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Optimal supply chains and power sector benefits of green hydrogen

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Optimal supply chains and power sector benefits of green hydrogen

Fabian Stöckl[1,2], Wolf-Peter Schill[1,3] & Alexander Zerrahn[1]

Green hydrogen can help to decarbonize parts of the transportation sector, but its power sector interactions are not well understood so far. It may contribute to integrating variable renewable energy sources if production is sufficiently flexible in time. Using an open-source co-optimization model of the power sector and four options for supplying hydrogen at German filling stations, we find a trade-off between energy efficiency and temporal flexibility. For lower shares of renewables and hydrogen, more energy-efficient and less flexible small-scale on-site electrolysis is optimal. For higher shares of renewables and/or hydrogen, more flexible but less energy-efficient large-scale hydrogen supply chains gain importance, as they allow to temporally disentangle hydrogen production from demand via storage. Liquid hydrogen emerges as particularly beneficial, followed by liquid organic hydrogen carriers and gaseous hydrogen. Large-scale hydrogen supply chains can deliver substantial power sector benefits, mainly through reduced renewable curtailment. Energy modelers and system planners should consider the distinct flexibility characteristics of hydrogen supply chains in more detail when assessing the role of green hydrogen in future energy transition scenarios. We also propose two alternative cost and emission metrics which could be useful in future analyses.

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Research questions and contribution

Sector coupling as a strategy to

- (i) decarbonize other sectors
- (ii) provide flexibility to the power sector

  → potentially useful for integration of variable renewable energy sources

  → often under-represented in energy models

  → cp. López Prol & Schill 2021, *Annual Reviews of Resource Economics*, doi: 10.1146/annurev-resource-101620-081246

Focus here: green hydrogen

- Domestic (German) H_2 production and distribution, use for fuel-cell electric vehicles

We determine least-cost hydrogen supply chains

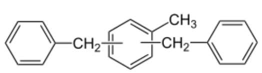
- Considering differences in energy efficiency, investment costs, and storage capabilities
- Considering electricity sector interactions → main contribution

Model: extension of DIETER

This calls for a numerical model

- Extension of open-source model DIETER: https://gitlab.com/diw-evu/dieter_public
- Here, co-optimization of power and hydrogen sector https://gitlab.com/diw-evu/dieter_public/dietergms/-/tree/1.4.0, or https://doi.org/10.5281/zenodo.3693306

New hydrogen module

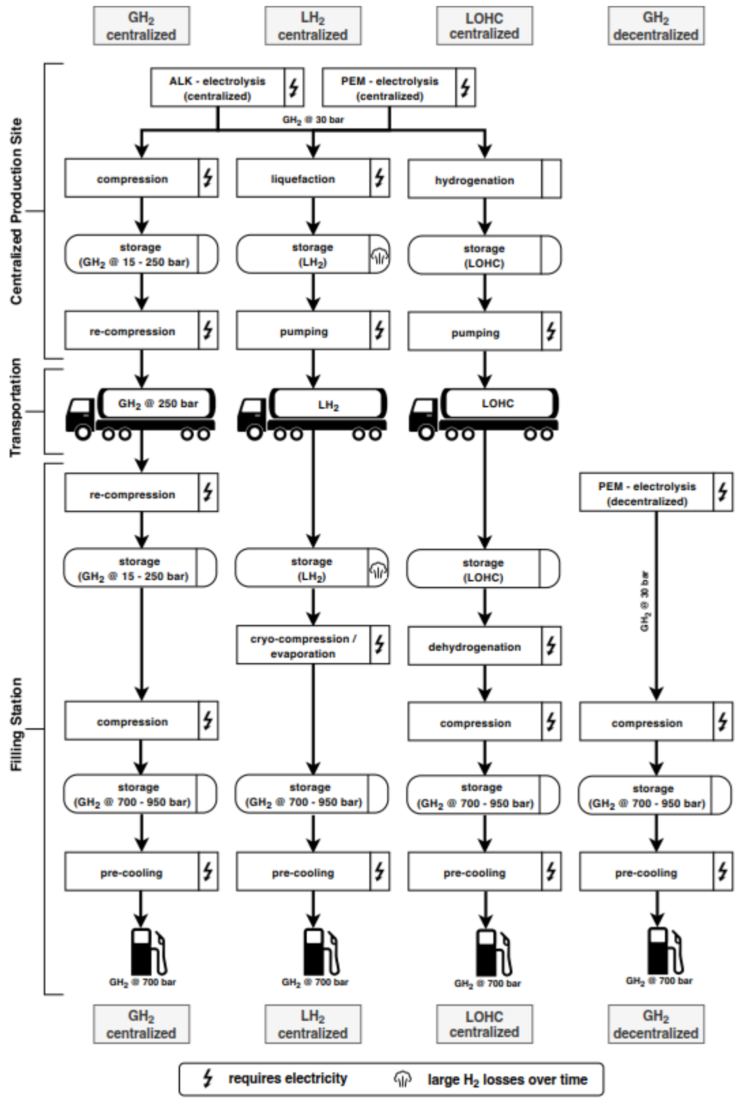
- Four channels for distributing H_2 to filling stations
  - On-site (decentralized) electrolysis
  - Central + gaseous H_2
  - Central + liquified H_2
  - Central + LOHC 

Applied to 2030 scenario for Germany

- RES shares between 65% and 80%
- Hydrogen demand: 0, 5%, 10%, 25% of passenger road traffic (0, 9, 18, 45 TWh_{H2})

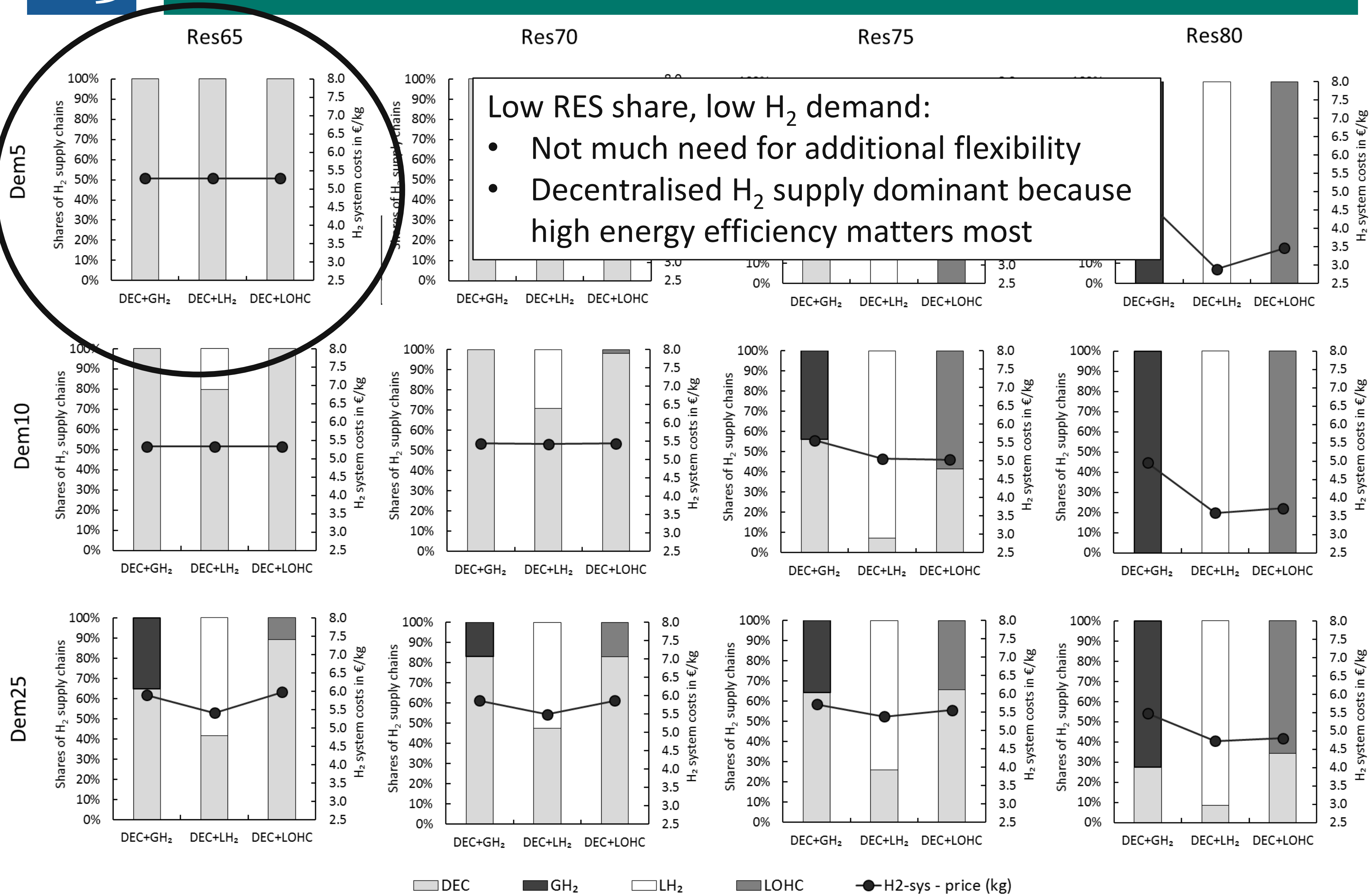
https://commons.wikimedia.org/wiki/File:Dibenzyltoluene_V1.svg

Overview of hydrogen supply chains in the model



→ We do not investigate all channels in one model run, but combinations of each centralized with the decentralized channel

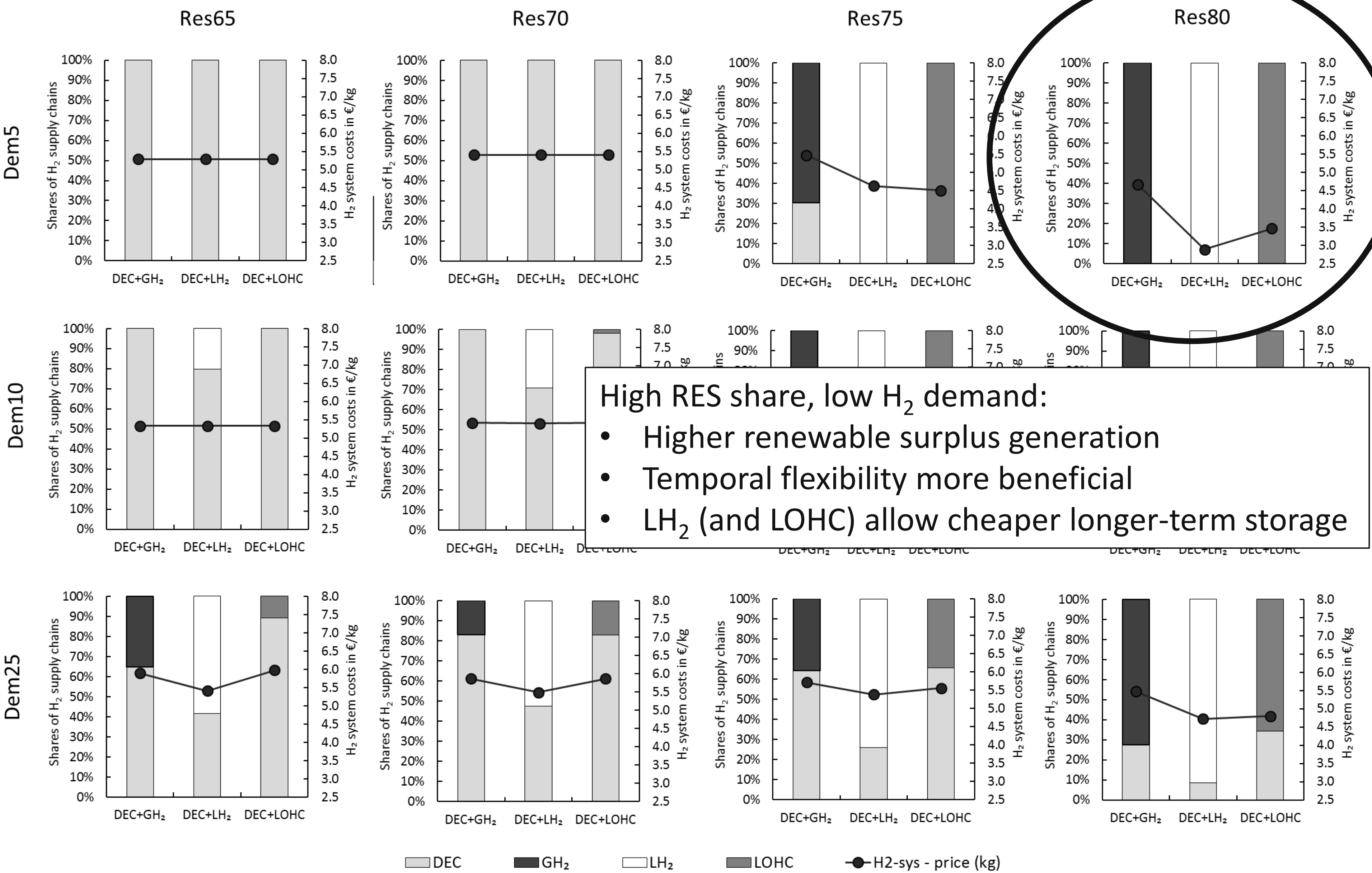
3 Results: hydrogen supply chains and H_2 supply costs



Low RES share, low H_2 demand:

- Not much need for additional flexibility
- Decentralised H_2 supply dominant because high energy efficiency matters most

3 Results: hydrogen supply chains and H_2 supply costs

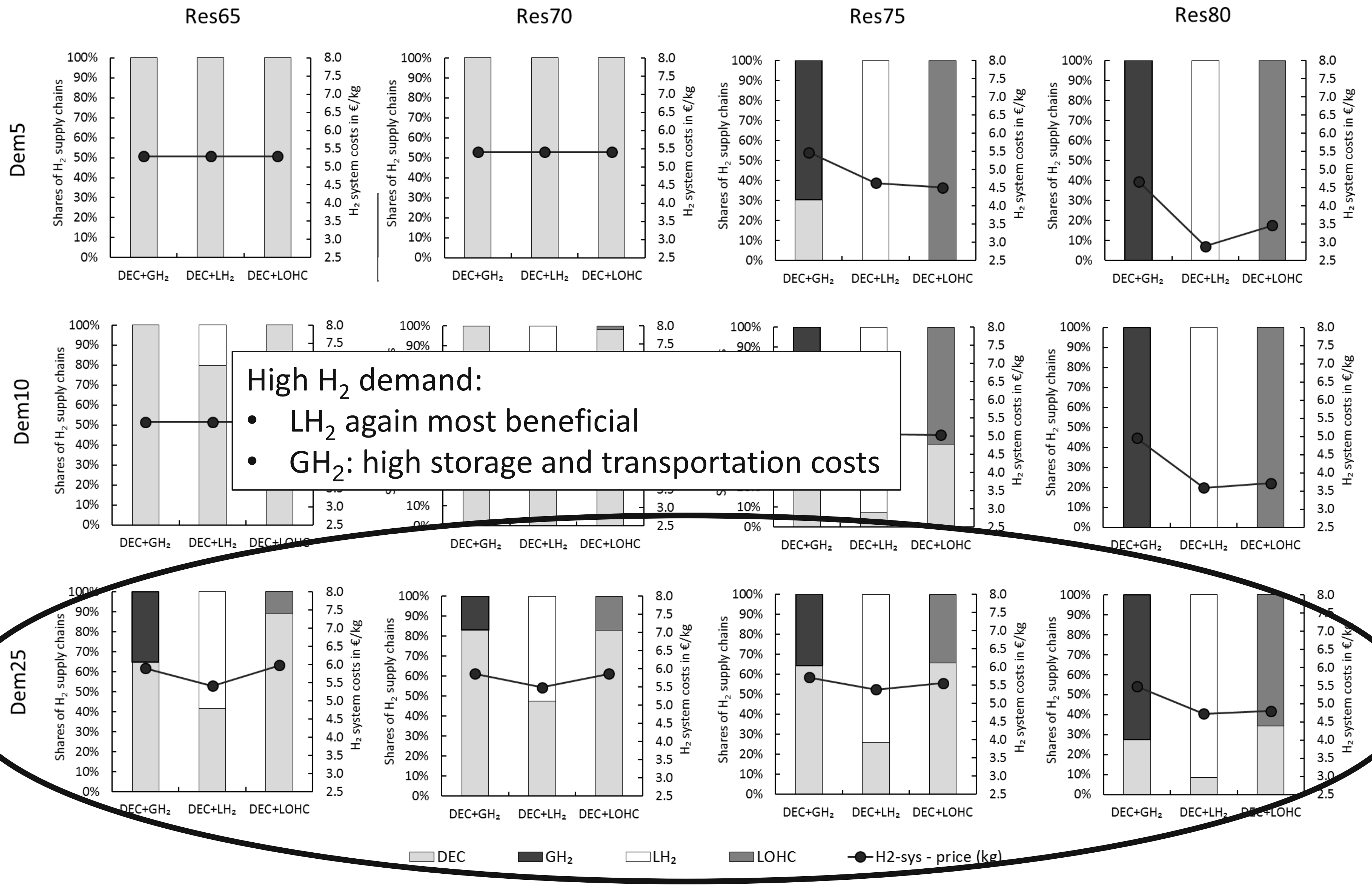


High RES share, low H_2 demand:

- Higher renewable surplus generation
- Temporal flexibility more beneficial
- LH_2 (and LOHC) allow cheaper longer-term storage

3

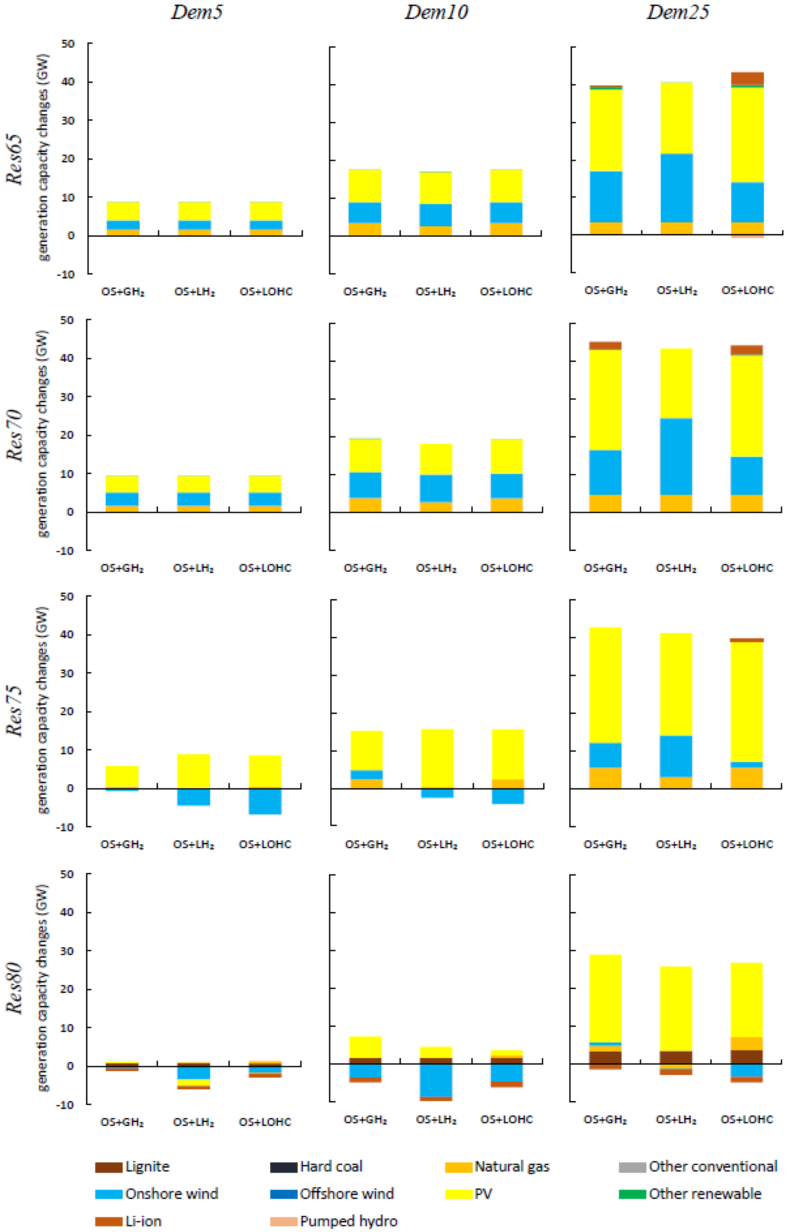
Results: hydrogen supply chains and H_2 supply costs



High H_2 demand:

- LH_2 again most beneficial
- GH_2: high storage and transportation costs

4 Effects on generation capacity (vs. baseline without hydrogen)

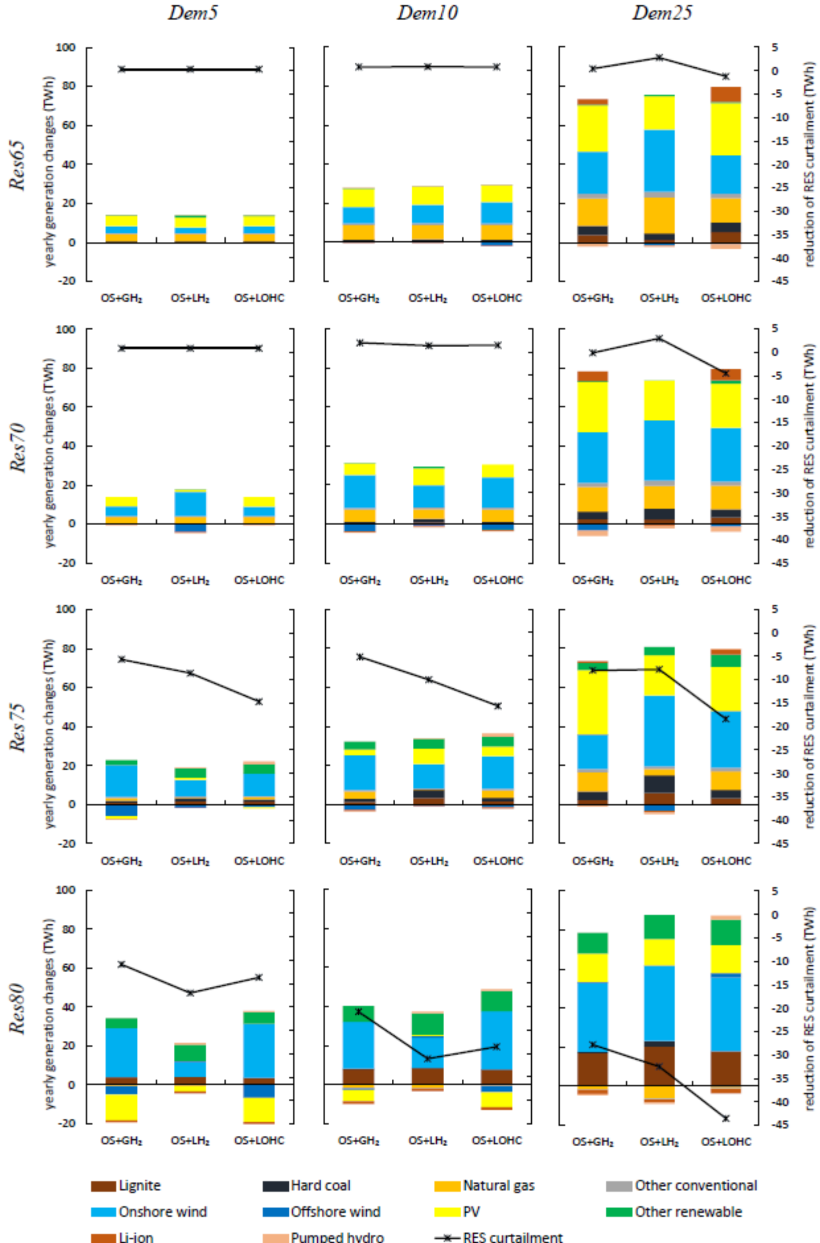


→ Larger effects with growing hydrogen demand

→ Smaller effects with growing RES penetration (better utilization)

→ Hydrogen favors PV deployment

4 Effects on yearly generation and curtailment (vs. baseline w/o hydrogen)

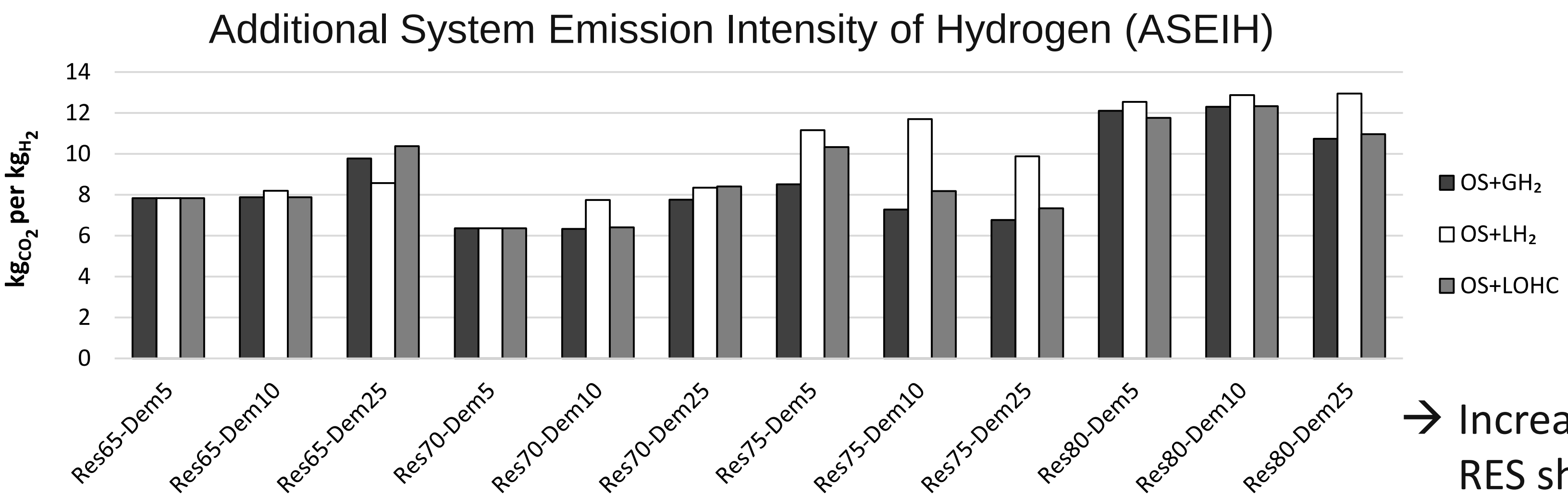


→ Flexible H_2 supply chains integrate RES that would otherwise be curtailed

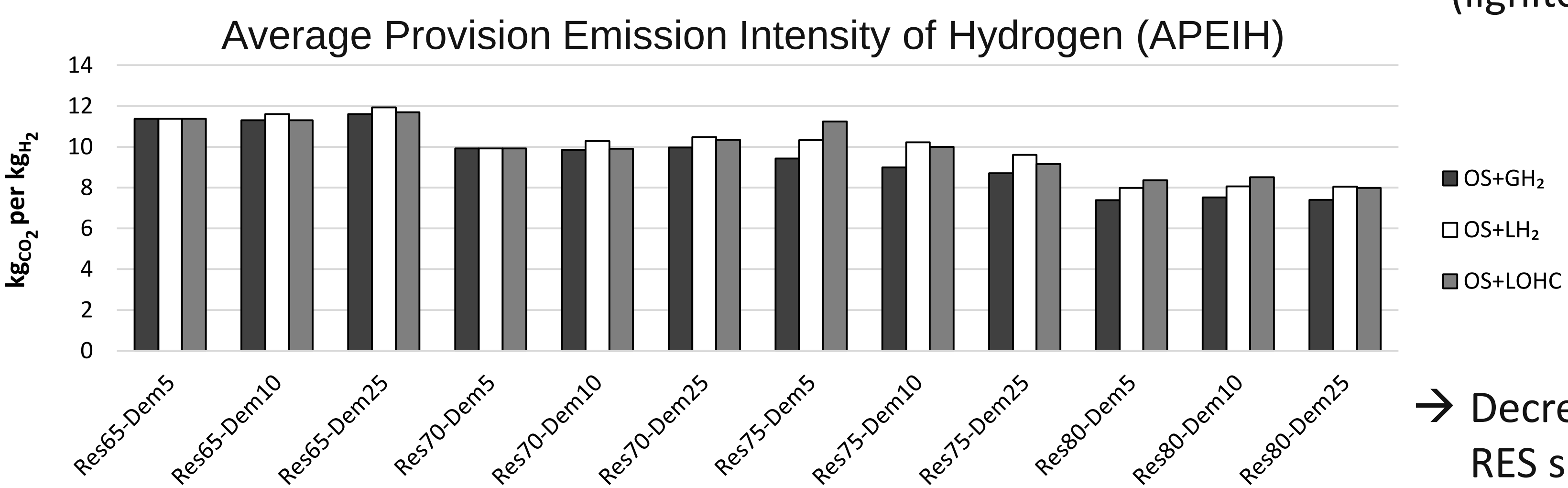
→ LOHC has the largest capability for this

→ „Mixed blessing of flexibility“: also helps integrating lignite

4 Two complementary metrics of CO_2 emission intensity

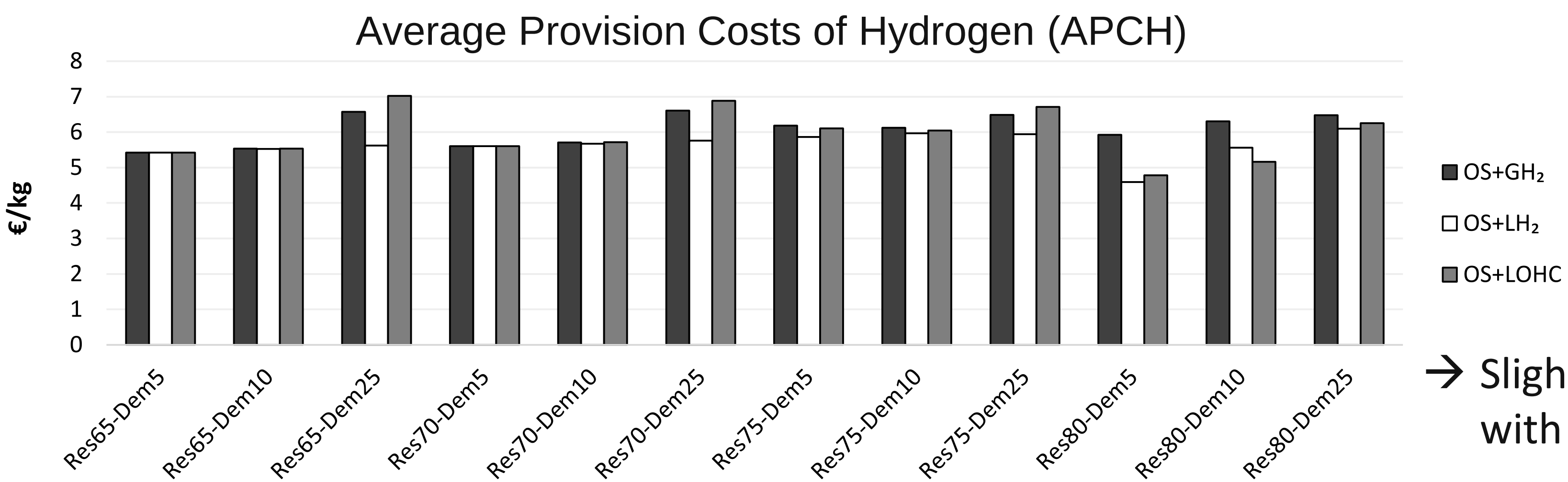


→ Increase with RES share (lignite effect)

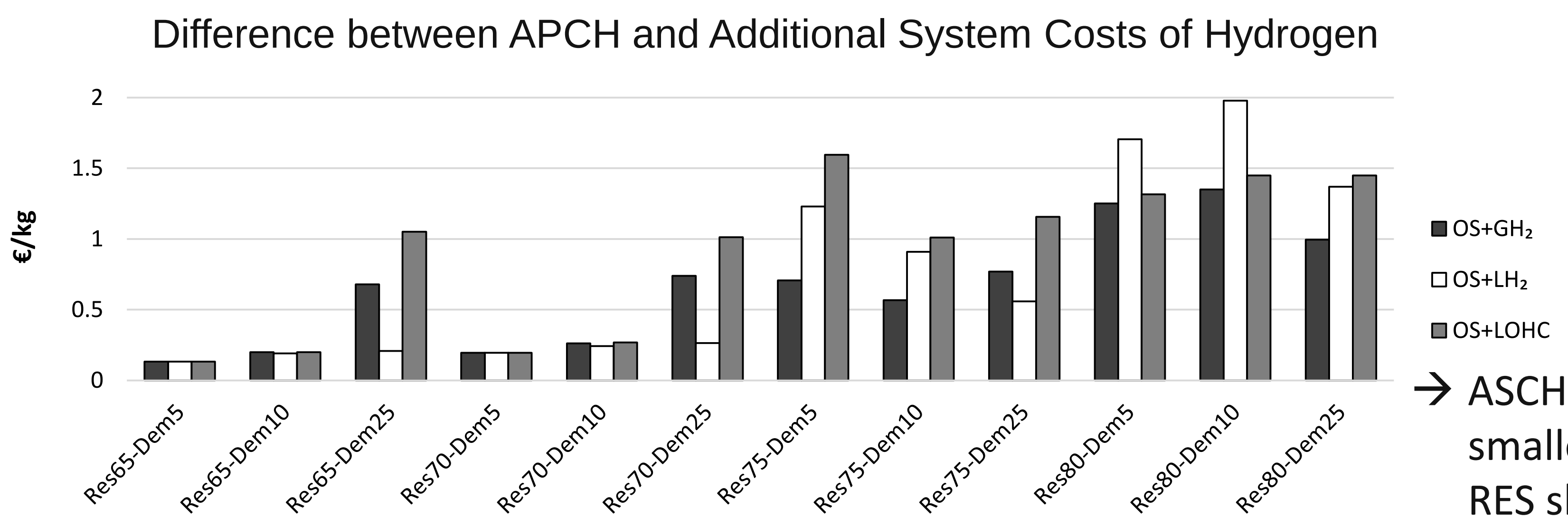


→ Decrease with RES share

4 Two complementary hydrogen cost metrics



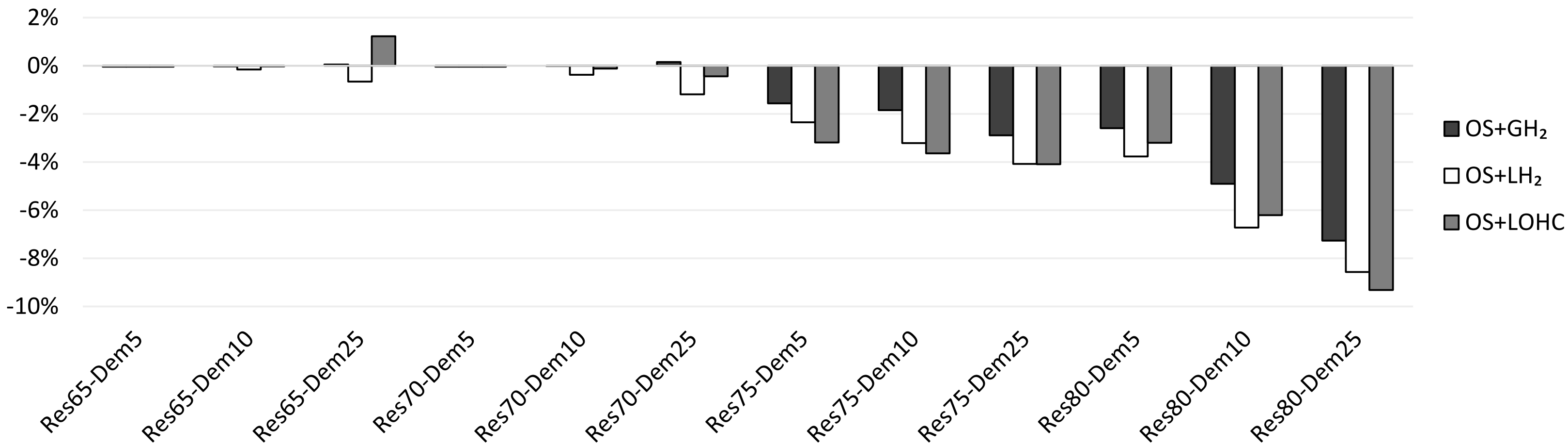
→ Slight increase with demand



→ ASCH much smaller for high RES shares

4

Effects of hydrogen on system costs of electricity (vs. baseline w/o hydrogen)



→ Benefits increase with RES shares because of better use of surpluses

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4 Sensitivity analyses (Supplementary Information)

Effects of central parameter assumptions

- Lower transportation distances: GH_2 and LOHC relatively improve
- Cavern storage: GH_2 becomes dominant
- LOHC would benefit from free waste heat, existing transportation and storage infrastructure

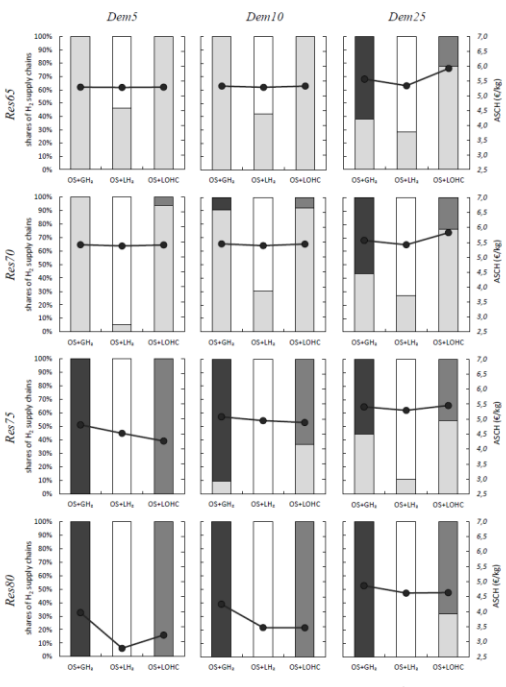

Figure SI.1: Optimal combinations of small-scale on-site and large-scale hydro supply chains and Additional System Costs of Hydrogen (ASCH) for differ scenarios - sensitivity with 100 km transportation distance.

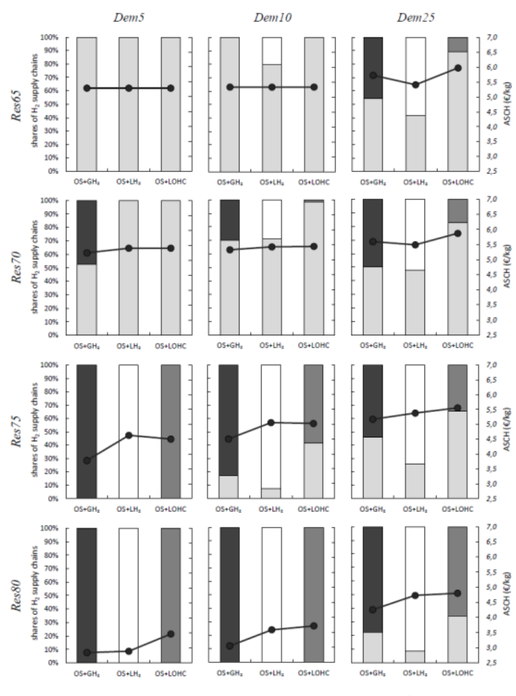

Figure SI.5: Optimal combinations of small-scale on-site and large-scale hydrogen supply chains and Additional System Costs of Hydrogen (ASCH) for different scenarios - sensitivity with cavern storage available for large-scale GH_2 production.

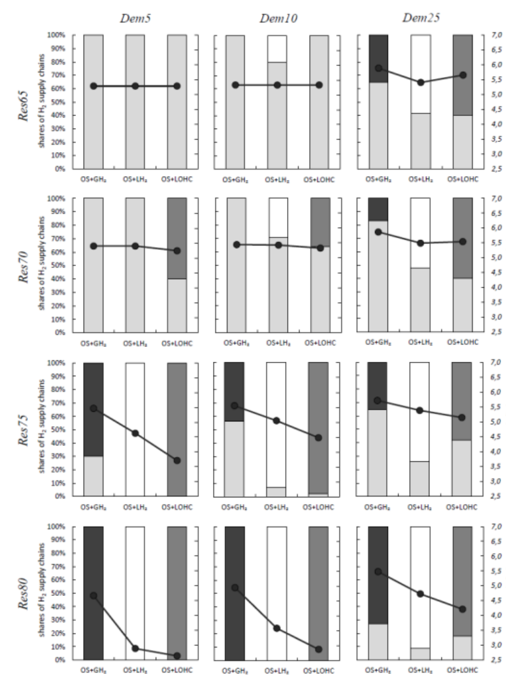

Figure SI.10: Optimal combinations of small-scale on-site and large-scale hydrogen supply chains and Additional System Costs of Hydrogen (ASCH) for different scenarios - sensitivity with free infrastructure for LOHC storage and transportation.

Summary and conclusion

Trade-off between energy efficiency and temporal flexibility

- Energy-efficient decentral electrolysis optimal for lower RES shares
- Less energy-efficient but more flexible centralized electrolysis better for higher RES shares

Possible co-benefits of green H_2 for RES integration

- Depend on storage capability of supply chain
- „Mixed blessing“: additional flexibility may also benefit dirty generators
- Different cost metrics raise complementary insights

Limitations

- Results driven by renewable surplus, no competing sector coupling options
- Limits to RES capacity deployment in Germany (and Europe)
- Hydrogen imports: export of power sectors benefits

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Fabian Stöckl[1,2], Wolf-Peter Schill[1,3]✉ & Alexander Zerrahn[1]

Green hydrogen can help to decarbonize parts of the transportation sector, but its power sector interactions are not well understood so far. It may contribute to integrating variable renewable energy sources if production is sufficiently flexible in time. Using an open-source co-optimization model of the power sector and four options for supplying hydrogen at German filling stations, we find a trade-off between energy efficiency and temporal flexibility. For lower shares of renewables and hydrogen, more energy-efficient and less flexible small-scale on-site electrolysis is optimal. For higher shares of renewables and/or hydrogen, more flexible but less energy-efficient large-scale hydrogen supply chains gain importance, as they allow to temporally disentangle hydrogen production from demand via storage. Liquid hydrogen emerges as particularly beneficial, followed by liquid organic hydrogen carriers and gaseous hydrogen. Large-scale hydrogen supply chains can deliver substantial power sector benefits, mainly through reduced renewable curtailment. Energy modelers and system planners should consider the distinct flexibility characteristics of hydrogen supply chains in more detail when assessing the role of green hydrogen in future energy transition scenarios. We also propose two alternative cost and emission metrics which could be useful in future analyses.

The increasing use of renewable energy sources in all end-use sectors is a main strategy to reduce greenhouse gas emissions[1]. This not only applies to the power sector, but also to other sectors such as transportation. There, energy demand may be satisfied either directly by renewable electricity or indirectly by hydrogen and derived synthetic fuels produced with renewable electricity[2–6]. The potential role of hydrogen-based electrification for deep decarbonization is widely acknowledged[7–10].

Yet, a central aspect is less understood so far: how hydrogen-based electrification interacts with the power sector. Hydrogen supply chains use different types of storage, which allow to temporally disentangle electricity demand for hydrogen production from the time profile of final hydrogen demand. Similar to other flexibility options in the power sector, such as load shifting or electricity storage, this increases the *temporal flexibility* of the power sector. Such flexibility can help make better use of variable renewable energy from wind and solar PV[11,12]. This, in turn, impacts the optimal electricity generation and storage capacities in the power sector, their hourly use, carbon emissions, and costs. Yet more flexible hydrogen supply chains may be less energy-efficient as they incur more conversion steps[13,14]. Thus, the overall power system impacts of different hydrogen supply chains, considering both their flexibility and energy efficiency characteristics, are a priori unclear.

We address this research gap on the power sector interactions of green hydrogen by investigating different supply chains of hydrogen for road-based passenger mobility for future scenarios with high shares of variable renewable electricity. Specifically, we determine least-cost options for the supply of electrolysis-based hydrogen at filling stations, while explicitly considering how they interact with the power sector. To this end, we use an open-source cost-minimization model with a technology-rich well-to-tank perspective that co-optimizes the power sector and four relevant hydrogen supply chains derived from the literature: small-scale on-site electrolysis at the filling station as well as three large-scale hydrogen production and distribution options.

As outlined in more detail in "Literature review", many previous power sector analyses that include hydrogen for mobility lack detail with respect to the representation of hydrogen production and distribution options[15–19]. In contrast, studies that include more techno-economic details of supply chains for hydrogen mobility often rely on exogenous electricity price inputs, include only rudimentary power sectors, tie hydrogen production to the availability of surplus electricity generation, and/or are restricted to a single supply chain[13,14,20–25]. Yet, none of these studies examines the interactions between hydrogen supply chains and power sectors with high shares of renewable energy sources in detail.

In this paper, we develop and apply an integrated hydrogen and power sector model to fill this gap in the literature. It minimizes overall system costs by endogenously optimizing electricity generation and storage

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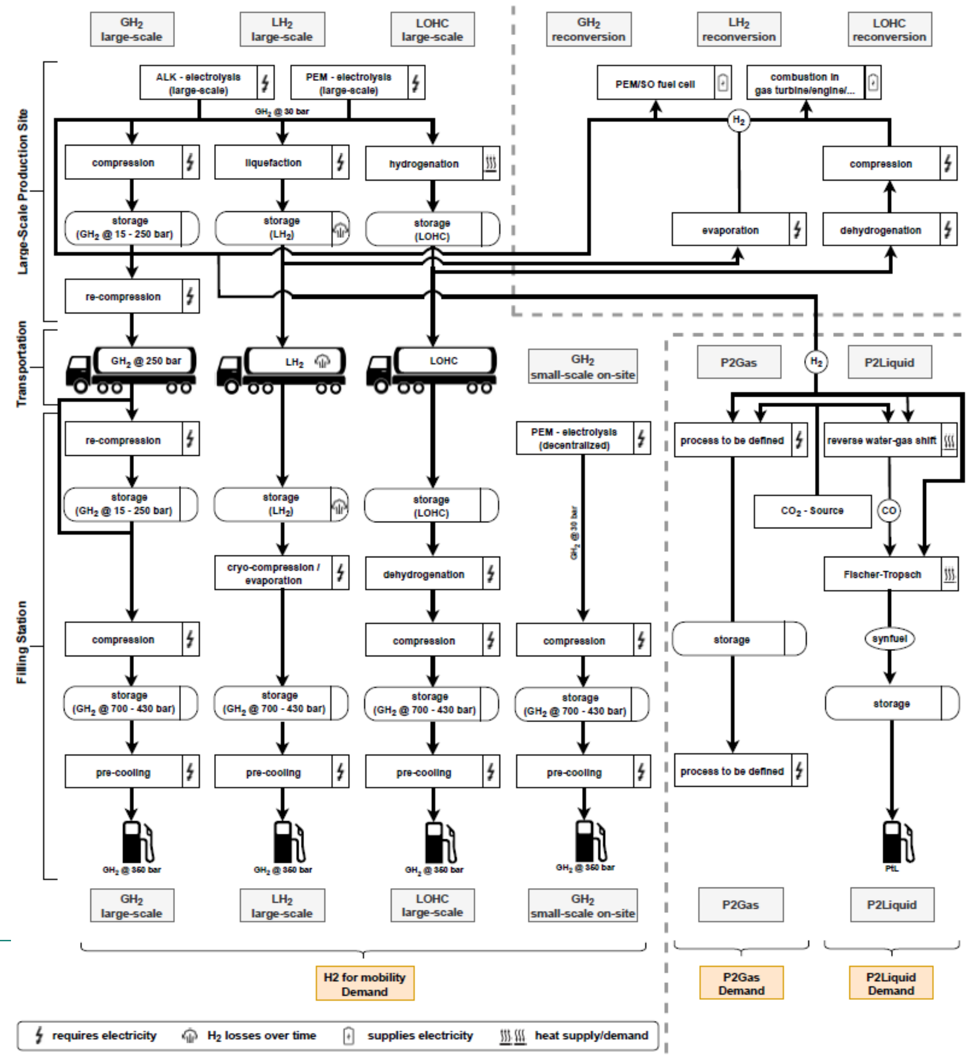
Some aspects we are interested in

- Reconversion to electricity in settings with high VRE shares
- Include PtG and PtL
- Road transport:
  E-trucks vs. H_2-trucks vs. E-Fuel-Trucks
- Interactions with other sector coupling
- Coupling to global hydrogen model



Thank you for listening

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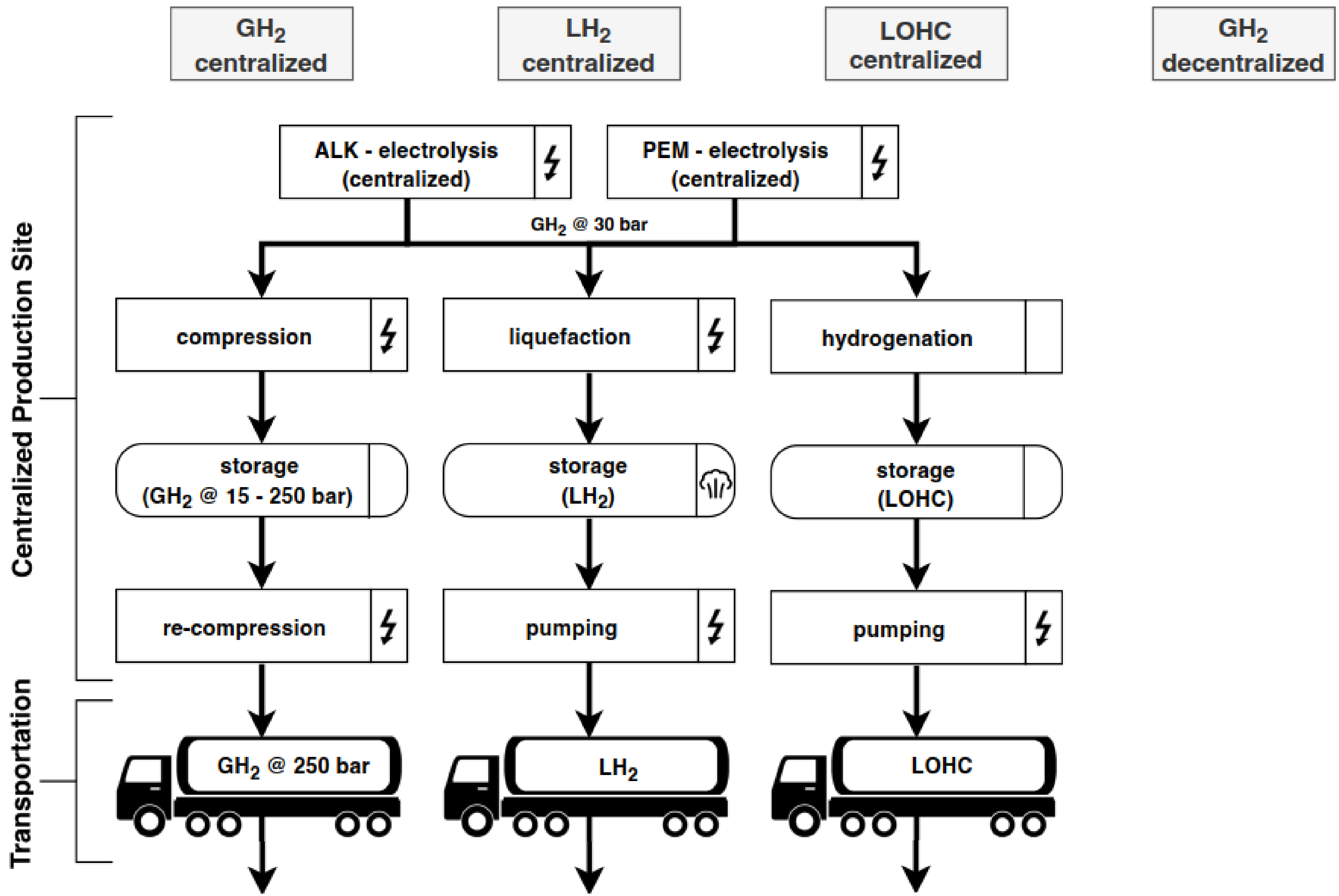
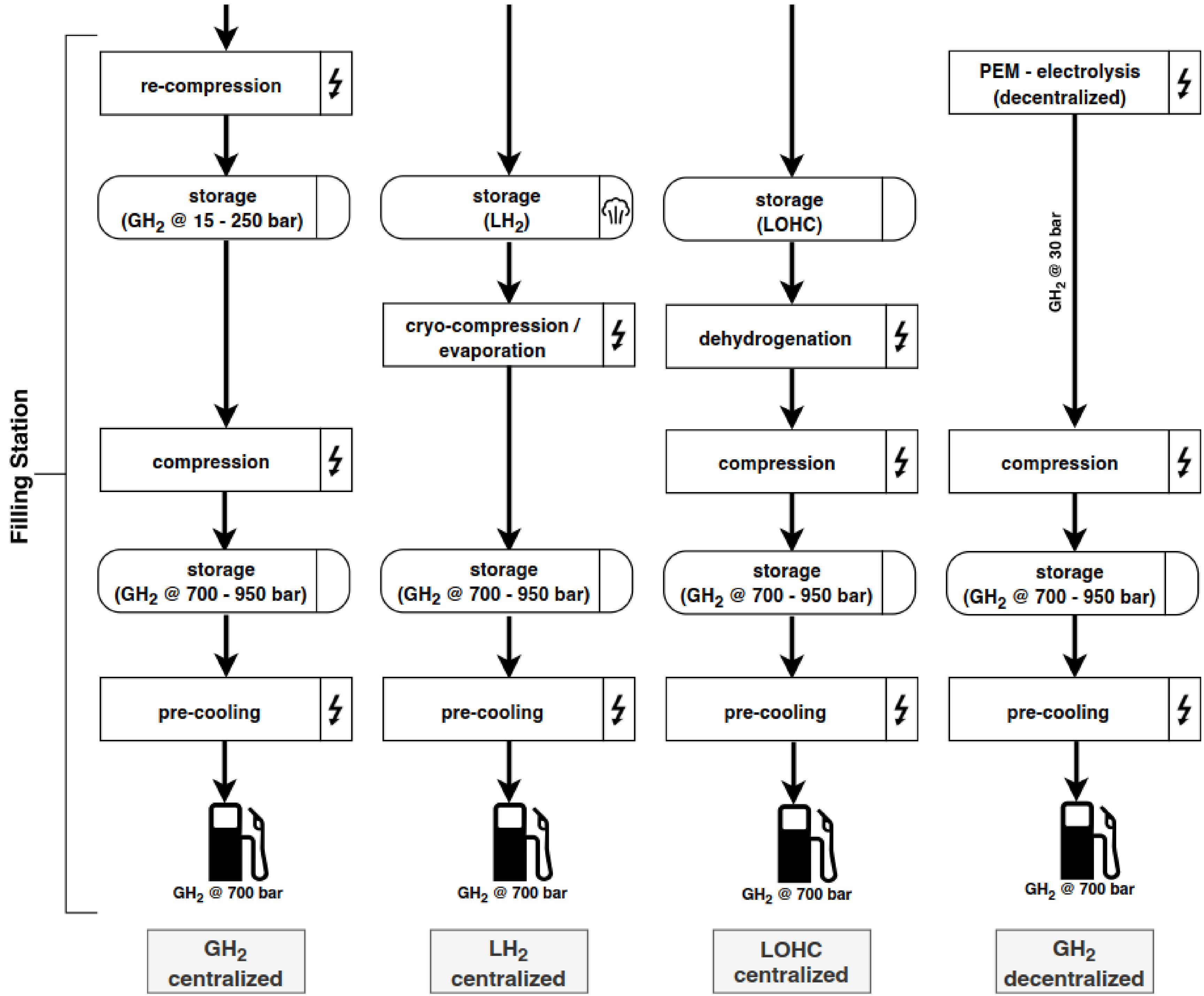


GH2 centralized
LH2 centralized
LOHC centralized
GH2 decentralized
Centralized Production Site
ALK - electrolysis (centralized)
PEM - electrolysis (centralized)
GH2 @ 30 bar
compression
liquefaction
hydrogenation
storage (GH2 @ 15 - 250 bar)
storage (LH2)
storage (LOHC)
re-compression
pumping
pumping
Transportation
GH2 @ 250 bar
LH2
LOHC

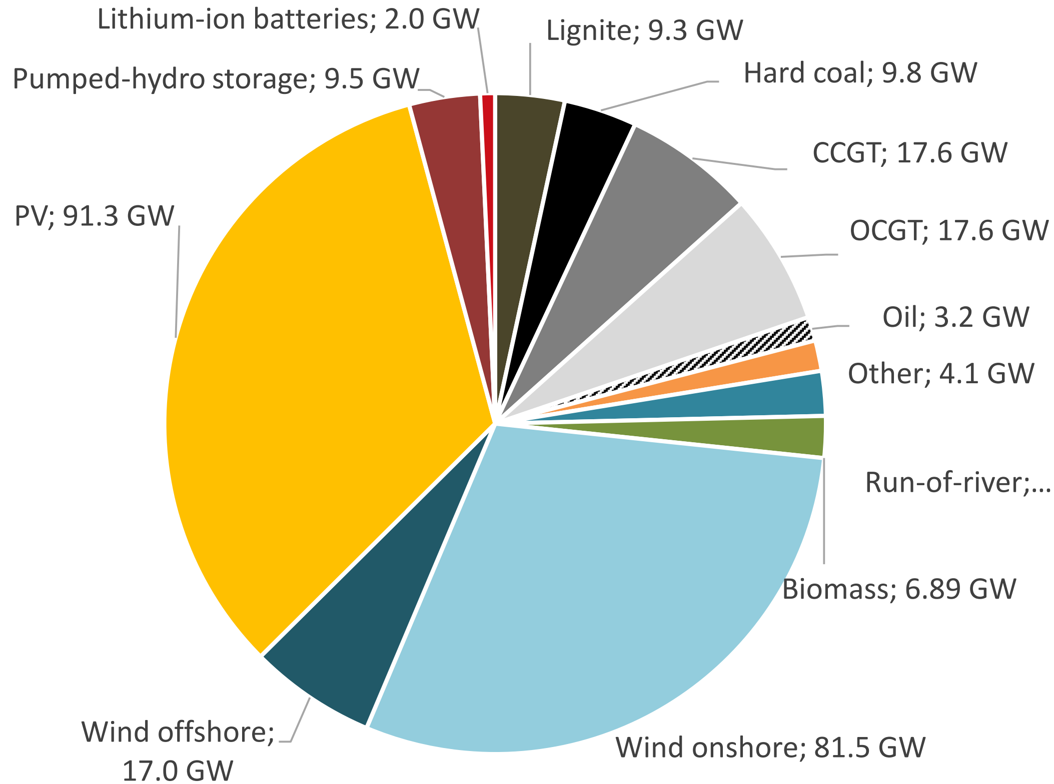


Filling Station
re-compression
storage
(GH2 @ 15 - 250 bar)
compression
storage
(GH2 @ 700 - 950 bar)
pre-cooling
GH2 @ 700 bar
storage
(LH2)
cryo-compression /
evaporation
storage
(GH2 @ 700 - 950 bar)
pre-cooling
GH2 @ 700 bar
storage
(LOHC)
dehydrogenation
compression
storage
(GH2 @ 700 - 950 bar)
pre-cooling
GH2 @ 700 bar
PEM - electrolysis
(decentralized)
GH2 @ 30 bar
compression
storage
(GH2 @ 700 - 950 bar)
pre-cooling
GH2 @ 700 bar
GH2
centralized
LH2
centralized
LOHC
centralized
GH2
decentralized

2 Data and scenarios

Electricity sector

- Brownfield scenario for 2030
- Capacities bounded by current grid development plan (NEP)
- Maximum investment into thermal plants, minimum investments into renewables and storage
- Time series provided by Open Power System Data & ENTSO-E
- Exogenous minimum renewables share of 65%, 70%, 75%, 80%



Hydrogen infrastructure

- Fully „greenfield“
- H_2 demand for mobility: 0, 5%, 10%, 25% of passenger road traffic in Germany (0, 9, 18, 45 TWh_{H2})
- General assumptions: each fuel station can only offer H_2 from one channel