Power to Methanol Solutions for Flexible and Sustainable Operations in Power and Process Industries

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#Mitsubishi Hitachi Power Systems Europe GmbH, Germany

*Carbon Recycling International, Iceland
About the cooperation towards large scale Power to Methanol Plants

- Carbon Recycling International (CRI)
- Mitsubishi Hitachi Power Systems Europe GmbH (MHPS-EDE)

Idea and technological background of Power to Methanol (PtMeOH)

- Electricity markets
- PtMeOH: Cross-sectorial energy storage and market flexibility

Process principles & applications

- State of the art (standard) methanol production
- PtMeOH process
  - Power plant & electricity application
  - Industrial H₂ sources

Economics

Conclusions
Carbon Recycling International at a brief

Making sustainable methanol from CO₂

- Founded in 2006
- Headquartered in Reykjavik, Iceland
- First to produce and sell renewable fuel from carbon capture
- A leader in MW-scale electrolysis, and kiloton scale of carbon dioxide (CO₂) capture and utilization (CCS & CCU)
- Applications of renewable methanol for mobility, shipping, and raw materials
- Operating a commercial production plant in Svartsengi, Iceland
- Full value chain from technology, project development to market
MHPS-EDE shareholders and key figures

- Start of Joint Venture
  Mitsubishi Hitachi Power Systems (MHPS):
  1 February 2014

- Number of MHPS Group companies: **59**
  (5 in Japan, 54 overseas)

- Total workforce: **approx. 23,000**

- MHPS-EDE is successor company of
  Hitachi Power Europe GmbH

- Subscribed capital: 148 Mio. EUR

- Number of employees: **approx. 2,000 (Group)**
Conventional power plants & components

- Coal-fired EPC power plants
- Power train
- Utility steam generator
- Firing systems
- Mills
- Ash handling systems
- Flue gas cleaning systems
- Steam turbines

- CCS/CCU-Technology
- Energy storage
- Combined-cycle power plants
- Gas turbines

- Rehabilitations
- Modernization

- Service for energy systems and power plants
- Delivery of all replacement parts
How is the situation on EU energy markets? Germany as an example

- **Thermal power still is and will stay the backbone of electricity supply**
  - providing today >95% of total load in winter time, >60% in summer time

- **RES often force hard coal and NG power plants to ramp down**
  - Utilization ratio of thermal plants & market price of electricity decreased
  - NG and hard coal plants have reduced income, many are mothballed

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**Load**

- 100%
- 80%
- 60%
- 40%
- 20%
- 0%

- **150MW Hard Coal, Sept. 2010**
- **700 MW Hard Coal, 2012**

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**Power production: March 2014**

- **Legend:**
  - Solar
  - Wind
  - PHS
  - Natural Gas
  - Coal
  - Lignite
  - Nuclear
  - Run-of-the-river

- **Source:** VGB PowerTech 11/2012 & own data

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Carbon recycling as a flexible solution for excess energy utilization

Industry

Emission-to-Liquid Technology

Markets

- CO₂ Capture
- Clean Conversion
- Methanol (CH₃OH)
- Liquid fuels
- Raw materials

Hydrogen generation from electricity

Hydrogen off-gas from industry

Methanol production as a new energy vector can

- prevent investments for grid lines & energy storage
- efficiently & competitively absorb & convert excess electricity & hydrogen to valuable fuels & chemicals
- reduce CO₂ emissions in transport & industry

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Why does *Power to Methanol* work commercially, why not *Power to Gas*?

Electricity €/MWh

Electricity price EEX 2013

- **NG price**: 30€/MWh (th)
- **Marginal cost allowed for Power to Gas**: 65%
- **Without subsidies not economically feasible**
- **Methane is too cheap!**

Less than 1000 full load operation hours for SNG production

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Why does Power to Methanol work commercially, why not Power to Gas?

**Electricity €/MWh**

- **MeOH price**: 400 €/t = 72 €/MWh (th)
- **NG price**: 30 €/MWh (th)

**Marginal cost allowed for Power to MeOH**: 65%

**Marginal cost allowed for Power to Gas**: 65%

- Without subsidies not economically feasible
- Less than 1000 full load operation hours for SNG production
- More than 6500 full load operation hours for MeOH production

**Methane is too cheap!**

**MeOH production is profitable!**
Where does today's methanol come from? Industrial GW scale ways to produce Methanol

**Methanol from natural gas (reforming)**

- **natural gas**
- desulpharisation
- pre-reforming
- steam reforming
- autothermal reforming
- methanol synthesis
- methanol distillation

**air separation**

**O₂**

**1730 MWₜₜ NG**

**commercial scale 5000t MeOH/d**

$\eta_{\text{th-th}} \approx 67\%$, MeOH output: 1160 MWₜₜ

**Methanol from coal (gasification)**

- **coal**
- preparation, drying
- gasification
- dust removal, scrubbing
- CO-conversion
- CO₂ & H₂S - removal
- CCGT plant

**air separation**

**O₂**

**steam**

**2060 MWₜₜ coal**

**commercial scale 5000t/d**

$\eta_{\text{th-th}} \approx 55\%$, MeOH output: 1140 MWₜₜ

High CAPEX requires large installation and reliable boundary conditions for investment (resource, energy policy, environmental regulation, product markets, supply chain)
What is technological status of emissions to liquid technology?

George Olah Plant at Carbon Recycling International
World’s First Power to CO₂ Methanol Plant in Svartsengi, Iceland

- 4,000 t/a methanol
- 6,000 t/a CO₂ recycled
- 6 MWₑₑ electrolysis

- Methanol has 90% lower carbon footprint than gasoline
- Methanol certified by SGS Germany according to “International Sustainability and Carbon Certification” (ISCC) standard
  - CO₂ captured from geothermal off-gas
  - Electrolysis operated with geothermal electricity
Implementation of a methanol plant in power plants - Methanol from electricity & CO₂ emission

- **Flexibility**: extension of operational range (e.g. -10% to 100% to grid, 50-150MWₐₑl electrolyzer, 4.5% - 18% Carbon Capture)
- **High utilization** of MeOH plant & Power Plant (MeOH plant fills utilization gaps)

**Base case**
- 130-710MWₑₑl net (η=46%)
- 1543MWₜₜh coal

**Max load PP**
- 658MWₑₑl to grid
- 52MWₑₑl
- 137 t MeOH/d
- 32MWₜₜh

**Min load PP**
- Import 14MWₑₑl
- 142MWₑₑl
- 410 t MeOH/d
- 95MWₜₜh
**Principle process differences**

**Megascale Methanol Plant (greenfield)**

- **80% CAPEX**
- Syngas preparation (partial combustion, steam reforming)
- Power cycle for heat integration and own consumption

**Syngas preparation**

- $\text{O}_2 \downarrow \downarrow \text{steam}$ up to 950 – 1050°C

**Power to Methanol Plant (existing infrastructure)**

- **$\Delta H_r = 8 \text{ MW} \ (\sim 8\%)$**
- Power plant

**Carbon Capture & Electrolysis**

- Low CAPEX process with CO$_2$ and H$_2$: small scale & “brown field” installations
- Simplified reactor design & heat integration: small heat exchange, low temp. level
- Flexible polygeneration as retrofit
Electric power to thermal power – MeOH lower heating value (LHV) based

\[ \eta_{el/th} = \frac{\dot{Q}_{MeOH}}{P_{el} + \Delta P} = \frac{\dot{m}_{MeOH} LHV_{MeOH}}{P_{el} + \Delta P} \]

- Own consumption electricity minus savings of own consumption
- Own consumption heat minus re-integrated heat

\[ P_{el} = P_{own} - \Delta P_{ASU} \]
Electrolyser, Compressors, ASU savings etc.

\[ \Delta P = \sum \Delta \dot{Q} \eta \]
Bleed steam, heat to preheaters

Thermal power to thermal power – Fuel/MeOH lower heating value (LHV) based

\[ \eta_{th/th} = \frac{\dot{Q}_{MeOH}}{\dot{Q}_{Fuel} + \Delta \dot{Q}} = \frac{\dot{m}_{MeOH} LHV_{MeOH}}{\dot{m}_{Fuel} LHV_{Fuel} + \Delta \dot{Q}} \]

- Own consumption electricity (converted to fuel heat)

\[ \Delta \dot{Q} = \Delta P_{el} / \eta_{PP} \]
High conversion efficiency by optimized heat integration

High conversion efficiency: $\eta_{el/th} = 61\%$ (w/o O$_2$ utilization)
Carbon Capture and Utilization + excess energy offers different business cases

- High operational flexibility of power plants
  - Reducing Minimum Load of PP
  - Utilizing excess electricity from renewables

- Product flexibility, “Polygeneration”
  - Creating new product for PP (methanol fuel)

- Increased income, reduced cost
  - stay synchronized, avoid shut-downs
    - Maintain or increase utilization
    - Maintain primary/secondary control services
    - High ramp speed (by PtMeOH), reduce wear (PP)
    - Reduce start-ups & reduce use of auxiliary fuels
    - production of valuable product MeOH for
      - support firing (own use)
      - peak electricity production (gas engines, GT)
    - easy storage or sales
    - CO₂ emission reduction

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1 MW<sub>el</sub> demonstration of full system in Lünen

- University of Duisburg-Essen, Germany
- Hydrogenics, Belgium
- Carbon Recycling International, Iceland

- Steag Power Plant, Lünen, Germany
- 1 MW<sub>el</sub> (peak)
- 1 t/day Methanol
- EUR 11 million
- 80% EU funding *
- Project start: 12.2014
- Duration: 4 years

Other partners:
- Genoa University (Italy)
- Cardiff University (UK)
- Catalysis Institute (Slovenia)
- I-deals (Spain).

**“Synthesis of methanol from captured carbon dioxide using surplus electricity” which is funded under the EU funded SPIRE2 -Horizon 2020 with the Grant agreement no: 637016**

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*Horizon 2020*
Methanol production in the integrated steel mill - base case

Steel mill capacity

<table>
<thead>
<tr>
<th></th>
<th>4 Mio t/a HRC (hot rolled coil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal mixture</td>
<td>1,739 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Coke</td>
<td>1,386 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Pulverized Coal injection</td>
<td>728 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>Coke Oven Gas (COG)</td>
<td>350 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt; amount of COG</td>
<td>133 MW&lt;sub&gt;th&lt;/sub&gt;</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; Emission</td>
<td>1.831 t/t HRC</td>
</tr>
</tbody>
</table>

Gas stream components

<table>
<thead>
<tr>
<th></th>
<th>Coke oven gas (COG)</th>
<th>Blast furnace gas (BFG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>61.99</td>
<td>3.75</td>
</tr>
<tr>
<td>CO</td>
<td>4.00</td>
<td>23.07</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.00</td>
<td>22.82</td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>23.99</td>
<td>0.00</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>6.00</td>
<td>50.36</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.20</td>
<td>0.00</td>
</tr>
<tr>
<td>C&lt;sub&gt;n&lt;/sub&gt;H&lt;sub&gt;m&lt;/sub&gt;</td>
<td>2.80</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>S in mg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>LHV in MJ/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>18.05</td>
<td>3.31</td>
</tr>
<tr>
<td>Volume flow m&lt;sup&gt;3&lt;/sup&gt;/h</td>
<td>78,570</td>
<td>724,570</td>
</tr>
</tbody>
</table>

All values in Vol.-% if not otherwise termed; dry basis. STP
HRC: Hot rolled coil
LHV: Lower heating value

Power plant

199 MW<sub>el</sub>
η<sub>el</sub>=42.1%
Methanol production in the integrated steel mill - only COG & PSA for hydrogen

- High efficiency
  - by chemical use of COG
    \[ \eta_{\text{th/th}} = 65\% \]
  - instead of electricity production
    \[ \eta_{\text{th/el}} = 42\% \]
- Reasonable CAPEX:
  PSA is cheaper than electrolyzers

**Base case**
- Export: 20 MW\(_{\text{el}}\)
- Steel mill demand: 179 MW\(_{\text{el}}\)

**H\(_2\) from COG**
- Import: 47 MW\(_{\text{el}}\)
- Power plant & PtMeOH: 149 MW\(_{\text{el}}\) - 17 MW\(_{\text{el}}\)
- Available Hydrogen: 120 MW\(_{\text{th}}\)
- Produced Methanol: 105 MW\(_{\text{th}}\)

Own consumption PtMeOH: 17 MW\(_{\text{el}}\)
Not-produced electricity: 50.5 MW\(_{\text{el}}\)
Methanol production in the integrated steel mill - only electrolyser for hydrogen

- **High product flexibility** & operational flexibility for the power plant
- **High PtMeOH efficiency** by saved ASU power (5MWel) & heat integration

\[ \eta_{el/th} = 65\% \]

**Base case**
- Export: 20MW\(_{el}\) to 179MW\(_{el}\) Steel mill demand

**Electrolyser**
- Import: 87MW\(_{el}\) to 199MW\(_{el}\) - 113MW\(_{el}\) + 5MW\(_{el}\)
- Power plant & PtMeOH: 110MW\(_{el}\) to 80MW\(_{th}\) H\(_2\)
- Export: 70MW\(_{th}\)
- Production: 301 t MeOH/d
Methanol production in the integrated steel mill - combined operation: electrolyser & PSA

- Easy implementation (brown field)
- High efficiency (el/th and th/th)
- High flexibility & high utilization of new equipment and power plant (operated according to grid requirements)

**Base case**

- Export: 20 MW<sub>el</sub>
- Steel mill demand: 179 MW<sub>el</sub>

**H<sub>2</sub> from COG**

- PtMeOH 17 MW<sub>el</sub>
- ΔP (H<sub>2</sub>) 50.5 MW<sub>el</sub>

**Electrolyser**

- PtMeOH 113 MW<sub>el</sub>
- Saved ASU -5 MW<sub>el</sub>

**H<sub>2</sub> from COG + Electrolyser**

- Import: 155 MW<sub>el</sub> (ΔP<sub>base</sub>=175 MW)
- 24 MW<sub>el</sub>

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Cost of methanol production

<table>
<thead>
<tr>
<th>MeOH market</th>
<th>Fossil fuel based production</th>
<th>Power to MeOH</th>
<th>H₂ to MeOH</th>
</tr>
</thead>
<tbody>
<tr>
<td>€/MWh</td>
<td>€/t</td>
<td>€/MWh</td>
<td>€/MWh</td>
</tr>
<tr>
<td>100</td>
<td>350 400 600</td>
<td>15 25 35 50</td>
<td>15 30</td>
</tr>
<tr>
<td>„green“ Methanol price range</td>
<td>„gray“ Methanol price range</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- MeOH [€/t]
  - EU: 350, 400, 600
  - US: 400, 600, 600

- NG reforming
  - EU: 67%
  - US: 67%

- Coal gasification
  - EU: 45%
  - EU: 55%

- Power
  - 15€ 60%
  - 25€ 60%
  - 35€ 60%
  - 50€ 60%

- H₂
  - 15€ 70%
  - 30€ 70%

- Profit
  - Profit + CAPEX + Tax

- Cost conversion loss
- Market price energy

- NG EU
- NG US
- Coal EU
- Power
- H₂

- EU NG price, 30€/MWh th (German border) and η_th/[%]
- US NG price, 10€/MWh_th and η_th/[%]
- Rotterdam market price 9€/MWh_th and η_th/[%]
- Electricity to MeOH with €/MWh_el and η_el/[%]
- H₂ to MeOH with €/MWh_th and η_th/[%]
### Utilization of Power Plants and H₂ for Methanol production - Market potential estimates

#### Electricity Production EU28 [TWh/a]
- **fossil and nuclear**: 2138 TWh/a
- **renewable electricity**: 657 TWh/a
- **not used capacity (fossil and nuclear)**: 2912 TWh/a

#### EU methanol market 2012
- 47 TWh/a
- (8.5 MMt/a)

#### Fuel consumption EU28
- 4157 TWh/a

#### Industrial H₂ sources
- 47 TWh/a

- **Data**: Eurostat 2012, own calculations

### Notes
- Only minor amounts of methanol are used for fuel blending today
- The “not used capacity” of thermal power is increasing
- Industrial H₂ sources shown are used for heat & electricity production

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Utilization of Power Plants and H₂ for Methanol production - Market potential estimates

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**EU methanol market 2012**

- 47 TWh/a (8.5 MMt/a)

**Methanol from Power and H₂ (New market)**

- **Industrial H₂ sources (own market review, estimates)** 47 TWh/a (100% η=65% (COG), η=70% (chemical plants))
- **20% η=61%**

**Fuel consumption EU28**

- 4157 TWh/a

- **Gasoline**
- **Diesel**
- **LPG**

**Data: Eurostat 2012, own calculations**

⇒ about 11% of the EU transport fuel sector could easily be substituted by CO₂ lean fuels today
Summary

- Power to Methanol is a cross-sectorial technology for energy storage,
  - avoids curtailment of RES and
  - avoids high investments in grid infrastructure and electricity storage

- Methanol production improves utilization of energy rich off-gases from industry and provides high value creation

- Power plants can become more flexible and profitable by integration of PtMeOH technology

- The carbon capture and PtMeOH technologies are available, proven and ready for deployment

- Carbon recycling together with CO₂-lean electricity or H₂ reduces overall CO₂ emissions

- MHPSE and CRI can provide the full value chain of technologies needed as well as long time experience
Thank you for your attention
How is the electricity market developing (I)

Power produktion: week 9, 25. February to 3. March 2013

Winter

Legend:
- Solar
- Wind
- PHS
- Gas
- Coal
- Lignite
- Nuclear
- Nuclear
- Run-of-the-river

During low RES production the variable gross margin is high enough to "make money" in the free market,

…. but ….

RES production is growing rapidly
How is the electricity market developing (I)

Power production: 17. to 23. March 2014

during a day in winter 2013/2014

- Daily peak covered by RES
  - CHP plants lose money on electricity sales
  - Many CCGT plants mothballed
- Reduced margin of thermal power plants + less operating hours
- Increased number of start-ups & higher fuel cost

Legend:
- Solar
- Wind
- PHS
- Gas
- Coal
- Lignite
- Nuclear
- Biomass
- Run-of-the-river

FIT (EEG)
yearly average

„missing money problem“

variable gross
margin

€/MWh

0 10 20 30 40 50 60 70 80 90 100

GW

Power production: 17. to 23. March 2014

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The example of Germany
> Plant system utilization over day-ahead prices

Hard coal power plants cover the fluctuating residual load (fleet utilization between 10 and 100%)

Gas power plants (GT+CCGTs) do not reach high utilisation ratios (many plants mothballed)

Source: Fraunhofer ISE, Johannes Mayer, Bruno Burger, 2014
What are now the other options when having “excess electricity” or “stranded hydrogen”?

<table>
<thead>
<tr>
<th>Electricity (30 €/MWh\textsubscript{el}) use</th>
<th>Overall efficiency</th>
<th>Production cost [€/MWh \textsubscript{el or th}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVDC Transport 700km - Restricted by consumption</td>
<td>86%</td>
<td>35</td>
</tr>
<tr>
<td>HVDC Transport 2x700km &amp; Storage (PHS, 80%)</td>
<td>60%</td>
<td>50</td>
</tr>
<tr>
<td>Power to Gas (decentralized)</td>
<td>55%</td>
<td>54</td>
</tr>
<tr>
<td>Power to Gas to Power (decentralized)</td>
<td>31%</td>
<td>95</td>
</tr>
<tr>
<td>Power to Methanol (Power plant integrated)</td>
<td>65%</td>
<td>46</td>
</tr>
<tr>
<td>Power to Heat</td>
<td>85%</td>
<td>35</td>
</tr>
<tr>
<td>Curtailment</td>
<td>0%</td>
<td>x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hydrogen (30 €/MWh\textsubscript{th}) use</th>
<th>Overall efficiency</th>
<th>Production cost [€/MWh \textsubscript{el or th}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>COG in Power plant (steel industry, COG: Coke oven gas)</td>
<td>42%</td>
<td>H\textsubscript{2} \Rightarrow +CO\textsubscript{2}+H\textsubscript{2} \Rightarrow \text{MeOH}\Rightarrow 60</td>
</tr>
<tr>
<td>Power plant (co-combustion)</td>
<td>46%</td>
<td>H\textsubscript{2} \Rightarrow 54</td>
</tr>
<tr>
<td>H\textsubscript{2} use in CCGT Power plant (medium size, co-combustion)</td>
<td>58%</td>
<td>H\textsubscript{2} \Rightarrow 43</td>
</tr>
<tr>
<td>Power to Methanol (Power plant integrated)</td>
<td>65%</td>
<td>CO\textsubscript{2}+H\textsubscript{2} \Rightarrow \text{MeOH}\Rightarrow 46</td>
</tr>
</tbody>
</table>
How does Power to Fuel reduce CO₂ emissions? - Carbon capture and utilization

1. Base

Emissions in
- Industry
- Fuel exploration, production & long distance transport
- Use in transport sector

2. CCS

CCS can avoid emissions in
- Industry

3. CCU e.g. Fuel Production

CCU can avoid emissions in
- Industry, fuel exploration & production & long distance transport

Educts Fossil → Industry or Power plant → Product → Fuel

Educts Fossil → Industry or Power plant → Long Distance Transport → Fuel

H₂ + CO₂ = Fuel
η_{el/th} > 0.5
Methanol as the most feasible new energy vector (technological view for transport sector)

- Electric cars
  - Can not become mainstream (limited distance, high cost) 
- Hydrogen
  - Has no infrastructure
  - Fuel cell not mature
  - Distance limited
- Compressed NG or SNG
  - CNG has not become „mature“ yet
  - LPG has ~10 times more fuel stations and applications (higher acceptance due to simplicity)
- Methanol
  - Is proven and applied in US, China, etc
  - Can be used as M5 M10 M85 …
  - Is as simple to distribute as gasoline, uses existing infrastructure
- Methanol derivates (OME, DME, …) are feasible but increase CAPEX, OPEX
The Future is an Integrated Industry System (IIS) utilizing local resources in the most economic way.

Conventional Power Plants
Electricity production

Processes Industry
e.g. Steel Industry

CO₂ Capture & Intermediate Storage
Storage of captured CO₂ for further use

Biogas Plants & PCC

Electricity Transport
To customers or excess electricity to electrolysis

Electrolysis
O₂ and H₂ from water

Methanol Synthesis
Methane from H₂ and CO₂

Methanation
Methane from H₂ & CO₂

Storage
(pipeline, cavern, etc.)

Renewable Energy

private customers

mobility

petro chemical industry

other industry

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