THE GLOBAL HYDROGEN MARKET 2050
A MODEL-BASED COMPARISON OF PATHWAYS AND POLICY CONSTRAINTS

Jefferson Riera, Lukas Barner, Franziska Holz
Lennart Rathje, Robin Sogalla, Christian von Hirschhausen

Fachgebiet Wirtschafts- und Infrastruktur Politik (WIP)
Today ~95% of hydrogen production comes from fossil fuels...

through steam reforming (SMR) of natural gas and coal.

• Hydrogen is primarily produced and used on site by the industrial sector
• Purpose: ammonia production and oil refining

So far there is no significant hydrogen production from renewables.
International Trade of Hydrogen?

Asian market will likely be the largest consumer of hydrogen opens doors for exporting countries with low-cost electricity and with high-capacity factors.

**Australia (south):** significant renewable generation capacity and limited interconnection with the rest of the country.
- Exports to Japan, South Korea, China, and Singapore

**Chile:** one of the best solar resources in the world (Atacama Desert)
- low-cost, high-capacity renewables → low-cost hydrogen production for Asia

**Norway:** Hydrogen can be produced by hydropower, offshore wind, and natural gas

**Saudi Arabia:** combination of complementary wind and solar PV to generate hydrogen, potentially transported as ammonia
GH2-MOD (current iteration)

• Static model of the year 2050
• Deterministic
• Ten regions
• Transport of hydrogen as liquid and gas
• Includes market power
• Models different player in the value chain
Hydrogen Economy: Value Chain and Actors

* Production via SMR or Electrolysis
Producer’s (Electrolysis) Optimization Problem

\[
\begin{align*}
\text{max } & \left( \pi^E_{n(e)}SALES^E_{e} - c^E_{e}SALES^E_{e} \right) \\
\text{s.t. } & \quad SALES^E_{e} \leq CAP^E_{e} \quad (\alpha^E_{e}) \\
& \quad SALES^E_{e} \leq CAP^{E\text{Reg}}_{e} \quad (\beta^E_{e}) \\
& \quad SALES^E_{e} \geq 0 \\
\end{align*}
\]

Market Clearing

\[0 \leq SALES^E_{e} - PURCH^{T_{e\leftarrow E}}_{\ell(e)n(e)} - \sum_{l \in L_{e}(e)} PURCH^{L_{e\leftarrow E}}_{l} \quad \forall e \quad (\pi^E_{n(e)})\]
Producer’s (Electrolysis) Optimization Problem

\[
\max \left( \pi^E_{n(e)} \text{SALES}^E_e - c^E_e \text{SALES}^E_e \right) \tag{1}
\]

s.t. \[
\text{SALES}^E_e \leq \text{CAP}^E_e \quad (\alpha^E_e) \tag{2}
\]
\[
\text{SALES}^E_e \leq \text{CAP}^{E\text{Reg}}_e \quad (\beta^E_e) \tag{3}
\]
\[
\text{SALES}^E_e \geq 0 \tag{4}
\]

Market Clearing

\[
0 \leq \text{SALES}^E_e - \text{PURCH}^{T_{e \leftarrow E}}_{t\left(e\right) n\left(e\right)} - \sum_{l \in L_e(e)} \text{PURCH}^{L_{e \leftarrow E}}_l \quad \forall e \quad (\pi^E_{n\left(e\right)}) \tag{5}
\]

Same type of optimization problem under constraints and market clearing conditions for all other players, including producer (SMR)
Producer’s (Electrolysis) KKT

\[ 0 \leq -\pi_n^E(e) + c^E_e + \alpha^E_e + \beta^E_e \perp SALES^E_e \geq 0 \quad (6) \]

\[ 0 \leq CAP_e^E - SALES^E_e \perp \alpha^E_e \geq 0 \quad (7) \]

\[ 0 \leq CAP_e^{EReg} - SALES^E_e \perp \beta^E_e \geq 0 \quad (8) \]

Market Clearing

\[ 0 \leq SALES^E_e - PURCH^{T_e \leftarrow E}_{t_e(e)n(e)} - \sum_{l \in L_e(e)} PURCH^{L_e \leftarrow E}_l \perp \pi_n^E \geq 0 \quad \forall e \quad (9) \]
Hydrogen Production Capacity (2050)

Electrolysis capacity significantly larger than SMR

Largest capacities:
1. Rest of Asia
2. China
3. India

Source: Löffler et al. 2017; Burandt et al. 2018
Production via electrolysis is generally more expensive than that by SMR.

Exceptions:
1. China
2. India
3. Africa

**Highest**
Rest of Asia (Electrolysis – $4.16/kg)
SMR – $2.353/kg

**Lowest**
China (Electrolysis – $1.61/kg)
Middle East (SMR – $1.23/kg)

Source: Heuser et al. (2019); Brändle et al. (2020); IEA 2019
Other Data Inputs

- Liquefaction / Regasification capacities and costs
- Transportation costs (shipping vessels and pipelines)
- Loss rates

Source: Heuser et al. (2019); Brändle et al. (2020); IEA 2019
Perfect Competition
Hydrogen Demand – Perfect Competition

Nearly half of Asia’s hydrogen demand is met by China.

Half of European demand is met by the Former Soviet Union and Africa.
Rest of Asia and Europe are sole importers

Africa, China and the Former Soviet Union are exporters

Electrolysis: 404 Mt/a
SMR: 230 Mt/a
Market Power – Flows

Most regions produce to meet their own hydrogen demands.
Market Power
Global Hydrogen Demand: 520 Mt/a

Largest hydrogen demand:
1. China
2. Africa
3. Rest of Asia

Makes up 50% of global demand
Hydrogen Demand – Market Power

- Total demand cut by ~ 20%
- India’s demand cut in half
- African hydrogen penetrates new markets
- Europe relies mostly on imports to meet demand

Total Demand 520 [Mt/a]
Market Power – Flows

- No trade in liquid H₂
- Costs of liquefaction/regasification too high
- Shipping costs also too high
China’s production accounts for a fourth of global production.

Strategic trading, countries import and export to take advantage of external hydrogen prices.
Hydrogen Prices

Prices are generally higher with market power

*Weighted Global Price*
Perfect Competition: $2.72/kg
Market Power: $3.36/kg
Future Work

Model Expansion

• Multi-period framework
• Addition of storage operators
• Addition of ammonia as a hydrogen carrier
  • Hydrogenator and Dehydrogenator players
• Spatial disaggregation of regions
Hydrogen Economy: Value Chain and Actors

Country A
- Storage
- Demand
- Trader
- Producer
- Hydrogenator
- Liquefier

Country B
- Storage
- Demand
- Regasifier
- LH2 Ships
- LNH3 Ships
- Dehydrogenator

Producer

IAEE 2021