The Potential of Hydrogen for Future Energy Systems

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Hydrogen Storage in the Context of a Transforming Energy System

This presentation aims at identifying major vectors for mass markets and technologies.

Results may be different in niche markets.
Modern CO$_2$ Level Rise is Unmatched in Human History

400 ppm Level: last sustainedly reached 14-20 million years ago, Middle Miocene, 5-10 °C warmer than today, no Arctic ice cap, sea level 25- 40 m higher

DOI: 10.1126/science.1178296

Life Expectancy of a baby born today in DE:
100 years $\rightarrow$ 2115
**GHG Emissions Shares by Sector in Germany (2010)**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Emissions</th>
<th>Remedies (major vectors)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy sector</strong></td>
<td>37%</td>
<td></td>
</tr>
<tr>
<td>• Power generation</td>
<td>30%</td>
<td>22.5 % Renewables</td>
</tr>
<tr>
<td><strong>Transport (90% petroleum-based)</strong></td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td>• Passenger vehicles</td>
<td>11%</td>
<td>8.3 % <strong>Hydrogen</strong> / renewable power</td>
</tr>
<tr>
<td>• Trucks, buses, trains, ships, airplanes</td>
<td>6%</td>
<td>4.5 % Liquid fuel substitutes (biomass/ <strong>hydrogenation</strong>)*</td>
</tr>
<tr>
<td><strong>Residential</strong></td>
<td>11%</td>
<td></td>
</tr>
<tr>
<td>• Residential heating</td>
<td>11%</td>
<td>8.3 % Insulation, heat pumps etc.</td>
</tr>
<tr>
<td>(electricity in power generation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Industry, trade and commerce</strong></td>
<td>23%</td>
<td></td>
</tr>
<tr>
<td>• Industry</td>
<td>19%</td>
<td>9.5 % <strong>CO₂-capture</strong> from steel, cement, ammonia; <strong>hydrogen</strong> for <strong>CO₂-use</strong></td>
</tr>
<tr>
<td>• Trade and commerce</td>
<td>4%</td>
<td>25 % already cleaned-up since 1990</td>
</tr>
<tr>
<td><strong>Agriculture and forestry</strong></td>
<td>8%</td>
<td>78.1% clean-up</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Source: Emission Trends for Germany since 1990, Trend Tables: Greenhouse Gas (GHG) Emissions in Equivalents, without **CO₂** from Land Use, Land Use Change and Forestry. Umweltbundesamt 2011

Transport-related values: supplemented with Shell LKW Studie – Fakten, Trends und Perspektiven im Straßengüterverkehr bis 2030.

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Timeline for CO₂-Reduction and the Implication of TRL Levels

• **2050**: 80% reduction goal fully achieved

• **2040**: start of market penetration

• **2030**: research finalized for 1st generation technology

Development period: until 2040

Research period: until 2030

⇒ 15 years left for research => TRL 5 and higher

TRL 4 at least

This is not to say research at lower TRL levels is not useful, it will just not contribute to the 2050 goal
Intermittant Power Entails Overcapacity
Development of Renewables According to Current German Policy

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak excess power*</td>
<td>GW₁ₑ</td>
<td>22</td>
<td>55</td>
<td>90</td>
</tr>
<tr>
<td>Excess energy*</td>
<td>TWhₑ</td>
<td>2.5</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Minimum storage size**</td>
<td>TWh</td>
<td>0.9</td>
<td>6</td>
<td>12</td>
</tr>
</tbody>
</table>
Hydrogen Generation from Electric Power
Options for Water Electrolysis

**Alkaline electrolysis**
- Mature technology
- <3.6 MW stacks
- Plants <156 MW
- Ni catalysts
- 750 €/kW - 1000€/kW

**PEM - electrolysis**
- Development stage
- < 1 MW in development
- Pt and Ir as catalysts
- Simple plant design
- €1500@ 2015
- € 500@ 2030 (FZJ)

**Solid Oxide Electrolysis**
- Laboratory stage
- Very high efficiency
- Brittle ceramics
- Hence, slow scale-up
- Just cost estimations
Hydrogen Storage and Transmission Technology
Decouple Power and Energy for Long-term Storage

Assumption: storage may add about the same price tag to the energy delivered, be it
- Short-term storage, or
- Long-term storage

<table>
<thead>
<tr>
<th></th>
<th>Storage cycles / a</th>
<th>Relative allowable invest / kWh*</th>
<th>Energy required</th>
<th>Energy specific investment cost</th>
<th>Power required</th>
<th>Additional cost for conversion units (electrolyzer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term</td>
<td>100 - 1000</td>
<td>100%</td>
<td>some GWh</td>
<td>Batteries 100-200</td>
<td>some 10GW</td>
<td>none</td>
</tr>
<tr>
<td>Long-term</td>
<td>1 - 10</td>
<td>1%</td>
<td>some 1000 GWh</td>
<td>Salt cavern &lt; 1</td>
<td>some 10GW</td>
<td>500 €/kW</td>
</tr>
</tbody>
</table>

Disjunction of Power and Energy

Batteries: Power and energy scale linearly with unit size
Hydrogen: **Power** scales less than **energy**

Electrolyzers

Gas caverns
<table>
<thead>
<tr>
<th></th>
<th>Depleted oil / gas fields</th>
<th>Aquifers</th>
<th>Salt caverns</th>
<th>Rock caverns / abandoned mines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working volume [scm]</td>
<td>$10^{10}$</td>
<td>$10^8$</td>
<td>$10^7$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Cushion gas</td>
<td>50 %</td>
<td>up to 80 %</td>
<td>20 - 30 %</td>
<td>20 - 30 %</td>
</tr>
<tr>
<td>Gas quality</td>
<td>reaction and contamination with present gases, microorganism and minerals</td>
<td></td>
<td>saturation with water vapor</td>
<td></td>
</tr>
<tr>
<td>Annual cycling cap.</td>
<td>only seasonal</td>
<td></td>
<td>seasonal &amp; frequent</td>
<td></td>
</tr>
</tbody>
</table>
## Near-Surface Gas Storage Facilities

<table>
<thead>
<tr>
<th></th>
<th>Gas holders</th>
<th>Spherical gas vessels</th>
<th>Ground storage assemblies</th>
<th>Pipe storage facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum pressure [bar]</td>
<td>1.01 - 1.5</td>
<td>5 - 20</td>
<td>40 - 1000</td>
<td>20 - 100</td>
</tr>
<tr>
<td>Storage capacity [scm]</td>
<td>&lt; 6 x 10^4</td>
<td>&lt; 3 x 10^5</td>
<td>&lt; 1 x 10^4</td>
<td>&lt; 9 x 10^5</td>
</tr>
<tr>
<td>Invest/ storage capacity ‡ [€/scm]</td>
<td>?</td>
<td>20 - 50</td>
<td>50 - 180</td>
<td>20 - 50</td>
</tr>
</tbody>
</table>

‡ Estimated costs.
Liquid Organic Hydrogen Carriers (LOHC)

- Liquid, heterocyclic, aromatic hydrocarbon as carriers
- Hydrogenation: saturation of aromatic rings with hydrogen
- **Chemicals:** N-ethylcarbazole, toluene and other aromatics
- Degradation by formation of unintended by-products

- Hydrogen storage density: 6 - 8 wt% [1,2]
- Transportation cost $\approx 0.2 \text{ €/kg}_{H_2}$ via ship (5000 km) [3]
- Japan seeks produce $H_2$ in Patagonia and transport it home (distance $\approx 20,000$ km)
## Power Line and Gas Pipelines Compared

<table>
<thead>
<tr>
<th></th>
<th>380 kV overhead line</th>
<th>Natural gas pipeline §</th>
<th>Hydrogen gas pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>4 x 564/72 double circuit</td>
<td>DN 1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>p&lt;sub&gt;in&lt;/sub&gt; = 90 bar</td>
<td></td>
</tr>
<tr>
<td>Energy transport capacity</td>
<td>1.2 GW&lt;sub&gt;el&lt;/sub&gt;</td>
<td>16 GW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>12 GW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Investment cost in M€/km</td>
<td>1 - 1.5</td>
<td>1 - 2</td>
<td>1.2 - 3</td>
</tr>
</tbody>
</table>
Spatial Requirements for Transmission

Width of protective strips:
- 70 m
- 57 m
- 48 m
- 10 m


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An Energy Scenario Coupling Power and Transportation
Principle of a Renewable Energy Scenario with Hydrogen
Hydrogen as an Enabler for Renewable Energy

262 GW
(onshore, offshore & PV peak simultaneously)

84 GW
Electrolysis

80 GW
Grid Load

Curtailment regime
37% of power curtailment
sacrifices 2% of energy *

Electrolysis regime
Fill power gaps
w/ NG via CC & GT

Power regime

* modeled for DE based on inflated input of
renewables w/ weather data of 2010
Cost Reduction through Curtailment

Curtailed energy

- 7% of excess energy
- 2.5% of all renewable energy
- ≈ 50% reduction in investment cost

1000 h
### Scenario of the Energy System for Germany

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Onshore Wind Power</strong></td>
<td>Same number of wind mills as of end 2011 (22500 units) Repowering from Ø 1.3 MW to 7.5 MW units =&gt; Σ 167 GW Average nominal operating hours: 2000 p.a. ¹</td>
</tr>
<tr>
<td><strong>Offshore Wind Power</strong></td>
<td>70 GW (potential according to BMU 2011², Fino =&gt; 4000 h)</td>
</tr>
<tr>
<td><strong>Photovoltaik</strong></td>
<td>24.8 GW as status of 12/2011³, volatility considered</td>
</tr>
<tr>
<td><strong>Other Renewables</strong></td>
<td>Constant as of 2010⁴</td>
</tr>
<tr>
<td><strong>Excess Energy</strong></td>
<td>Water electrolysis $\eta_{\text{LHV}} = 70%$⁵; &gt; 1000 operating hours Pipeline transport + storage in salt caverns</td>
</tr>
<tr>
<td><strong>Transportation</strong></td>
<td>Hydrogen for fuel cell cars: cruising range 14900 km/a⁶, consumption 1kg/100km</td>
</tr>
<tr>
<td><strong>Residential Sector</strong></td>
<td>50% savings on natural gas as of 2010</td>
</tr>
<tr>
<td><strong>Back-up Power</strong></td>
<td>Open gas turbines; combined cycles &gt; 700 operating hours/a Part load considered by 15% reduction on nominal efficiency</td>
</tr>
</tbody>
</table>

¹ Average nominal operating hours: 2000 p.a.
² Potential according to BMU 2011
³ Volatility considered
⁴ Constant as of 2010
⁵ Water electrolysis efficiency
⁶ Hydrogen consumption for fuel cell cars
First Fuel Cell Vehicles in Market Introduction Phase

- **1994**: MB NECAR 1 (H₂)
  - **1999**: Honda FCX V1 (H₂)
  - **2002**: Honda FCX-V4: 1st FCV commercially certified *
  - **2004**: Clean Energy Partnership (D)
  - **2012/13**: Hyundai ix35 FCEV 1st manufact. plant
  - **2015**: Toyota Mirai 2nd series prod.

Fuel cell APUs for passenger cars, trucks, train, ships & airplanes

- **60s**: MB NECAR 1 (H₂)
- **70s**: Honda FCX V1 (H₂)
- **80s**: Honda FCX-V4: 1st FCV commercially certified *
- **90s**: Clean Energy Partnership (D)
- **2000s**: Hyundai ix35 FCEV 1st manufact. plant
- **2010s**: Toyota Mirai 2nd series prod.

Small series for demonstration projects

- **2001**: MB NECAR 5.2, methanol reformer
  - **2001**: GM Chevrolet S-10 gasoline reformer
  - **2006**: Cold start at -20°C (GM)
  - **2008-2009**: HT-PEM (Volkswagen)
  - **2002**: First FCV
  - **2009**: First Fuel Cell Vehicles in Market Introduction Phase

*First fuel-cell vehicle certified by the U.S. EPA and California Air Resources Board (CARB) for commercial use*

MB: Mercedes-Benz; GM: General Motors

All cars with PEFC except GM Electrovan with AFC

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Decrease of precious metal requirement in FCVs


Platinum in ICEs: 5-7 g/ vehicle
Progress in Volumetric Power Density and Mass-specific Power of FCV Stacks


Results

Total amount of electricity produced: 745 TWh
Vertical grid load: 488 TWh
Electricity for hydrogen production: 257 TWh => 5.4 mn tons H₂
Hydrogen fuel for about 30 mn cars
Installed power capacity = 3.3 x max. grid load
Harnessed electricity = 1.5 x vertical grid load

[Diagram showing energy sources: Wind 80%, Natural Gas 10%, PV 3%, Other RE 7%]
Minimum $H_2$ transmission costs as a function of $H_2$ flow and transport distance

Estimated seasonal storage capacity: 27 TWh_{LHV}

Storage capacity 60 day reserve: 90 TWh

Storage capacity until 2040 regularly over weeks and months: 40 TWh

(Pumped Hydro Power in Germany: 0.04 TWh_{e})

Seasonal storage capacity required: 9 bn scm

Existing NG-storage in Germany: 20.8 bn scm
thereof salt dome caverns in use: 8.1 bn scm
Salt cavern in construction/planned: 12.9 bn scm

Source: Sedlacek, R: Untertage-Gasspeicherung in Deutschland; Erdöl, Erdgas, Kohle 125, Nr.11, 2009, S.412–426.
Overview of Cost for a Renewable Hydrogen Infrastructure for Transportation

Additional gas and combined cycle power plants

Electrolyzers (84 GW)

Rock salt caverns 150 x 750,000 scm

Pipeline grid (43-59.000 km)

Fueling stations (9800)

Investment in bn €

0 5 10 15 20 25 30 35 40 45

24 42 4,5 19-25 20
## Cost Estimation of Battery Charging Infrastructure for Vehicles

### Data and Assumptions for Germany / Fast

<table>
<thead>
<tr>
<th></th>
<th>1 Million BEV</th>
<th>30 Million BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Percentage of private garages</strong></td>
<td>100%</td>
<td>60% – 37% ¹)</td>
</tr>
<tr>
<td><strong>Public charging stations per vehicle</strong></td>
<td>0.25–0.5</td>
<td>0.25–0.5</td>
</tr>
<tr>
<td><strong>Number Million units</strong></td>
<td><strong>Cost bn €</strong></td>
<td><strong>Number Million units</strong></td>
</tr>
<tr>
<td>Private charging (garage), 1,000 € each</td>
<td>1,0</td>
<td>1,0</td>
</tr>
<tr>
<td>Public charging stations, 6,500 € ²) each</td>
<td>0.25–0.50</td>
<td>1,6–3,3</td>
</tr>
<tr>
<td>Grid extension, 700 € each</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td><strong>Total in bn €</strong></td>
<td><strong>2,6–4,3</strong></td>
<td><strong>171–264</strong></td>
</tr>
</tbody>
</table>


Information used: 63% of households in DE (39,1 mn @ 2009) dispose of a garage / parking space; thereof 61% are used by the owner

²) Data from: Zweiter Bericht der Nationalen Plattform Elektromobilität. Nationale Plattform Elektromobilität (NPE), Berlin, 2011; Information used: cost for charging station, metering and automated settlement, installation of charging station, connection to electric distribution grid, designation of e-parking space, cost for right of dedicated use (average values, respectively)
Hydrogen for Transportation

- W/o back-up power plants
- Including grid cost
- Curtailment of 25% of peak power; \( \Delta W = -2 \%

Cost Comparison of Power to Gas Options – Pre-tax

Hydrogen or Methane to be Fed into Gas Grid

- OPEX
- Interest cost
- Depreciation cost
- Energy cost
- H2 appreciable cost
- Gasoline pre-tax

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
- Interest rate 8 % p.a.

Other Assumptions:
- 5.4 million t\( \text{H}_2 \)/a from renewable power via electrolysis
- Electrolysis: \( \eta = 70 \%_{\text{LHV}} \), 84 GW; investment cost 500 €/kW
- Methanation: \( \eta = 80 \%_{\text{LHV}} \)
- Grid fee for power transmission: 1.4 ct/kWh\( _e \) [1]

* Appreciable cost @ half the specific fuel consumption

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Market Introduction:
Cost Evolution for Full-fledged Pipeline and 100% Fueling Stations w/ Incremental Installation of Electrolyzers and Storage Capacities

Pre-tax

Cost brake-down at 100 %
- O&M
- Capital charge
- Capital
- Feedstock
- Gasoline (reference)

28 million passenger cars*
17 million passenger cars*

break-even pre-tax

Total cost**, ct/kWh
break-even pre-tax

Economical investment

0% 20% 40% 60% 80% 100%
H₂ delivered, million t/a

Cost of 28 million passenger cars at 100%

Mix of passenger cars (92.5 %), light trucks (6.8 %) and buses (0.6 %)

** Total cost = feedstock + capital depreciation + capital interest + O&M
*** Wind energy input 6 ct/kWh, 8% capital interest rate

16 (at 1.0 kg/100km)
17 million passenger cars*
Market Introduction:
Cost Evolution for Full-fledged Pipeline Grid and Fueling Stations w/ Incremental Installation of Electrolyzers and Storage Capacities
Tax Considered (100% on-top of fuel cost)

Cost brake-down at 100 %

- Total cost = feedstock + capital depreciation + capital interest + O&M

**Wind energy input 6 ct/kWh, 8% capital interest rate**

* Mix of passenger cars (92.5 %), light trucks (6.8 %) and buses (0.6 %)

**Total cost = feedstock + capital depreciation + capital interest + O&M**
The Systems Analysis Team

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Thank You for Your Attention!

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