Country Wide Infrastructure for Zero Emission Transportation

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  Residential & Storage solutions

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Methodology

Hydrogen Demand Potential

Technology Diffusion Scenarios

Demand Localization

Introduction phase

2020 2035 2050

Penetration rate %

Supply Chain Development

Hydrogen Supply Chain Analysis

Electrolysis

Mobility:
FCEVs, Bus, Train, LDV, HDV

Industry:
Forklifts, Methanol, Ammonia, Refinery

GH₂ tank GH₂ trailer Fuel station

LH₂ tank LH₂ trailer

GH₂ cavern GH₂ pipeline

FCEV: Fuel cell electrical vehicle, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle,
GH₂: Gaseous Hydrogen, LH₂: Liquid Hydrogen
## Methodology: Criteria for Hydrogen Demand Distribution at the County Level

<table>
<thead>
<tr>
<th>Local bus</th>
<th>Regional train</th>
<th>Passenger car</th>
<th>LDV/HDV</th>
<th>MHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>Diesel train lines</td>
<td>Population</td>
<td>Loaded road freight mass</td>
<td>Logistic space</td>
</tr>
<tr>
<td>Federal support</td>
<td>Federal support</td>
<td>Population density</td>
<td>Unloaded road freight mass</td>
<td>Freight intensity</td>
</tr>
<tr>
<td>Income</td>
<td>Fuel stations</td>
<td>Income</td>
<td>Fleet size</td>
<td></td>
</tr>
</tbody>
</table>

- HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3)
Methodology: Hydrogen Supply Chain Analysis

- General model to calculate supply chain costs based on source-sink distance and demand
- Geo-spatial analysis of relevant infrastructure constraints
- Investigation of supply pathways for different supply and demand structures

GH\textsubscript{2}: Gaseous hydrogen
LH\textsubscript{2}: Liquid hydrogen
LOHC: Liquid organic hydrogen carrier
HDV: Heavy duty vehicle
LDV: Light duty vehicle
MHV: Material handling vehicle (forklift class 1-3)

What are the impacts on different market segments?
Market Choice: Idealized Mix of Demand Sectors

- **Assumptions for introduction phase:** LCOE = 6 ct/kWh, CAPEX$_{PEM}$ = 1500 €/kW, $\eta_{LHV,2018}$ = 67%, Storage = 60 days

- **Approach:**
  - Introduction phase: up to 400 kt p.a.
  - Each technology can be considered either with a demand of 0 or 50 kt p.a.
  - Evaluate all $2^8$ combinations
  - Calculate the gap to the conventional system for a given market combination

Choice of demand market has a significant impact on system cost

<table>
<thead>
<tr>
<th>Fuel</th>
<th>pre-Tax</th>
<th>after-Tax*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>8 ct/kWh</td>
<td>15,2 ct/kWh</td>
</tr>
</tbody>
</table>


* Including energy related taxes (mineral oil tax), excluding value-added tax
Market Choice: Single Markets in the Introduction Phase (50 kt p.a.)

- Assumptions for **introduction phase**: LCOE = 6 ct/kWh, CAPEX_{PEM} = 1500 €/kW, η_{LHV,2018} = 67%, Storage = 60 days

- **Assumption**: commercial fleets with access to commercial HRS\(^1\) do not fuel in public HRS

- **Public HRS** introduction strategy requires significantly higher upfront investment per vehicle

- Transportation sectors with **predictable demand and MHV** enable the cost gap to conventional fuels to be significantly reduced

\(^1\)28% of passenger cars and 56% HDV/LDV \[^1\]

*Including energy related taxes (mineral oil tax), excluding value-added tax

HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3)

HRS: Hydrogen Refueling Station  HSC: Hydrogen Supply Chain, HSC: Hydrogen Supply Chain

\[^1\]28% of passenger cars and 56% HDV/LDV [1]
What is the impact of market growth?
Market Penetration Scenarios

- **Scenario data** base for key technologies and application fields in the introductory phase
- Formulation of **exploratory** scenarios to analyze how hydrogen infrastructure costs might develop
- Formulation of **high, medium and low diffusion scenarios** for each hydrogen application depending on level of:
  - political support
  - economic incentives
  - technological progress
  - technology acceptance
  - willingness to pay for emission-free applications

Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3), Chemical industry: Ammonia, Methanol, Petrochemical industry
### Scenario and Input Parameters

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>WACC</td>
<td>8</td>
<td>%</td>
</tr>
<tr>
<td>LCOE</td>
<td>6</td>
<td>ct/kWh</td>
</tr>
<tr>
<td>Natural gas cost</td>
<td>4</td>
<td>ct/kWh</td>
</tr>
<tr>
<td>Imported H₂ cost</td>
<td>11.7 [1]</td>
<td>ct/kWh</td>
</tr>
<tr>
<td>Storage time</td>
<td>60 [2,3]</td>
<td>days</td>
</tr>
<tr>
<td>Max. electrolytic H₂ production</td>
<td>3160 [2]</td>
<td>kt/a</td>
</tr>
<tr>
<td>Electrolysis efficiency (2050)</td>
<td>70</td>
<td>%</td>
</tr>
<tr>
<td>Electrolysis investment (2023)</td>
<td>1500 [4]</td>
<td>€/kW</td>
</tr>
<tr>
<td>Electrolysis learning rate</td>
<td>20 [5]</td>
<td>%</td>
</tr>
<tr>
<td>Max. SMR H₂ production</td>
<td>96* [6]</td>
<td>kt/a</td>
</tr>
<tr>
<td>SMR efficiency</td>
<td>80 [7]</td>
<td>%</td>
</tr>
<tr>
<td>Fuel station learning rate</td>
<td>6 [8]</td>
<td>%</td>
</tr>
</tbody>
</table>

Regional train: non-electrified lines only, HDV: Heavy Duty Vehicle, LDV: Light Duty Vehicle, MHV: Material Handling Vehicle (Forklift Class 1-3), Chemical industry: Ammonia, Methanol, Petrochemical industry

#### Medium hydrogen demand scenario

- **Dominating technology:**
  - 2023 - 2030: **LDVs & HDVs, MHVs, public transport**
  - After 2030: **Passenger cars, chemical industry**

*5% of todays industrial hydrogen output*
Infrastructure Cost Development: Medium Scenario

- Very long distribution pipeline network incurs a high cost to the system
- Even at low total hydrogen demand (300 kt p.a.), hydrogen is cost-competitive with conventional fuels

**Hydrogen is cost-competitive with conventional fuels (after-tax) by 2024-2029**

* Benchmark = \((\text{gasoline cost } (8 \frac{ct}{kWh}) + \text{mineral oil tax } (7.2 \frac{ct}{kWh})) \times \frac{\eta_{\text{Fuel Cell}}}{\eta_{\text{ICE}}}\)

**Excluding value-added tax

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Summary and Conclusion
Summary and Conclusion

➢ High demand potential during the introduction phase for hydrogen applications with requirements for high utilization, fast fueling, long range and high power capacity:
  ▪ Regional non-electrified trains
  ▪ Local busses
  ▪ Forklifts of the class 1 to 3
  ▪ Heavy and light duty vehicles

➢ Focus on non-public fueling infrastructure significantly reduces the upfront costs of fuel stations and distribution

➢ Choice of demand market segment has a significant impact on the system cost

➢ Hydrogen is cost-competitive with conventional fuels (after-tax) by 2024-2029

Cost-competitive countrywide hydrogen infrastructures can be developed within 5-10 years of investment
Thank you for your attention!
Backup
Methodology: Criteria for Hydrogen Demand Distribution at the HRS Level

<table>
<thead>
<tr>
<th>Early phase</th>
<th>Sizes</th>
<th>Method</th>
<th>Max.</th>
<th>Linearly based on demand</th>
<th>Linearly among existing stations</th>
<th>Minimize investment</th>
<th>Based on commercial area</th>
<th>Minimize investment</th>
<th>Based on the commercial area</th>
<th>Based on the logistic area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus HRS</td>
<td>Train HRS</td>
<td>Public HRS: 700 bar</td>
<td>Non-Public HRS: 700 bar</td>
<td>Public HRS: 350 bar</td>
<td>Non-Public HRS: 350 bar</td>
<td>MHV HRS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>402</td>
<td>170</td>
<td>9800</td>
<td>7148</td>
<td>8000</td>
<td>2345</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predictable demand</td>
<td>Predictable demand</td>
<td>S, M, L, XL, XXL*</td>
<td>Predictable demand</td>
<td>S, M, L, XL, XXL*</td>
<td>Predictable demand</td>
<td>Predictable demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean fleet for regional adoption: 25</td>
<td>Mean fleet for regional adoption: 5</td>
<td>Only S until 10 % of FS**</td>
<td>Mean fleet for regional adoption: 50</td>
<td>Only S until 10 % of FS**</td>
<td>Mean fleet for regional adoption: 20</td>
<td>Mean fleet for regional adoption: 70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* S-size: 212 kg/d, M-size: 420 kg/d, L: 1000 kg/d, XL: 1500 kg/d, XXL: 3000 kg/d
** Widely adopted view in the literature regarding the percentage of existing fuel stations for AFVs to reach sufficient infrastructure coverage: 5 - 20% [1-4]