrm{OC}_s + \omega \cdot \mathrm{cvar}$$

Source: PyPSA Pull Request, 2025

Conclusions

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- Global restructuring of energy-intensive value chains as well as supply bottlenecks are **examples of uncertainty** strongly affecting infrastructure planning
- Need for **agile, near-optimal** solutions that avoid **infrastructure lock-ins**
- A **minimal methanol economy** avoids long-distance transport of methane or hydrogen, **de-links the scale-up** of infrastructures (storage, pipelines), avoids frictions of hydrogen
- Using methanol in this way as a **gap filler** for backup power and heat is only **24 billion euros per year (3% of system cost)** more expensive than a methane/hydrogen system
- Increasing reliance on the power system means we need to focus on **resilience**
- **System restoration needs** could alter system design, also favour liquid fuels