Global Renewable Hydrogen Potentials for the TIAM Model

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IEK-3: Institute of Techno-Economic Systems Analysis
Agenda

- Methodology
- Results
  - Optimal energy system design for exporting countries
  - Comparison of global green hydrogen potentials
ETHOS: Energy Transformation Pathway Optimization Suite

Integrated Hourly Optimization

Renewable Energy Resources

Electricity transmission & distribution grids

Societal feasibility

Gas transmission grid

Technology Database

H₂ and PtX Infrastructure

Macroeconomics

Life Cycle Assessment

Buildings

H₂ global

Districts

Activity-based transport demand

From demand to load profile

Cost optimized energy systems

Regionalized via local demand and infrastructure

Transport sector
- Passenger
- Freight

Today 2030 2040 2050

JÜLICH Forschungszentrum
Design of Local Export Energy Systems for Each Export Region

Input: RES generation profiles

Onshore Generation

OFPV Generation

Output: Hydrogen cost-potential: LH₂ at export harbor

- **RES Potentials:**
  - Own calculations based on joint ETSAP-Germany project approach

- **FINE.Export:**
  - Energy system model for calculating hydrogen export systems
  - Minimizing total system cost
  - Based on FINE model framework within the ETHOS model suite from IEK-3 [1]

- **System boundaries:**
  - 28 countries with high RES potential
  - Period: 2020 – 2050 (10 years steps)

[2] Potentials from own calculations within ETSAP-Germany project
Structure of Each FINE.Export Model: Example Namibia

Regionalization: Federal state

Optimal trade-off between H₂-grid distance and best RES-technology

High accuracy of potential curve: 22 different generation time series for each region

Optimal curtailment and PV/ wind combination for each region

Regionalization:

Local electric grids

LH₂-storage

Liquefaction

Export

Electrolysis

Hydrogen

Electricity

Local demands considered later in TIAM model

RES: renewable energy source
Local Electrical Grids to Consider Subregional Electricity Infrastructure

- Postprocessing of electricity grid costs within energy system regions
- Heuristic approach:
  1. Clustering of neighboring installations to parks
  2. Minimum spanning trees represents local electrical grid (Dijkstra)

Complete process chain for hydrogen export considered

Example: Ireland
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Wind Countries: German Green Hydrogen Potential

- German hydrogen from combining PV + onshore wind (30 - 50% PV and 70 - 50% wind energy)
- Biggest cost share is RES (2020: 70%, 2050: 60%)
- Local costs decreasing from 150 €/MWh (5 €/kg\(_{H_2}\)) in 2020 to 90 €/MWh (2.7 €/kg\(_{H_2}\)) in 2050
- Total potential ca. 520 TWh/a

RES: Renewable energy source, PV: photovoltaic, TOTEX: total expenditures
Solar Countries: Libyan Green Hydrogen Potential

- Libyan hydrogen PV dominated (> 90% PV energy)
- Despite good PV potential (3 ct/kWh in 2050) cost share of > 40 - 45%
- Low cost: ~4.0 €/kg$_{H_2}$ (2020) and ~2.1 €/kg$_{H_2}$ (2050)
- High potential: > 160 PWh/a only for Libya
  - U.S. primary energy consumption 2021: 28.52 PWh/a [1]

RES: Renewable energy source, PV: photovoltaic, TOTEX: total expenditures [1]
https://www.eia.gov/energyexplained/us-energy-facts/
Increasing Full Load Hours of Electrolysis by 80% due to RES Curtailment in India

Flexibility to balance volatile RES:
1. Batteries
2. Spatial compensation of generation fluctuations with electrical grid
3. Optimal Curtailment
   - Preferred option from energy system view

![Graph showing average full load hours in India, 2050](image)

Capacity of Renewables at 22 PWh Hydrogen Export
- 319 GW
- 3434 GW

RES: Renewable energy source, PV: photovoltaic
Increasing Full Load Hours of Electrolysis by 80% due to RES Curtailment in India

Flexibility to balance volatile RES:
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 ▪ Preferred option from energy system view

RES: Renewable energy source, PV: photovoltaic

Curtailment for even load on electrolysis:
39% capacity, 7% energy
Low-Cost Large-Scale Hydrogen Generation From Open-Field Photovoltaic

- All low-cost hydrogen countries (< 70 EUR/MWh) based on PV only
  - No utilization of onshore wind for PEM FLH increase
- Countries with cheap wind potentials still utilize > 57% PV
- PV could be very relevant for large scale green hydrogen production
- Still competitive onshore locations exist

PEM: Proton exchange membrane fuel cell, FLH: full load hours
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Global Map of Hydrogen Export Costs 2050

Lowest costs in European energy systems from wind in northern Europe (< 80 EUR/MWh)

Lowest costs < 70 EUR/MWh in solar regions

OFPV: Open field PV, Source: ETSAP-D project results
Hydrogen Export Curves for Each TIAM Region in 2050

- Total potentials for 28 countries: 1,540 PWh/a
- Nearly 9x world primary energy consumption in 2019 [1]
- Middle East, Africa and South America could provide total world primary energy at low costs
- ~ 100 PWh/a of hydrogen at 2 EUR/kg in 2050
- >85% from Middle East Asia (MEA)

*selected countries from: Western Europe (WEU), Korea (KOR), Japan (JPN), Germany (DEU), Eastern Europe (EEU), India (IND), USA, Former soviet union (FSU), China (CHN), Mexico (MEX), Canada (CAN), Middle East Asia (MEA), Africa (AFR), Central South America (CSA), Australia New Zealand (ANZ), Other developing Asia (ODA) [1] https://ourworldindata.org/energy-production-consumption
Potential H₂ Demand Regions Bear Their Own Promising H₂ Potentials

- Potential hydrogen demand centers with interesting own hydrogen potentials:
  - India: 64 EUR/MWh (solar)
  - USA: 75 EUR/MWh (solar)
  - Ireland, Great Britain and Iceland: 80 EUR/MWh (onshore wind potentials)

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Countries with Small Potentials Still Could use Domestic Hydrogen

- Smaller industrialized countries:
  - EEU: Bulgaria, Estonia, Poland
  - WEU: Great Britain, Ireland, Iceland, Norway
- Comparable smaller potentials (1% of global potentials)
- Cost starting from nearly 80 to roughly 90 EUR/MWh
- Although more expensive than global optimal regions still interesting potentials:
  - Local use: decrease of cost due to leaner domestic infrastructure than needed for export (max -30%)
  - No shipping costs
  - No energy dependency

German primary energy consumption: 3387 TWh/a [1]

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Minor Impact of Local Electricity Demand

- Local electricity demands of 2020 [1] reduce the potential by 3%
- Nearly no impact for African continent with current electricity demand
- Pure technical potentials are unexploitable huge and may face societal restrictions

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Development of Green Hydrogen Costs: 2020 to 2050

- Largest drop from 2020 to 2030
  - - 40 EUR/MWh
- First hydrogen potentials below 3 EUR/kg in 2030
- First hydrogen potentials below 2 EUR/kg in 2040
- Cost reduction (2020 → 2050)
  - Main drivers are reduction in PV and electrolysis costs
- Bigger cost reduction in PV regions than in onshore wind regions

Cost at 20% max. export

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Key Take Aways

- Technical green hydrogen potentials are huge (1,540 PWh/a in 28 countries).
- Significant amount of hydrogen costs below 2 EUR/kg in 2050 (100 PWh/a).
- Electricity generation and electrolysis have the highest impact on cost (~70%).
- Sun-rich regions dominate cheap hydrogen production.
- North Africa / Middle East could play an important role for future hydrogen imports.
Thank you!

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Backup
Local Green Hydrogen Production Account for 70% of the Export Cost

Photovoltaic dominant energy systems:
- About 70% of the cost from electricity generation and electrolysis in 2050
  - RES: 45±5%
  - Electrolysis: 25±5%
- Share of grid and pipeline cost up to 15-20%
- Liquefaction cost share low (<3%) due to scaling effects for large H₂ supply systems

RES: Renewable energy source, PEM: Proton exchange membrane fuel cell, PV: photovoltaic
Wind Regions Have a Higher RES Cost Share and Higher Cost Deviations

Wind dominant energy systems:

- Also about 70% of the cost from electricity generation and electrolysis in 2050
  - RES: 55±5% (PV: 45%)
  - Electrolysis: 15±5% (PV: 25%)
- Impact of grid and pipeline up to 15-20% (as PV)
- Liquefaction cost share low (<3%) due to scaling effects for large energy systems (as PV)
- Generally larger increase of cost

RES: renewable energy source
### Backup: Cost Assumptions Hydrogen Infrastructure

<table>
<thead>
<tr>
<th></th>
<th>Capex [EUR/kW(h)]</th>
<th>OPEX</th>
<th>Lifetime</th>
<th>Source</th>
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<tbody>
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<td></td>
<td>2020</td>
<td>2030</td>
<td>2040</td>
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<tr>
<td>Onshore</td>
<td>1,257</td>
<td>1,137</td>
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<td>OFPV</td>
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<td>395</td>
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<td>PEM</td>
<td>792</td>
<td>616</td>
<td>506</td>
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<td>Batteries</td>
<td>226</td>
<td>173</td>
<td>166</td>
<td>159</td>
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<tr>
<td>Liquefaction</td>
<td>610.57 MEUR/GW$^{-0.34}$ * (size)$^{-0.34}$</td>
<td>4</td>
<td>20</td>
<td>[4]</td>
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# Country Definition for the ETSAP Project

<table>
<thead>
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<th>TIMES-TIAM Region</th>
<th>Countries</th>
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<tr>
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<td>Libya, Namibia</td>
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<td>Other Developing Asia</td>
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<td>United States of America</td>
<td>United States of America</td>
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<tr>
<td>Western Europe</td>
<td>Great Britain, Iceland, Norway</td>
</tr>
</tbody>
</table>
Land Eligibility Approach considers >40 criteria for determining useable land area

- Land eligibility specifies available areas for onshore wind / open field PV
- > 40 Constraints:
  - Sociopolitical
  - Physical
  - Conservation
- Avoidance of land use conflict:
  - No usage of croplands / pastures for OFPV
  - Full exclusion of nature protected areas
  - 1 km distance of wind turbines to cities
  - Calculated for all 28 global regions

LEA: land eligibility approach, OFPV: open field photovoltaic [Picture] Ryberg et al..
“Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe”. Energies. 2018