

Ramping Up Low-Emission Hydrogen Imports to Europe: Case Studies and Transition Pathways

Nima Farhang-Damghani, Veronika Grimm, Kiana Niazmand

Energy Systems and Market Design Lab (ESMD)
University of Technology Nuremberg (UTN)

Motivation

- Challenge of sufficient timely supply in low-emission hydrogen
- Limitations in scaling up electrolysis capacity and seaborne imports of H₂ carriers
- Low-carbon (blue) hydrogen can play a role in the transition

Perspective on transition of fossil fuel exporting countries:

Use natural gas + infrastructure for low-carbon H₂ production with later transition to renewable hydrogen

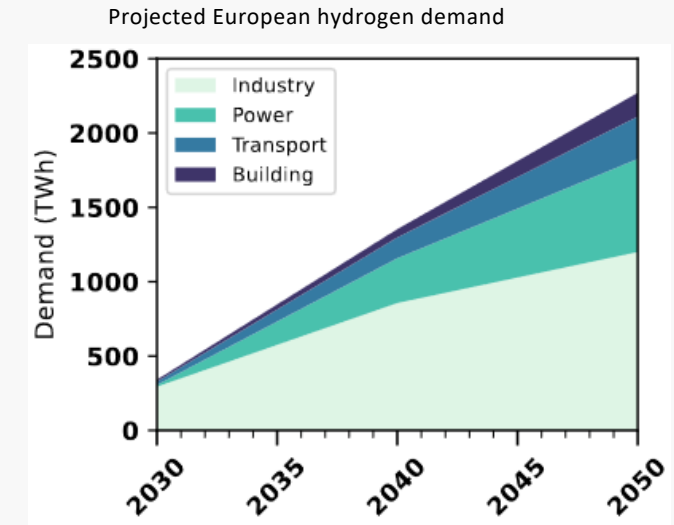
Case Study: Norwegian/Algerian switch from natural gas to H₂ exports

Research questions:

What are timelines and switching points from natural gas directly to renewable hydrogen or via low-carbon hydrogen?

What are the related costs and emission implications for H₂ exports?

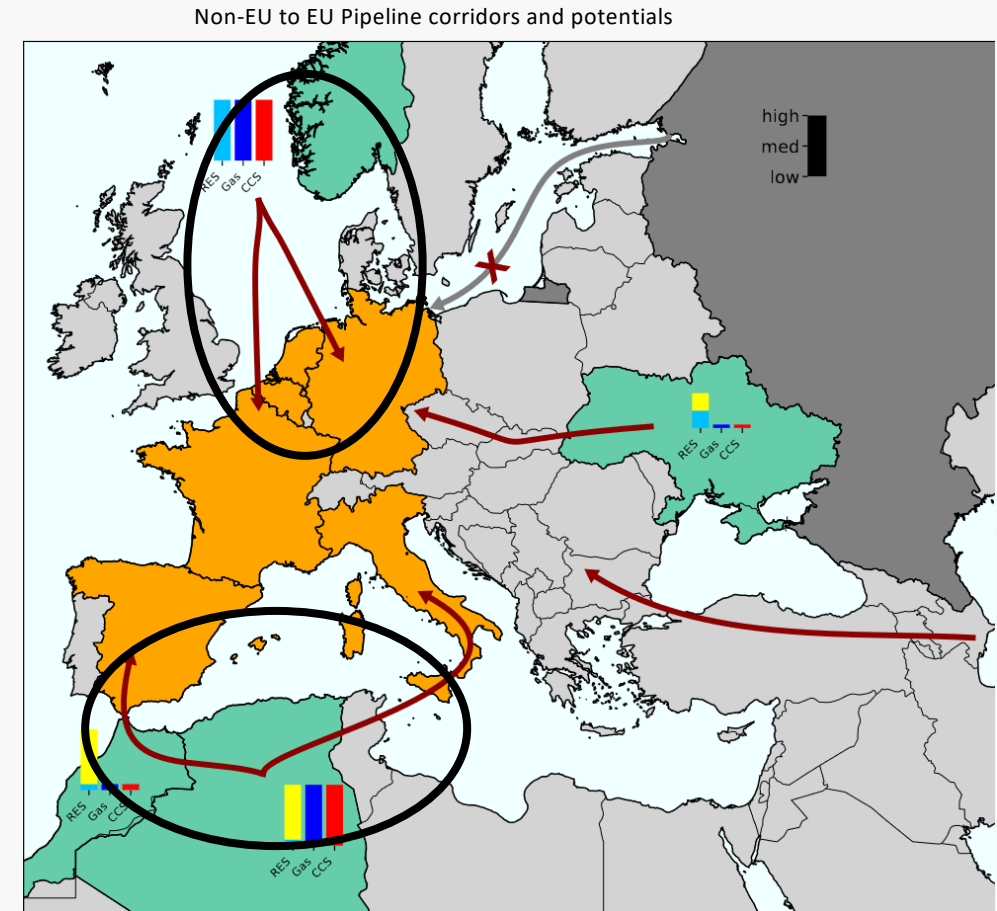
What are the impacts of different scenarios when utilizing blue hydrogen?



Data source: European Hydrogen Backbone

Case Studies – Ramping Up Hydrogen Exports

- Hydrogen production at feed-in points of existing NG pipelines in the Norwegian North Sea and at Algerian gas fields
- Retrofitting along existing routes possible
- CO₂ transport: 150/650 km of average distance to CO₂ storage sites
- RES: Offshore Wind (Norway); PV/Onshore Wind (Algeria)



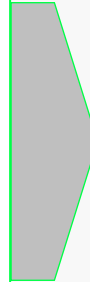
Methodology

Objective function of techno-economic MIP Model

Minimize total system costs over the whole transition timeframe 2025 – 2050

Inputs

- Hourly RES profiles
- Country-dependent existing infrastructure
- Capital and operational costs
- Learning curves for RES/H₂ production
- Price assumptions for CO₂/NG
- Ramp-up limitations (infrastructural capacities, blue hydrogen limits, ...)
- Annual energy demand
- ...

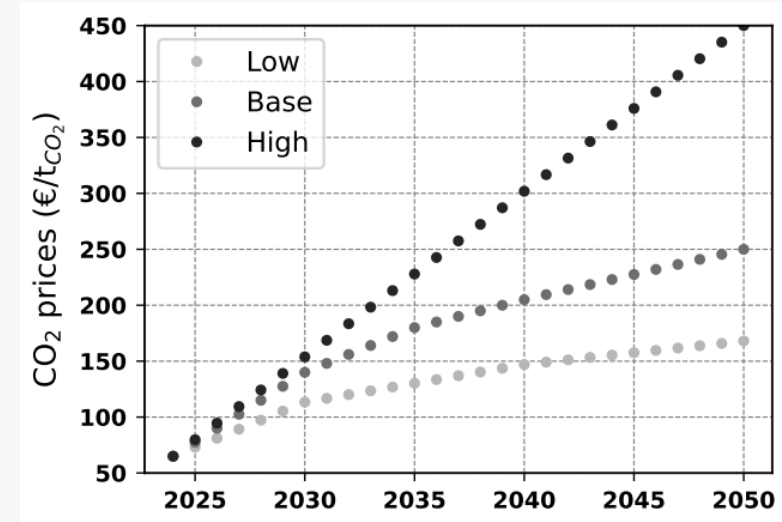


Outputs

- Total and annual supply costs and production costs over time frame
- Capacity expansions H₂/CO₂:
 - Production and transport infrastructure
 - RES
 - Storages
- CO₂ emitted and captured (from NG/BH₂ production)
- Retrofitting decisions
- ...

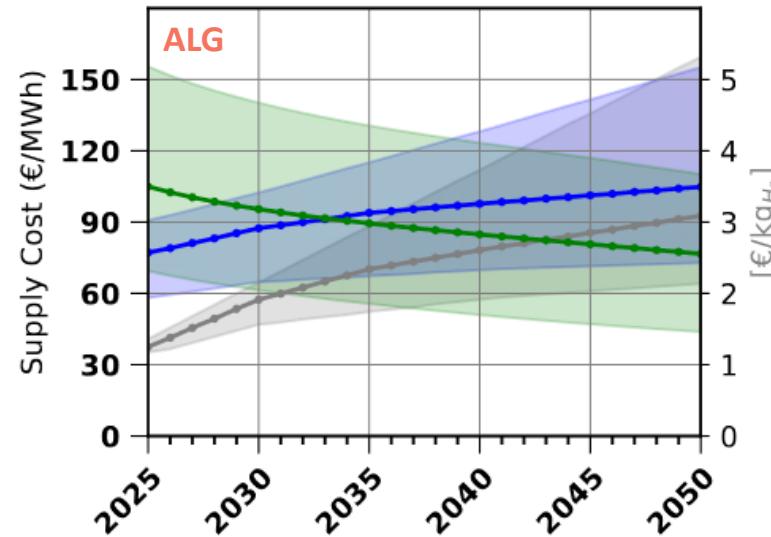
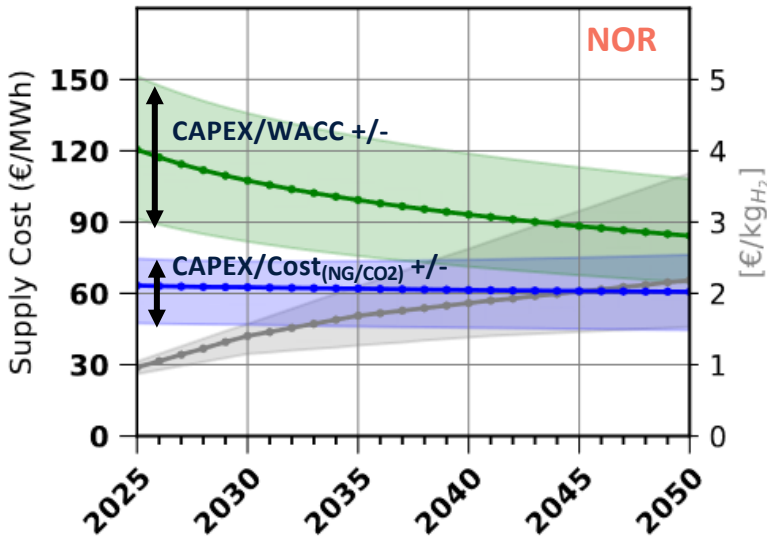
Base assumptions

- **CO₂ price scenarios (2025 – 2050)**
 - 70 – 168 €/t (TYNDP2024, low)
 - 70 – 250 €/t (IEA, base)
 - 70 – 450 €/t (high)
- **Natural Gas extraction cost: 10 €/MWh (constant)**
- **Natural Gas market price: 25 €/MWh (constant)**
- **WACC of 6.6% (NOR) and 10.2% (ALG)**
- **Learning Curves H₂ technologies/RES**
- **Upstream and midstream leakages**



Annual change in supply costs for greenfield H₂ supply chain

With upstream/midstream emissions

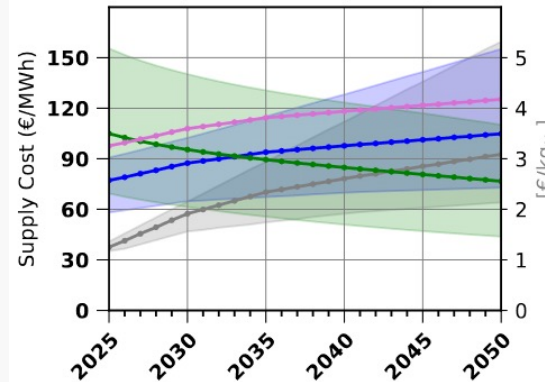
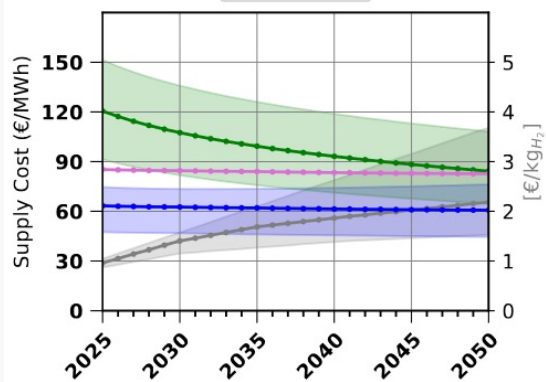


- Base, minimum and maximum supply costs
- NG extraction cost = ~ 10 €/MWh
- NG market price = 25 €/MWh

Blue H₂ scenarios:

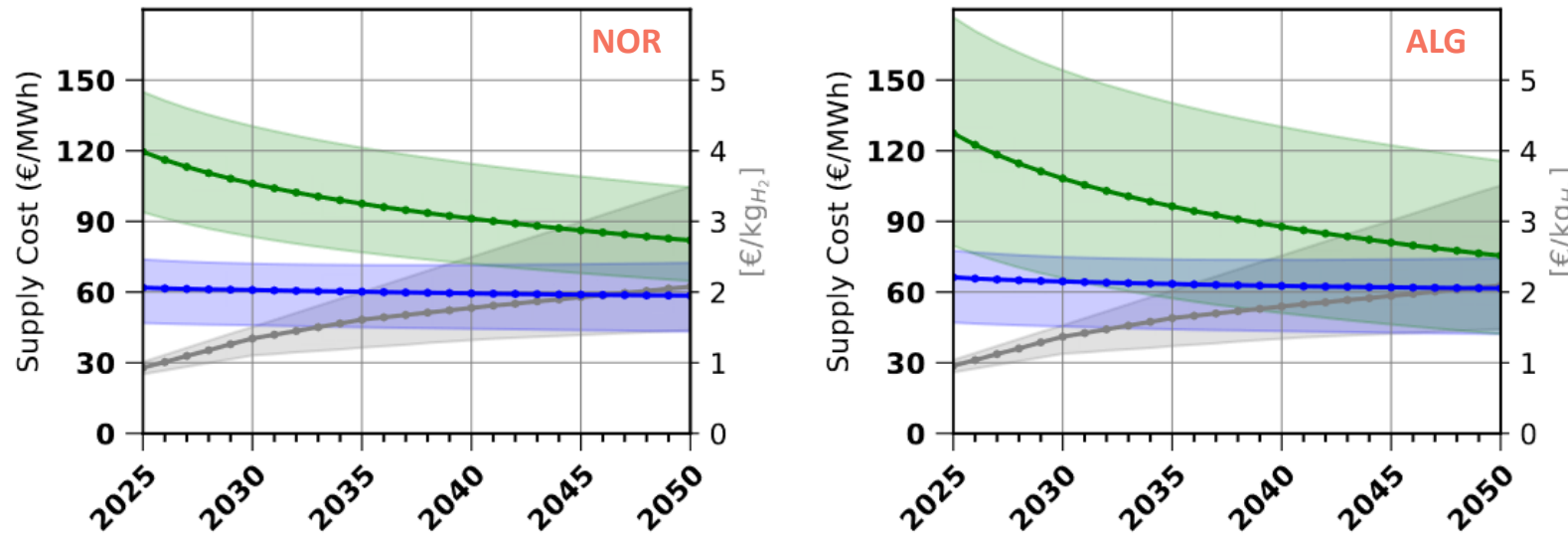
- BH₂ in NOR/ALG with NG extraction cost
- BH₂ in NOR/ALG with NG market price

- Using **new H₂ pipelines** would **increase** cost by around **5 €/MWh (0.17 €/kg)**



Annual change in supply costs for greenfield H2 supply chain

Without upstream/midstream emissions



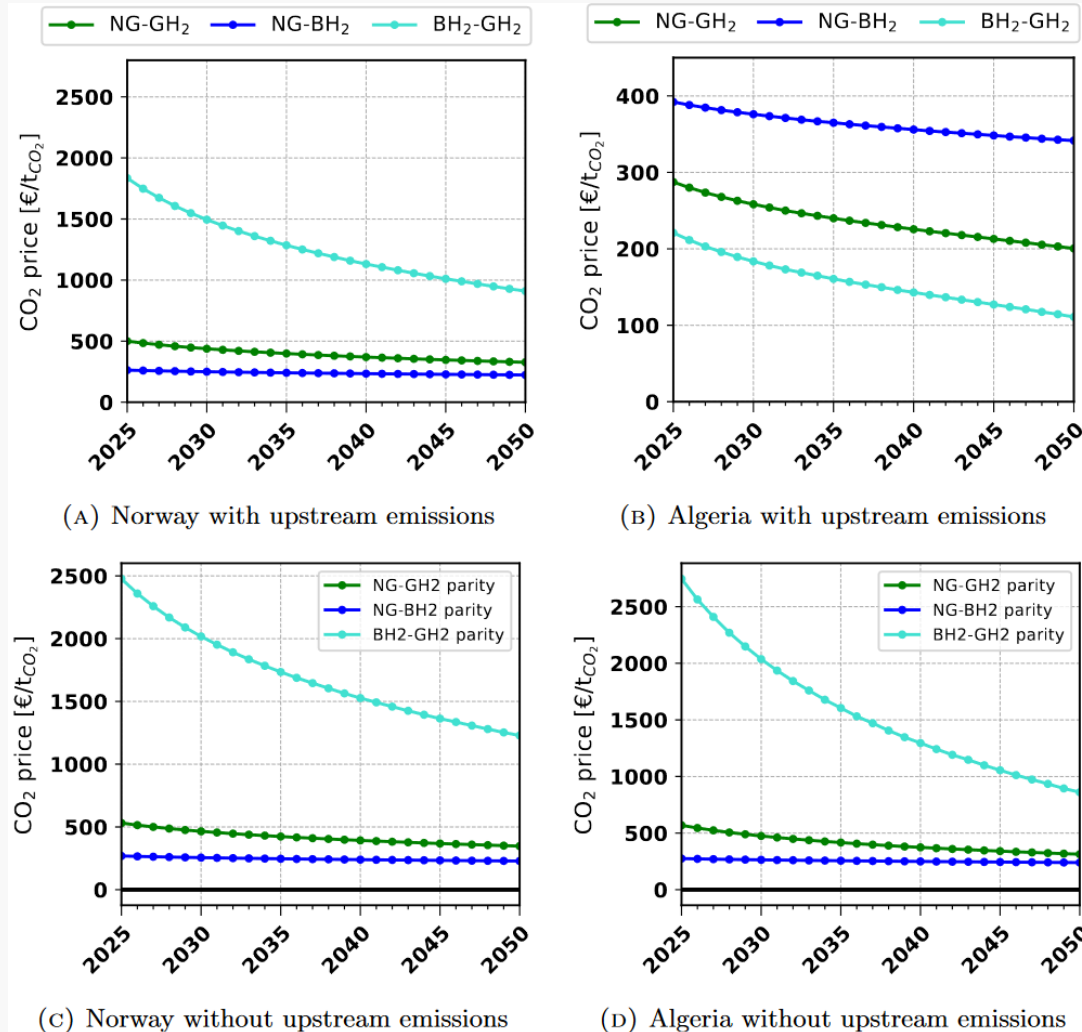
- Base, minimum and maximum supply costs
- NG extraction cost = ~ 10 €/MWh
- NG market price = 25 €/MWh

Blue H2 scenarios:

- BH2 in NOR/ALG with NG extraction cost
- BH2 in NOR/ALG with NG market price

- Using **new H₂ pipelines** would **increase** cost by around **5 €/MWh (0.17 €/kg)**

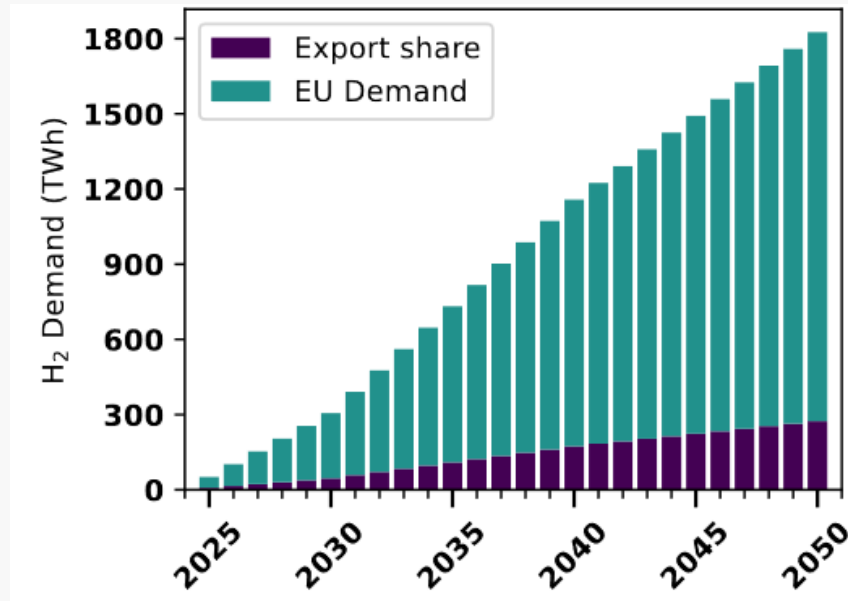
Required CO₂ price in given year for BH₂ or GH₂ to reach supply cost parity with Natural Gas



- Pricing upstream emissions:
 - (High) CO₂ price has low effect on switch due to low upstream emissions in Norway, high prices required for switch
 - Without reduction of Algerian upstream emissions, low CO₂ prices are sufficient for switch to GH₂

- Without upstream emissions:
 - GH₂ would need very high CO₂ prices from 2500€ (2025) to 1000€ (2050) for cost parity with BH₂ if no upstream emissions are priced

Hydrogen Demand Supply: System and Abatement Costs

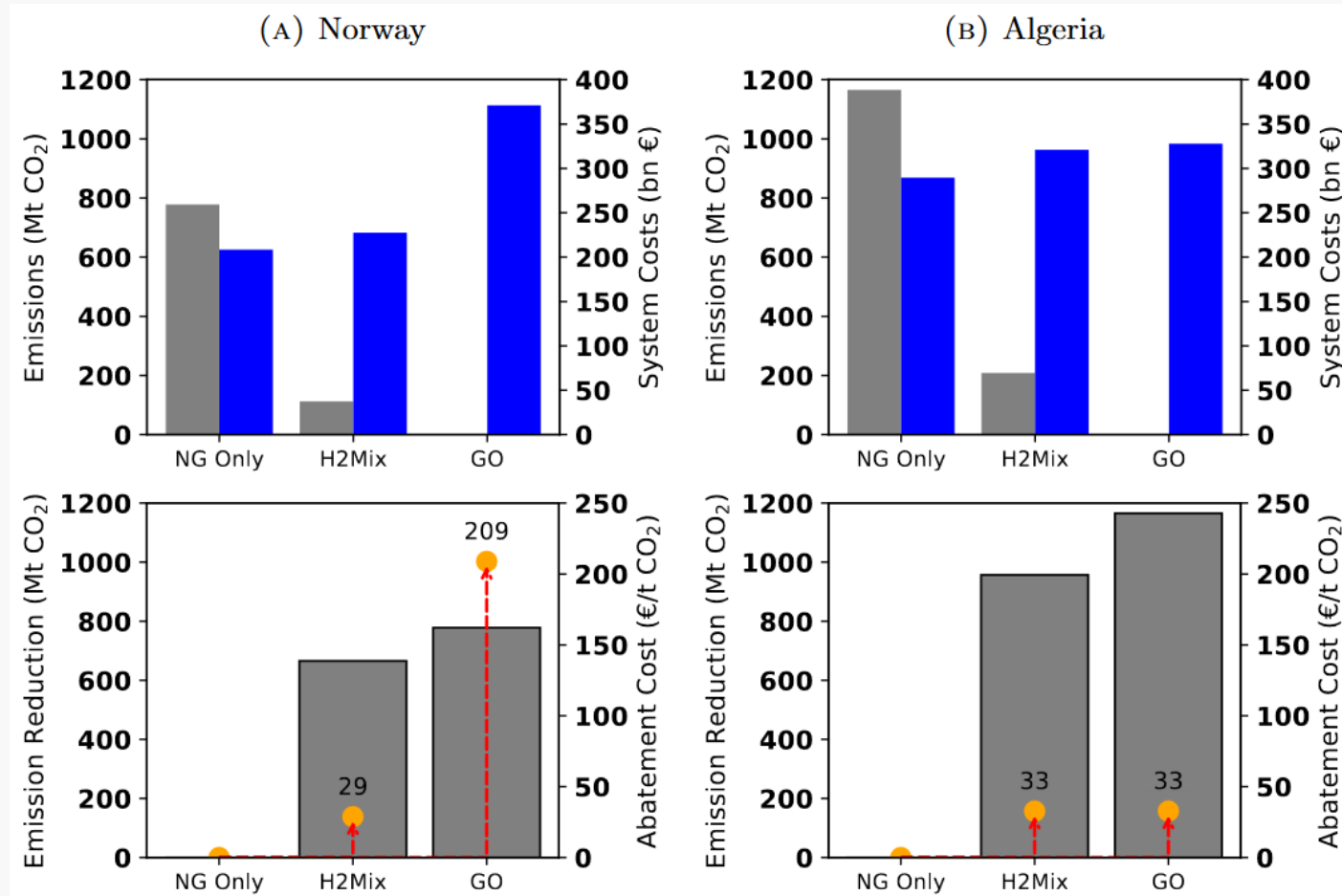


Scenarios

- NG Only (Reference): Hydrogen does not substitute Natural Gas
- Hydrogen Mix: BH₂ and GH₂ compete freely
- Green Only: Only GH₂ allowed without any restrictions

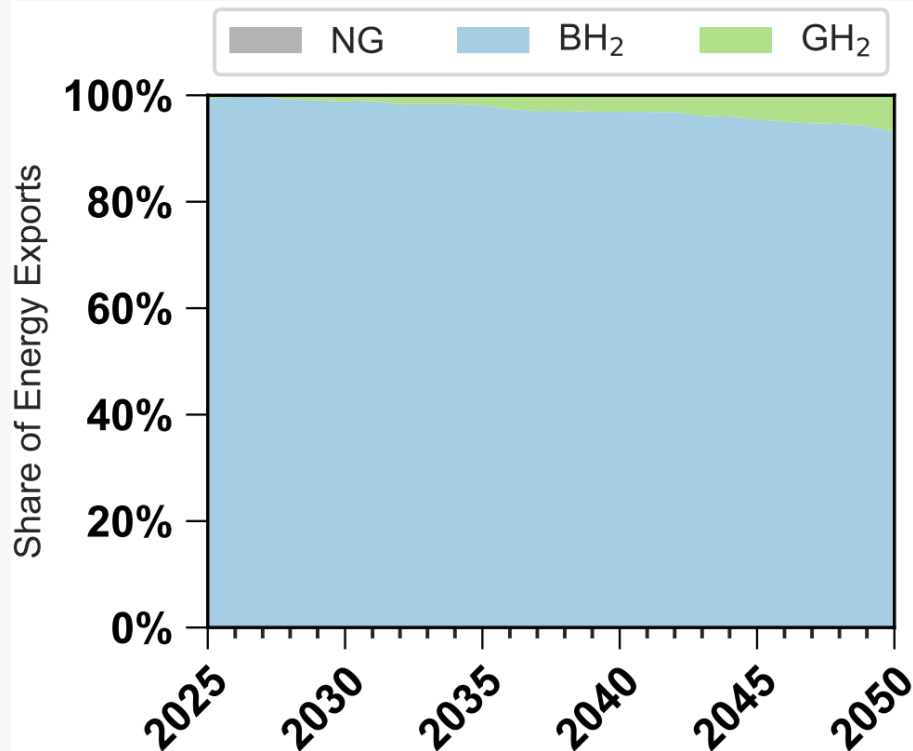
Total European Hydrogen Demand until 2050 (only industry and power sector, EHB) and assumed export country supply share of 15 %

System Cost and Average Abatement Cost

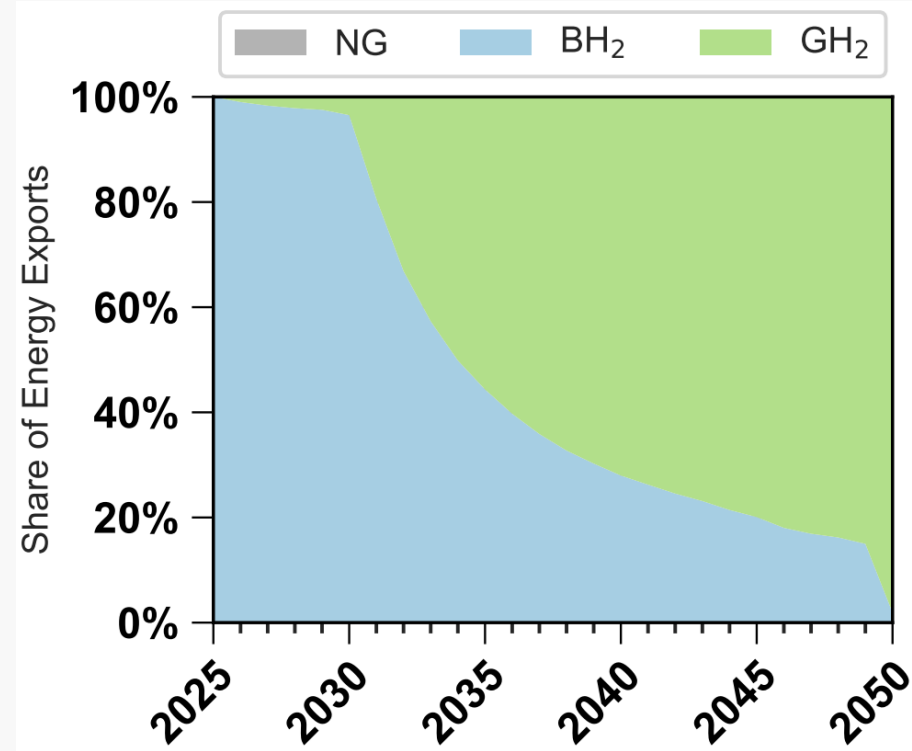


System Cost and Average Abatement Cost

Norway H2Mix

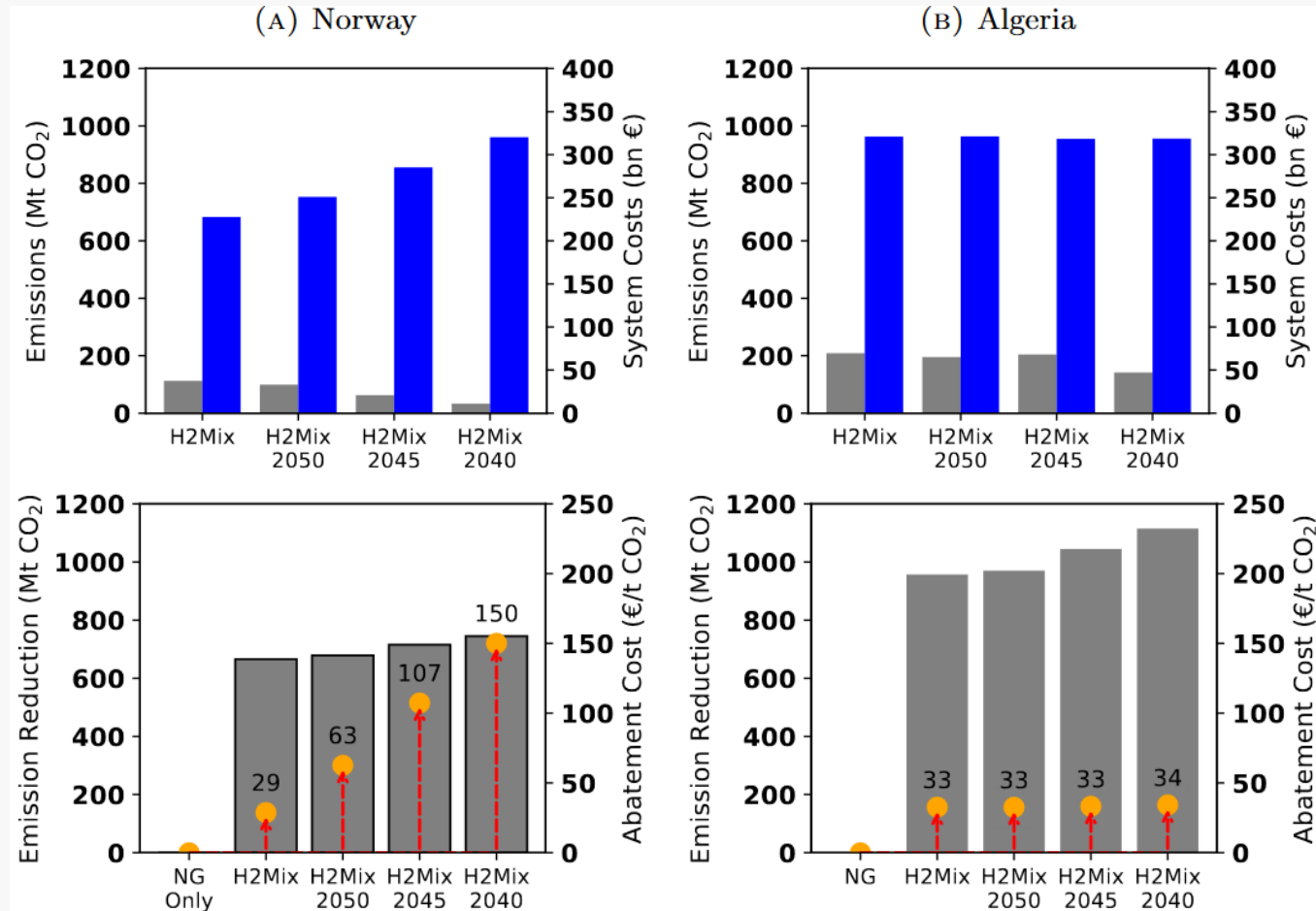


Algeria H2Mix



Early Blue Hydrogen phase-out

- H2Mix-*YEAR***: Additional condition, that all blue hydrogen production plants have to be depreciated until *YEAR* and blue hydrogen as energy carrier cannot be used to meet any share of demand from *YEAR* onwards.



Norway

Implications

- **CO₂ prices and current cost reduction projections for RES and electrolysis not enough for timely and sufficient competitiveness of green hydrogen against natural gas and blue hydrogen**
- **High CO₂ price may force earlier switch Natural Gas → Hydrogen but not specifically Blue Hydrogen → Green Hydrogen as it only insignificantly affects the cost of BH₂**
 - Further incentives needed to accelerate green hydrogen production and exports?
- **Low risk of stranded investments into blue hydrogen supply chain under the presented assumptions**
 - Forcing BH₂ phase-out before 2050 significantly increases overall system and abatement cost

Implications

- **CO₂ prices and current cost reduction projections for RES and electrolysis could lead to sufficient competitiveness of green hydrogen against natural gas and blue hydrogen in the medium-term (mainly due to methane upstream emissions)**
- **High CO₂ price may force earlier switch Natural Gas → Hydrogen, without using Blue Hydrogen as a transitional technology (only from a cost-perspective)**
 - Strategically, implementation gap between hydrogen needs and green hydrogen deployment may cause further issues
- **Higher risk of stranded investments into blue hydrogen supply chain under the presented assumptions**
 - Forcing BH2 phase-out before 2050 has low impact on overall system and abatement cost

Thank you for your attention

**Nima Farhang-Damghani – Research Associate
Energy Systems and Market Design Lab**

nima.farhang-damghani@utn.de

Norway as an energy exporter

Energy product	Production	Import	Export	Total domestic supply
Natural Gas	1269.9	0.7	1223.7	46.4
Oil and oil products (excl. bio)	1075.0	106.1	1083.6	84.0
Electricity	144.3	13.3	25.8	131.8
Biofuels	15.0	5.5	1.4	19.2
Waste	5.4	0.0	0.0	5.4
All energy products	2510.5	134.9	2335.1	296.2

Status-quo:

- Excellent partnerships with Europe
- Existing infrastructure (fossil fuel industry) and financial strength
- Available natural gas production, CO₂ storage and experience in CO₂ infrastructure
- 100% RES electricity with large seasonal storage but dependent on annual precipitation, but also integration with neighbors

Perspective:

- Increasing electricity demand requires additional RES and plans for new electricity interconnectors
- Temporal export of blue hydrogen could provide a timely alternative for the reduction in European fossil gas demand which can rely on existing infrastructure
- Potential of offshore wind to replace blue hydrogen over time (30 GW by 2040)
- Cost of hydrogen important result for Norway using transition through blue hydrogen
- Export of surplus electricity could phase lower prices due to low prices on electricity spot market

Pipeline	Length [km]	Capacity [bcm]	Capacity [GW]	Max. energy flow [TWh]
Norpipe	440	16.0	18.2	159.5
Europipe I	620	16.7	19.0	166.3
Europipe II	658	26.0	29.6	259.1
Franpipe	840	20.0	22.8	199.4
Zeepipe	844	15.4	17.5	153.6

Case Studies – Ramping Up Hydrogen Exports

Objective function of MIP Model

Minimize total system costs over the whole timeframe 2025 – 2050

$$\text{Minimize } z = C^{NG} + C^{RE} + C^{GH_2} + C^{BH_2} + C^{H_2T} \quad (1)$$

$$C^{NG} = \sum_{t \in T} \left[\sum_{h \in H} y_{t,h}^{NG} (\xi_t^{NG} + (\varepsilon_{NG} + \mu_{NG}) \rho_t^{CO_2}) + \sum_{p \in P} x_{p,t}^{NG} \delta_p \nu_{p,t} + \bar{y}_{NGC,t} \nu_{NGC,t} \right] \quad (1-1)$$

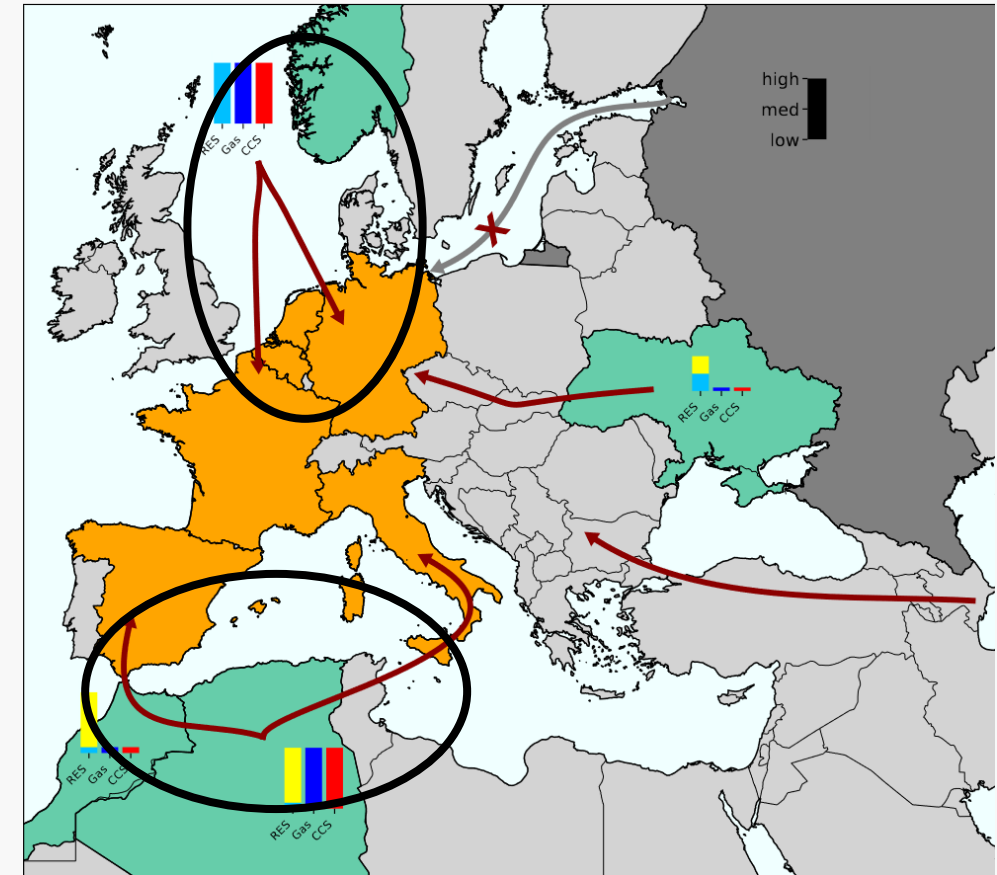
$$C^{RE} = \sum_{i \in I} \sum_{t \in T} \sum_{\tau = \max(1, t-LT_i+1)}^t \bar{n} y_{i,\tau} (\phi_{i,\tau} + \nu_{i,\tau}) \quad (1-2)$$

$$C^{GH_2} = \sum_{j \in J} \sum_{t \in T} \sum_{\tau = \max(1, t-LT_j+1)}^t \bar{n} y_{j,\tau} (\phi_{j,\tau} + \nu_{j,\tau}) \quad (1-3)$$

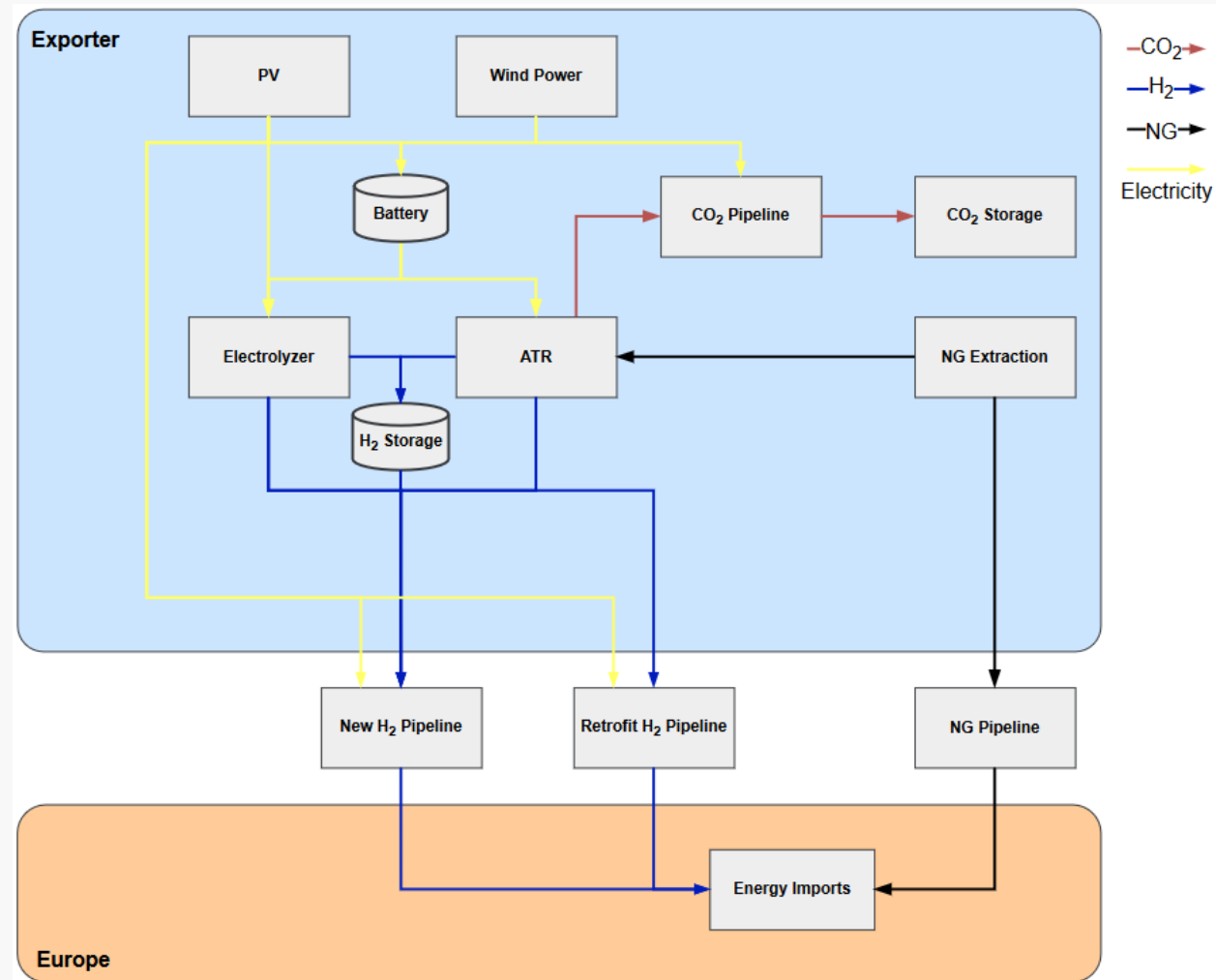
$$C^{BH_2} = \sum_{t \in T} \left[\sum_{k \in K} \sum_{\tau = \max(1, t-LT_k+1)}^t \bar{n} y_{k,\tau} (\phi_{k,\tau} + \nu_{k,\tau}) + \sum_{l \in L} \sum_{\tau = \max(1, t-LT_l+1)}^t \bar{n} x_{l,\tau}^{CO_2} \delta_l (\phi_{l,\tau} + \nu_{l,\tau}) \right. \\ \left. + \sum_{h \in H} d_{ATR,t,h}^{NG} (\xi_t^{NG} + \mu_{NG} \rho_t^{CO_2}) + \sum_{h \in H} y_{t,h}^{BH_2} (1 - \eta_{CCS}) \varepsilon_{ATR} \rho_t^{CO_2} \right] \quad (1-4)$$

$$C^{H_2T} = \sum_{t \in T} \left[\sum_{rp \in RP} x_{rp,t}^{H_2} \delta_{rp} (\phi_{rp,t} + \nu_{rp,t}) + \sum_{np \in NP} \sum_{\tau = \max(1, t-LT_{np}+1)}^t \bar{n} x_{np,\tau}^{H_2} \delta_{np} (\phi_{np,\tau} + \nu_{np,\tau}) \right. \\ \left. + \sum_{m \in M} \sum_{\tau = \max(1, t-LT_m+1)}^t \bar{n} y_{m,\tau} (\phi_{m,\tau} + \nu_{m,\tau}) \right] \quad (1-5)$$

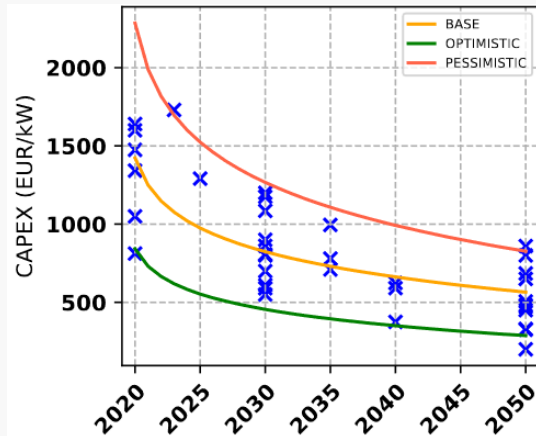
Non-EU to EU Pipeline corridors and potentials



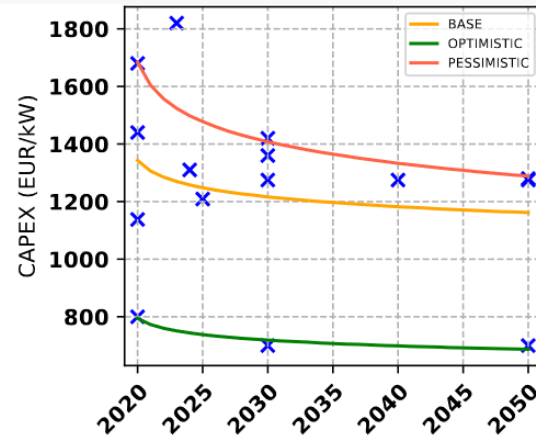
Methodology



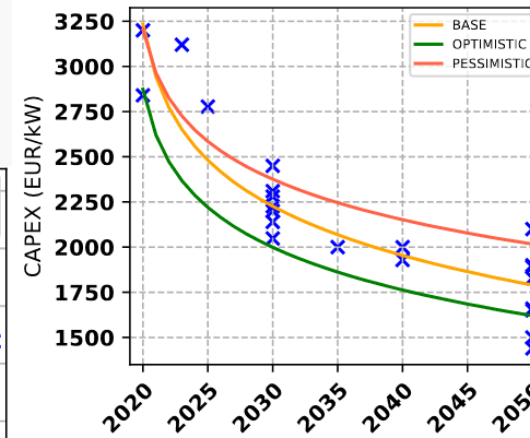
Learning Curves



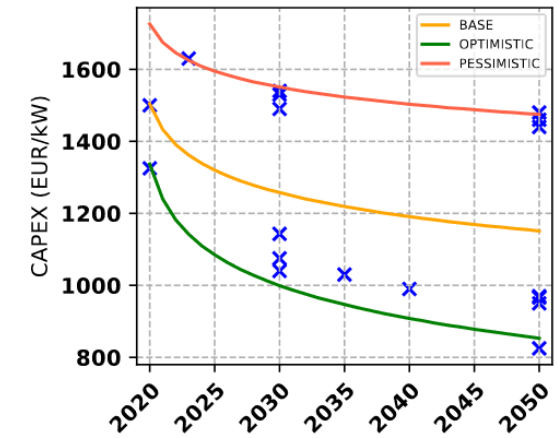
(A) PEM electrolyzer



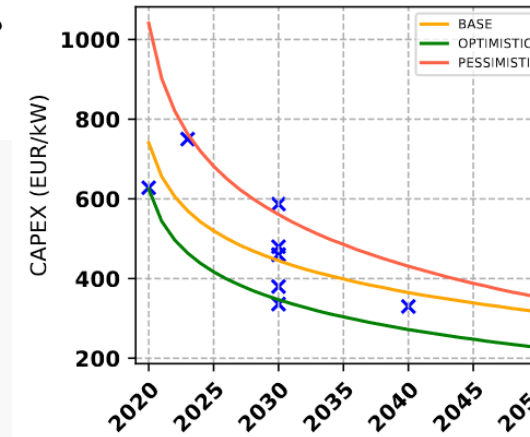
(B) ATR+CCS



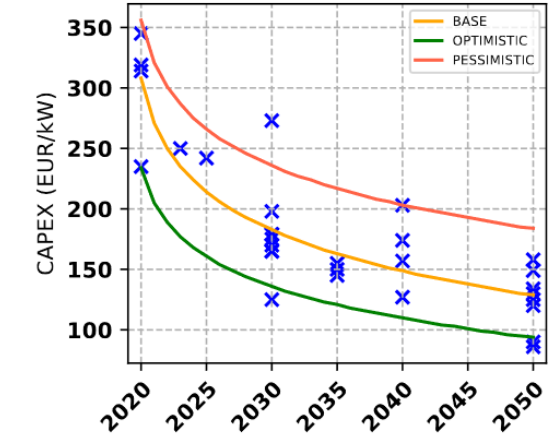
(A) Offshore Wind



(B) Onshore Wind



(C) Photovoltaics

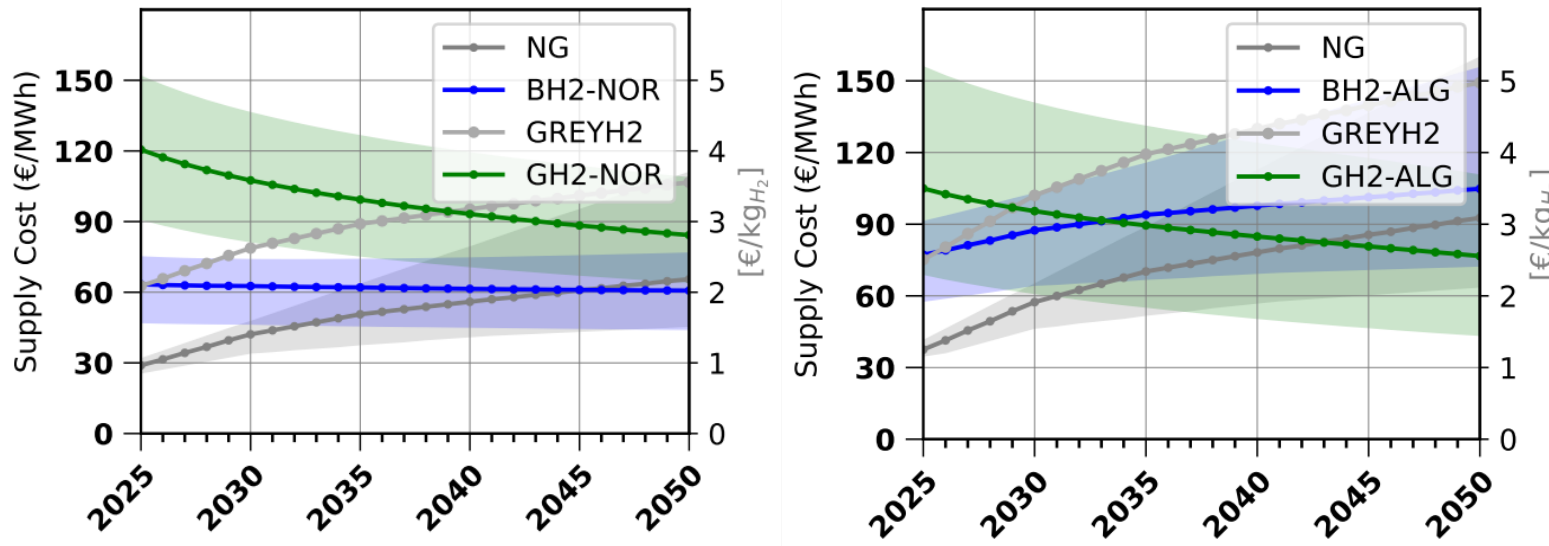


(D) Battery Energy Storage System

Annual change in supply costs for greenfield H2 supply chain

With upstream emissions and Grey H2

PROVISORISCH

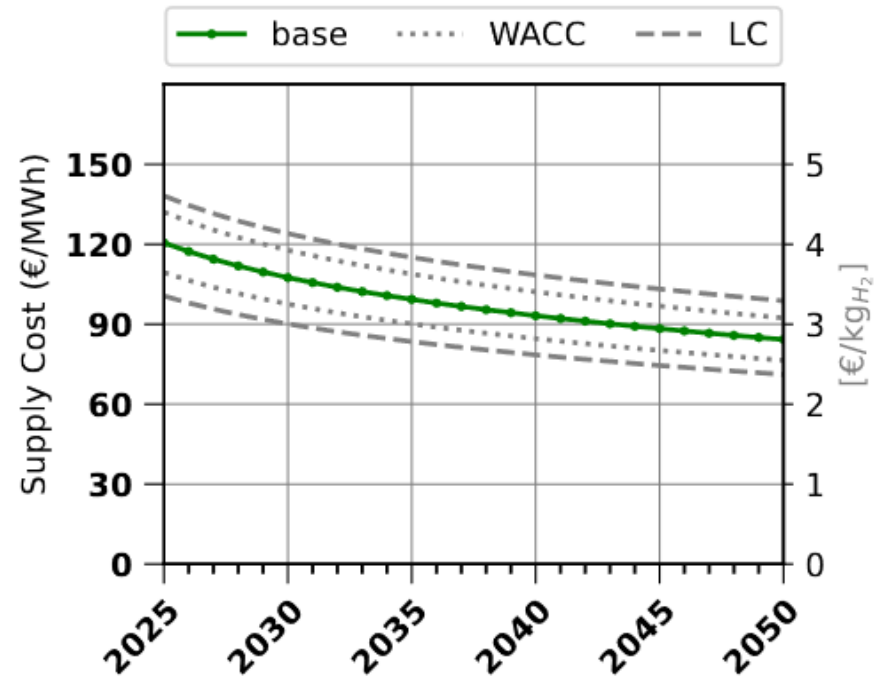


- Grey H2 not competitive against BH2 and NG due to advantage offset by carbon pricing
- NG extraction cost = ~ 10 €/MWh
- NG market price = 25 €/MWh

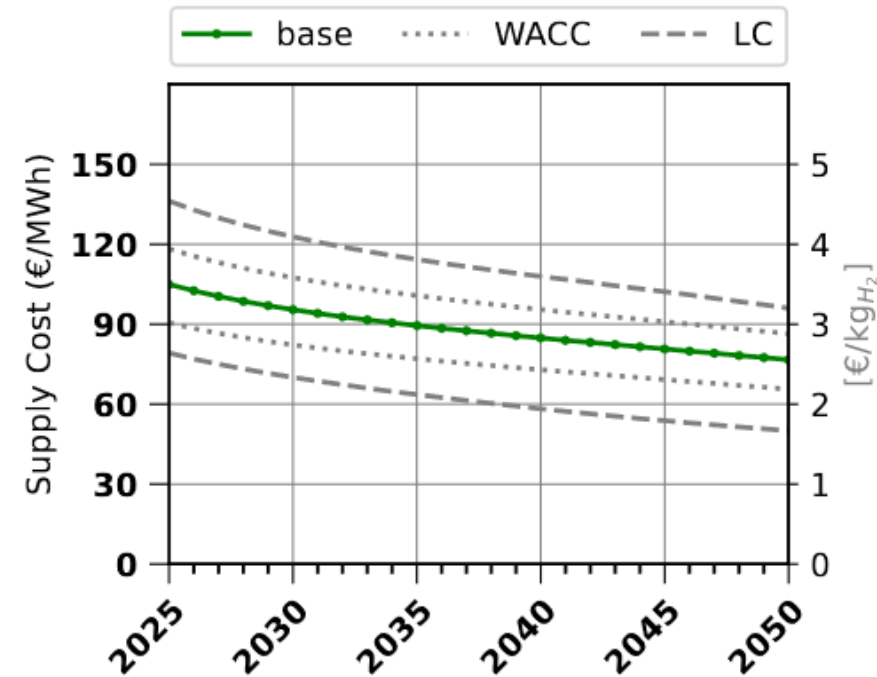
Blue H2 scenarios:

- BH2-NOR = BH2 in NOR with extraction cost
- Variations in CO₂ prices for NG
- Using **new H₂ pipelines** would **increase** cost by around **5 €/MWh (0,15 €/kg)**

Preliminary results



(A) Norway

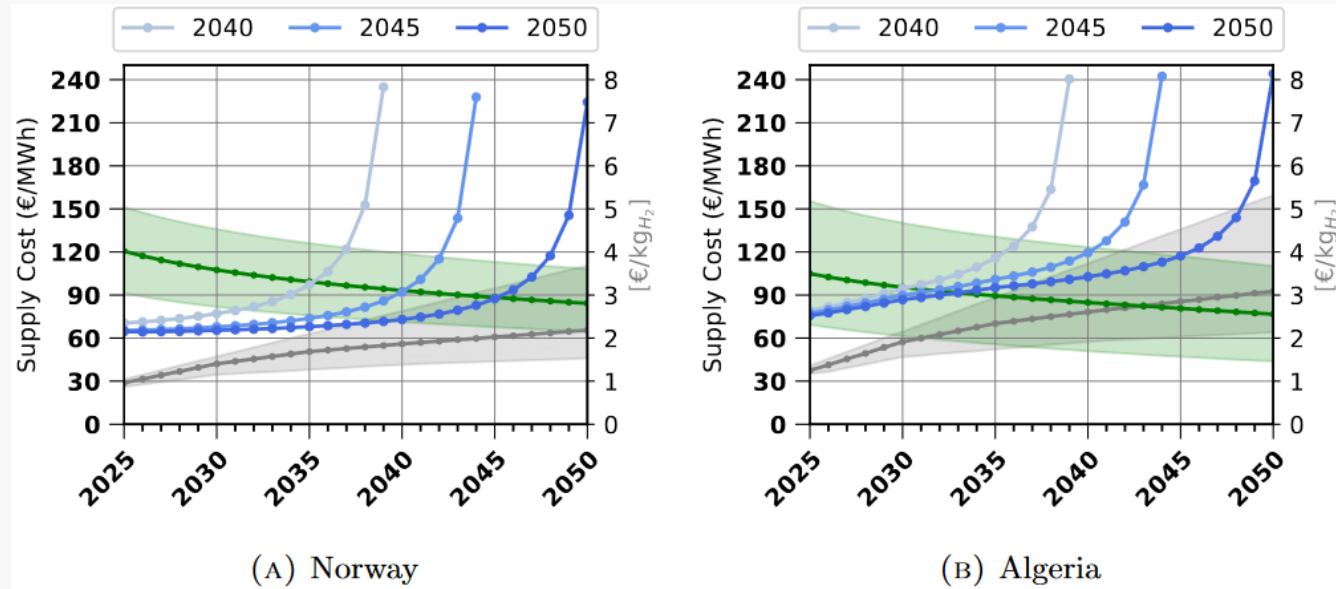


(B) Algeria

FIGURE 15. Sensitivities for green hydrogen supply costs

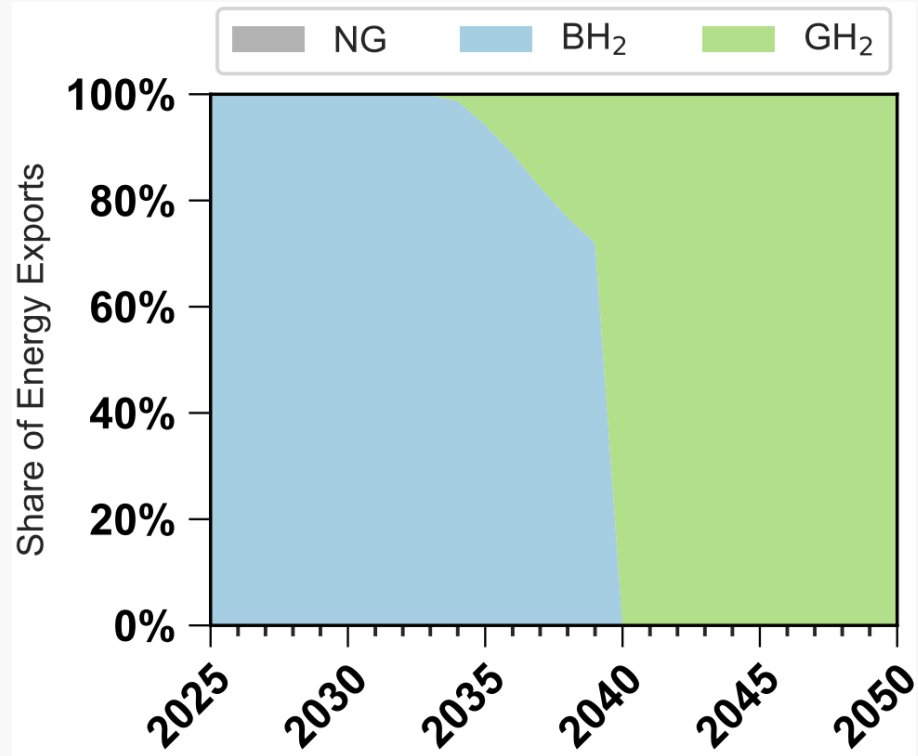
System Cost and Abatement Cost

PROVISORISCH

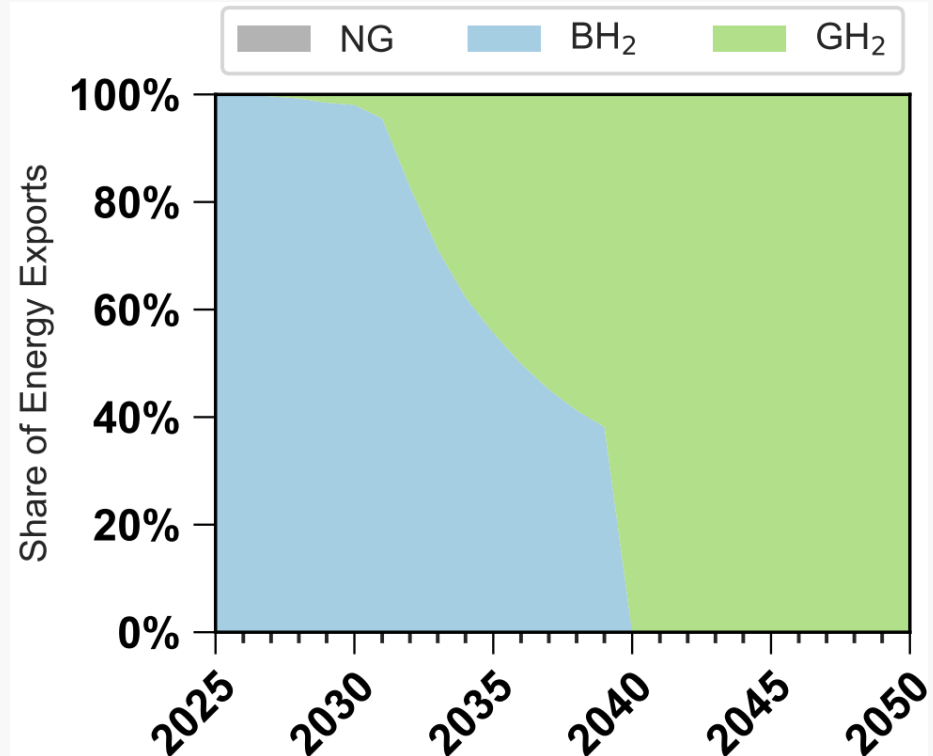


System Cost and Abatement Cost

Norway H2Mix-2040



Algeria H2Mix-2040



Abatement scenarios H2Mix unrestricted and H2Mix-2040

Norway

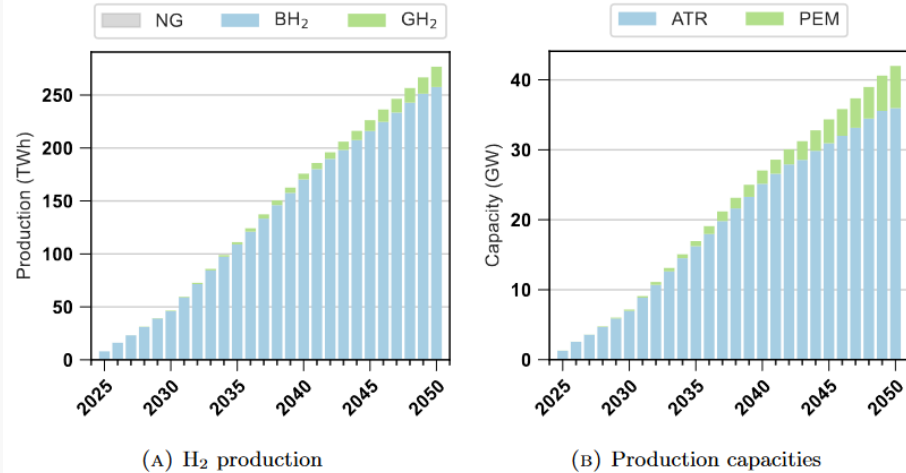


FIGURE 19. *H2Mix-unrestricted*: Production and Capacities (Norway)

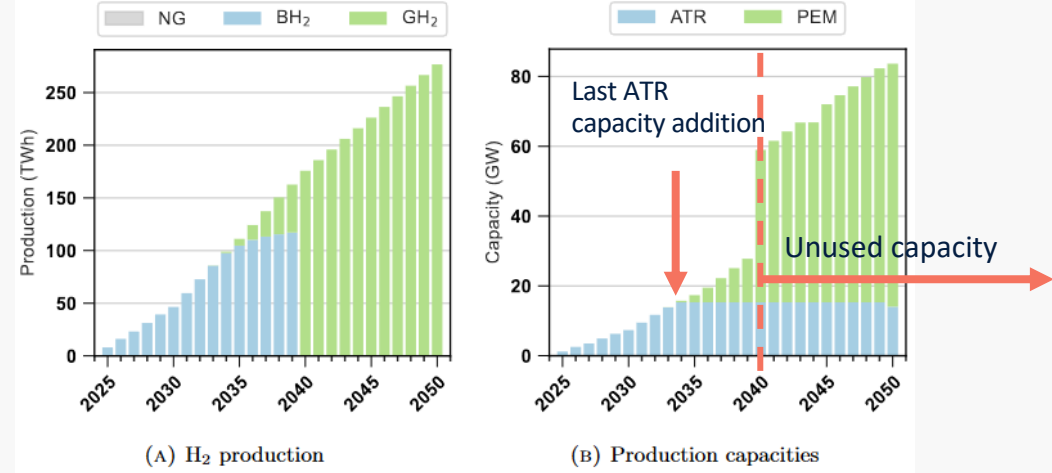


FIGURE 21. *H2Mix-2040*: Production and Capacities (Norway)

Algeria

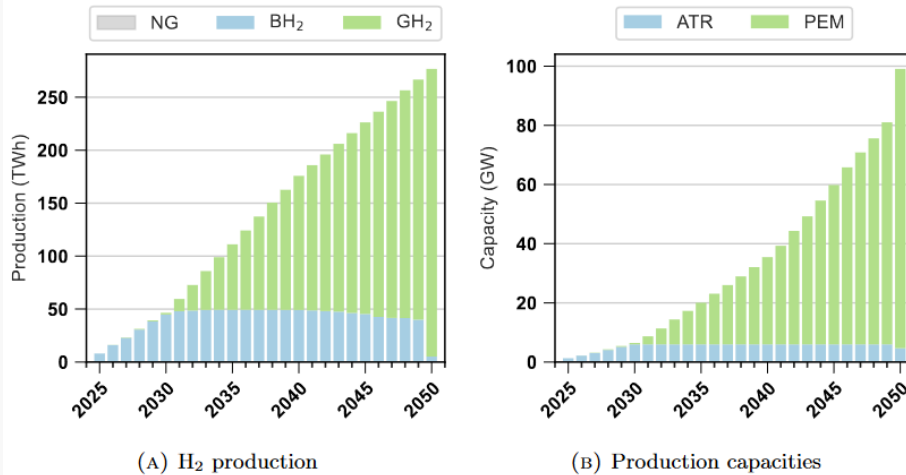


FIGURE 20. *H2Mix-unrestricted*: Production and Capacities (Algeria)

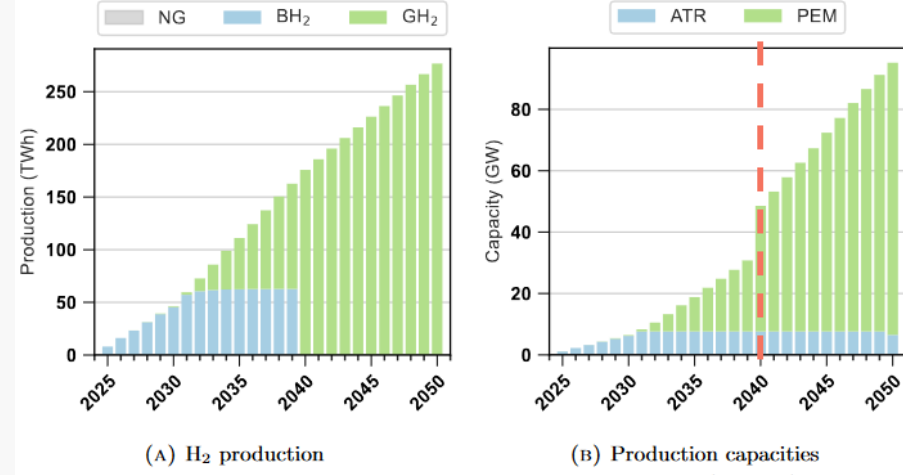


FIGURE 22. *H2Mix-2040*: Production and Capacities (Algeria)