Hydrogen infrastructure and production in Europe with and without imports

Professor Marie Münster, DTU Management
SustainED, CBS 08/09 2023

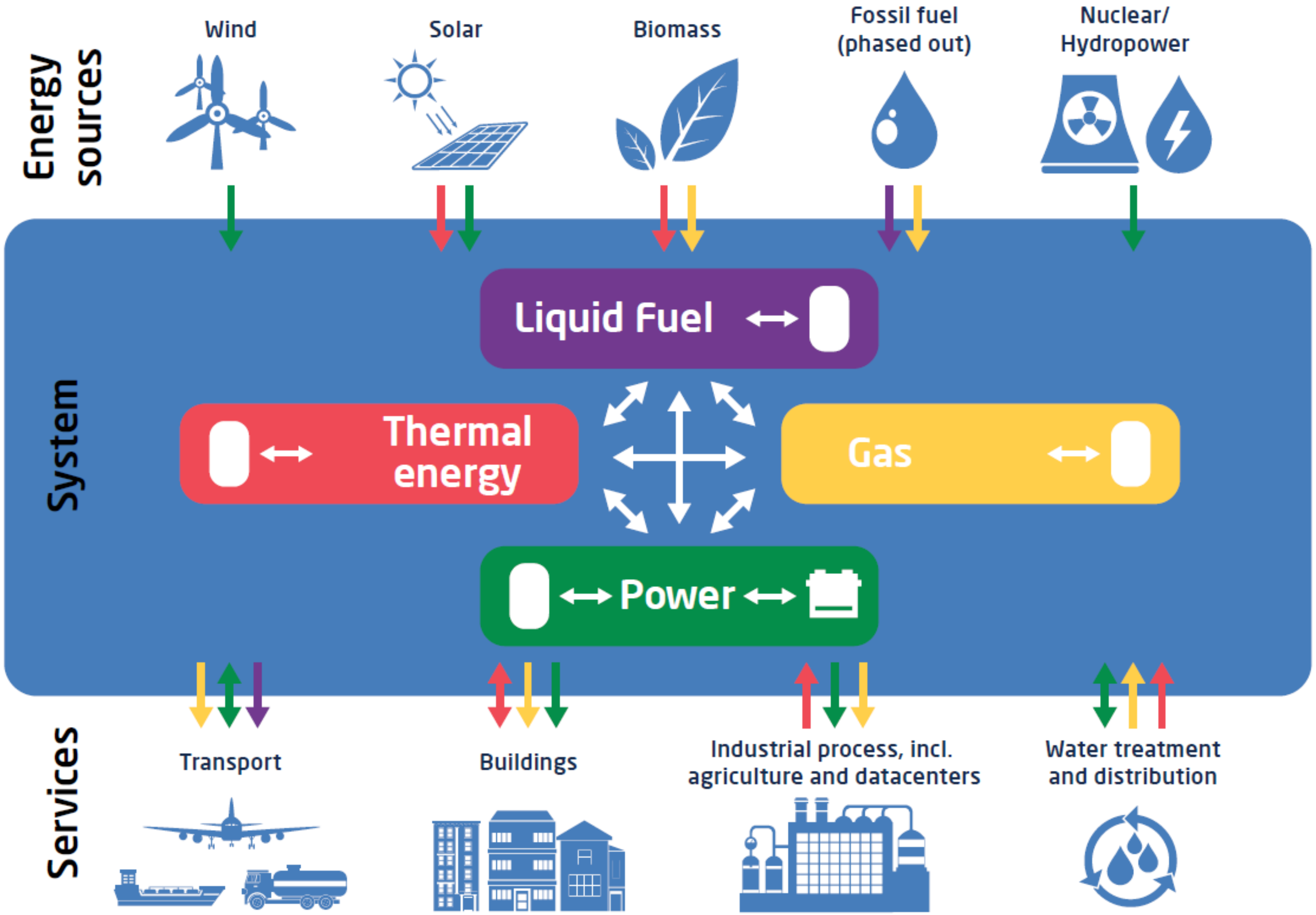
Smart energy systems and sector coupling

Power to other sectors

- First direct
- and then indirect electrification

Services to power sector

- Flexibility and storage



UK Summary of DTU Sector Development report about Smart Energy Systems. July 2020

Power-to-X and infrastructure
Projects + PhDs

SuperP2G - Modeling and analysis of P2G in EU (recent) (Balmorel and EnerHub2X)

- www.superp2g.eu

PtX Sector Coupling - including district heating (DK and EU) (Balmorel)

- https://missiongreenfuels.dk/ptx-sector-coupling-and-lca/

ENABLE - Norwegian green transition (Balmorel)

- https://orbit.dtu.dk/en/projects/enabling-the-green-transition-in-norway

BaltHub: Interconnecting the Baltic Sea countries via offshore energy hubs (Balmorel)

- https://www.nordicenergy.org/project/balthub/

PtX Infrastructure - Power, H2 and CO2 grids (DK and EU) (Balmorel)

- (Starting up)

Resilient energy systems (Balmorel)

- (Starting up)

PhDs: **Mathias Berg Rosendal, Ioannis Kountouris**

Green fuels for the Maritime sector
Projects + PhDs

MarEFuel - Electro-fuels for long range maritime sector and pathways (recent) (SEAMAPS and OptiPlant)

- https://orbit.dtu.dk/en/projects/electro-fuels-for-long-range-maritime-transport

Feasibility of PtX on Bornholm (OptiPlant)

- https://orbit.dtu.dk/en/projects/feasibility-study-for-power-to-x-production-on-bornholm

Nord_H2ub - Renewable Fuels - Infrastructure and Investment in the Nordics (Balmorel)

- www.csei.eu/nord_h2ub

PhDs: **Nicolas Campion, Sebastian Franz**

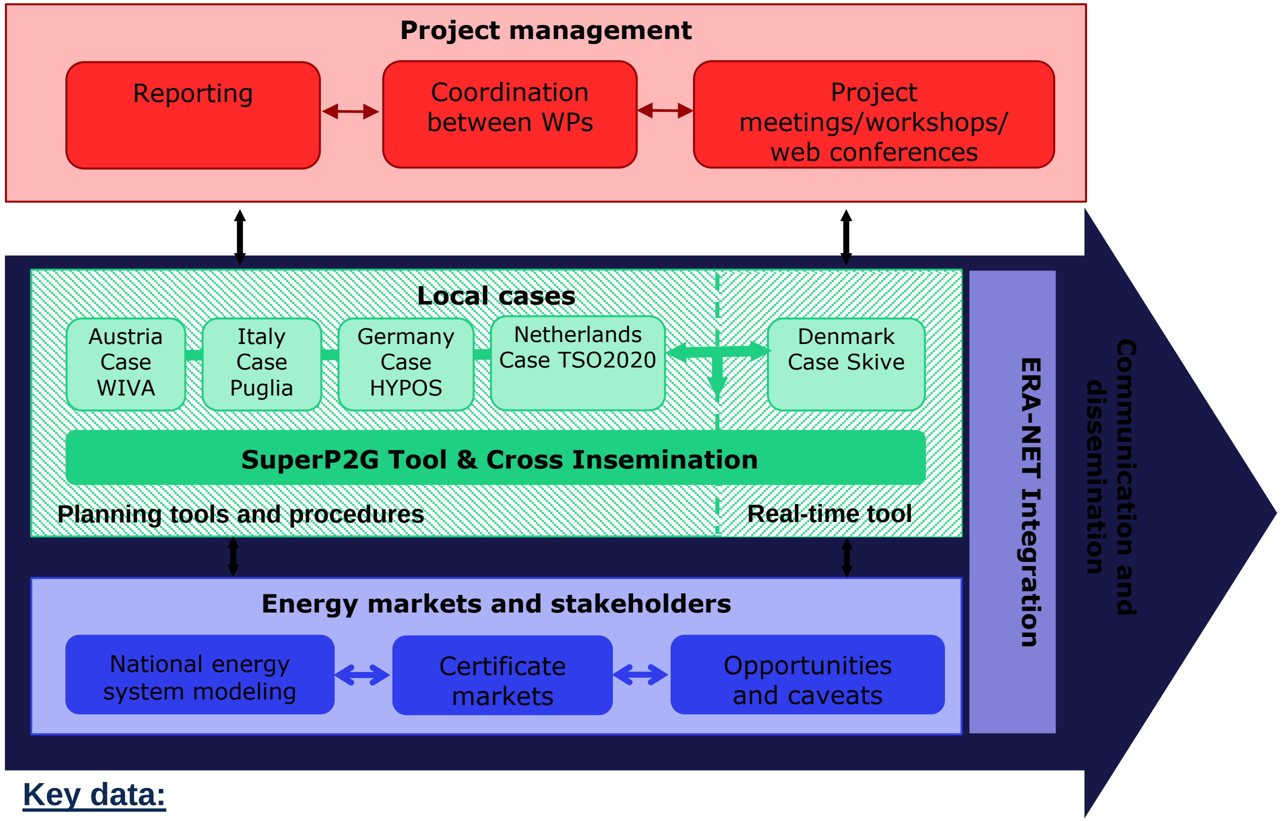
SuperP2G - Synergies Utilising renewable Power REgionally by means of Power-To-Gas

The Project at a glance

- SuperP2G interconnects leading P2G initiatives in five countries, ensuring joint learning.
- Each national project focuses on different challenges, where researchers team up with local need-owners to co-create solutions.
- SuperP2G focuses on improving existing evaluation tools including open access, as well as develop a new open tool.
- This is supplemented with analysis of regulation and markets, as well as stakeholder involvement.

www.superp2g.eu

https://superp2g.external.dbi-gruppe.de/



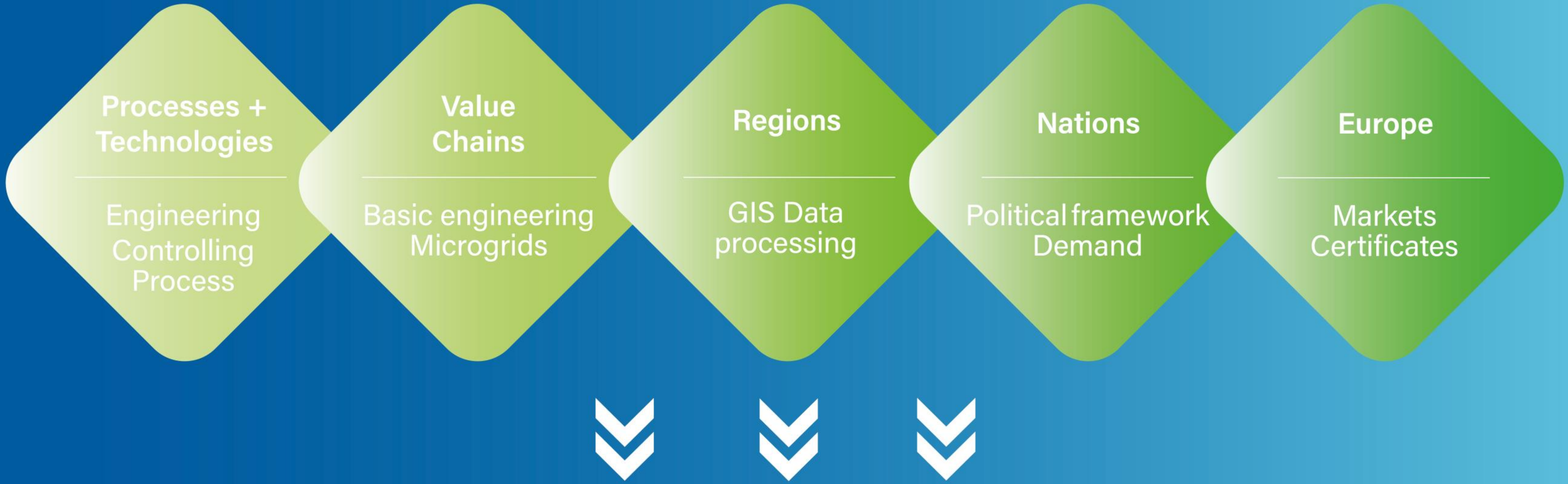
Key data:

- 01.11.2019 to 31.03.2023

Research partners:

- **Denmark:** DTU ME, DTU Elektro, GreenLab Skive
- **Austria:** JKU Linz
- **Germany:** DBI-GTI, DVGW-EBI
- **Italy:** CNR, Uni Bologna
- **Netherlands:** RUG-FEB
- **Europe:** ERIG

SUPER P2G



Establishing a common ground for Power-to-Gas calculations in Europe.

https://superp2g.external.dbi-gruppe.de/

Navigating the European Hydrogen Economy and Infrastructure: Green Hydrogen, Blue Hydrogen, or Imports?

Authors: Ioannis Kountouris*, Rasmus Bramstoft, Theis Madsen, Juan Gea-Bermúdez, Marie Münster, Dogan Keles

Agenda

1 | Motivation

2 | Methodology and Modelling

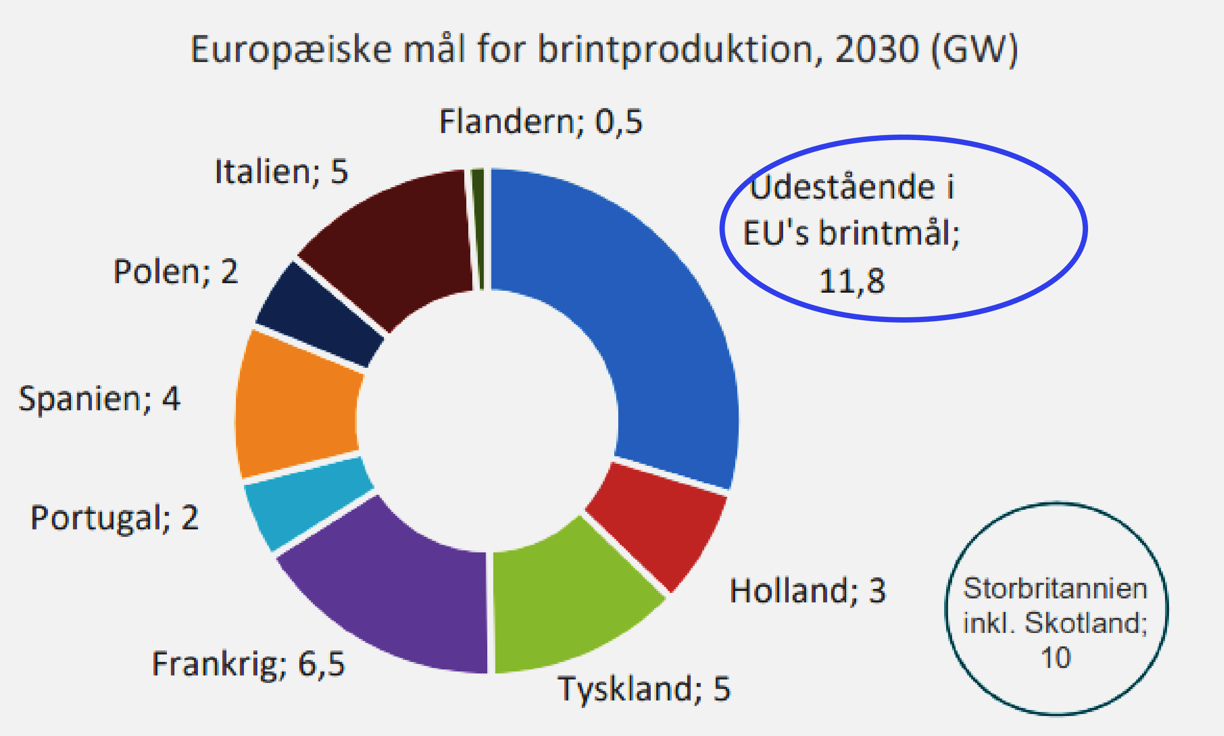
3 | Data - Scenarios

4 | Results

5 | Conclusions

Background:

Fit 55 package, by 2030 *40GW*, December 2021



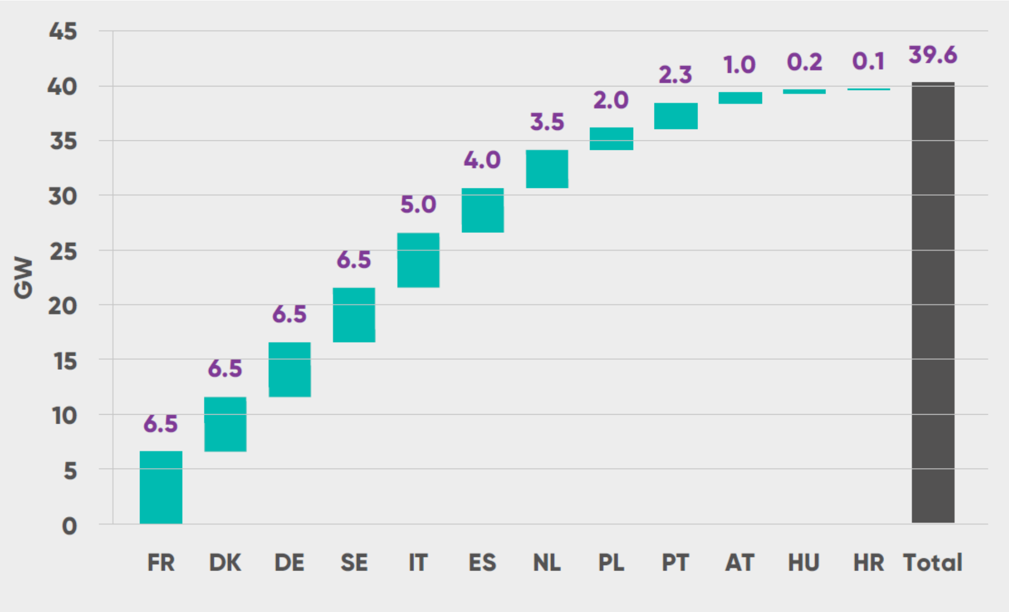
Source: Regeringens Strategi for POWER-TO-X, 2021

REPowerEU by 2030, March 2022

- **10 Mt** of annual domestic production and
- **10 Mt** of imports of renewable hydrogen
- Requires ***64 GW*** EU Electrolysis installed capacity

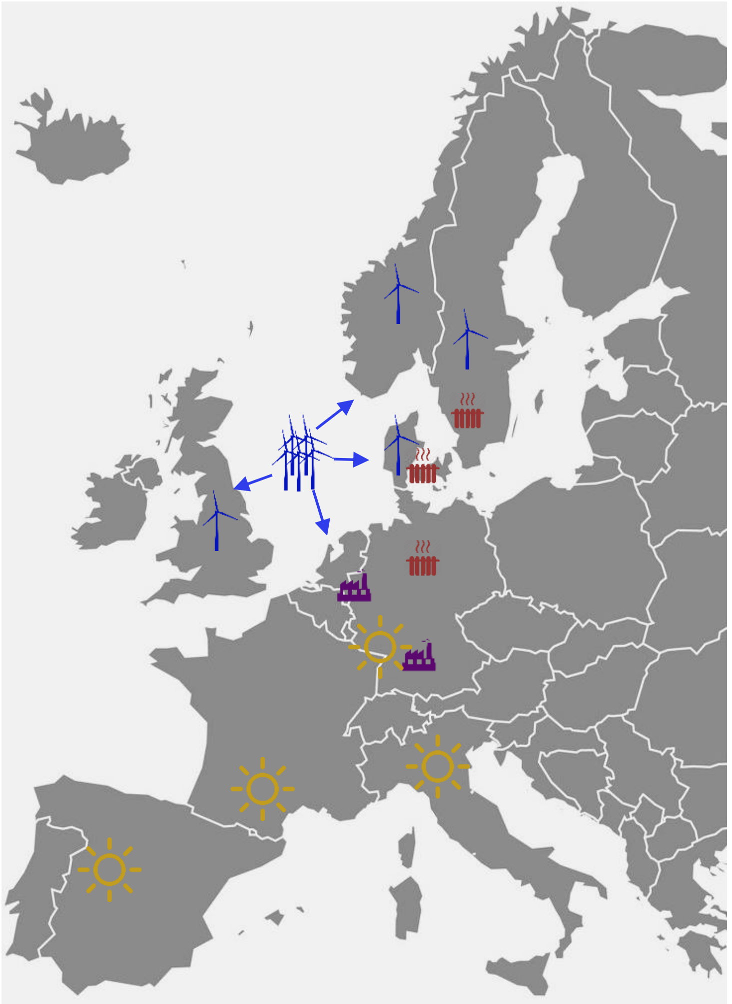
More and more ambitious targets!

Committed electrolyser capacity from EU national strategies by 2030 in the EU



Source: Clean Hydrogen monitor, 2022

Main investigation: Where/When to produce hydrogen in the future?



North European countries

- Large potentials for offshore wind
- District heating
- Cheap onshore wind

Central and south European countries

- Cheap solar PV
- Close to North Africa – Possible imports of H2
- Repurpose and new

Hydrogen infrastructure in the future?

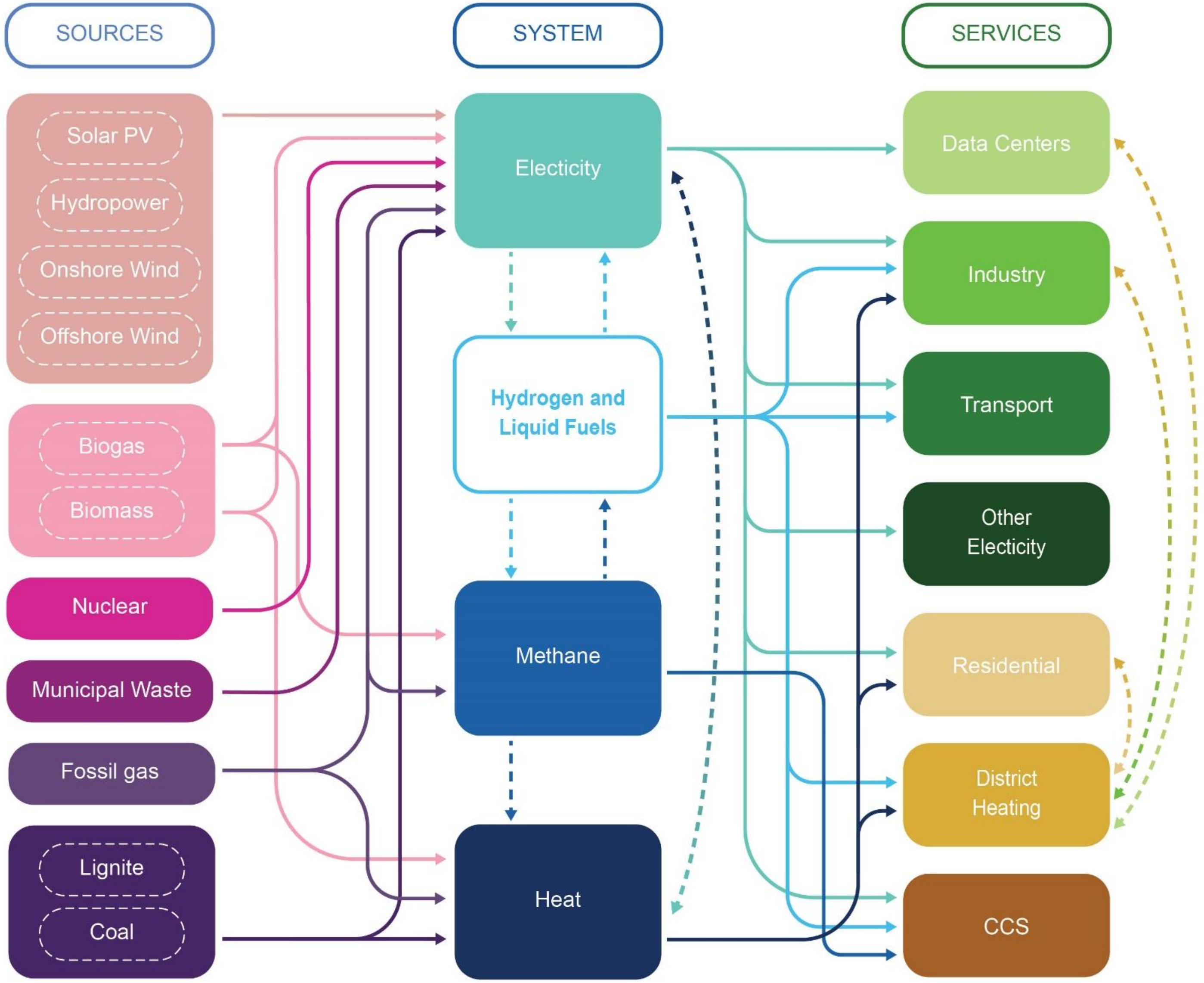
Competition with green blue hydrogen and imports?.

Sector coupled energy systems analysis - Balmorel

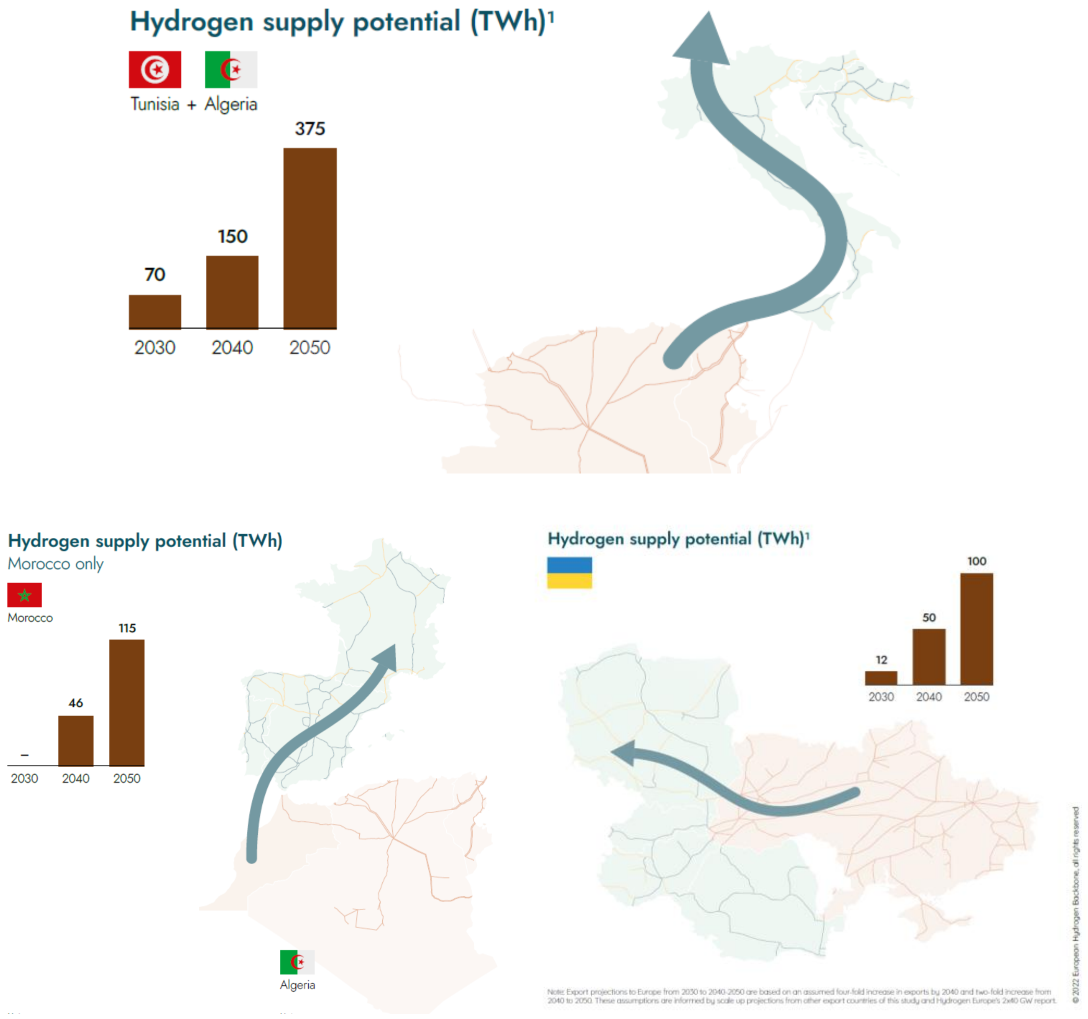
Open source (GAMS based)

Balmorel stands for: Baltic Model of Regional Electricity Liberalisation (2001).

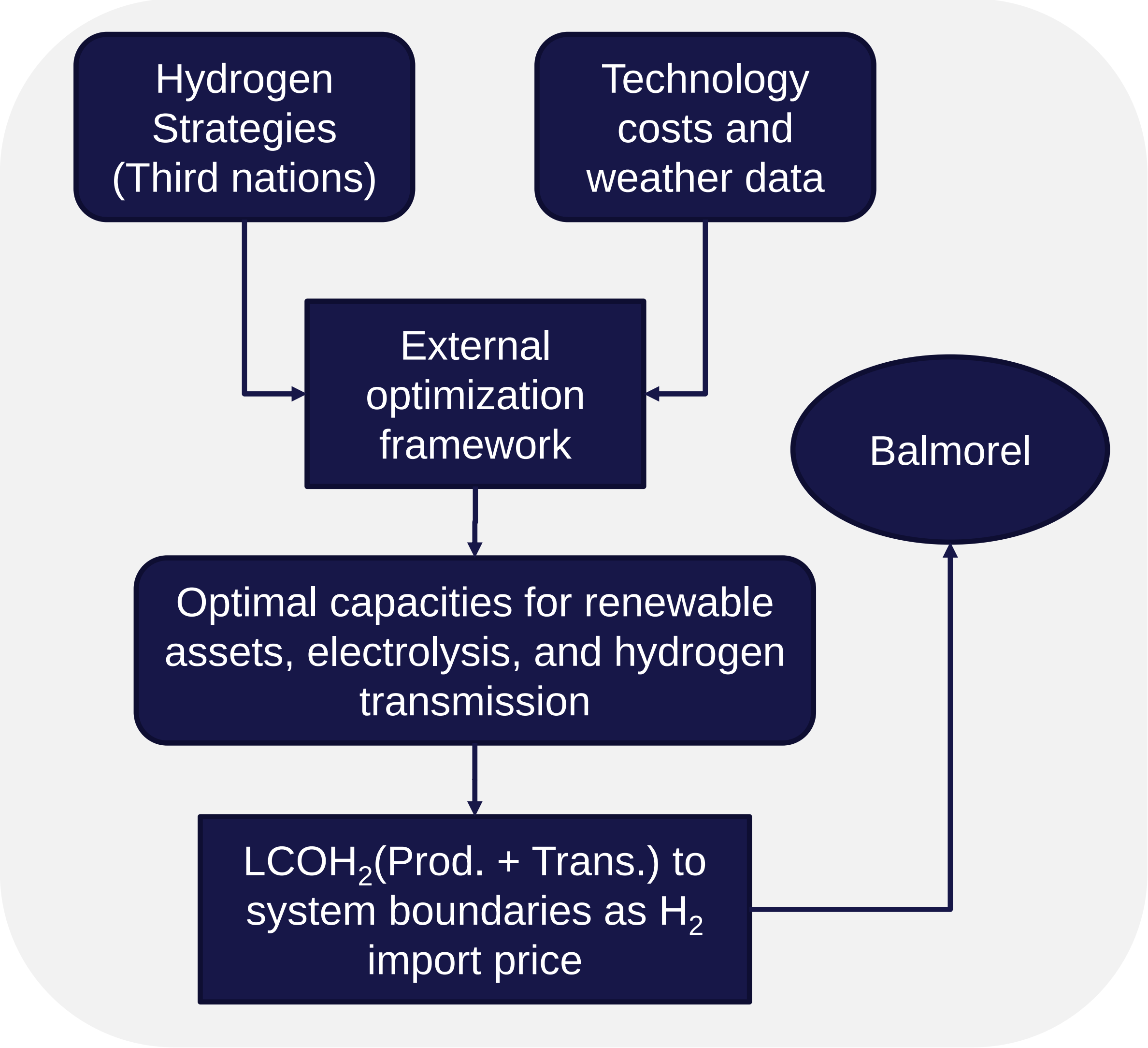
Partial Equilibrium model, Objective Function: Min cost of operations and investments.



Hydrogen production import - modeling

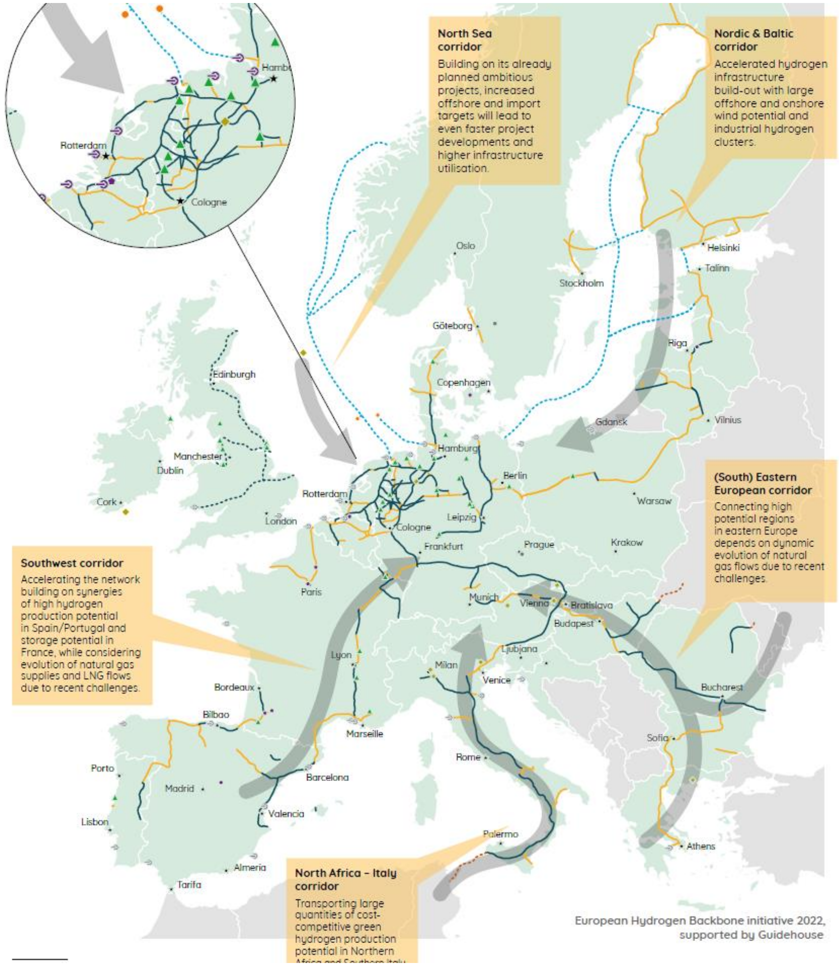


Source: Five hydrogen supply corridors for Europe in 2030, EHB, May 2022



DATA: European Hydrogen BackBone (EHB) – 28 Gas TSOs

5 main corridors

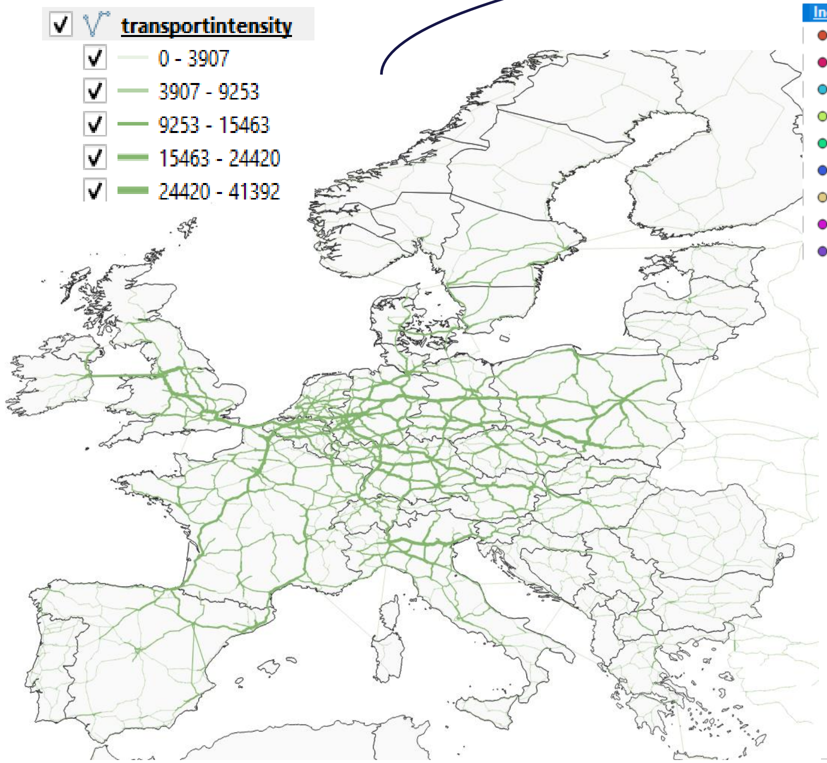


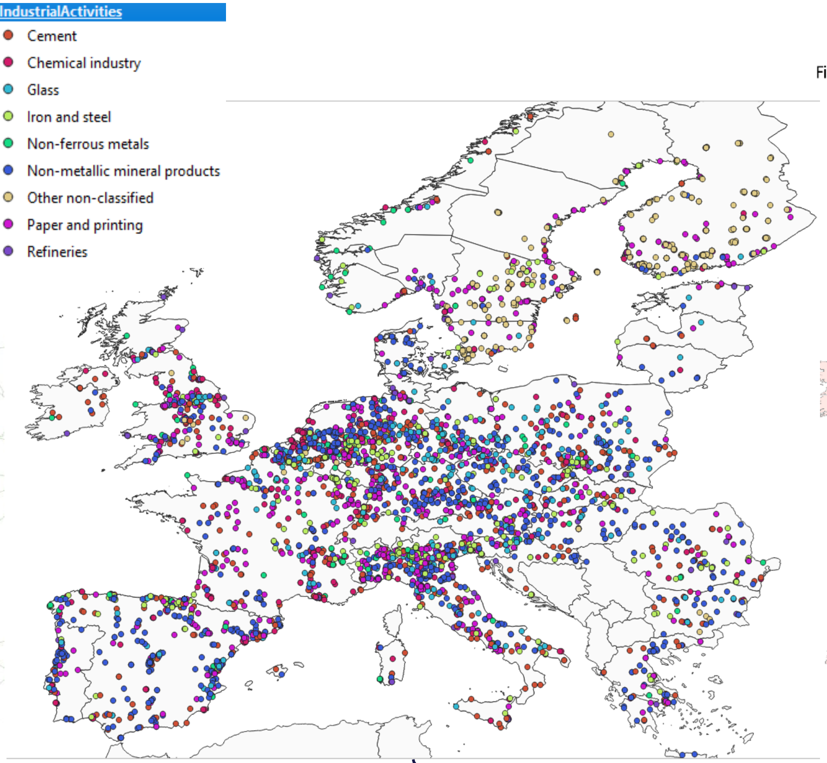
Source: A European Hydrogen infrastructure vision covering 28 countries, April 2022

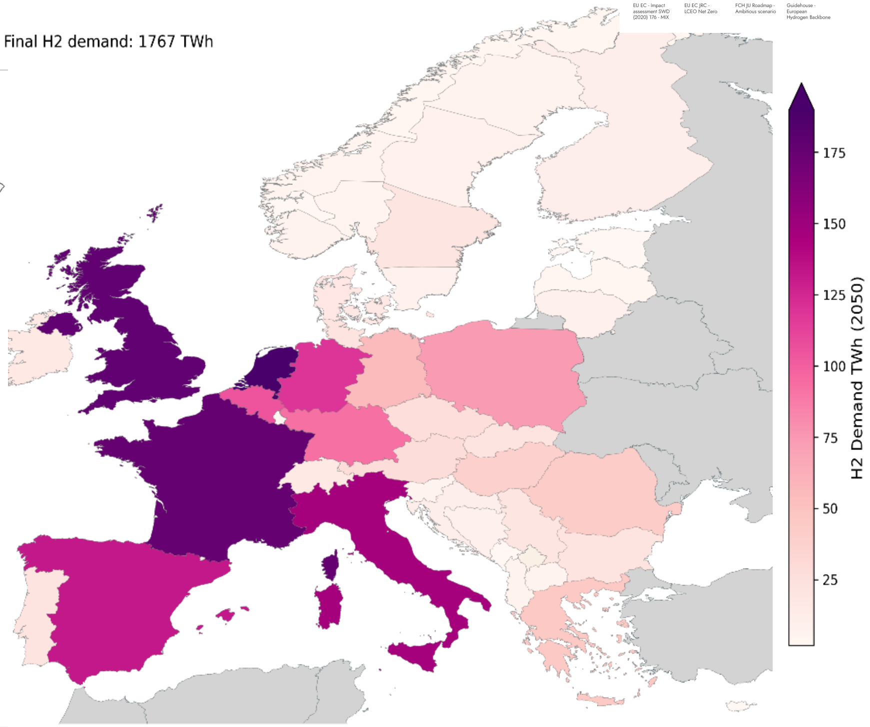
2050 allocation

Source: Analysing future demand, supply, and transport of hydrogen, June 2021

DATA: H2 demand, applying geospatial tools (QGIS) (2050)



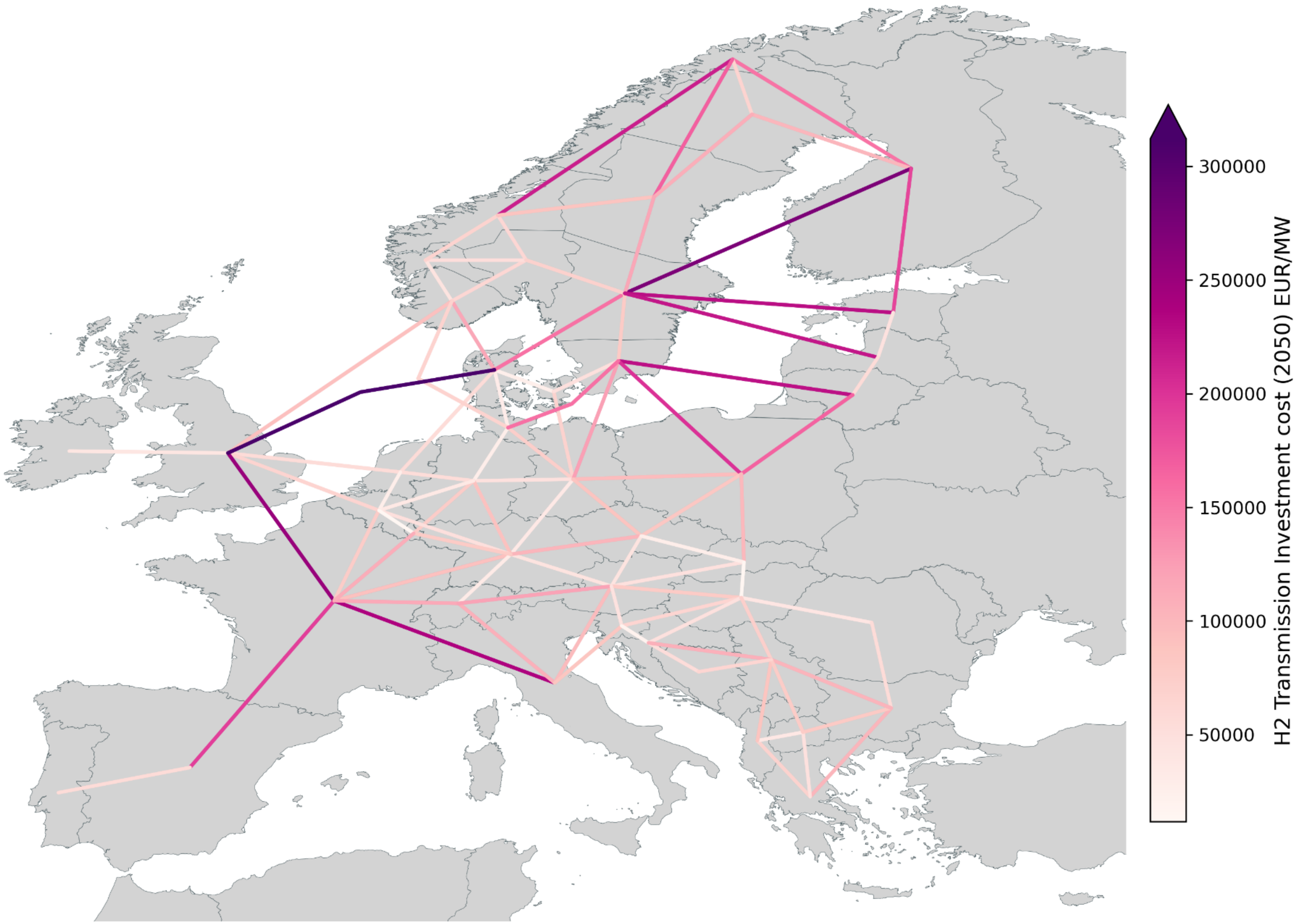




Speth et al. (2022)

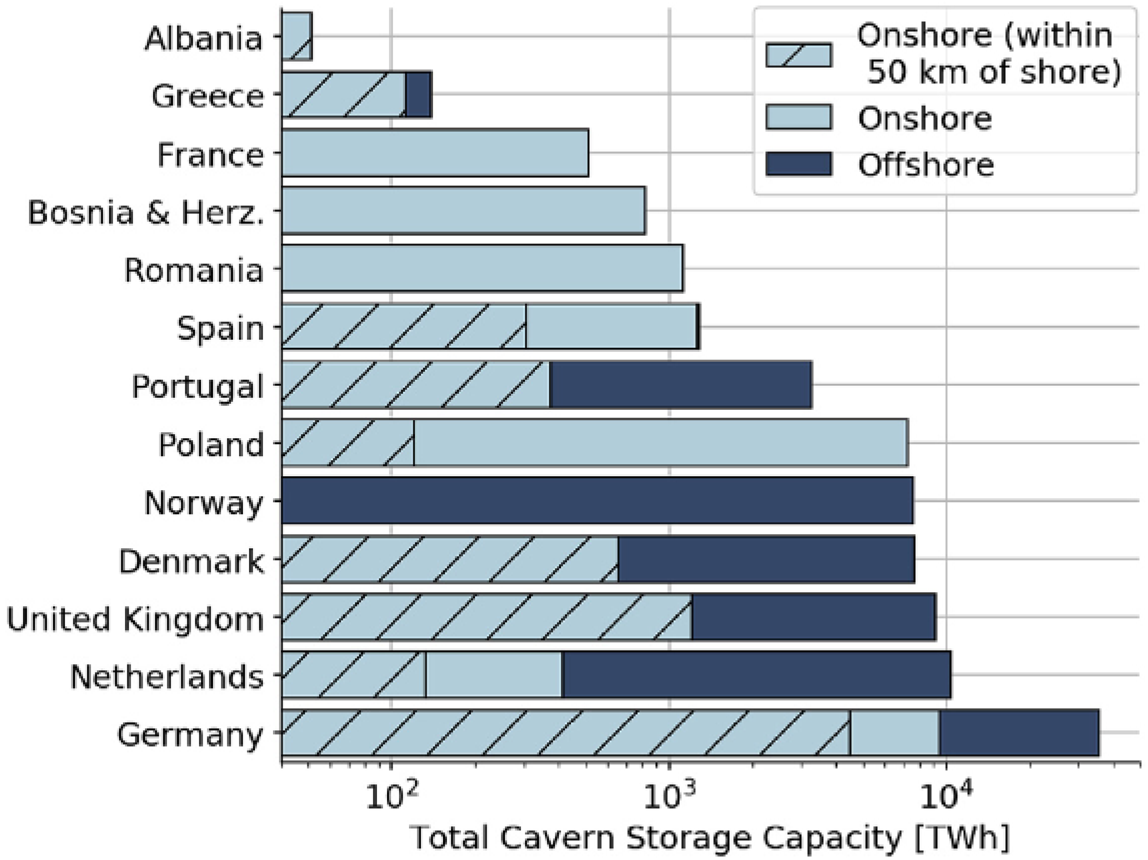
Pia Manz et al. (2018)

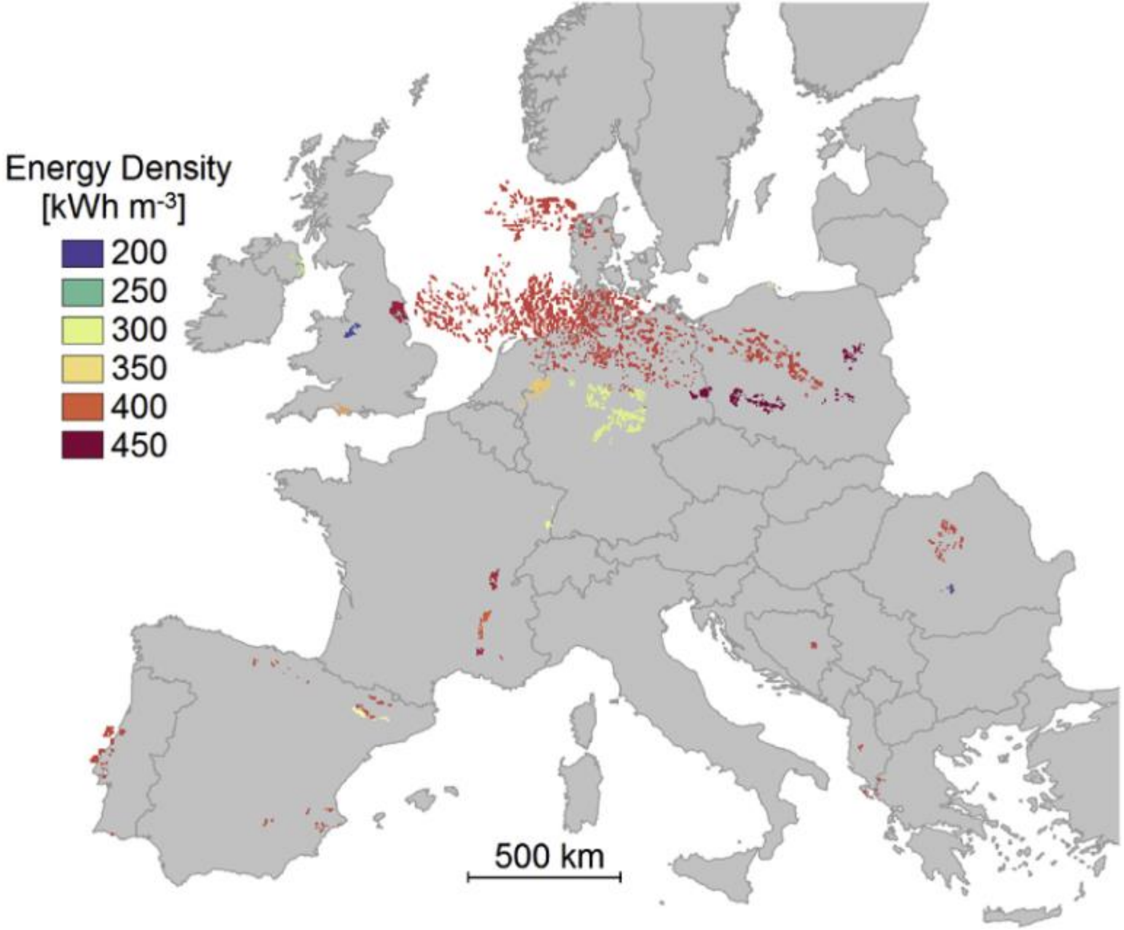
DATA: Hydrogen backbone report into Balmorel (2050)



- Costs for hydrogen transmission grids vary from 50,000 €/MW to 300,000 €/MW
- Depends on the length, status (off- or onshore), new or repurposed

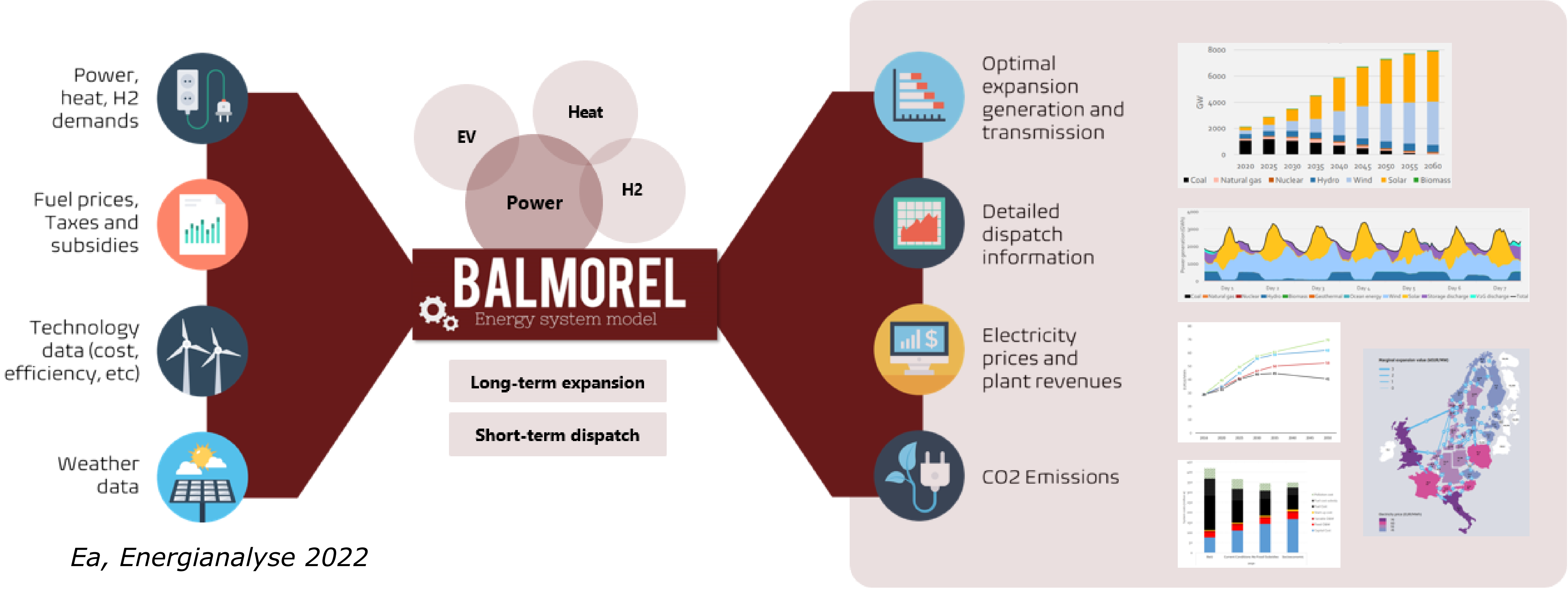
Caverns – spatial allocation and potential





Caglayan et al. (2020)

Sector coupled energy systems analysis - Balmorel



Ea, Energianalyse 2022

Open source (GAMS based) * DTU course in June * www.balmorel.com

Scenarios

Hydrogen Europe (H2E)

H_2 production pathways:

Green H2 Europe (GH2E)

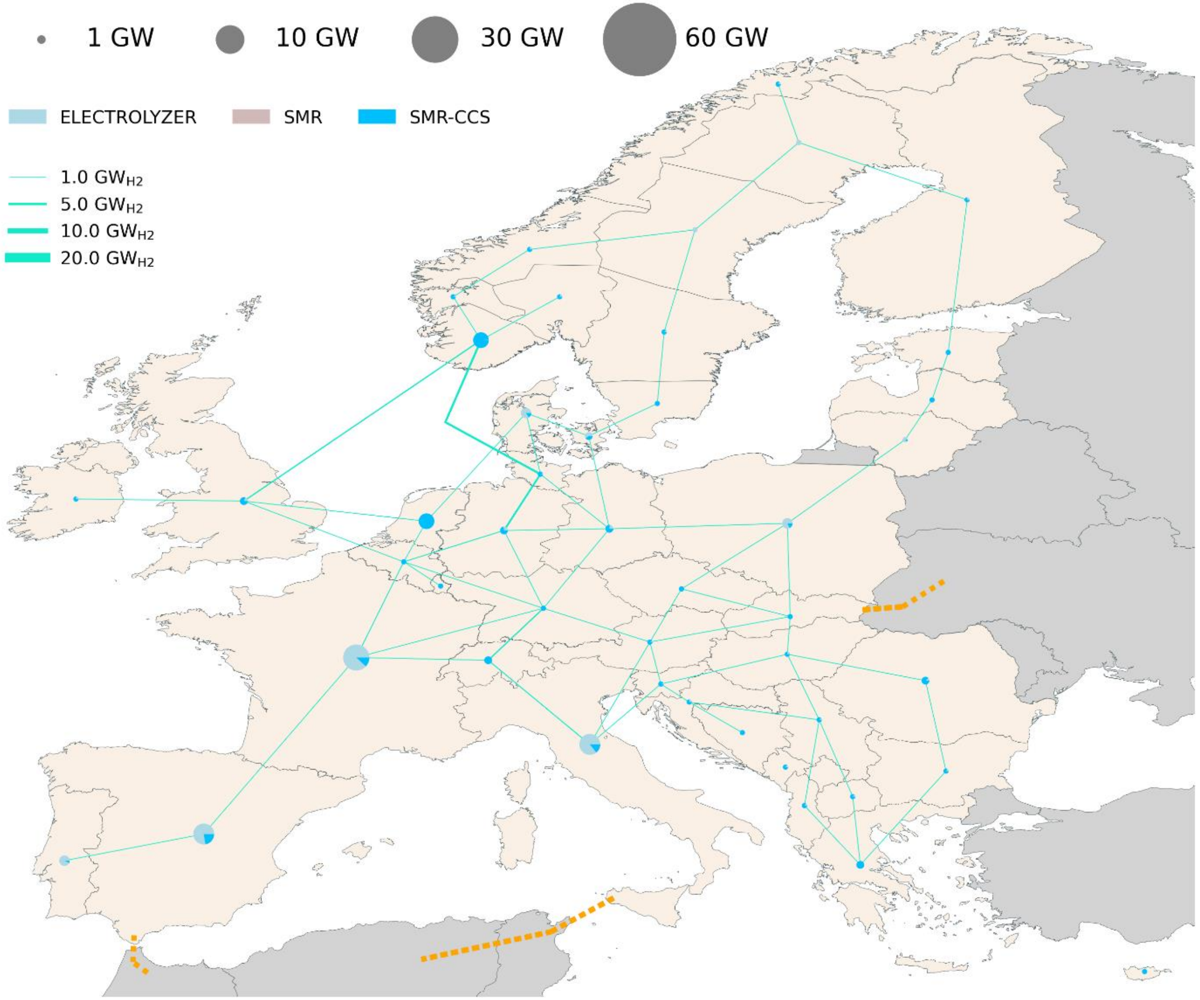
H_2 production pathways:

Self Sufficient Green H2 Europe (SSGH2E)

H_2 production pathways:

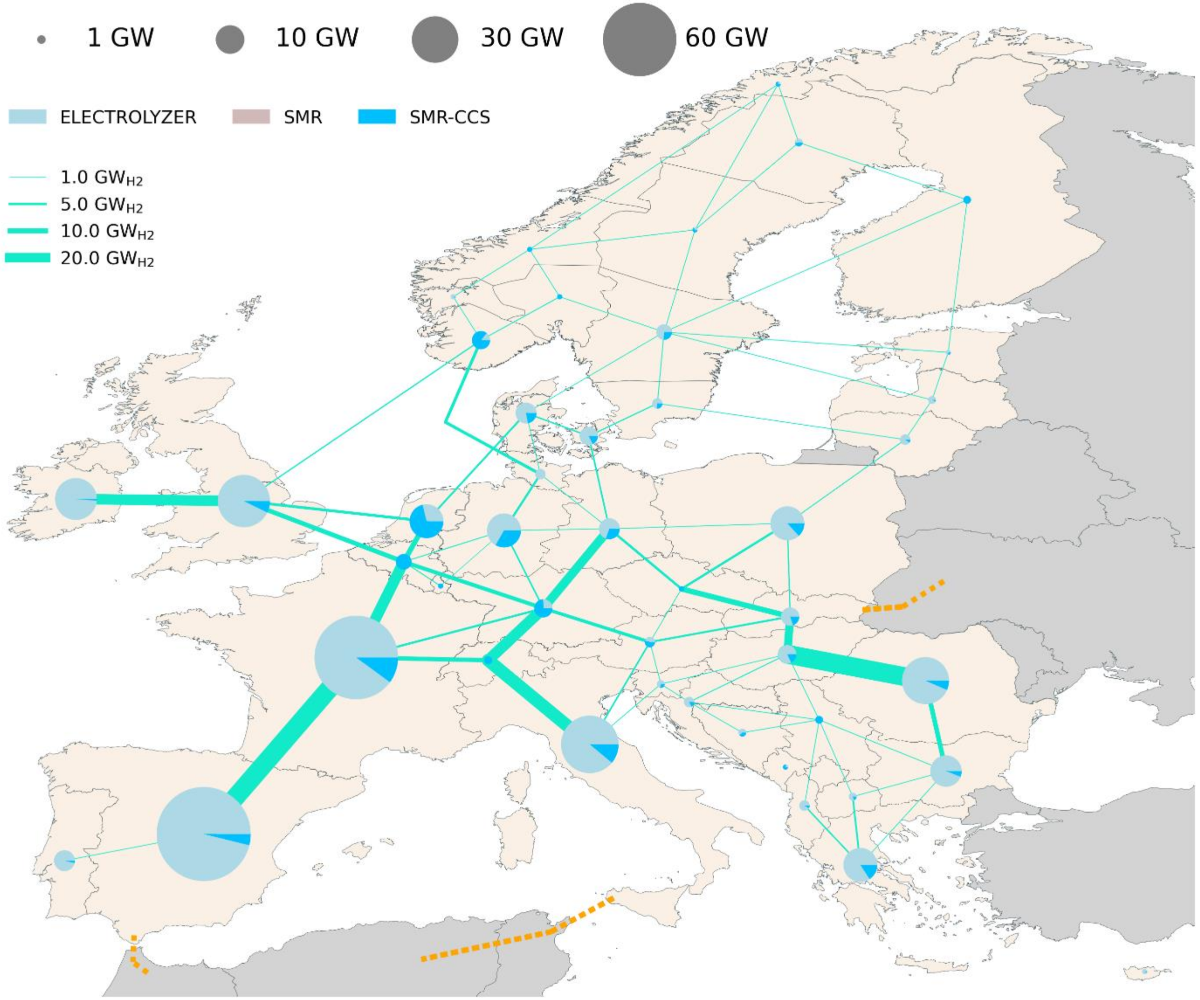
Results

Results: BASE - Where, when and how to produce H2?



2030

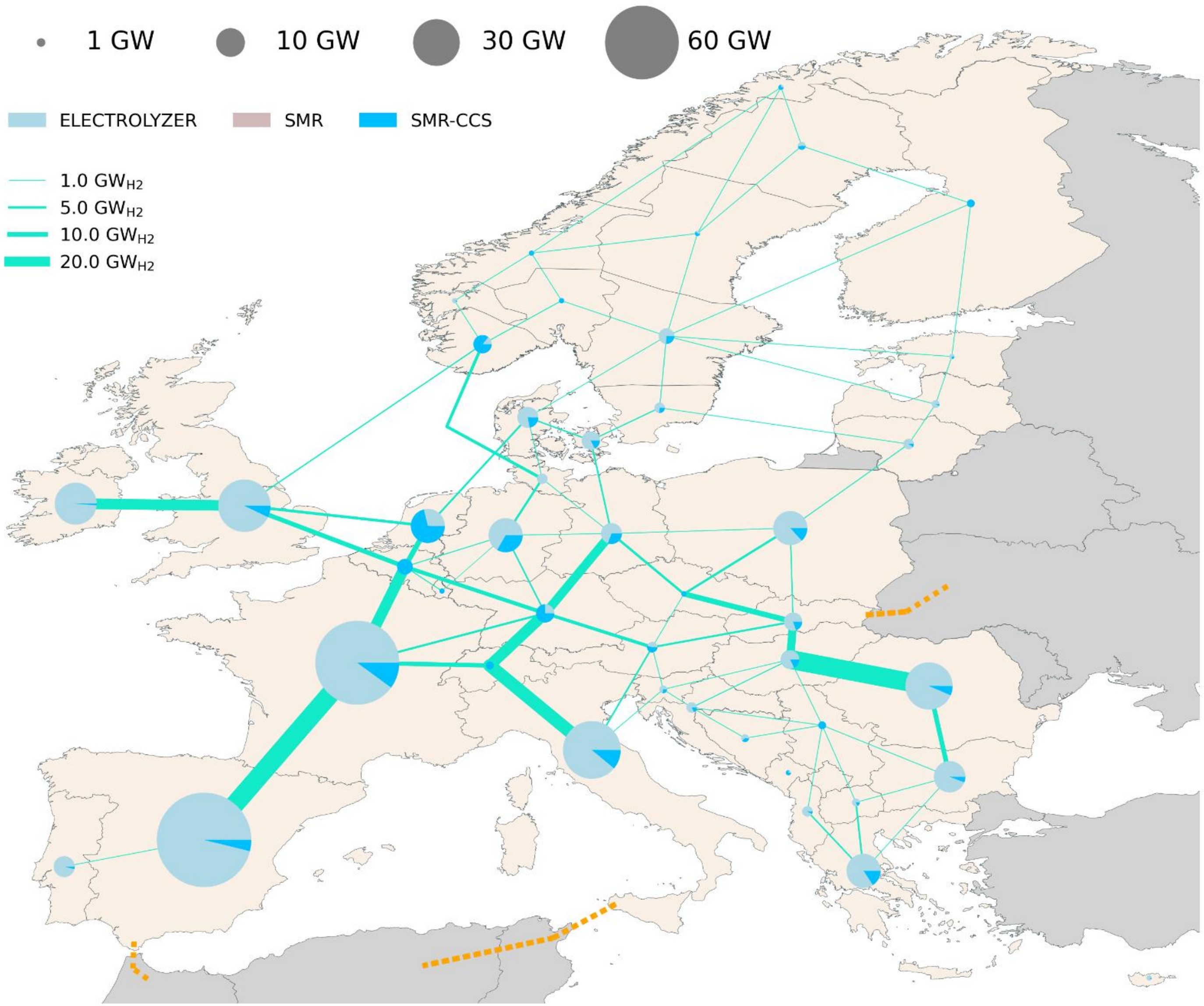
H2 Demand: 332 TWh



2050

1768 TWh

Hydrogen Imports from 3rd nations



Scenario: Base

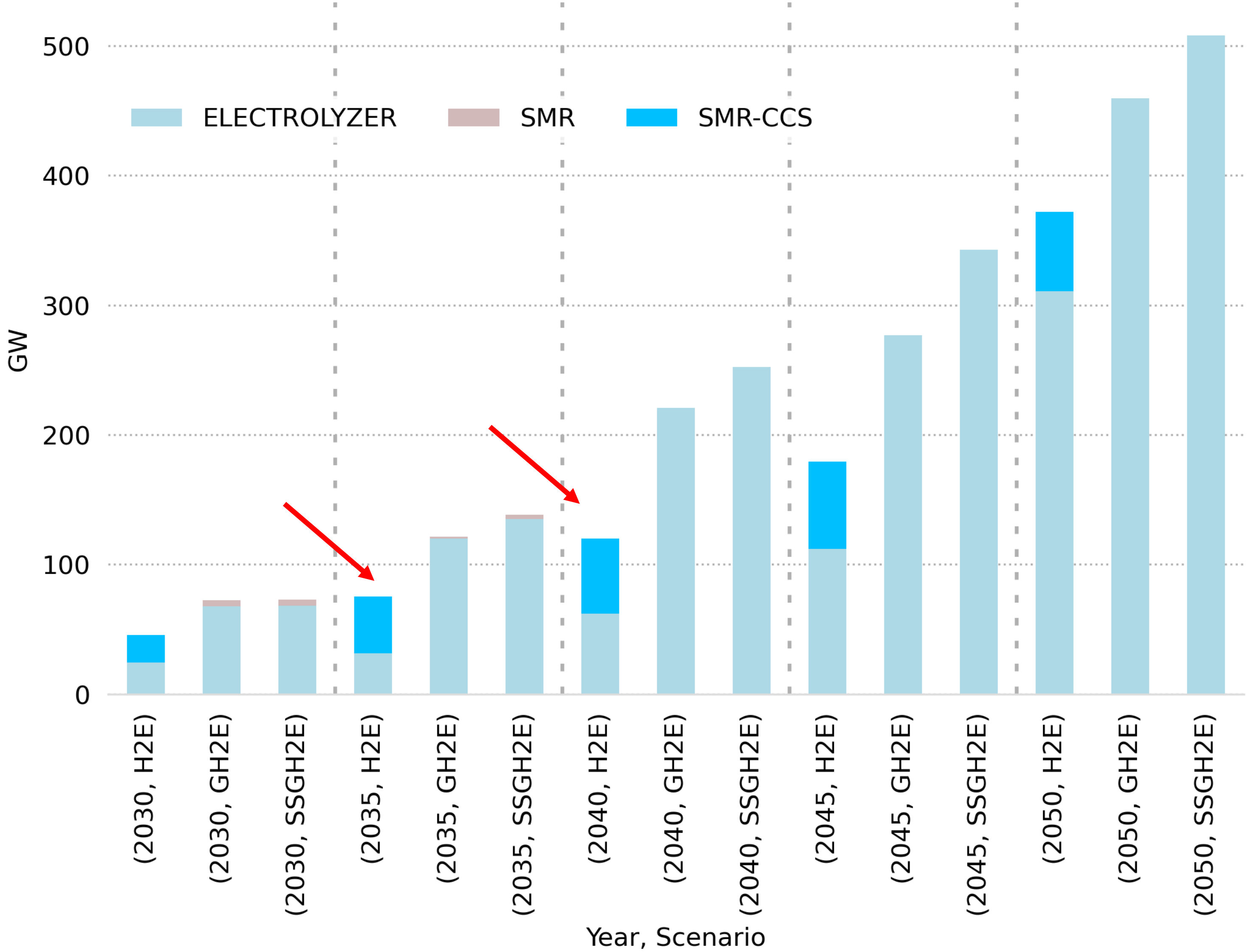
Hydrogen Capacities (2050)

- Electrolysis capacity: 305GW_{h2}
- SMR-CSS capacity: 61 GW_{h2}

Importing H_2 from 3rd nations (2050)

- Marroco: 42/115 (TWh)
- Tunisia: 61/375 (TWh)
- Ukraine: 23/100 (TWh)

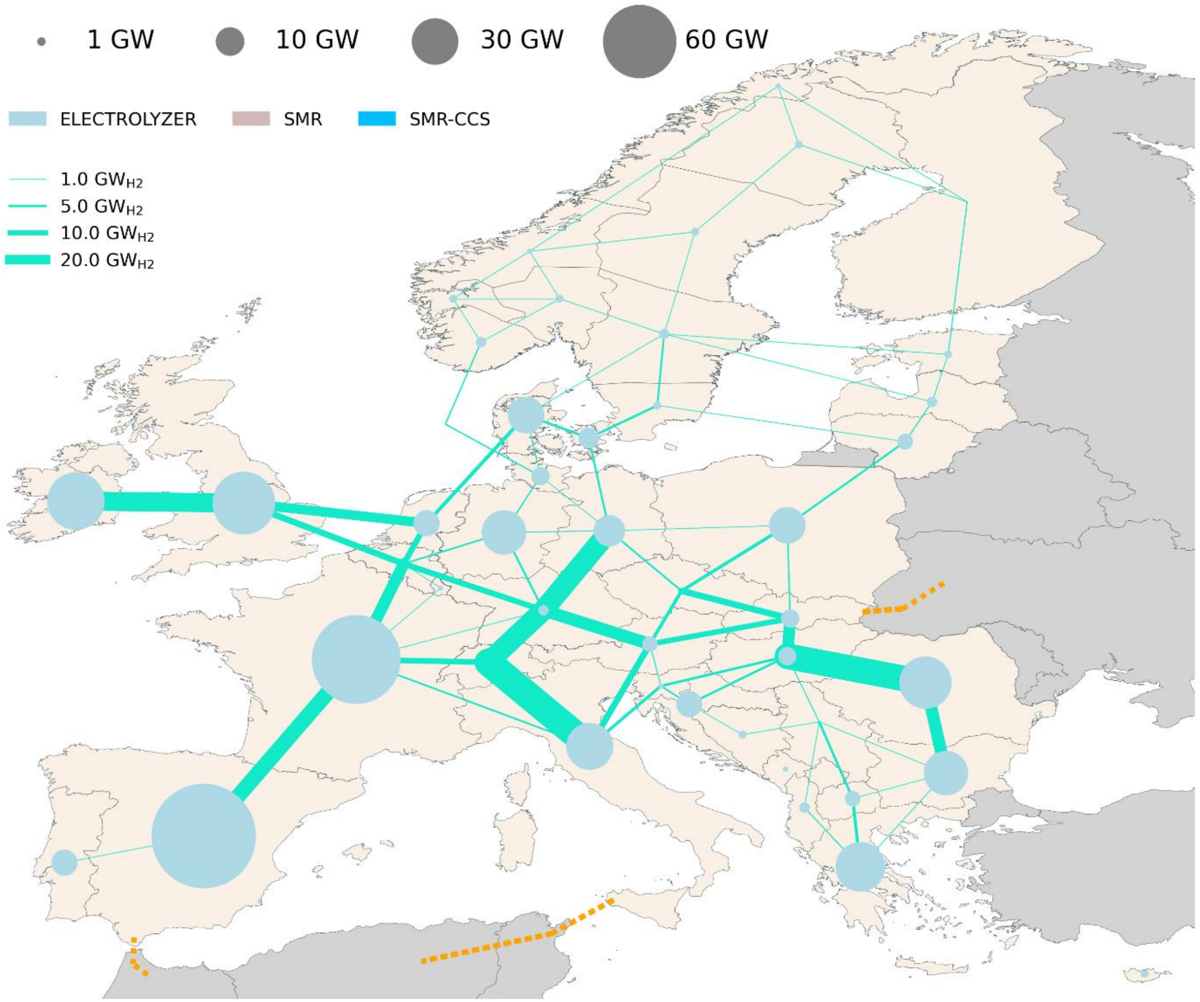
Blue Hydrogen: A possible lock in effect!



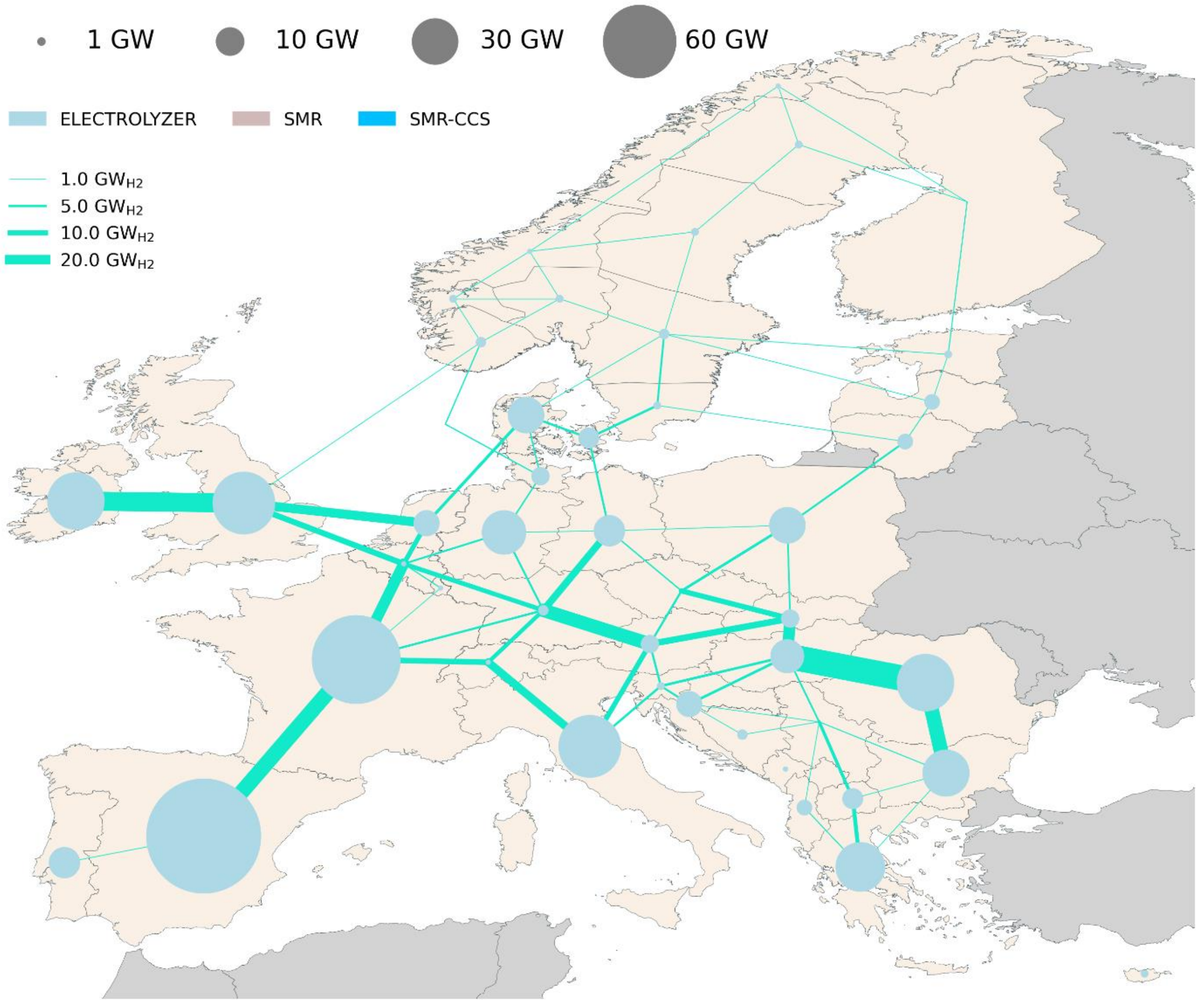
What could be the effect if not importing ? (2050)

From 450 GW to 505 GW Electrolysis

Scenario: Green H2 Europe

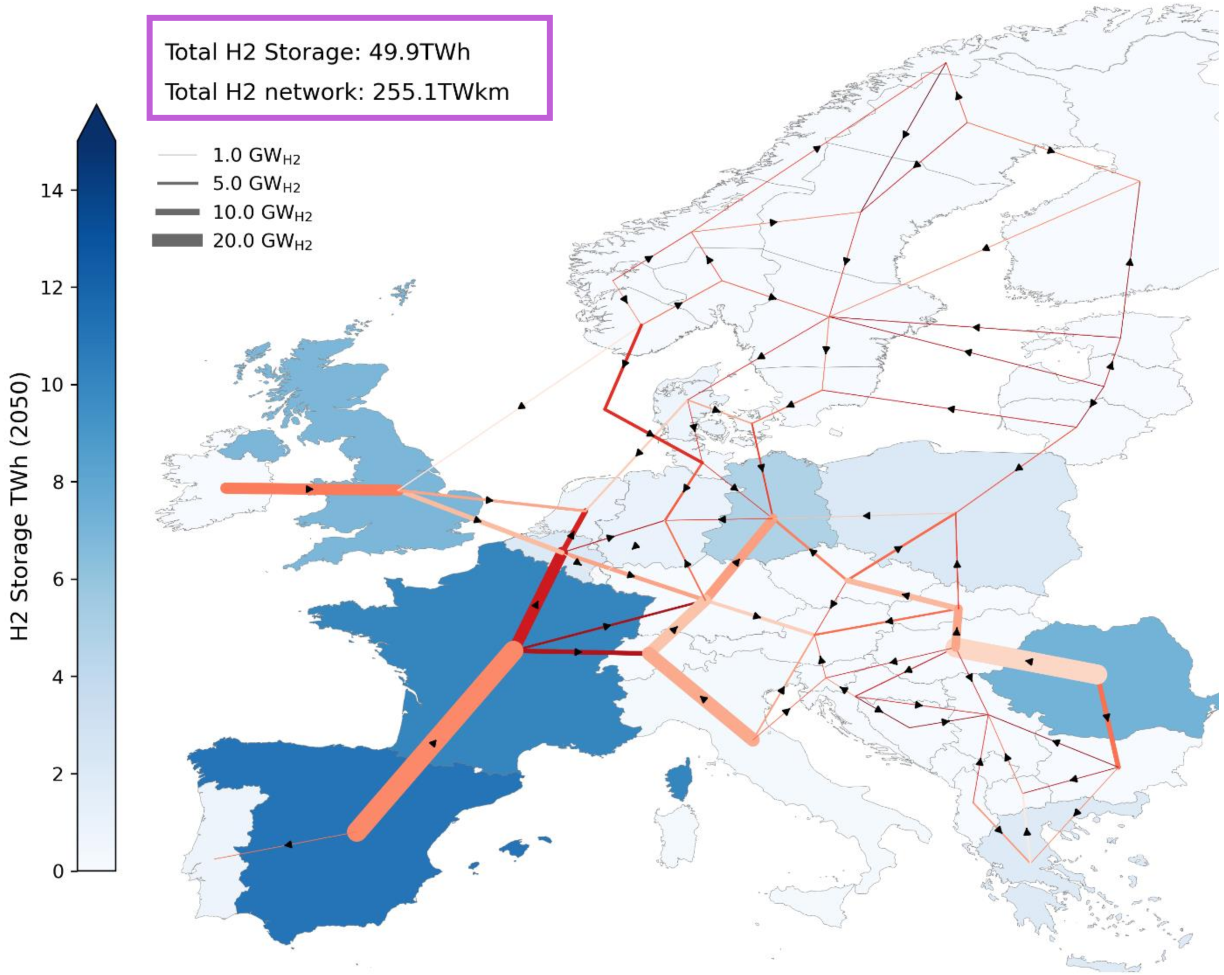


Scenario: Self-sufficient EU

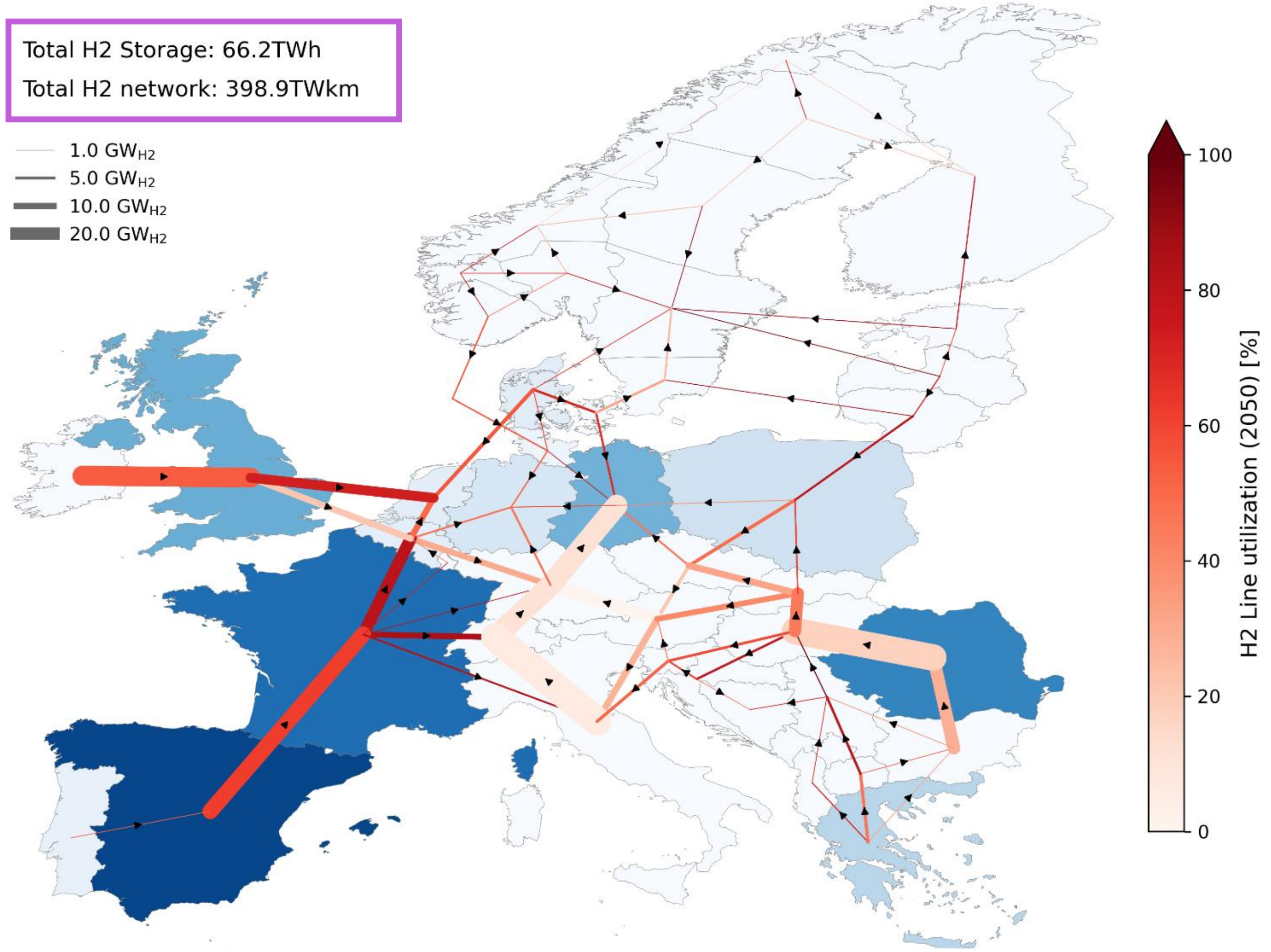


Blue Hydrogen and the role of Hydrogen Infrastructure (2050)

Scenario: BASE

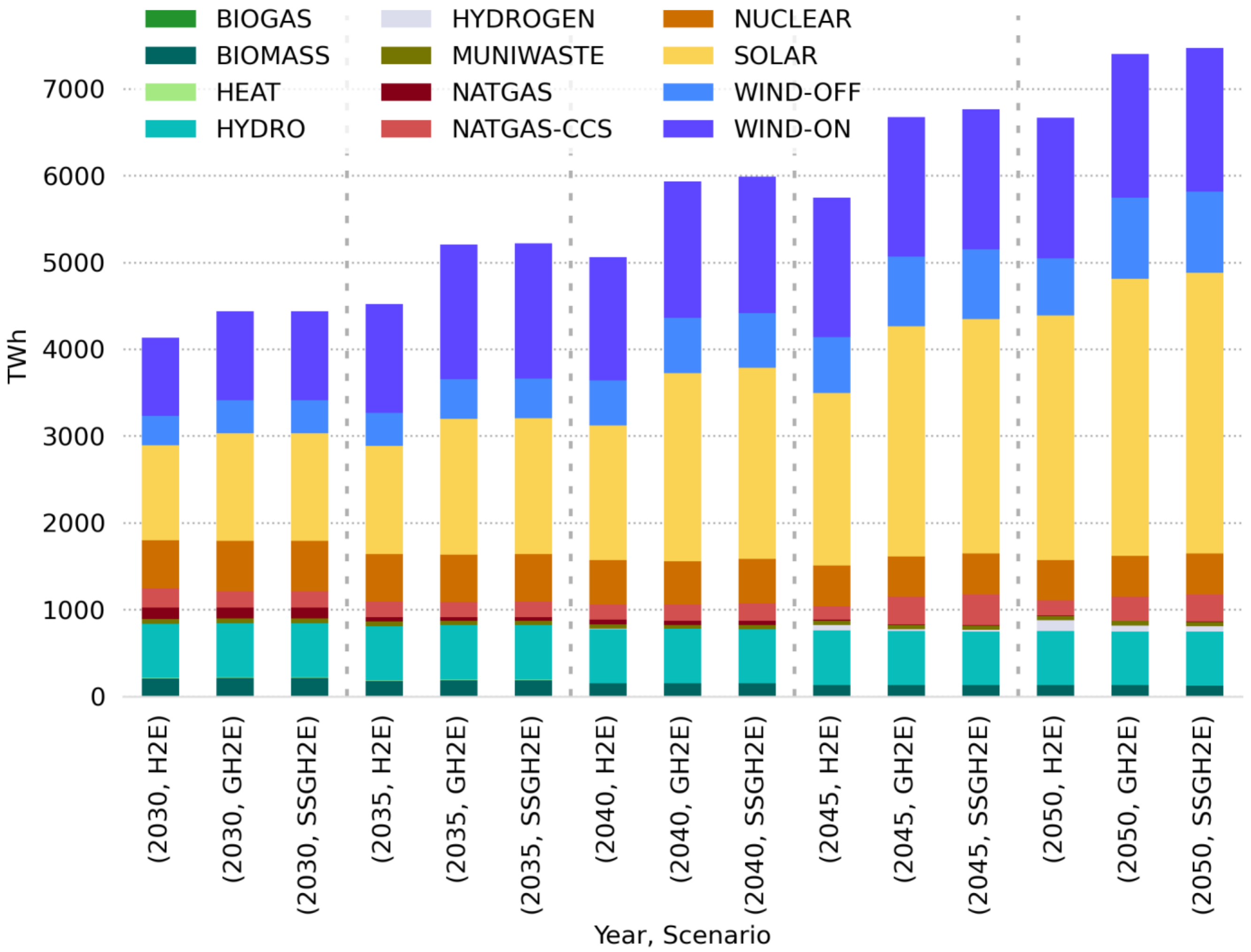


Scenario: Green H2 Europe

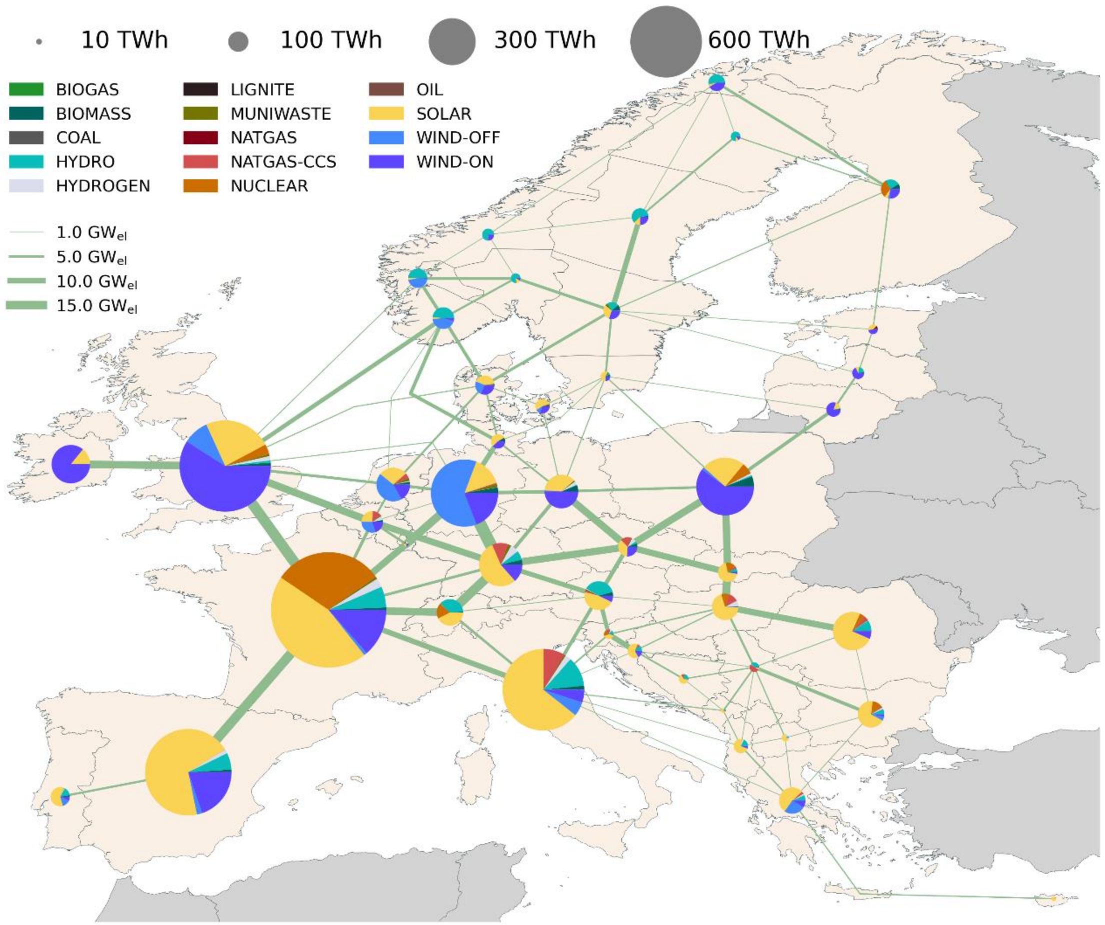


Blue Hydrogen and the effects in the electricity mix (2050)

Approximately additional **800 TWh** of electricity demand



Scenario: BASE



System costs (2050)

System cost difference to BASE 2050:

GH2E	2.77 % ~ 9.4 bil. €/year
SSGH2E	3.86% ~ 13.2 bil. €/year

Conclusions

- Hydrogen production is located in the periphery (mainly the South) to supply West/ Central Europe.
- Lock-in effect of blue hydrogen by 2035, implying a long-term dependence on natural gas.
- Some hydrogen imports to Europe via pipelines from third nations.
- A green hydrogen European economy would require a rapid infrastructure scale-up and additional renewable investments.
- Europe can become self-sufficient and utilize green hydrogen by 2050 at relatively small additional system costs

SuperP2G Conclusions

The competition between electrolytic and blue H_2 in Europe is impacted by a range of parameters:

- Hydrogen demand levels (very uncertain)
- Electricity prices and availability of low-cost green electricity potentials
- Electrolyser flexibility and costs
- Natural gas prices and CO_2 quota prices
- Hydrogen import availability and prices (EU goals in line with no import)
- Availability of H_2 grids
- Storage provides flexibility (intra day and seasonal) integration of PV and less need for grids

Recent related articles

A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production
Kountouris, I., Bramstoft, R., Madsen, T., Bermudez, JG., Münster, M. & Keles, D., 2023 (preprint), In: Research Square

Data-driven scheme for optimal day-ahead operation of a wind/hydrogen system under multiple uncertainties
Zheng, Y., Wang, J., You, S., Li, X., Bindner, H. W. & Münster, M., 2023, In: Applied Energy. 329, 12 p., 120201.

Power-to-X in energy hubs: A Danish case study of renewable fuel production
Kountouris, I., Langer, L., Bramstoft, R., Münster, M. & Keles, D., 2023, (Accepted/In press) In: Energy Policy.

Techno-economic assessment of green ammonia production with different wind and solar potentials
Campion, N., Nami, H., Swisher, P. R., Hendriksen, P. V. & Münster, M., 2023, In: Renewable and Sustainable Energy Reviews. 173, 22 p., 113057.

Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050
Swisher, P., Murcia Leon, J. P., Gea-Bermúdez, J., Koivisto, M., Madsen, H. A. & Münster, M., 2022, In: Applied Energy. 304, 14 p., 118043.

Data-driven robust optimization for optimal scheduling of power to methanol
Zheng, Y., You, S., Li, X., Bindner, H. W. & Münster, M., 2022, In: Energy Conversion and Management. 256, 14 p., 115338.

Incorporating optimal operation strategies into investment planning for wind/electrolyser system
Zheng, Y., You, S., Bindner, H. W. & Münster, M., 2022, In: CSEE Journal of Power and Energy Systems. 8, 2, p. 347-359

Optimal day-ahead dispatch of an alkaline electrolyser system concerning thermal–electric properties and state-transitional dynamics
Zheng, Y., You, S., Bindner, H. W. & Münster, M., 2022, In: Applied Energy. 307, 13 p., 118091.

Requirements for a maritime transition in line with the Paris Agreement
Franz, S., Campion, N., Shapiro-Bengtsen, S., Bramstoft, R., Keles, D. & Münster, M., 2022, In: iScience. 25, 12, 14 p., 105630.

Less recent related articles

Should Residual Biomass be used for Fuels, Power and Heat, or Materials? Assessing Costs and Environmental Impacts for China in 2035
Shapiro-Bengtsen, S., Hamelin, L., Møllenbach Bregnbæk, L., Zou, L. & Münster, M.,, Energy Environ. Sci., 2022,15, 1950-1966

Competitiveness of a low specific power, low cut-out wind speed wind turbine in North and Central Europe towards 2050
Swisher, P., Murcia Leon, J. P., Gea-Bermúdez, J., Koivisto, M., Madsen, H. A. & Münster, M., Applied Energy. 304, 14 p., 118043.

The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050
J Gea-Bermúdez, IG Jensen, M Münster, M Koivisto, JG Kirkerud, Y Chen, H Ravn, Applied Energy 289, 116685

Modelling of renewable gas and renewable liquid fuels in future integrated energy systems
R Bramstoft, A Pizarro-Alonso, IG Jensen, H Ravn, M Münster, Applied Energy 268, 114869

Analysis on electrofuels in future energy Systems: A 2050 case study
MS Lester, R Bramstoft, M Münster, Energy, 117408

Potential role of renewable gas in the transition of electricity and district heating systems
IG Jensen, F Wiese, R Bramstoft, M Münster, Energy Strategy Reviews 27, 100446

Pathways to climate-neutral shipping: A Danish case study
T ben Brahim, F Wiese, M Münster, Energy 188, 116009

Uncertainties towards a fossil-free system with high integration of wind energy in long-term planning
A Pizarro-Alonso, H Ravn, M Münster, Applied Energy 253, 113528

Impact and effectiveness of transport policy measures for a renewable-based energy system
G Venturini, K Karlsson, M Münster, Energy Policy 133, 110900

How to maximise the value of residual biomass resources: The case of straw in Denmark
G Venturini, A Pizarro-Alonso, M Münster, Applied Energy 250, 369-388

Balmorel open source energy system model
Wiese, F., Bramstoft, R., Koduvere, H., Pizarro Alonso, A. R., Balyk, O., Kirkerud, J. G., Tveten, Å. G., Bolkesjø, T. F., Münster, M. & Ravn, H. V., 2018, Energy Strategy Reviews. 20

Sector coupling in EU

Focus on electrification

Technological overview

1. Power to heating and cooling (PtH)
2. Power to mobility (EV)
3. Power to gas/ fuels (PtX)
   - Status
   - Potential
   - Barriers

www.superp2g.eu

https://energypolicycast.podbean.com/e/sector-vector-and-smart-sector-coupling/

https://www.etip-snet.eu/sector-coupling-concepts-state-art-perspectives/

The end ☺

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Website: https://orbit.dtu.dk/en/persons/marie-münster

Extra

Other Data

- TYNDP 2030 ambitious, 60% are delayed Susser et al. 2022, tradeoff between electricity and hydrogen grids Neyman et al. 2023, Allowing for el. Trans. Inv after 2030.
- WEO 2022, conventional fuel prices (NZE scenario), high co2 tax 140 €/ton for 2030, to 250 €/ton for 2050.
- Backbone costs regarding h2 pipelines, repurposing, and new, compressors costs.
- Storage hydrogen Salt Cavern or steel tanks.
- Investment costs (DEA catalogue and other sources).
- Variable renewable potential, validate across sources (Atlite, TransnetBW, ENSPRESSO)
- Variable renewable profiles CORRES (DTU WIND).
- 4% social interest rate
- Simulation Years, 2020, 2025, 2030,2035,2040,2045,2050 (myopic approach)
- Time aggregation 7 weeks (aka seasons), 24 steps per week, Gea-Bermúdez (2022)
- Total system Hydrogen demand for 2050 1414 TWh

DTU

Similarities to PyPsa study

- Large-scale energy system models
- Partial equilibrium models
- Similar objective minimizing total systems costs
- Covering all Europe
- Handling uncertainty through sensitivity analysis

Differences to PyPsa study

- **Myopic pathway analysis every 5 years (7 steps until 2050), allowing for lock-ins vs overnight investments in 2050**
- **Import of hydrogen from North Africa, Ukraine**
- Hydrogen demands for PtX vs optimizing liquid fuel production
- Hierarchical approach: countries, regions (electricity and hydrogen), areas (district heating) vs nodes
- One region per country (apart from North Europe with more) vs 181 nodes
- Cross-border corridors vs network representation
- Time aggregation vs every 3rd hour
- CO2 quota price (250 EUR/t in 2050 WEO - NZE) vs CO2 budget in 2050
- Optimising district heating vs district heating expansion scenarios
- Intra-day and intra-seasonal storage modeling (time for charging and discharging)