Opportunities and Challenges for Power-to-Liquid Technologies towards Sustainable Aviation

Sandra Adelung, Friedemann G. Albrecht, Zoé Béalu, Stefan Estelmann, Simon Maier, Moritz Raab, Ralph-Uwe Dietrich

Research Area Alternative Fuels
Institute of Engineering Thermodynamics
DLR e.V.

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Agenda

1. Motivation for Alternative Fuels
   • Need for GHG emission reduction
   • Actual GHG emissions in Europe
   • Biofuels options in European transport
   • Options to reduce GHG emissions

2. Alternative Fuels Options
   • Raw materials and available energy sources
   • Fuel potential in Europe

3. Process Evaluation of Renewable Kerosene
   • Introduction to DLR methodology
   • Example: PtL – Jet fuel by Fischer-Tropsch

4. Summary and Outlook
1. Climate Change – Driver for Renewable Fuels?

- Historic natural fluctuation between 180 and 280 ppm CO\textsubscript{2} concentration
- Undeniable break-out since 1960’s
- No visible impact of renewables introduction since 2000’s

Source: https://www.co2.earth/daily-co2
1. GHG emission trend in Europe

- European GHG reduction behind target (slow reduction in Germany)
- Transport GHG emissions grow considerable
1. Growth in Aviation Sector

Assuming a saturation at around 3000 km/capita\(^a\)

<table>
<thead>
<tr>
<th>Region</th>
<th>2000</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>750</td>
<td>1210</td>
</tr>
<tr>
<td>North America</td>
<td>2720</td>
<td>2880</td>
</tr>
<tr>
<td>China</td>
<td>60</td>
<td>510</td>
</tr>
</tbody>
</table>

(in billion passenger kilometers /a)

(source: Thess et al., DGLR-Mitgliedermagazin „Luft- und Raumfahrt“ edition 2/2016, p.20)
1. IATA Technology Roadmap

Aviation Self-commitments:

1. Improvement of fuel efficiency
   ≈ 1.5 % p.a. until 2020

2. Carbon-neutral growth from 2020

3. CO₂ emission reductions of 50 % by 2050 (comp. to 2010)

Planned Measures:
- Improvement of technologies, operations, infrastructure
- Economic measures (CORSIA signed 2016)
- Radical technology transitions and alternative fuels

(optimistic assumption until 2050: biofuels are 100% CO₂-“neutral"
 demand of ≈ 56 - 60 Mt kerosene equivalent EU)

European Aviation fuel demand: ca. 56.5 Mt\textsuperscript{[1]} in 2010

Source: iata.org

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4. Summary and Outlook
2. Sources & Routes for Alternative FT-Kerosene

The supply of large quantities of alternative kerosene within low GHG emissions is possible by coupling the sectors electricity generation and fuel markets (without biomass imports).
2. Renewable Energy Potential for Europe

Potential for Europe? – e.g. jet fuel from wind power

- Current jet fuel consumption: \( \approx 56 \text{ Mt/a} \)\(^{[1]} \)
- Power demand for exclusively power based kerosene in Europe: \( \approx 1,410 \text{ TWh (} \eta_{\text{xtL}} \text{ ca. 50 \%)} \)
- European wind power potential\(^{[2]} \): 12,200 – 30,400 TWh \( \approx 8.6 - 22 \text{ times of power based kerosene demand!} \)

\(^{[1]}\) Eurostat database, 2015
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4. Summary and Outlook
3. Process Evaluation @ DLR

- Technical evaluation
- Economic assessment (TEA)
- Ecological evaluation (LCA)

Efficiencies (X-to-Liquid, Overall)
Carbon conversion
Specific feedstock demand
Exergy analysis

DLR-evaluation and optimization tool

PTL

Economic assessment
Ecological evaluation

Economic/Ecological evaluation
3. Multiple Options for Power-to-Liquid

**FT technologies**
- High Temp./Low Temp.
- Fe- / Co-Catalyst

**Electrolysis technologies**
- Alkaline
- Proton exchange membrane (PEM)
- Solid oxide (SOEC)

**CCU technologies**
- Adsorption
- Absorption
- Membrane Sep.

**Fuel production**
- Oxy-fuel burner + steam cycle
- Separation & upgrading
- FT-Product

**Syngas supply**
- Off gas
- Power
- Biomass

**Oxy-fuel burner**
- Steam cycle

**Tail gas**
- CO₂-recycle

**Reverse water-gas-shift (900°C)**
- Water-gas-shift (230°C) + CO₂ removal

**FT product distribution**
- \( \alpha = 0.75 \)
- \( \alpha = 0.85 \)
3. Process Evaluation @ DLR

- Technical evaluation
- Ecological evaluation
- Economic assessment

DLR-evaluation and optimization tool

- CAPEX, OPEX, NPC
- Sensitivity analysis
- Identification of most economic feasible process design
3. Techno-Economic Assessment (TEA) Methodology

- Adapted from **best-practice chem. eng. methodology**
- Meets AACE class 3-4, accuracy: +/- 30 %
- **Year specific** using annual CEPCI Index
3. TEA: Base Case definition

**PtL Plant capacity:**

- Power Input: 293 MWₑ
- Fuel Production: 100 kt/a

**Investment costs:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM-Electrolyzer (stack)</td>
<td>720</td>
</tr>
<tr>
<td>PEM-Electrolyzer (system)</td>
<td>1,350</td>
</tr>
<tr>
<td>Fischer-Tropsch reactor</td>
<td>17.44</td>
</tr>
</tbody>
</table>

**Raw materials and utility costs:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>German Grid Power</td>
<td>83.7</td>
</tr>
<tr>
<td>Oxygen (export)</td>
<td>23.7</td>
</tr>
<tr>
<td>Steam (export)</td>
<td>14.7</td>
</tr>
</tbody>
</table>

**General economic assumptions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>2016</td>
</tr>
<tr>
<td>Full load hours</td>
<td>8,260 h/a</td>
</tr>
<tr>
<td>Plant lifetime</td>
<td>30 years</td>
</tr>
<tr>
<td>Interest rate</td>
<td>5%</td>
</tr>
</tbody>
</table>

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[6] Own calculations based on natural gas price from Eurostat database
3. Base Case Results of TEA

- **Electrolyzer**
- **Fischer-Tropsch**
- **Remaining (CAPEX)**
- **Power**
- **Remaining (Utilities)**
- **Maintenance**
- **Labor costs**
- **Remaining (OPEX)**

### Power-to-Liquid (PTL)

- **Investment:** ca. 742 mio. €
- **Fuel production:** 100 kt/a
- **Fuel costs:** ca. 2.25 €/l

- **CAPEX:** 17.0 %
- **65 % (1.47 €/l)**

- **Renewable kerosene can't compete against fossil kerosene**

- **Renewable electricity price has to decrease tremendously in order to make PtL fuels competitive**

- **How to reduce the costs for renewable kerosene?**
  - Increasing and subsidizing renewable power production
  - Increase efficiency (e.g. electrolyzer)
  - Reduce PtL CAPEX (e.g. electrolyzer, FT synthesis)
  - System integration (Sector coupling and multiple products: Fuel, chemicals, district heat, steam, oxygen, power-storage, etc.)
3. Process Evaluation @ DLR

- Technical evaluation
- Ecological evaluation
- Economic assessment

DLR-evaluation and optimization tool

- CO₂-footprint
- CO₂-abatement costs
3. CO₂-Footprint Calculation - Methodology

Power footprint

Carbon dioxide footprint

Carbon footprint of feedstock and energy sources defines carbon footprint of product!

efficiency losses

Footprint of products: Fuel/Heat/H₂ etc.

PtX - Concept

System integration

Accounting for by-products

Plant efficiency

Plant emissions

$CO₂$ Abatement Costs $\left[ \frac{€}{t_{CO₂}} \right] = \frac{\text{Difference in Fuel/Heat/H}_2 \text{ Costs}}{CO₂ \text{ Emission Reduction}}$
3. CO₂-Footprint calculation - Bounderries

<table>
<thead>
<tr>
<th>Functional unit</th>
<th>[kg\textsubscript{CO₂eq}/MWh]\textsuperscript{a}</th>
<th>[kg\textsubscript{CO₂eq}/t]\textsuperscript{b}</th>
<th>[kg\textsubscript{CO₂eq}/t]\textsuperscript{c}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low boundary</td>
<td>10</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>Average</td>
<td>272.5</td>
<td>77.5</td>
<td>250</td>
</tr>
<tr>
<td>High boundary</td>
<td>535</td>
<td>150</td>
<td>400</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Low boundary value for pure wind electricity taken from\cite{1}. High value corresponds to the actual CO₂-footprint of the German electricity sector \cite{2}.

\textsuperscript{b} Based on own calculations. The carbon footprint represents emissions arising from sequestration of CO₂ from flue gas. Flue gas from cement industry and coal fired power plants were investigated. The probably fossil nature of the flue gas was not taken into account. Low/high value: energy demand of CO2-sequestration is covered with wind energy/German electricity mix.

\textsuperscript{c} Taken from ProBas databank \cite{1}. Low/high value due to different electricity sources.

\cite{1} Umweltbundesamt, “Prozessorientierte Basisdaten für Umweltmanagementsysteme,” http://www.probas.umweltbundesamt.de/php/index.php.

3. CO₂-Footprint - Results

### CO₂-Abatement costs:

**Case 1 – Status quo:**
- Price of fossil kerosene: ca. 0.5 €/l
- Power price: 83.7 €/MWh

**Case 2 – Pressure on fossil energy:**
- Price of fossil kerosene: ca. 1.0 €/l
- Power price: 30 €/MWh

<table>
<thead>
<tr>
<th>CO₂-Abatement costs</th>
<th>€ / tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>PtL-Low</td>
</tr>
<tr>
<td>1</td>
<td>827</td>
</tr>
<tr>
<td>2</td>
<td>155</td>
</tr>
</tbody>
</table>

Current CO₂ price of EU Emissions Trading System: ca. 5-15 €/tCO₂.eq

PtL-concepts only viable using CO₂-neutral power!
3. Long-term Target: Merit-Order of Carbon Mitigation Technologies

EU instrument to reduce GHG emissions: CO₂-certificates

Goal: CO₂ reduction @ minimized GHG-Abatement cost, either by reducing GHG footprint or costs!

Standardized and verified methodology for LCA and TEA required!
4. Summary & Outlook

• European GHG emission reduction by 1 % p.a. required – only 5 EU28 countries on track

• Renewable kerosene will be long-term required for aviation

• Transparent and standardized methodology for cost estimation and GHG-footprint calculation available @ DLR

• European green fuels have large potential to contribute to GHG emission reduction

• Research, development, demo and **market introduction** of sustainable aviation fuels need to speed up
  - R&D&D alone will never achieve (energy price) competitiveness
THANK YOU FOR YOUR ATTENTION!

VISIT US @ HALL 5.1, BOOTH C41

German Aerospace Center (DLR)
Institute of Engineering Thermodynamics, Stuttgart
Research Area Alternative Fuels

ralph-uwe.dietrich@dlr.de
http://www.dlr.de/tt/en