Spatio-temporal Models for the Analysis of Future Energy Systems with Power to Hydrogen Pathways

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Institute of Electrochemical Process Engineering (IEK-3)
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The Task 38 of the IEA HIA
Power-to-Hydrogen and Hydrogen-to-X: System Analysis of the techno-economic, legal and regulatory conditions

Over 50 experts from 34 organizations in 15 countries

Major objectives:
- To provide a comprehensive understanding of the various technical and economic pathways for power-to-hydrogen applications in diverse situations
- To provide a comprehensive assessment of existing legal frameworks
- To provide business developers and policy makers with general guidelines and recommendations that enhance hydrogen system deployment in energy markets

The Task 38 of the IEA HIA  
**Power-to-Hydrogen and Hydrogen-to-X:**  
System Analysis of the techno-economic, legal and regulatory conditions

<table>
<thead>
<tr>
<th>Subtask</th>
<th>Subtask Name</th>
<th>Subtask Leader</th>
<th>Subtask Activities</th>
</tr>
</thead>
</table>
| 1       | Management, strategy and communication | Paul Lucchese and Christine Mansilla, CEA, France | - Involving new experts  
- Coordination (meeting organization, private website update, ST/TF activity follow-up)  
- Interfacing (IEA, HyLaw, Task 36, CEN/CENELEC) |
| 2       | Mapping and review of existing demonstration projects | Joris Proost, Université Catholique de Louvain, Belgium | - Review of existing databases  
- Proposal of a roadmap |
| 3A      | Review and analysis of the existing techno-economic studies on PtH HtX | Martin Robinius, Forschungszentrum Jülich, Germany | - Literature review and analysis  
- Database establishment |
| 3B      | Review of the existing legal context and policy measures | Francesco Dolci, JRC, European Commission | - Review of existing legal frameworks and policy measures  
- Database establishment for mapping relevant national legislation |
| 4       | Systemic approach | Sheila Samsatli, University of Bath, United Kingdom | - Analysis of energy system models  
- Outlook for hydrogen from a system perspective |
| 5       | Case studies | Gema Alcalde and Carlos Funez, Centro Nacional del Hidrógeno, Spain | - Identification and analysis of relevant case studies |
Who we are

- Process and Systems Analysis (VSA)
  Head of Department: Dr.-Ing. Martin Robinius

Jochen Linßen
Renewable Energies, and Storage

Areas of Expertise VSA:

- Dr.-Ing. Peter Markewitz
  Residential Sector

- Dr.-Ing. Thomas Grube
  Industry

Transport
- The IEA HIA Task 38
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The overall GHG emission goals of Germany require a holistic transformation of all sectors.

GHG emissions in Germany since 1990 [1]

<table>
<thead>
<tr>
<th>Year</th>
<th>Power Sector</th>
<th>Industry and commerce</th>
<th>Residential</th>
<th>Mobility</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>1000 Mt</td>
<td>800 Mt</td>
<td>600 Mt</td>
<td>400 Mt</td>
<td>200 Mt</td>
</tr>
<tr>
<td>2010</td>
<td>800 Mt</td>
<td>600 Mt</td>
<td>400 Mt</td>
<td>200 Mt</td>
<td>100 Mt</td>
</tr>
</tbody>
</table>

Goals of the BRD in reference to 1990 [2]

- 2020: 60% reduction
- 2030: 45% reduction
- 2040: 30% reduction
- 2050: 5-20% reduction

GHG emission reduction per sector 1990 to 2013 [1]

- Others: 43%
- Industry/commerce: 34%
- Residential: 21%
- Power Sector: 15%
- Mobility: 3%

The mobility sector lags behind in comparison to the achieved emission reductions of the other sectors.

The National Climate Action Plan 2016

<table>
<thead>
<tr>
<th></th>
<th>1990 tCO₂eq</th>
<th>2014 tCO₂eq</th>
<th>2014 vs. 1990</th>
<th>Goals 2030 tCO₂eq</th>
<th>Goals 2030 vs. 1990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion</td>
<td>466</td>
<td>358</td>
<td>- 23,2 %</td>
<td>175 - 183</td>
<td>62 – 61 %</td>
</tr>
<tr>
<td>Buildings</td>
<td>209</td>
<td>119</td>
<td>- 43,1 %</td>
<td>70 - 72</td>
<td>67 – 66 %</td>
</tr>
<tr>
<td><strong>Transport</strong></td>
<td>162</td>
<td>160</td>
<td>- 1,2 %</td>
<td><strong>95 - 98</strong></td>
<td><strong>42 – 40 %</strong></td>
</tr>
<tr>
<td>Industry</td>
<td>283</td>
<td>181</td>
<td>- 36 %</td>
<td>140 - 143</td>
<td>51 – 49 %</td>
</tr>
<tr>
<td>Agriculture</td>
<td>88</td>
<td>72</td>
<td>- 18,2 %</td>
<td>58 - 61</td>
<td>34 – 31 %</td>
</tr>
<tr>
<td>Others</td>
<td>39</td>
<td>12</td>
<td>- 69 %</td>
<td>5</td>
<td>87 %</td>
</tr>
<tr>
<td><strong>Summe</strong></td>
<td><strong>1248</strong></td>
<td><strong>902</strong></td>
<td>- 27,7 %</td>
<td><strong>543 - 562</strong></td>
<td><strong>56 – 55%</strong></td>
</tr>
</tbody>
</table>


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VSA Highlights

1 Power-to-Steel [1]

2 Aggregated optimization model for industry and mobility sectors [2]


4 Flexible hydrogen supply model [4]


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The Year 2050 – Energy Concept 2.0
Assessment based on municipal level and an hourly resolution of grid load and RES feed-in

**Power-Sector**

### RES power [GW | TWh]:
- onshore: 170 | 350;
- offshore: 59 | 231;
- PV: 55 | 47;
- hydro: 6 | 21;
- bio: 7 | 44

### Further assumptions:
- grid electricity: 528 TWh;
- imports: 28 TWh;
- exports: 45 TWh;
- pos. residual: natural gas

### “Copper plate“ & 40 GWh pumped hydro:
- 191 TWh (→ 4.0 million t\(_{\text{H}_2}\))

### Grid capacity constraints considered:
- 293 TWh (→ 6.2 million t\(_{\text{H}_2}\))

### RES: Renewable Energy Sources

**Residual load** = **Load** - **∑ RES**

**(Example PV only)**

**Conventional Power Plants**

**Electrical Grid**
- 380 and 220 kV

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Linking the Power and Transport Sector

Positive residual energy

Negative residual energy
(Surplus)

Residual energy [MWh/km²]

-3000000 to -2500
-2500 to -1700
-1700 to -1200
-1200 to -830
-830 to -460
-460 to -120
-120 to 175
175 to 545
545 to 1535
1535 to 50600
Energy Concept 2.0
Assessment based on county level

<table>
<thead>
<tr>
<th>H₂ Demand/a</th>
<th>FCV [kg/100 km]:</th>
<th>0.92 (2010) → 0.58 (2050) [1], linear decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FCV fleet:</td>
<td>curve fit; until 2033 according to [2]; maximum share in 2050: 75 % of German fleet</td>
</tr>
<tr>
<td></td>
<td>Further assumptions:</td>
<td>14,000 km annual mileage 12 years lifetime; total vehicle stock: 44 million cars</td>
</tr>
<tr>
<td></td>
<td>Peak annual H₂ demand:</td>
<td>2.93 million tₕ₂ (2052) (Surplus 2050 Copper plate scenario → 4.0 million tₕ₂)</td>
</tr>
</tbody>
</table>

**S-Curve based on:**
- Target is 75 % of total passenger cars are FCV → 32.9 million FCV in 2050
- Reference points are based on H₂Mobility

## Energy Concept 2.0
### Assessment based on county level

<table>
<thead>
<tr>
<th>Results</th>
<th>Description</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ sources</td>
<td>28 GW electrolysis power in 15 districts in Northern Germany</td>
<td>15 billion</td>
</tr>
<tr>
<td>H₂ sinks</td>
<td>9,968 refueling stations with averaged sales of 803 kg/d</td>
<td>20 billion</td>
</tr>
<tr>
<td>H₂ storage</td>
<td>48 TWh (incl. 60 day reserve)</td>
<td>8 billion</td>
</tr>
<tr>
<td>Pipeline invest [3]</td>
<td></td>
<td>6.7 billion</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>LCOE Onshore: 5.8 ct/kWh</td>
<td></td>
</tr>
<tr>
<td>Total H₂ cost (pre-tax)</td>
<td></td>
<td>17.5 ct/kWh WACC: 8 %</td>
</tr>
</tbody>
</table>

### Results Diagram
- Neg. RL (Surplus)
- High Hydrogen Demand
- Transmission
- Hubs
- Distribution


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Cost Comparison of Power to Gas Options – Pre-tax
Hydrogen for Transportation with a Dedicated Hydrogen Infrastructure is Economically Reasonable

CAPEX via depreciation of investment plus interest
- 10 a for electrolysers and other production devices
- 40 a for transmission grid
- 20 a for distribution grid and refueling stations
- Interest rate 8.0 % p.a.

Other Assumptions:
- 2.9 million t\textsubscript{H2}/a from renewable power via electrolysis
- Electrolysis: $\eta = 70 \%_{\text{LHV}}$, 28 GW; investment cost 500 €/kW
- Methanation: $\eta = 80 \%_{\text{LHV}}$

[1] Energy Concept 2.0

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Impact of time series aggregation on optimal energy system design\[1\]

Considered residential supply systems

Prediction error of the system cost for different number of typical days

Go to: https://github.com/FZJ-IEK3-VSA/tsam

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Optimization

**Investigated system**
- Eligible land: For wind turbines, pipelines, and salt caverns
- Weather data: Wind speeds and solar radiation
- Demand data: For electricity and hydrogen, resolved on the district level
- Techno-economic data: Cost parameters depending on the technology design

**Methodology**
- Spatio-Temporal Optimization
  - \( \min \) Total annual costs
  - \( s.t. \) demand & technical constraints are considered
- Complexity reduction
  - Time series aggregation
  - Decomposition algorithms
  - Network reduction
- Thermodynamic modelling
  - Pressure drop along pipeline
  - Technology design and determination of operating limits
- Case studies
  - “The value of X” analyses (X not included in superstructure)
  - Sensitivity analyses

**Output**
- Energy system’s cost
  - Capital and operational cost contribution from each technology
- Structure and design
  - Placement and size of each technology for each considered region
- Operation
  - Operation modes/inventories of the technologies
- Recommendations
  - Recommend feasible and cost-effective scenarios
  - Point out value of key technologies

Figures from:
Optimization of a Future Energy System for “Power-to-Mobility” and “Power-to-Industry” Applications in Germany

Investigation of a green field scenario for a Power-to-Mobility (2.9 Mio. t\textsubscript{H2}/year) and Power-to-Industry (1.1 Mio. t\textsubscript{H2}/year) applications in Germany*.

**SELECTED RESULTS\textsuperscript{[1]}**

Even when adding distribution costs (3.4 €/kg\textsubscript{H2}), costs are below current hydrogen price (9.5 €/kg\textsubscript{H2}) at German fueling stations.

Value of salt caverns in the energy system:
The costs increase by 1.5 €/kg\textsubscript{H2} if the construction of salt caverns is prohibited during optimization.

\* Technology options: Onshore wind turbines, electrolyzers, salt caverns, vessels, pipelines.

Demands: PtM 2.9 Mio. t\textsubscript{H2}/year, PtI (1.1 Mio. t\textsubscript{H2}/year), no electricity demand.

Thank you for your attention
Process and Systems Analysis (VSA)

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