Hydrogen as Future Fuel
Used in
Minimum Change Derivatives of the Airbus A321

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Content

- Background
- Motivation
- Introduction

- Research Question
- Hypothesis

- Aspects of Hydrogen Tank Integration
- Overview of Aircraft Configurations in this Study
- Aircraft Design for Hydrogen
  - The Baseline Aircraft (A320)
  - Design of A321-HS (stretch)
  - Design of A321-HW (with wing mounted pods)
  - Design of A321-H19 (with A319 cabin)

- Conclusions
- References
Background

Literature / Previous Projects

**FINAL TECHNICAL REPORT**

(Publishable Version)

**CONTRACT N°:** C4RD-CT-2000-00192  
**PROJECT N°:** GRD1-1999-10014  
**ACRONYM:** CRYPLOANE  
**TITLE:** Liquid Hydrogen Fuelled Aircraft System Analysis

**PROJECT CO-ORDINATOR:** Airbus Deutschland GmbH


**SEECKT, Kolja:**

Conceptual Design and Investigation of Hydrogen-Fueled Regional Freighter Aircraft.  

2012: Dan BREWER (93) [1], [2]

Green Freighter  
HAW Hamburg (lead)  
TU Braunschweig (IFL)  
Airbus, Hamburg  
Bishop GmbH  
09/2006 to 04/2010
The Availability of Energy is Important!

- Depletion of fossil fuels => aviation energy carrier instead of aviation fuel

- The search for the aviation energy carrier of the future is ongoing:
  # biofuel, synthetic fuel, drop-in fuel  advantage: aircraft stay the same
  # batteries                          advantage: direct use of electricity
  # hydrogen                           advantage: best known technology

- Current focus: CO2, Global Warming, Climate Change, but:
- There are more issues than CO2
- Needed: Balanced look with Life Cycle Assessment
- Ensure:
  Future availability of energy in aviation!
  (or tell your kids the party is over)

1. water
2. energy
3. CO2 global warming

SCHOLZ, DLRK 2012 [5]
Note the Scale of the Energy Consumption in Aviation!

- **Global energy consumption in aviation** (2009):
  - # 230 Mtoe (million ton oil equivalent) per year
  - # with 0.8 t/m³ this is 9.1 m³/s (flow of a smaller tributary of the river Elbe; p.t.o.)
  - # with heating value, $H = 41.9$ MJ/kg this is 300000 MW or
    300 nuclear power plants (simple energy comparison)

- How does this relate to **biofuel production**?

  **BIOREFLY Project**

  2,000 TON/Y INDUSTRIAL SCALE DEMONSTRATION BIOREFINERY ON LIGNIN-BASED AVIATION FUEL

  This [6] is **0.00087 %** of global energy consumption in aviation.

- Clearly, after peak oil (2050?) there will be **more than one energy carrier** in aviation => necessary. **Hydrogen** must be one of these energy carriers! Or we won't make it.
Global aviation fuel consumption 9.1 m³/s is roughly Hamburg's water discharge into the Elbe.
Hydrogen Production …

… with Natural Gas Steam Reforming

Hydrocarbons are catalytically split in the presence of a steam with a temperature near 900 °C. A gas is produced (syngas) mainly consists of hydrogen and CO.

Inexpensive. Used in 97 % of the cases.

… with Renewable Energy

# Solar energy using photovoltaics
# Solar thermal energy
# Wind power source
# Hydro power source
# Biomass energy source (Biomass gasification)

based on [10]
Motivation

Hydrogen Life Cycle

Storage and long distance short distance at airport

Liquid Hydrogen Production

Hydrogen Production by Electrolysis

Energy production upon Renewable Energy Sources (Solar, Wind, Hydropower, Solar thermal, Biomass)

Energy Transport

Long distance

Hydrogen Liquefaction

Liquid Hydrogen Transportation

Short distance

Use of Liquid Hydrogen

Storage
Characteristics of Hydrogen – Important for Aircraft Design

- Comparison at equal energy:

- Boil-off

- Hydrogen embrittlement (Wasserstoffversprödung) of materials
Introduction

Hydrogen Aircraft Configurations

- The selection of a type of aviation energy carrier needs to be seen together with the resultant aircraft configuration!

Findings from CRYOPLANE

Various tank layouts appeared to be optimal depending on aircraft category. Crucial element is balancing of the aircraft’s center of gravity. Due to the large and heavy tanks, aircraft empty weight will go up by some 25% compared to kerosene aircraft. However, due to the light LH2 maximum take-off weights will go down, especially with increasing fuel fraction. As a consequence of the bulky tanks the energy consumption increases as well, resulting in a 25% increase in DOC as of today for a 1000 nm mission. When LH2 production cost drops to levels below that of kerosene, DOC’s for LH2 and kerosene fuelled aircraft may reach a crossover point as far away as 2040. This is in line however with the motivation behind LH2 technology: a long-term alternative for kerosene when crude oil production comes to an end.
Erkenntnisse aus dem Projekt "Grüner Frachter"

Vorteile von LH2:

- Fliegen bleibt auch nach dem Ende fossiler Kraftstoffe möglich!
- Bereits heute ist die LH2-Technologie im Flugzeug bekannt und anwendbar.
- Die Verbrennung von Wasserstoff ist umweltfreundlicher als die von Kerosin.

Nachteile von LH2:

- Herkömmliche Flugzeuge können nicht genutzt werden.
- Es ist eine neue Infrastruktur am Flughafen erforderlich: Wasserstoffproduktion, Wasserstoffverflüssigung
- Um die gleiche Nutzlast über die gleiche Reichweite zu transportieren müssen größere Unterbringungsräume für die (nahezu) zylindrischen LH2-Tanks gefunden werden. LH2-Flugzeuge sind aufgrund der großen Tanks größer und zeigen damit einen höheren Nullwiderstand.
- Alle untersuchten LH2-Flugzeugkonfigurationen haben leicht höhere Betriebskosten.
- Trotz der Isolierung der Tanks, erwärmt sich der Wasserstoff und wird teilweise wieder gasförmig.
  # Im Flug kann dieser Wasserstoff verbraucht werden.
  # Am Boden würde der Druck im Tank steigen und Wasserstoff müsste abgeblasen werden.
- Ein betanktes Flugzeug kann also nicht einfach so auf dem Vorfeld stehen gelassen werden. Eine Betankung ist erst kurz vor dem Start sinnvoll.
- Der Flugbetrieb muss diesen Umstand berücksichtigen und wird damit etwas weniger flexibel.

Doch, können – siehe dieser Vortrag!
LH2-Technology already Tested in Aviation

**TU-155** was the first aircraft to fly on hydrogen already in 1988.
Hydrogen's **Show Stopper in Aviation**

Hydrogen's show stopper in aviation is the necessary **big investments**

1.) in new aircraft

2.) in new airport infrastructure
   * liquid hydrogen production
   * new refueling equipment at airports

**In contrast:**

Drop-in fuel (biofuel, synthetic fuel) needs **no investment in the aviation system**

1.) same aircraft

2.) same airport infrastructure
   * no extra production fascility at airport
   * same refueling equipment
Research Question

Hydrogen’s Show Stopper in Aviation

Hydrogen's show stopper in aviation is the necessary big investments

1.) in new aircraft

2.) in new airport infrastructure
   * liquid hydrogen production
   * new refueling equipment at airports

Can we reduce the investment by using modified existing aircraft for the new energy carrier hydrogen?

In contrast:
Drop-in fuel (biofuel, synthetic fuel) needs no investment in the aviation system

1.) same aircraft

2.) same airport infrastructure
   * no extra production fascility at airport
   * same refueling equipment
The Idea

Hypothesis: Use an existing (longer) fuselage to integrate the hydrogen tanks to limit investment!!!

Fuselage Length Compared:
- A320: 44.51 m (145.03 ft)
- A321: 37.57 m (123.27 ft)

The Idea
A320 Family

Dimensions of the A320 family (Airbus Technical Data)
Hydrogen Storage in the Fuselage (Front and Rear)

Distribution of the tank in the front and in the back to balance CG.

Two tanks forward and two tanks aft. Assume no double tank failure or aircraft robust against CG shift.

Use of some portion of the front and aft cabin.

Use of an even bigger portion of front and aft cargo compartment.
Hydrogen Storage over the Fuselage (Not Selected for this Project)
## Aspects of Hydrogen Tank Integration

### Trade-Off for Tank Location in Fuselage

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>Over the fuselage</th>
<th>Front and Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access for crew and passengers</td>
<td>3†</td>
<td>1</td>
</tr>
<tr>
<td>Surface to volume considerations</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Control of C.G.</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Security in case of damage</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Drag Increase</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Weight increase</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Manufacturing process consideration</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>13</strong></td>
<td><strong>17</strong></td>
</tr>
</tbody>
</table>

† 3 is High; 2 is Medium; 1 is Low

The winner!

Not compatible with fuselage stretch.

Scoring Model
Additional (!) Hydrogen Storage in Underwing Pods
Aspects of Hydrogen Tank Integration

Passage Way for Cockpit Crew to Reach the Cabin

- For certification: No need for passage way (Roskam)
- Passage way selected here for convenience. But: Reduces tank volume in the front tank.
  Leads to longer fuselage
Overview of Aircraft Configurations in this Study

Baseline

A321-HW

A320-200

A321-HS

A321-H19

A319 Cabin

**H:** LH2 Aircraft  
**W:** A321 with additional hydrogen tanks under wing  
**S:** A321 with additional stretch (to give more volume for LH2 tanks)  
**19:** A321 filled only with 156 (instead of 180) one-class passengers (more room left for LH2 tanks). Same payload & range kept
**Baseline Aircraft: A320**

List of fundamental aircraft and cabin variables with the values of the reference aircraft.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{MPL} ) [kg]</td>
<td>19256</td>
</tr>
<tr>
<td>( R_{MPL} ) [NM]</td>
<td>1510</td>
</tr>
<tr>
<td>( M_{CR} )</td>
<td>0.76</td>
</tr>
<tr>
<td>( s_{TOFL} ) [m]</td>
<td>1767.8</td>
</tr>
<tr>
<td>( s_{LFL} ) [m]</td>
<td>1447.8</td>
</tr>
<tr>
<td>( n_{PAX} )</td>
<td>180</td>
</tr>
<tr>
<td>( m_{PAX} ) [kg]</td>
<td>93</td>
</tr>
<tr>
<td>( SP ) [in]</td>
<td>29</td>
</tr>
</tbody>
</table>

Calculation tool adapted and used: **OPerA – Optimization in Preliminary Aircraft**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Value A320-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing field length [m]</td>
<td>( s_{LFL} )</td>
<td>1448</td>
</tr>
<tr>
<td>Take-off field length [m]</td>
<td>( s_{TOFL} )</td>
<td>1768</td>
</tr>
<tr>
<td>Max. lift coefficient, landing</td>
<td>( C_{L_{max,L}} )</td>
<td>3.14</td>
</tr>
<tr>
<td>Max. lift coefficient, take-off</td>
<td>( C_{L_{max,TO}} )</td>
<td>2.82</td>
</tr>
<tr>
<td>Mass ratio, max landing to max take-off</td>
<td>( m_{ML}/m_{MTO} )</td>
<td>0.88</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>( \lambda )</td>
<td>9.5</td>
</tr>
<tr>
<td>Number of engines</td>
<td>( n_E )</td>
<td>2</td>
</tr>
<tr>
<td>Number of passengers</td>
<td>( n_{PAX} )</td>
<td>180</td>
</tr>
<tr>
<td>Number of seats abreast</td>
<td>( n_{SA} )</td>
<td>6</td>
</tr>
<tr>
<td>Wing sweep at 25% chord [°]</td>
<td>( \phi_{25} )</td>
<td>25</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>( \lambda )</td>
<td>0.213</td>
</tr>
<tr>
<td>Position of the vertical tail in case of cruciform config.</td>
<td>( z_{H}/b_{y} )</td>
<td>0.56</td>
</tr>
<tr>
<td>Minimum distance from engine to wing over nacelle diam.</td>
<td>( z_{P_{min}}/D_{N} )</td>
<td>0.15</td>
</tr>
<tr>
<td>By-Pass ratio</td>
<td>( BPR )</td>
<td>6</td>
</tr>
<tr>
<td>Mach number, cruise</td>
<td>( M_{CR} )</td>
<td>0.76</td>
</tr>
<tr>
<td>Seat pitch [m]</td>
<td>( SP )</td>
<td>0.74</td>
</tr>
<tr>
<td>Aisle width [m]</td>
<td>( w_{aisle} )</td>
<td>0.51</td>
</tr>
<tr>
<td>Seat width [m]</td>
<td>( w_{seat} )</td>
<td>0.51</td>
</tr>
<tr>
<td>Armrest width [m]</td>
<td>( w_{armrest} )</td>
<td>0.051</td>
</tr>
<tr>
<td>Sidewall Clearance (at armrest) [m]</td>
<td>( s_{clearance} )</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Breakdown of the OEW, DOC and Drag Component for the A320-200
Comparison of A321-HS with A320-200

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A321-HS</th>
<th>Variation (A320)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{MTO}$ [kg]</td>
<td>73578</td>
<td>+1.8</td>
</tr>
<tr>
<td>$m_{OE}$ [kg]</td>
<td>47658</td>
<td>+18.6</td>
</tr>
<tr>
<td>$m_{F}$ [kg]</td>
<td>6664</td>
<td>-48.0</td>
</tr>
<tr>
<td>DOC (AEA) [€/NM/t]</td>
<td>1.68</td>
<td>+26.7</td>
</tr>
<tr>
<td>DOC (TUB) [€/NM/t]</td>
<td>1.49</td>
<td>+29.3</td>
</tr>
<tr>
<td>$l_F$ [m]</td>
<td>49.4</td>
<td>+28.8</td>
</tr>
<tr>
<td>$S_W$ [m²]</td>
<td>131.1</td>
<td>+9.0</td>
</tr>
<tr>
<td>$b_{W,geo}$ [m]</td>
<td>35.3</td>
<td>+4.4</td>
</tr>
<tr>
<td>$A_{W,eff}$</td>
<td>9.5</td>
<td>0</td>
</tr>
<tr>
<td>$\varphi_{25}$ [°]</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>17.6</td>
<td>+0.4</td>
</tr>
<tr>
<td>$T_{R0}$ [kN]</td>
<td>103.9</td>
<td>-5.0</td>
</tr>
<tr>
<td>$BPR$</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>$SFC$ [kg/N/s]</td>
<td>5.79E-06</td>
<td>-65.0</td>
</tr>
<tr>
<td>$h_{CR}$ [ft]</td>
<td>37706</td>
<td>-3.0</td>
</tr>
<tr>
<td>$m_{MTO}/S_W$ [kg/m²]</td>
<td>560.7</td>
<td>-6.6</td>
</tr>
</tbody>
</table>

A321: $l_F = 44.5$ m
Delta: 4.9 m
energy up 46 %

Details of the tanks for the A321-HS
Aircraft Design for Hydrogen

Breakdown of the OEW, DOC and Drag Component

A320-200

A321-HS
## Comparison of A321-HW with A320-200

### Details of the tanks for the A321-HW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A321-HW</th>
<th>Variation (A320)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{MT0}$ [kg]</td>
<td>70716</td>
<td>-2.2</td>
</tr>
<tr>
<td>$m_{OE}$ [kg]</td>
<td>44871</td>
<td>+11.6</td>
</tr>
<tr>
<td>$m_F$ [kg]</td>
<td>6588</td>
<td>-48.6</td>
</tr>
<tr>
<td>$DOC$ (AEA) [€/NM/t]</td>
<td>1.63</td>
<td>+23.3</td>
</tr>
<tr>
<td>$DOC$ (TUB) [€/NM/t]</td>
<td>1.45</td>
<td>+25.9</td>
</tr>
<tr>
<td>$l_F$ [m]</td>
<td>45.2</td>
<td>+18.0</td>
</tr>
<tr>
<td>$S_W$ [m$^2$]</td>
<td>126.1</td>
<td>+4.8</td>
</tr>
<tr>
<td>$b_{W,geo}$ [m]</td>
<td>34.6</td>
<td>+2.4</td>
</tr>
<tr>
<td>$A_{W,eff}$</td>
<td>9.5</td>
<td>0</td>
</tr>
<tr>
<td>$q_{25}$ [$^\circ$]</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>16.9</td>
<td>-3.9</td>
</tr>
<tr>
<td>$T_{TO}$ [kN]</td>
<td>99.8</td>
<td>-8.8</td>
</tr>
<tr>
<td>$BPR$</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>$SFC$ [kg/N/s]</td>
<td>5.82E-06</td>
<td>-64.8</td>
</tr>
<tr>
<td>$h_C$ [ft]</td>
<td>36720</td>
<td>-5.6</td>
</tr>
<tr>
<td>$m_{MT0}/S_W$ [kg/m$^2$]</td>
<td>560.7</td>
<td>-6.6</td>
</tr>
</tbody>
</table>

### Energy Up 44%

A321: $l_F = 44.5$ m  
Delta: 0.7 m
Bank angle clearance for the wing tanks of A321-HW
Comparison of A321-H19 with A320-200

Fuselage comparison between A321-HS (upper a/c) and A321-H19 (lower a/c)

Details of the tanks for the A321-H19

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A321-H19</th>
<th>Variation (A320)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{MTO}$ [kg]</td>
<td>70916</td>
<td>-1.9</td>
</tr>
<tr>
<td>$m_{OE}$ [kg]</td>
<td>45208</td>
<td>+12.5</td>
</tr>
<tr>
<td>$m_{F}$ [kg]</td>
<td>6443</td>
<td>-49.7</td>
</tr>
<tr>
<td>DOC (AEA) [€/NM/t]</td>
<td>1.78</td>
<td>+34.9</td>
</tr>
<tr>
<td>DOC (TUB) [€/NM/t]</td>
<td>1.61</td>
<td>+39.8</td>
</tr>
<tr>
<td>$l_{F}$ [m]</td>
<td>46.2</td>
<td>+20.5</td>
</tr>
<tr>
<td>$S_{W}$ [$m^2$]</td>
<td>126.5</td>
<td>+5.1</td>
</tr>
<tr>
<td>$b_{W,geo}$ [m]</td>
<td>34.7</td>
<td>+2.5</td>
</tr>
<tr>
<td>$A_{W,eff}$</td>
<td>9.5</td>
<td>0</td>
</tr>
<tr>
<td>$\varphi_{25}$ [°]</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>$E_{max}$</td>
<td>17.6</td>
<td>+0.3</td>
</tr>
<tr>
<td>$T_{TO}$ [kN]</td>
<td>100.2</td>
<td>-8.4</td>
</tr>
<tr>
<td>BPR</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>$SFC$ [kg/N/s]</td>
<td>5.82E-06</td>
<td>-64.8</td>
</tr>
<tr>
<td>$l_{cR}$ [ft]</td>
<td>37676</td>
<td>-3.1</td>
</tr>
<tr>
<td>$m_{MTO}/S_{W}$ [kg/$m^2$]</td>
<td>560.7</td>
<td>-6.6</td>
</tr>
</tbody>
</table>

If DOC are based on A319:
- DOC (AEA) +17%
- DOC (TUB) +21%

Energy up 41%  
A321: $l_{F} = 44.5$ m  
Delta: 1.7 m
## Overall Comparison

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_F ) [m]</td>
<td>38.4</td>
<td>49.4</td>
<td>45.2</td>
<td>46.2</td>
</tr>
<tr>
<td>( m_{MTO} ) [kg]</td>
<td>72274</td>
<td>73578</td>
<td>70716</td>
<td>70916</td>
</tr>
<tr>
<td>( m_{OE} ) [kg]</td>
<td>40199</td>
<td>47658</td>
<td>44871</td>
<td>45208</td>
</tr>
<tr>
<td>( m_{ML} ) [kg]</td>
<td>63457</td>
<td>69164</td>
<td>66473</td>
<td>66661</td>
</tr>
<tr>
<td>( m_F ) [kg]</td>
<td>12819</td>
<td>6664</td>
<td>6588</td>
<td>6443</td>
</tr>
<tr>
<td>( E_{max} )</td>
<td>17.5</td>
<td>17.6</td>
<td>16.9</td>
<td>17.6</td>
</tr>
<tr>
<td>( T_{TO} ) [kN]</td>
<td>109.4</td>
<td>103.9</td>
<td>99.8</td>
<td>100.2</td>
</tr>
<tr>
<td>BPR</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>( SFC ) [kg/N/s]</td>
<td>1.65E-05</td>
<td>5.79E-06</td>
<td>5.82E-06</td>
<td>5.82E-06</td>
</tr>
<tr>
<td>( m_T ) [kg]</td>
<td>-</td>
<td>2531</td>
<td>2473</td>
<td>2517</td>
</tr>
<tr>
<td>( n_{PAX} )</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>156</td>
</tr>
<tr>
<td>( DOC ) [€/NM/t]</td>
<td>1.32</td>
<td>1.68</td>
<td>1.63</td>
<td>1.78</td>
</tr>
<tr>
<td>( DOC ) [€/NM/t]</td>
<td>1.15</td>
<td>1.49</td>
<td>1.45</td>
<td>1.61</td>
</tr>
</tbody>
</table>

\( A321: \ l_F = 44.5 \ \text{m} \)
Overall Comparison

Comparison of MTOW, OEW, MLW related to the original A320-200
Comparison of DOC related to the original A320-200

If DOC are based on A319:
DOC (AEA) +17%
DOC (TUB) +21%
Overall Comparison

Payload-Range diagram comparison between a kerosene and a hydrogen-fueled aircraft
Conclusions

News where at one time distributed via Newspapers –
• then via Newspapers and Radio,
• then via Newspapers and Radio and TV,
• then via Newspapers and Radio and TV and Interent,
• …

We will say: Aircraft flew at one time with Kerosene –
• then with Kerosene and Drop-In Fuel,
• then with Kerosene and Drop-In Fuel and Hydrogen,
• …

The question will NOT be one or the other energy carrier?, but what mixture of energy carriers for the aviation system?
Hydrogen as Future Fuel Used in Minimum Change Derivatives of the Airbus A321

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Aircraft Sketches Done with OpenVSP (NASA) and OpenVSP-Connect (HAW Hamburg)

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OpenVSP.ProfScholz.de
This presentation is strongly based on the coauthor's thesis:


References


Price Increase of Kerosene

- The increase of kerosene price in the future is predicted by Airbus to be linear: 2 US$/bbl/year
- Barrel: 1bbl (US) = 159 l; 1,3 US$/€; 0,8 kg/l
- Future fuel price: current fuel price (2013: 0,53 €/kg) plus price increase