Brainstorming Workshop
Sustainable methanol:
An alternative green fuel for the future
22./23.11.2011, IASS, Potsdam

Experimental Data on
Renewable Methanol/Methane Generation
from Atmospheric CO$_2$ in Pilot Plants

Michael Specht, Ulrich Zuberbühler, Andreas Bandi

Centre for Solar Energy and Hydrogen Research (ZSW), Stuttgart
Centre for Solar Energy and Hydrogen Research (ZSW): New Energy Technologies

- Applied Research & Development
- Close Cooperation with Industry and Universities
- 25 Million € Turnover, 200 Employees

- Photovoltaic – Thin Film Technologies (CIS) & Application Systems
- Renewable Fuels and Processes
- Fuel Cells – Technology, Systems, Test Centre
- Batteries & Super Capacitors – Materials, Systems, Qualification
- Systems Analysis and Policy Consulting

Stuttgart  Widderstall  Ulm
C-Resource: “CO₂ from Air” → “CO₂ from Biogas”

Fuel: MeOH → SNG
Agenda Part I: Power-to-Methanol / CO\textsubscript{2} from Air
Agenda Part II: Power-to-Gas (P2G)

Goal (CO\textsubscript{2} from Air)
Concept 1996 (Batch Mode)
Results 1996
Concept 2009 (Continuous Mode)
Results 2009
Conclusions

Goal (P2G)
SNG Production Routes from RE
P2G Concept
CO\textsubscript{2} Resources
Conversion Efficiency
Environmental Benefits
Results from 25 kW\textsubscript{e} P2G Pilot Plant
Conclusions / Next Steps

SNG: Substitute Natural Gas
RE: Renewable Energy

Fraunhofer IWES
SOLARFUEL
Goal:
Energy System with Closed Carbon Loop
Goal:
Carbon-Based Fuels via H$_2$/CO$_2$ Route

\[
\begin{align*}
\text{CO}_2 + 3 \text{H}_2 & \rightarrow - \text{CH}_2 - + 2 \text{H}_2\text{O} \\
\Delta H_{298} &= -119 \text{ kJ/mol} \\
\text{CO}_2 + 3 \text{H}_2 & \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \\
\Delta H_{298} &= -50 \text{ kJ/mol}
\end{align*}
\]
# Thermodynamic Efficiency Calculations for the Conversion of Syngas to Synfuels

<table>
<thead>
<tr>
<th></th>
<th>SYNGAS CO / H₂</th>
<th>SYNGAS CO₂ / H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta H_{298}$ [kJ/mol]</td>
<td>$\eta = 1 - \frac{\Delta H_{298}}{LHV_{Syngas}}$</td>
</tr>
<tr>
<td>CH₃ OH</td>
<td>-90,625</td>
<td>0,882</td>
</tr>
<tr>
<td>CH₃ O CH₃</td>
<td>-204,932</td>
<td>0,866</td>
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<tr>
<td>CH₄</td>
<td>-206,158</td>
<td>0,796</td>
</tr>
<tr>
<td>C₅ H₁₂</td>
<td>-802,865</td>
<td>0,803</td>
</tr>
</tbody>
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SNG: Substitute Natural Gas
RE: Renewable Energy
Concept: Methanol from Atmospheric CO₂
“Artificial Photosynthesis”

- **Absorber**
- **Electrodialysis**
- **Stripper**
- **Electrolysis**
- **Methanol Synthesis**

**Renewable Energies**
- Wind
- Hydropower

**Reagents**
- KOH
- H₂SO₄
- K₂CO₃

**Products**
- Methanol
- CO₂
- H₂
Principle Flow Sheet: Methanol from Atmospheric CO$_2$ with Electrodialysis Regeneration

**Electrodialysis**

K$_2$SO$_4$ + 2H$_2$O $\rightarrow$ 2KOH + H$_2$SO$_4$

**CO$_2$-separation**

K$_2$CO$_3$ + H$_2$SO$_4$ $\rightarrow$ H$_2$O + CO$_2$ + K$_2$SO$_4$

**MeOH-Synthesis**

CO$_2$ + 3H$_2$ $\rightarrow$ CH$_3$OH + H$_2$O
CO$_2$ + H$_2$ $\rightarrow$ CO + H$_2$O
CO + 2H$_2$ $\rightarrow$ CH$_3$OH

**Reactor:**
- 50 – 100 bar
- 250 – 280 °C
- Di = 66.1 mm
- VKat ca. 300 ml

**Catalyst:**
- Cu/ZnO-based

**Air:**
- 1600 m$^3$/kgCO$_2$
- Fluegas >5% CO$_2$: 10 m$^3$/kgCO$_2$

**Electrolysis**

2H$_2$O $\rightarrow$ 2H$_2$ + O$_2$

**Synthesis offgas**

Raw methanol: Ca. 0.2 kg/h

**Exhaust**

KOH

**Synthesis**

O$_2$

K$_2$CO$_3$

H$_2$SO$_4$

H$_2$

H$_2$O

$\text{H}_2/\text{CO}_2=3$
**CO₂ from Atmosphere with Caustic Air Scrubber**

“Artificial Photosynthesis”

Design Data of Absorber Column:
- Height: 3.5 m
- Diameter: 0.5 m
- Air Throughput: 1000 m³_N/h
- CO₂ Absorption: ca. 70 % (1 mol KOH)
Chemical Reactions in Absorber / Stripper / Electrodialysis (ED) Unit

Absorber:

\[ 2 \text{KOH} + \text{CO}_2 \rightarrow \text{K}_2\text{CO}_3 + \text{H}_2\text{O} \]

Stripper:

\[ \text{K}_2\text{CO}_3 + 2 \text{KHSO}_4 \rightarrow 2 \text{K}_2\text{SO}_4 + \text{CO}_2 + \text{H}_2\text{O} \]

Electrodialysis Unit:

\[ \text{K}_2\text{SO}_4 + \text{H}_2\text{O} \rightarrow \text{KHSO}_4 + \text{KOH} \]
Regeneration of Scrubbing Liquid and Acidic Solution: Bipolar Membrane Electrodialysis of $\text{Na}_2\text{SO}_4$ Solution
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SOLARFUEL
Results: CO₂ from Atmosphere via Caustic Air Scrubber

Goal → absorber with low pressure drop

Absorption column:
• Gas velocity: ca. 1 m/sec
• Fluid load: 10 m³/(m²h)
• Pressure drop: ~ 1 mbar/m

Overall pressure drop: ca. 5 mbar
⇒ ca. 50 kJₑ/mol₃CO₂
Incl. humidification and pumps:
80 kJₑ/mol₃CO₂

Result from scrubber operation:
94 m²/(mol₃CO₂ sec)
(Mellapak 250, 72 % Absorption)

Regeneration:
• Electrodialysis: 275 kJₑ/mol₃CO₂
• Limestone-Process: 244 kJₜₘ/mol₃CO₂
• MEA Prozess: ~ 200 kJₜₘ/mol₃CO₂
(CO₂ from flue gas)

Incl. humidification and pumps: 80 kJₑ/mol₃CO₂

For 100 MWₑinput power:
→ Absorber ca. 80 m Ø
or 10 Absorber á 25 m Ø

LHVMeOH: - 639 kJ/molMeOH
measured
calculated
Methanol Synthesis from H₂/CO₂: Reaction Conditions / Results

\[ \text{CO} + 2 \text{H}_2 \rightarrow \text{CH}_3\text{OH} \quad \Delta H = -92 \text{ kJ/mol} \]

\[ \text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \quad \Delta H = -50 \text{ kJ/mol} \]

**Reaction Conditions:**
250 - 280°C
50 - 100 bar
Cu / ZnO-based Catalyst

**Results:**
SV: 8000 \( \frac{\text{l}_{\text{syngas}}}{\text{l}_{\text{cat}}\text{h}^{-1}} \)
0.7 \( \frac{\text{kg}_{\text{MeOH}}}{\text{l}_{\text{cat}}\text{h}^{-1}} \)
Methanol Synthesis from $\text{H}_2/\text{CO}_2$: Energetic Efficiency (Power-to-Methanol)

Renewable Methanol for Road Transport produced from $\text{H}_2$ and Atmospheric $\text{CO}_2$ at ZSW in 1996

Energetic Efficiency calculated from ED results ($\text{LHV}_{\text{MeOH}}/\text{Electricity}_{\text{Input}}$):

- Atmospheric $\text{CO}_2$: < 46 %
- Flue Gas $\text{CO}_2$: < 48 %
- “free” $\text{CO}_2$: < 61 %
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Power-to-Gas - Concept: Basic Layout of the Demonstration Plant in 2009
CO$_2$-Absorber

Diagram showing the flow of carbon dioxide (CO$_2$) through absorber columns, with NaOH and Na$_2$CO$_3$ as absorbents.
Coupling of Absorber / Electrodialysis Unit for Continuous CO₂-Production
CO₂ Container (left) / SNG Container (right)
Absorber Packing

Design Data of Absorber Column:

Height: 2 x 1.05 m

Diameter: 1.2 m

CO₂ Production: 40 mol\textsubscript{CO₂}/h

Air Throughput: 3600 m³/h

Absorption liquid: 800 l

Absorption liquid flow: 5 - 10 m³/h
Electrodialysis stack with 80 cells (bipolar / cation exchange membranes)
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## Caustic Air Scrubber/Electrodialysis: Experimental Data, Design Data, Optimization

<table>
<thead>
<tr>
<th>Measurement 2010-08-19</th>
<th>Design Data</th>
<th>Optimization</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>CO2 abs. mol/h</td>
<td></td>
<td>single absorber</td>
<td></td>
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<tr>
<td></td>
<td>35.30°*)</td>
<td>12:10-12:30</td>
<td></td>
</tr>
<tr>
<td>kW</td>
<td>kWh/m³CO₂</td>
<td>kWh/m³CO₂</td>
<td>kWh/m³CO₂</td>
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<tr>
<td>ED ges.</td>
<td>7.00</td>
<td>8.85</td>
<td>4.56</td>
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<tr>
<td>ED Stack</td>
<td>5.00</td>
<td>6.32</td>
<td>3.93</td>
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<tr>
<td>Σ Pumps</td>
<td>2.00</td>
<td>2.53</td>
<td>0.63</td>
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<tr>
<td>Absorber ges.</td>
<td>4.30</td>
<td>5.43</td>
<td>1.67</td>
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<tr>
<td>Air fan</td>
<td>1.30</td>
<td>1.64</td>
<td>1.04</td>
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<tr>
<td>Σ Pumps</td>
<td>3.00</td>
<td>3.79</td>
<td>0.63</td>
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<tr>
<td>Humidifier</td>
<td>0.40</td>
<td>0.51</td>
<td>0.50</td>
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<tr>
<td>Abs. 3.0.0</td>
<td>1.30</td>
<td>1.64</td>
<td>0.50</td>
</tr>
<tr>
<td>Abs. 4.0.0</td>
<td>1.30</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>Abs. &amp; ED</td>
<td>11.30</td>
<td>14.28</td>
<td>6.23</td>
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<tr>
<td>CO₂ Container</td>
<td>13.60</td>
<td>17.19</td>
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</tbody>
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Conclusion: Power-to-Methanol / CO₂ from Air

- All components of the system “CO₂ from air” were tested in two pilot plants
- Realised technology 1995: Batch operation
- Realised technology 2009: Continuous operation
- Worldwide first demonstration plants for CO₂ generation from atmosphere (?)
- From technical point of view C-based fuels can be generated from atmospheric CO₂
- Energetic efficiency MeOH from air-CO₂: up to 46 %
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Long Term Storage of Renewable Energy (RE) - FAQ -

- How is long-term storage of energy realised today?

- How much capacity do we need for RE storage?

- What is the best way to collect and to store RE?

- Can the existing infrastructure be used to store and to distribute RE?

- What is “the” future fuel for mobility?
## Energy Consumption and Storage Capacity in Germany (2008)

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>Natural gas</th>
<th>Liquid fuels&lt;sup&gt;1)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption</td>
<td>[TWh/a]</td>
<td>615</td>
<td>930</td>
</tr>
<tr>
<td>Average power</td>
<td>[GW]</td>
<td>70</td>
<td>106&lt;sup&gt;2)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Storage capacity</td>
<td>[TWh]</td>
<td>0,04&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>217&lt;sup&gt;4)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Calculated operating range of installed storage capacity&lt;sup&gt;6)&lt;/sup&gt;</td>
<td>[h]</td>
<td>0,6</td>
<td>2000</td>
</tr>
</tbody>
</table>

1) Petrol, diesel, kerosene  
2) Seasonally fluctuating  
3) Pumped hydro storage  
4) 47 Underground gas storage facilities [Landesamt für Bergbau, Energie und Geologie (LBEG), Hannover]  
5) Provisioning of petrol, diesel, kerosene and heating oil  
6) Related to average power

Required storage capacity for electricity grid in DE: tens of TWh !
How can Renewables supply balancing power?
Options for Long Term (Seasonal) Energy Storage: Chemical Energy Carriers

- Methanol
- Hydrogen
- Substitute Natural Gas (SNG)
- Liquid Hydrocarbons
Renewable Energy Storage Systems: Capacity and Discharge Time

Storage capacity of different storage types

CAES Compressed air energy storage
PHS Pumped hydro storage
SNG Substitute natural gas

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SNG: Substitute Natural Gas
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Path 1: (Digestive) Biomass → SNG
State-of-the-Art - Technology

Digestive Biomass → Anaerobic Digester Plant → Bio-Gas 50 - 70 vol.-% CH₄ → Gas Cleaning / Conditioning → SNG (to Grid or Filling Station)

- Separation of
  - CO₂
  - H₂O
  - Impurities

Compost
Path 1: (Digestive) Biomass → SNG
Pressure Swing Adsorption (PSA) Gas Upgrading

Biogas → Water separator → Water desulphurisation

- Adsorber unit
- Vacuum pump
- Compressor
- Off-gas (CO₂)
- Flushing gas

SNG
Path 2: (Woody) Biomass $\rightarrow$ SNG  
“BtG” Biomass-to-Gas

1st Step

Gasification

2nd Step

Synthesis

Biomass  $\rightarrow$ Producer Gas  $\rightarrow$ SNG  

$\text{(CH}_{1.52}\text{O}_{0.65})$  

\text{Producer Gas (Synthesis Gas)}

$\text{CO, H}_2, \text{CO}_2, \text{CH}_4$  

(Gas conditioning, stoichiometry adjustment)
Path 3: CO$_2$ + H$_2$ (via Electrolysis) $\rightarrow$ SNG
Power-to-Gas (P2G)
Path 2 and 3: Methanation of CO / CO₂

**Methanation:**

\[
3 \text{H}_2 + \text{CO} \leftrightarrow \text{CH}_4 + \text{H}_2\text{O} \quad \Delta H_R^0 = -206,4 \text{ kJ/mol}
\]

\[
4 \text{H}_2 + \text{CO}_2 \leftrightarrow \text{CH}_4 + 2 \text{H}_2\text{O} \quad \Delta H_R^0 = -164,9 \text{ kJ/mol}
\]

**Shift- Reaction:**

\[
\text{H}_2\text{O} + \text{CO} \leftrightarrow \text{H}_2 + \text{CO}_2 \quad \Delta H_R^0 = -41,5 \text{ kJ/mol}
\]
CO / CO$_2$ Methanation: Development Status

- Methane synthesis from CO/H$_2$-based Syngas is a state-of-the-art technology.

Methane synthesis from CO$_2$/H$_2$-based Syngas is not a state-of-the-art technology.

Source Dakota Gasification Company: Coal to Electricity / SNG / CO$_2$

- Methane synthesis from CO$_2$/H$_2$-based Syngas is not a state-of-the-art technology.
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Power-to-Gas (P2G) - Concept: Basic Layout

CCPP: Combined Cycle Power Plant; μ-CHP: micro Combined Heat and Power Plant
Power-to-Gas (P2G) - Concept: Interconnection with Mobility

- **EV**: Electric Vehicle
- **BEV**: Battery Electric Vehicle
- **FCEV**: Fuel Cell Electric Vehicle
- **CNG-V**: Compressed Natural Gas Vehicle
- **Plug-In HEV**: Plug-In Hybrid Electric Vehicle
  (especially: Plug-In Electric Drive Motor Vehicles / Range-Extended Electric Vehicle)

**POWER GENERATION**

- Wind
- Solar

**ELECTRICITY STORAGE**

- CCPP / B-CHP
- Electrolysis / H₂ buffer
- CO₂ buffer
- Methanation

**GAS DISTRIBUTION SYSTEM**

- Gas underground storage
- H₂
- CH₄

**METHANATION**

- H₂ + CO₂ → CH₄

**MOBILITY**

- BEV
- FCEV
- Plug-In HEV
- CNG-V
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Utilisation of Biogenic CO$_2$ Resources for P2G-Process

**Biogas production:**

\[ \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 3 \text{CH}_4 + 3 \text{CO}_2 \]

**Ethanol production:**

\[ \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 2 \text{C}_2\text{H}_5\text{OH} + 2 \text{CO}_2 \]
Market for P2G at Biogas Plants in Germany:  
Number of Installed Plants and Power Range

Number of biogas plants: ca. 5900 (end of 2010)
Installed power: 2.3 GW_{el}
 Average power per plant: 380 kW_{el}
(corresponding to ca. 1 MW_{biogas output})

Corresponding electrolysis power for Methanation of CO_{2} in biogas:
ca. 1 MW_{el} (for 1 MW_{biogas output})

* depending on CH_{4}/CO_{2} ratio in biogas and on electrolysis efficiency

Source: DBFZ

* depending on CH_{4}/CO_{2} ratio in biogas and on electrolysis efficiency

Source: DBFZ

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Market for P2G at Biogas Plants in Germany: Alternative Options - *Electricity* or Gas Feed-in

Operating state 1: electricity feed-in

- Biomass feed
- Biogas plant
- Gas engine
- 1 MW
  - Biogas output
- 0.4 MW$_{el}$

Sources: www.ge-energy.com, www.rehau.at
Market for P2G at Biogas Plants in Germany: Alternative Options - Electricity or Gas Feed-in

Biomass feed → Biogas plant → Power-to-Gas plant → Gas feed-in

1 MWbiogas output → Power-to-Gas plant

Operating state 2: gas feed-in

1 MWel

1,6 MW_{SNG}

→ Total SNG production potential from Bio-Gas (Bio-Methane and P2G-Gas): ca. 65 TWh_{gas}/a
→ Overall control power via Gas Feed-in: ca. 8 GW

Sources: photos: www.ge-energy.com, www.rehau.at
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**Agenda Part II: Power-to-Gas (P2G)**

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- Conclusions / Next Steps

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SNG: Substitute Natural Gas
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Schematic Diagram of a P2G - Plant for IPSEpro Process Simulation (Feed: CO₂/H₂ and Biogas/H₂)

Settings
Energy demand electrolysis: 4 kWhₐₑ/mₙ³ H₂
System pressure: 7 barₐₑₐₜₙ
Grid pressure: 16 barₐₑₐₜₙ
Energy Flow of a P2G - Plant

Case 1: "CO₂/H₂-to-SNG"
Case 2: "Biogas/H₂-to-SNG" (50 / 50 [Vol.%CH₄ / Vol.%CO₂] in biogas)
Case 3: "Biogas/H₂-to-SNG" (70 / 30 [Vol.%CH₄ / Vol.%CO₂] in biogas)
Influence of Electrolysis Efficiency on P2G System Efficiency (CO$_2$/H$_2$-to-SNG)
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Land Consumption: Pumped Hydro Storage vs. Power-to-Gas Storage

Pumped hydro power

Water surface, Dam, Bank reinforcement

Land use: 2 - 44 kWh_{pot}/m^2
\eta_{\text{turbine}} = 88 \%
\eta_{\text{pump}} = 85 \%

Underground storage facilities / PtG

Well site: 40 m x 60 m; Over ground facility, gas compression station: 200 m x 200 m; Security area

Land use: ca. 100 000 kWh_{SNG}/m^2
\eta_{\text{SNG \rightarrow electricity}} < 60 \%
\eta_{\text{electricity \rightarrow SNG}} = 60 - 65 \%
Land Consumption: SNG Transmission vs. Electricity Transmission

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Diameter</th>
<th>Gas</th>
<th>Transmission power</th>
<th>Protection strip</th>
<th>Electricity</th>
<th>Transmission power</th>
<th>Overhead line, Route width</th>
<th>Underground cable, Protect. strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>[bar]</td>
<td>[DN]</td>
<td></td>
<td>[GW]</td>
<td>[m]</td>
<td>[kV]</td>
<td>[GW]</td>
<td>[m]</td>
<td>[m]</td>
</tr>
<tr>
<td>&lt; 0,1</td>
<td>50-600</td>
<td></td>
<td>&lt; 0,1</td>
<td>2 - 10</td>
<td>0,4 (low)</td>
<td>10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>&gt; 0,1-1</td>
<td>100-400</td>
<td></td>
<td>0,01 - 0,2</td>
<td>2 - 8</td>
<td>1-24 (medium)</td>
<td>20</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>&gt; 1-16</td>
<td>300-600</td>
<td></td>
<td>0,8 - 3</td>
<td>6 - 10</td>
<td>50-170 (high)</td>
<td>0,3</td>
<td>44</td>
<td>7</td>
</tr>
<tr>
<td>&gt; 16</td>
<td>900</td>
<td></td>
<td>9 - 12</td>
<td>8 - 10</td>
<td>220 (high)</td>
<td>0,5</td>
<td>55</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>12 - 16</td>
<td>8 - 10</td>
<td>380 (high)</td>
<td>2</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td></td>
<td>21 - 28</td>
<td>8 - 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Transmission power:
Gas pipeline < 70 GW
Power line < 7 GW

Sources: Wuppertal Institut für Klima, Umwelt und Energie; P. Konstantin; G. Wossog; H. Brakelmann; OMV
Environmental Benefits:
Emissions Reduction through CNG-Vehicles

<table>
<thead>
<tr>
<th></th>
<th>in relation to gasoline</th>
<th></th>
<th>in relation to Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>-80%</td>
<td>CO</td>
<td>-10%</td>
</tr>
<tr>
<td>NMHC</td>
<td>-80%</td>
<td>NMHC</td>
<td>-60%</td>
</tr>
<tr>
<td>GHG 1)</td>
<td>-20%</td>
<td>NOx</td>
<td>-90%</td>
</tr>
<tr>
<td>OZONE</td>
<td>-40%</td>
<td>GHG 1)</td>
<td>-10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OZONE</td>
<td>-80%</td>
</tr>
</tbody>
</table>

1) Green house gas reduction by using natural gas; nearly 100 % reduction by using renewable SNG!

Source: nach Fachverband der Gas- und Wärmeversorgungsunternehmen, Wien
Environmental Benefits via CNG-Vehicles: Audi balanced mobility / e-gas project (12.05.2011)

e-gas: SNG via P2G-plant

→ Sustainable mobility with CNG vehicles powered with e-gas
Agenda Part I: Power-to-Methanol / CO$_2$ from Air
Agenda Part II: Power-to-Gas (P2G)

Goal (CO$_2$ from Air)
- Concept 1996 (Batch Mode)
- Results 1996
- Concept 2009 (Continuous Mode)
- Results 2009
- Conclusions

Goal (P2G)
- SNG Production Routes from RE
- P2G Concept
- CO$_2$ Resources
- Conversion Efficiency
- Environmental Benefits
- Results from 25 kW$_e$ P2G Pilot Plant
- Conclusions / Next Steps

SNG: Substitute Natural Gas
RE: Renewable Energy
Power-to-Gas - Technology:
Process Flow Sheet (Principle)

CH\textsubscript{4}-Filling station ca. 15 kg, 200 bar

\text{CO}_2\text{-Recovery}

Electrolyser
SNG Generation in Fixed Bed Molten Salt Cooled Reactor

Producer Gas from AER-Process

Catalyst
Salt Loop
Zone III Zone II Zone I
Decreasing Temperature

Goal:
Once-through reactor

Demo-plant: 100 kW_{SNG}

Concept presented at ACHEMA Fair in May 2009 (cooperation ZSW with MAN-DWE, Germany)
CO₂ + H₂ (via Electrolysis) → SNG
Experimental Results: Gas Composition

Parameter of methanation:
- T: 250 - 550°C
- pₑ: < 10 bar
- SVₑₑ: > 2000 1/h

Feed Gas → Catalyst → Substitute Natural Gas

Natural Gas Feed Gas Composition:
- H₂: 79.5 Vol.%
- CO₂: 20.5 Vol.

Methanation Gas Composition:
- CH₄: 92.0 Vol.%
- H₂: 3.9 Vol.
- CO₂: 4.1 Vol.
**CO₂ + H₂ (via Electrolysis) → SNG**

**Experimental Results: Gas Composition**

Reactor concept: Fixed bed reactor with recycle loop and intercooler

Feed: CO₂ 20 Vol.%db, H₂ 80 Vol.%db

T = 250 - 550 °C, p = 7 bar-abs, SV = 2000 l / (l_cat * h)

No downstream processing!
Biogas + Power → SNG: Biogas as CO₂ Resource - 2 Process Options

1. 
- Biomass → Biogas-Plant → CO₂ Separation → CO₂ Buffer → Methanation → SNG (Feed-in)
- H₂ from Electrolysis → H₂ Buffer → H₂
- SNG (Feed-in)
- if H₂-Deficit → CO₂ to Atmosphere

2. 
- Biomass → Biogas-Plant → Biogas Buffer → Methanation → SNG (Feed-in)
- H₂ from Electrolysis → H₂ Buffer → H₂
- if H₂-Deficit → Power Generation from Biogas
Power-to-Gas - Container: Operation with CO$_2$ and at Biogas Plants with Biogas and PSA Off-Gas
Power-to-Gas (P2G) - Concept: Option 1- Interconnection with Biogas Plant (via Biogas)

- Grid
- Power Generation
- Electricity Storage
- Gas Distribution System
- Biogas Plant
- CCPP / μ-CHP
- Electrolysis / H₂ Buffer
- Methanation
- CH₄/CO₂ Buffer

CCPP: Combined Cycle Power Plant; μ-CHP: micro Combined Heat and Power Plant
Power-to-Gas - Container: Operation with Biogas at Werlte Biogas Plant

![Graph showing the concentration of CH4, H2, CO2, and O2 over time. The graph indicates the concentration of each gas as a percentage of the total mixture, with CH4 consistently at 90% and CO2, H2, and O2 fluctuating.]
Power-to-Gas (P2G) - Concept: Option 2- Interconnection with Biogas Plant (via Off-gas)

- **Grid**
- **Electricity Storage**
- **Power Generation**

**Biogas plant with “Bio-CH₄” production**

- **Electrolysis / H₂ buffer**
  - H₂
  - Off-gas (CO₂)
  - Heat

- **CO₂ buffer**
  - CO₂

- **Methanation**
  - CH₄
  - H₂

**CCPP / µ-CHP**

**Gas distribution system**

- **Gas storage**

**CCPP: Combined Cycle Power Plant; µ-CHP: micro Combined Heat and Power Plant**
Power-to-Gas - Container: Operation with **Off-Gas** at Werlte Biogas Plant

![Graph showing Dauer [hh:mm] vs. y_CH4 [Vol-%], y_CO2, y_H2, y_O2 [Vol-%] with lines for CH4, H2, CO2, O2]
Award for Power-to-Gas - Concept: SolarFuel / ZSW / IWES

Award “ASUE” of the German Gas Industry in the field “Innovation and Climate Protection”, 29.09.2010, Berlin
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SNG: Substitute Natural Gas
RE: Renewable Energy
Conclusion:
Advantages of P2G - Technology

- Inspired by nature: “P2G as artificial photosynthesis”
- Increasing importance of (S)NG backup power for load balancing
- SNG is an ideal chemical storage medium for renewable energy (RE)
- Storage of RE with “unlimited” storage capacity in the gas grid
- Utilisation of existing underground gas storage facilities
- Stabilization of electricity grid (positive and negative control power)

- Merging of the energy sectors “electricity grid”, “gas grid”, and “mobility”
Timeline Commercialisation

- Alpha-plant ($25 \text{ kW}_{\text{el}}$): 2009
- Alpha-plus-plant ($250 \text{ kW}_{\text{el}}$): 2012
- Beta-plant ($6 \text{ MW}_{\text{el}}$): 2013
- Gamma-plant
  (> $6 \text{ MW}_{\text{el}}$, commercial product): 2015

Beta-plant co-operation partners:
Visit of the President from Turkey Abdullah Gül and Prime Minister Kretschmann at ZSW (21.09.2011)
An interesting discussion!

Thanks for your kind attention.