Technical Economic Evaluation of Renewable Jet Fuel from Power, Biomass and/or Carbon Dioxide

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**Agenda**

1. **Motivation – Explaining the need for renewable jet fuel**
   - GHG emission reduction need
   - Political framework conditions – Paris Agreement
   - IATA reduction targets

2. **Renewable jet fuel options**
   - By ASTM certified sustainable jet fuels
   - Technical development potentials

3. **Economic and environmental evaluation of renewable jet fuel**
   - Introduction to methodology applied by DLR
   - Example: Green jet fuel from Biomass, Power and/or CO₂

4. **Summary and outlook**
1. Climate Change – fact versus fake


- Global annually averaged surface air **temperature has increased by about 1.0 °C** over the last 115 years (1901–2016)
- No convincing alternative explanation available other than **human activities**, especially emissions of greenhouse gases, are the dominant cause of the observed warming
- **Undeniable effects**, e.g.
  - melting glaciers
  - diminishing snow cover
  - shrinking sea ice
  - rising sea levels
  - ocean acidification
  - increasing atmospheric water vapor
  - climate-related weather extremes (heavy rainfall, heatwaves, forest fires, …)
1. Political willingness needs scientific support

Global long term targets

• COP21 targets:
  - Decarbonization of Society
  - Global average temperature increase below 1.5 °C

European mid term goals

• EU-targets until 2030\(^1,2\)
  - 40 % reduction of GHG (base year 1990)
  - 27 % increase of renewable energies in primary energy consumption
  - 10 % renewable energy in transport and 6.8 % advanced renewable fuels in fuel supply

\(^1\) European Council, “2030 Climate and Energy Policy Framework,” Brussels 2014
\(^2\) European Commission, “Proposal for a directive on the promotion of the use of energy from renewable sources (recast),” Brussels 2016
1. Growth in aviation sector

Fuel for sustainable aviation

Assuming a saturation at about 3,000 km/capita*a

Europe

North America

China

<table>
<thead>
<tr>
<th>Year</th>
<th>Europe (in billion passenger kilometers /a)</th>
<th>North America (in billion passenger kilometers /a)</th>
<th>China (in billion passenger kilometers /a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>440</td>
<td>750</td>
<td>60</td>
</tr>
<tr>
<td>2014</td>
<td>760</td>
<td>1030</td>
<td>510</td>
</tr>
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</table>

(in billion passenger kilometers /a)


+150%    +4%    +710%
1. IATA Technology Roadmap

**Aviation Self-commitments:**

1. Improvement of fuel efficiency
   \[ \approx 1.5 \% \text{ p.a. until 2020} \]

2. Carbon-neutral growth from 2020

3. Potential CO₂ emissions reductions by 2050

**Planned Measures:**

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

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* ICAO-Resolution A39-3: Carbon Offsetting and Reduction Scheme for International Aviation

Source: iata.org

2050 demand forecast:
\[ \approx 56 - 60 \text{ Mt } \text{“CO₂-neutral” kerosene equivalent} \]
2. Jet fuel options: Certified sustainable jet fuels (ASTM D7566 – 14c [1])

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Synthesis technology</th>
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<tr>
<td>Coal, natural gas, biomass, $CO_2$ &amp; $H_2$</td>
<td>Fischer-Tropsch (FT) synthesis</td>
<td>Synthetic paraffinic kerosene</td>
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**Future role of 1st generation jet fuels within the aviation sector questionable due to:**

- Direct competition with food markets
- Low area-related energy yields and limited cultivation area within the EU
- Low technical development potential

**Technical Potential of 1st generation sustainable jet fuel in Europe [2-6]:**

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Kerosene yield from total EU crop production [Mt/a]</th>
<th>Share of EU kerosene consumption$^3_{2014}$ [%]</th>
<th>Share of total cultivation area in EU [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>23.0 – 32.9</td>
<td>41.8 – 59.8</td>
<td>30.2</td>
</tr>
<tr>
<td>Sugar</td>
<td>3.9</td>
<td>7.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>7.3</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>Σ</td>
<td>34.3 – 44.2</td>
<td>62.4 – 80.4</td>
<td>45.2</td>
</tr>
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2. Jet fuel options: Certified sustainable jet fuels (ASTM D7566 – 14c [1])

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<tr>
<td>Lipids from Biomass (e.g. algae, soya, jatropha)</td>
<td>Hydroprocessed esters and fatty acids (HEFA)</td>
<td>Synthetic paraffinic kerosene</td>
</tr>
<tr>
<td>Sugar from Biomass</td>
<td>Direct Sugars to Hydrocarbons (DSHC)</td>
<td>Synthetic iso-paraffins / Farnesane</td>
</tr>
<tr>
<td>Bioethanol (-propanol, -butanol)</td>
<td>dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)</td>
<td>AD-SPK</td>
</tr>
</tbody>
</table>

**Fischer-Tropsch synthesis**

- Large scale, commercial technology
- Based on synthesis gas (Produced from almost any carbon and hydrogen source possible)
- Fully synthetic kerosene achievable[2]

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

- Current jet fuel consumption: $\approx 56$ Mt/a[3]
- Power demand for exclusively power based kerosene in Europe: $\approx 1,410$ TWh
- European wind power potential[4]: $12,200 - 30,400$ TWh
  $\approx 8.6 - 22$ times of power based kerosene demand!

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2. Production routes of alternative FT-Kerosene

The supply of large quantities of alternative kerosene within low GHG emissions is possible by coupling the sectors renewable electricity generation and fuels (without biomass imports).
3. Techno-Economic and ecological assessment (TEA) of renewable jet fuel

DLR’s Techno economic process evaluation tool

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

- CAPEX, OPEX, NPC
- Sensitivity analysis
- Identification of most economic feasible process design

- CO₂-footprint
- CO₂-abatement costs
### 3. Investigated Fischer-Tropsch concepts

**Three concepts to compare**

#### Syngas supply
- Industry flue gases
  - CO₂ purification (Options: Selexol™, Rectisol, MEA …)
- Water-electrolysis
  - (Options: Alkalic PEM, High-temperature (SOEC))
- Biomass
  - Pyrolysis and gasification (gasification options: fixed-bed, fluidized bed, entrained-flow)

#### Syngas conditioning
- Power-to-Liquid (PtL)
  - Reverse Water-Gas-Shift Reaction (900°C)
- Power & Biomass-to-Liquid (PBtL)
  - Water-Gas Shift Reaction (230°C) + CO₂ purification
  - Heat

#### Fuel synthesis
- External recycle
  - O₂ (Tail gas)
- Oxy-fuel burner + steam cycle
- Internal recycle
  - Fischer-Tropsch Synthesis (Options: High/low temperature, cobalt/iron cat.)
- Product separation & conditioning (depending on the required fuel specifications)

3. Technical results: Yield, Efficiency

**Case study equipment selection and assumptions:**
- PEM, $\eta_{\text{LHV}} = 67\%$ [1]
- Entrained flow gasifier, $T = 1,200$ °C, $p = 30$ bar, pure $O_2$ [2]
- Fischer-Tropsch synthesis, $T = 225$ °C, $p = 25$ bar, $\alpha = 0.85$, $X_{\text{CO}} = 40\%$ [3]

**Technical evaluation results:**

More fuel output per carbon unit in PBtL and PtL concept!

More fuel output per MWh in PBtL and PtL concept!

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3. Techno-Economic and ecological assessment (TEA) of renewable jet fuel

- Efficiencies (X-to-Liquid, Overall)
- Carbon conversion
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- Sensitivity analysis
- Identification of most economic feasible process design
- CO₂-footprint
- CO₂-abatement costs
3. Methodology applied for TEA

According to AACE class 3-4 – Cost estimation accuracy +/- 30%

Process simulation results

Plant and unit sizes

Capital costs
- Equipment costs
- Piping & installation
- Factory buildings
- Engineering services ...

Operational costs
- Raw materials
- Operating materials
- Maintenance
- Wages ...

Material and energy balance

Production costs €/l, €/kg, €/MJ

TEPET-ASPEN

Aspen Plus®

Raw materials
- Operating materials
- Maintenance
- Wages ...

Capital costs
- Equipment costs
- Piping & installation
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Material and energy balance

Production costs €/l, €/kg, €/MJ

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### 3. TEA: Base Case definition

#### Investment costs:

<table>
<thead>
<tr>
<th>Process Type</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM-Electrolyzer</td>
<td>723/kW</td>
</tr>
<tr>
<td>Fischer-Tropsch reactor</td>
<td>95,650/(m³)</td>
</tr>
</tbody>
</table>

#### Raw material & by-products market prices:

<table>
<thead>
<tr>
<th>Material</th>
<th>Price (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>83.7/MWh</td>
</tr>
<tr>
<td>CO₂</td>
<td>12.1/t</td>
</tr>
<tr>
<td>Oxygen (export)</td>
<td>23.7/t</td>
</tr>
<tr>
<td>Steam (export)</td>
<td>14.7/t</td>
</tr>
</tbody>
</table>

#### Other economic assumptions:

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

### Plant capacities:

#### BtL:
- 100 MW<sub>LHV</sub> biomass
- Fuel production: 24.2 kt/a

#### PBtL:
- 100 MW<sub>LHV</sub> biomass
- 165 MW power
- Fuel production: 91.3 kt/a

#### PtL:
- 267 MW power
- Fuel production: 91.3 kt/a

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

**Biomass-to-Liquid (BTL)**

- **Investment:** ca. 395.2 mio. €
- **Fuel production:** 24.2 kt/a
- **Fuel costs:** ca. 2.37 €/l

**Power & Biomass-to-Liquid (PBTL)**

- **Investment:** ca. 751 mio. €
- **Fuel production:** 91.3 kt/a
- **Fuel costs:** ca. 1.95 €/l

**Power-to-Liquid (PTL)**

- **Investment:** ca. 672.5 mio. €
- **Fuel production:** 91.3 kt/a
- **Fuel costs:** ca. 2.26 €/l

CAPEX:
- **Power[3]:** 45.2%
- **Biomass[4]:** 22.0%
- **Remaining (Utilities):** 6%
- **Remaining (CAPEX):** 20%
- **Remaining (OPEX):** 22%

- **Maintenance:** 46%
- **Labor costs:** 65%
3. Sensitivity analysis – Economy of scale and Power Price

“optimal” production concept depends on local feedstock availability/costs!
3. Techno-Economic and ecological assessment (TEA) of renewable jet fuel

- Efficiencies (X-to-Liquid, Overall)
- Carbon conversion
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DLR’s Techno economic process evaluation tool

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- CO₂-footprint
- CO₂-abatement costs
### 3. CO₂-Abatement Cost – Footprint of Feedstocks

<table>
<thead>
<tr>
<th>Functional unit</th>
<th>Biomass [kg CO₂eq/t]</th>
<th>Power [kg CO₂eq/MWh]</th>
<th>Carbon dioxide [kg CO₂eq/t]</th>
<th>Oxygen [kg CO₂eq/t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low boundary</td>
<td>13.6</td>
<td>10</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>Average</td>
<td>134.3</td>
<td>272.5</td>
<td>77.5</td>
<td>250</td>
</tr>
<tr>
<td>High boundary</td>
<td>255</td>
<td>535</td>
<td>150</td>
<td>400</td>
</tr>
</tbody>
</table>

a Based on own calculations taking into account biomass type (forest residues, straw etc.) and transport distances. CO₂-emissions during cultivation and harvesting are accounted for.

b Low boundary value for pure wind electricity taken from[1]. High value corresponds to the actual CO₂-footprint of the German electricity sector [2].

c 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.

d Taken from ProBas databank [1]. Low/high value due to different electricity sources.

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3. CO₂-Abatement Cost – Results

\[
\text{CO}_2 - \text{Abatement costs} = \frac{\text{Difference in fuel/heat/H}_2 \text{ costs}}{\text{CO}_2 - \text{emission reduction}}
\]

Cost comparison:

Case 1 – Status Quo:
- Price of fossil kerosene: ca. 0.5 €/l
- Power price: 105 €/MWh
- Biomass price: 100 €/t

Case 2 – Pressure on Fossil Energy:
- Price of fossil kerosene: ca. 1.0 €/l
- Power price: 30 €/MWh
- Biomass price: 60 €/t

<table>
<thead>
<tr>
<th>CO₂-Abatement costs $/t_{CO₂}$</th>
<th>BtL-Low</th>
<th>BtL-Av.</th>
<th>BtL-High</th>
<th>PBtL-Low</th>
<th>PtL-Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>662</td>
<td>985</td>
<td>2,756</td>
<td>631</td>
<td>827</td>
</tr>
<tr>
<td>2</td>
<td>406</td>
<td>605</td>
<td>1,183</td>
<td>134</td>
<td>155</td>
</tr>
</tbody>
</table>

Current CO₂ Price of EU-ETS: 5-7 €/t_{CO₂.eq}
Conclusions

- Large quantities of renewable jet fuel are required to reduce GHG emissions in the growing aviation sector
- Technical potential of 1st generation jet fuel from energy crops is very limited
- Fischer-Tropsch based jet fuel can replace fossil fuel as drop-in fuel
- Large refinery capacities are required in order to convert FT-syncrude into valuable jet fuel (ASTM-quality)
- A standardized and transparent methodology for the evaluation of alternative jet fuels with respect to technical, economic and ecological key performance parameters is available

Outlook

- 2021 will start the Global GHG compensation policy CORSIA in 66 countries, becoming fully obligatory 2027-2035
- United Nations Framework Convention on Climate Change (UNFCCC) certifies GHG emission reduction projects
- European refinery industry shall volunteer for large scale renewable jetfuel production helping to fulfill aviation long term goals
Outlook: Power&Biomass-to-Liquid Proof of concept

Techno-economic assessment

Biomass

- Biomass preparation
  - Slurry
  - Biomass gasification

Gas cleaning

External Recycle

Reverse water-gas-shift reactor

Internal Recycle

Fischer-Tropsch synthesis

Internal Recycle

H₂

Tail gas processing

Tail gas

Product separation

Syncrude

Project partner required

Gasoline
Jet fuel
Diesel

Power & H₂O

Electrolysis

O₂

Fuel usage
THANK YOU FOR YOUR ATTENTION!

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

ralph-uwe.dietrich@dlr.de
http://www.dlr.de/tt/en
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10MW | 30MW | 100MW ELECTROLYSER SYSTEMS

Deployment of world's largest PEM electrolyser with Shell at Wesseling Refinery

- Utilises proven and modular PEM electrolysis system
- The Wesseling refinery currently uses 160,000/yr of H₂
- This equates to 1,000MW of electrolysis, worth €1 billion
- Fully integrated & autonomous
- Expandable & industrial scale
- Replication maintains standardisation
- 10MW building 20 x 14m

ELECTROLYSER SCALE-UP
HYDROGEN ENERGY SYSTEMS