Bauhaus Luftfahrt
Neue Wege.

Sustainable energy and fuel options for future aviation

Arne Roth
Future Technologies and Ecology of Aviation

Contents

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- >> Alternative fuels & aviation: Key drivers & challenges
- >> Background: What is jet fuel?
- >> Synthetic jet fuel: Review of selected pathways
- >> Alternatives beyond biomass
- >> Conclusions and outlook

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Alternative fuels: Key drivers & challenges

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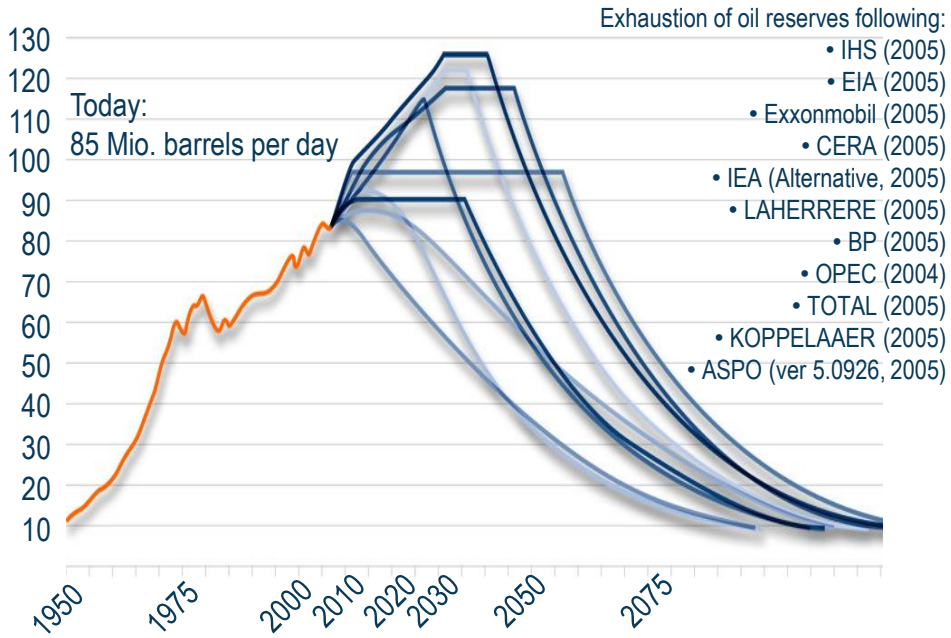
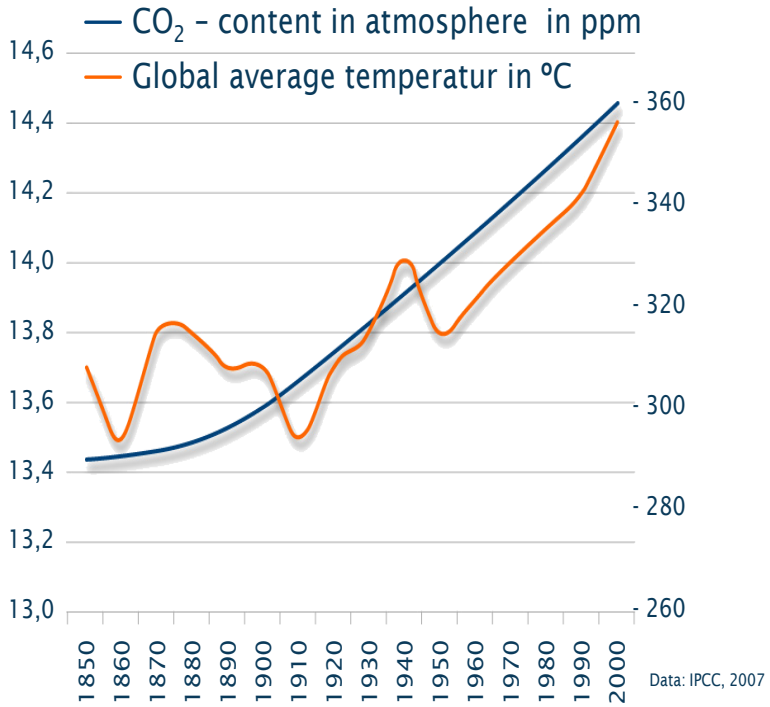
>> Supply security for aviation fuels

>> Growing mobility demand

>> Reduction of greenhouse gas emissions





Alternative fuels: Key drivers & challenges

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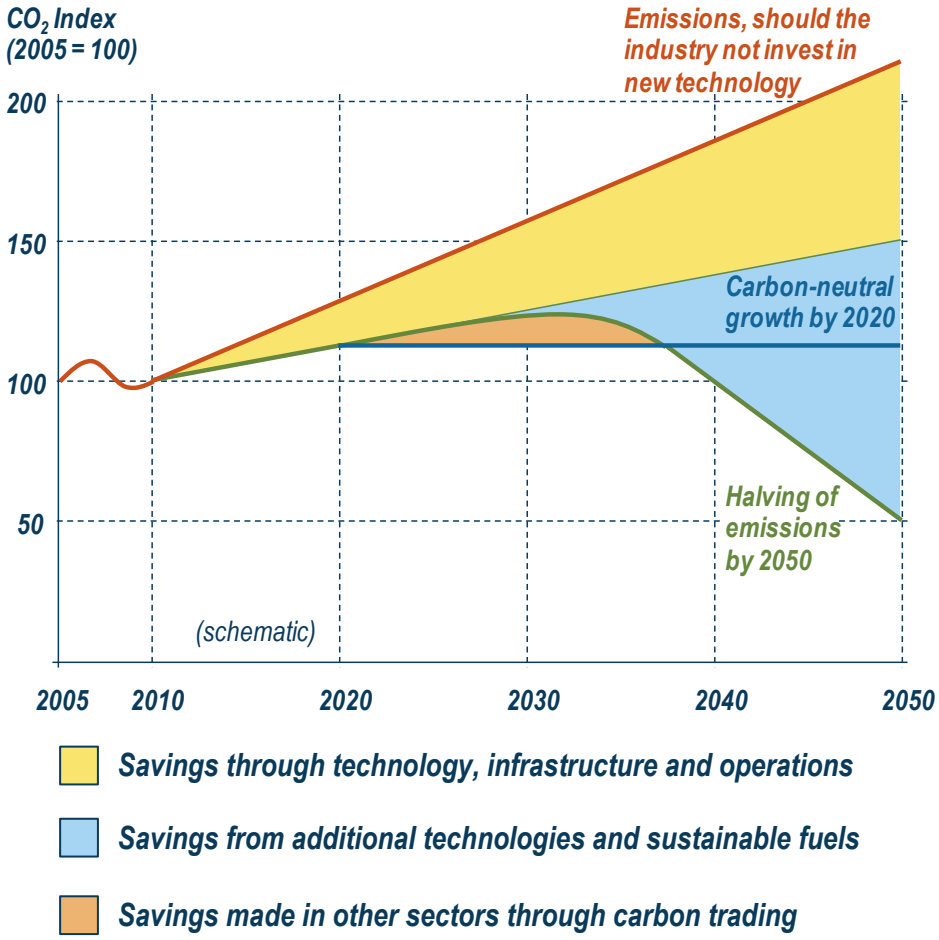
- >> Efficiency gains through aircraft technology & innovation
- >> Efficiency gains through infrastructure and operations
- >> Economic measures
- >> Sustainable fuels: will be a key component



Source: **IATA**, 2010

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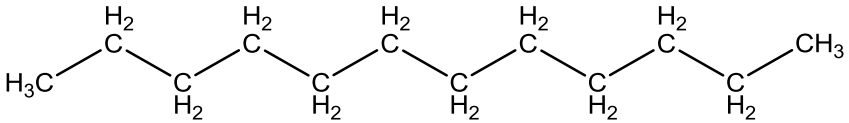
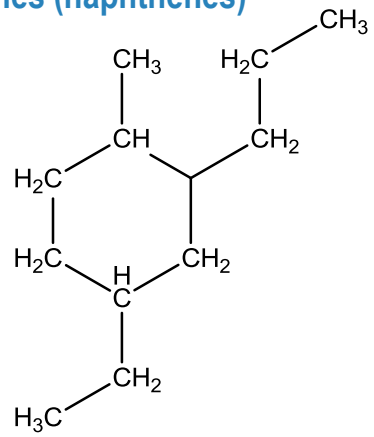
What is jet fuel?



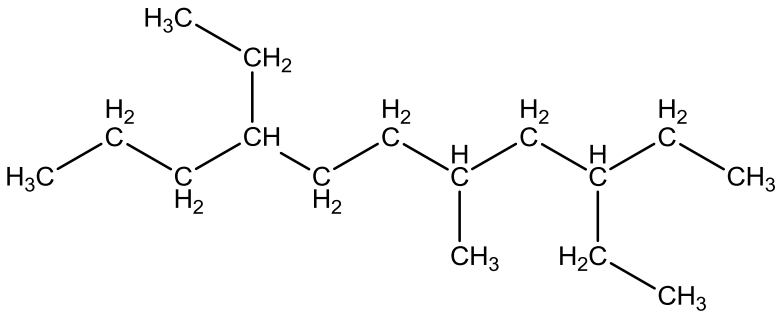
n-alkanes (*n*-paraffines)

cycloalkanes (naphthenes)

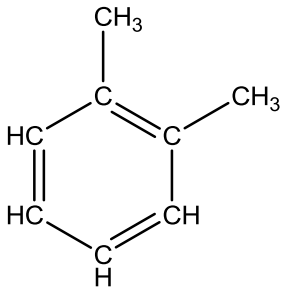


ca. 80% alkanes („saturates“)

complex(!) mixture of hydrocarbons



iso-alkanes (*iso*-paraffines)



ca. 18% aromatics

How can jet fuel be produced?

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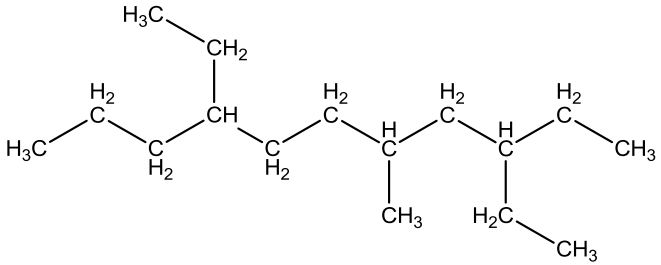
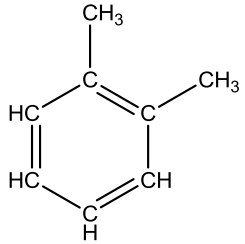
>> Traditionally from petroleum

- > Already a crude mixture of hydrocarbons
- > Availability?
- > Ecobalance?





>> Alternatives will have to be synthesized (i.e. synthetic)

>> In principle, hydrocarbons can be synthesized from any carbon-based feedstock!

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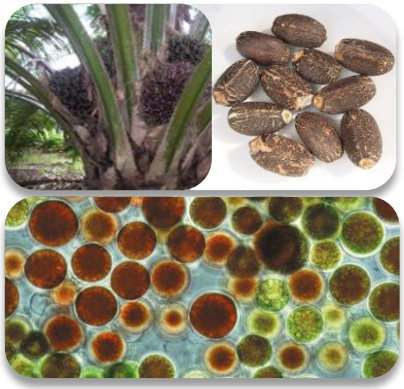
Selected feedstocks and processes

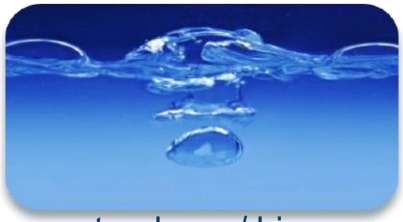


triglycerides (fat and oil)

HEFA (hydroprocessing)

coal

CtL (gasification, FT)



natural gas / biogas

GtL (reforming, FT)

(ligno)cellulosic material

BtL (gasification, FT)
AtJ (fermentation, oligom.)
PRJ (pyrolysis, hydropr.)
Hydrothermal conversion
CRJ (chemical conversion)
FRJ (fermentative conversion)

sugar / starch

AtJ (fermentation, oligom.)
CRJ (chemical conversion)
FRJ (fermentative conversion)

plastic waste

WtL (gasification, FT)

Assessment of synthetic fuel options

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>> *Various options!*

>> *But which make sense?*

>> *Suitability*

> Drop-in capability?

> Near-term: drop-in mandatory

> min. 8% aromatics

ASTM INTERNATIONAL

>> *Scalability*

> Economics

> Technical scalability

> Feedstock availability

> European Advanced Biofuels Flightpath Initiative: 2 Mt biojet fuel in 2020

> Less than 1% of global jet fuel demand

> More than 3 Mha (rapeseed) required!

>> *Sustainability*

> Ecology (e.g. GHG balance)

> Socio-economics

> Mandatory, especially w.r.t. long-term implementation

> Complex w.r.t standards and evaluation

Biogenic feedstock: Risks and drawbacks

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>> Primary problem:

Low overall efficiency

> **Photosynthesis**

> Energy efficiency of about 1% (upper limit for C_3 plants: 4.5%)

> **Multi-step conversion of biomass required**

>> Secondary problem:

High input required

> **Energy, water, land, nutrients, etc.**

>> Suitability

> **No principle problem**

>> Scalability

> **High production costs**

> **Restricted land/feedstock availability**

>> Sustainability

> **Food vs. fuel**

> **LUC and land grabbing**

> **Emissions (GHG, toxicants, eutrophication)**

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Beyond biomass: General considerations

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>> What we are doing:

$$\text{E-carrier} + O_2 \longrightarrow CO_2 + H_2O + \text{energy}$$

>> Respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

carbohydrates

>> Combustion

$$2\,„CH_2“ + 3O_2 \rightarrow 2CO_2 + 2H_2O + \text{energy}$$

hydrocarbons

Beyond biomass: General considerations

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>> *What we are doing:*

$$E\text{-carrier} + O_2 \longrightarrow CO_2 + H_2O + energy$$

>> *What we want to do:*

$$E\text{-carrier} + O_2 \longleftarrow CO_2 + H_2O + energy$$

>> *In nature: Photosynthesis*

> Sunlight (energy)

> Water (electrons)

>> *And in the laboratory?*

Solar Fuels

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>> Solar-driven thermochemical splitting of H_2O and CO_2

> H_2O + energy → H_2 + ½ O_2

> CO_2 + energy → CO + ½ O_2

Synthesis gas

>> Fischer-Tropsch synthesis

> CO + $2H_2$ → „CH_2“ + H_2O

> Refinement of hydrocarbon (C_nH_m) product mixture yields SPK jet fuel

>> „Reverse combustion“

Chueh, W. C. *et al*, *Science* **2012,** *330* , 1797-1801

Electrochemical pathways

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>> Utilization of electric energy for re-energizing carbon

>> Electrolysis of H_2O

> H_2O + energy → H_2 + ½ O_2

> CO_2 + H_2 → CO + H_2O

>> Electrolysis of H_2O and CO_2

> H_2O + energy → H_2 + ½ O_2

> CO_2 + energy → CO + ½ O_2

> FT synthesis → C_nH_m product

>> Ecologic value depends on electricity production

Photo-catalytic approach

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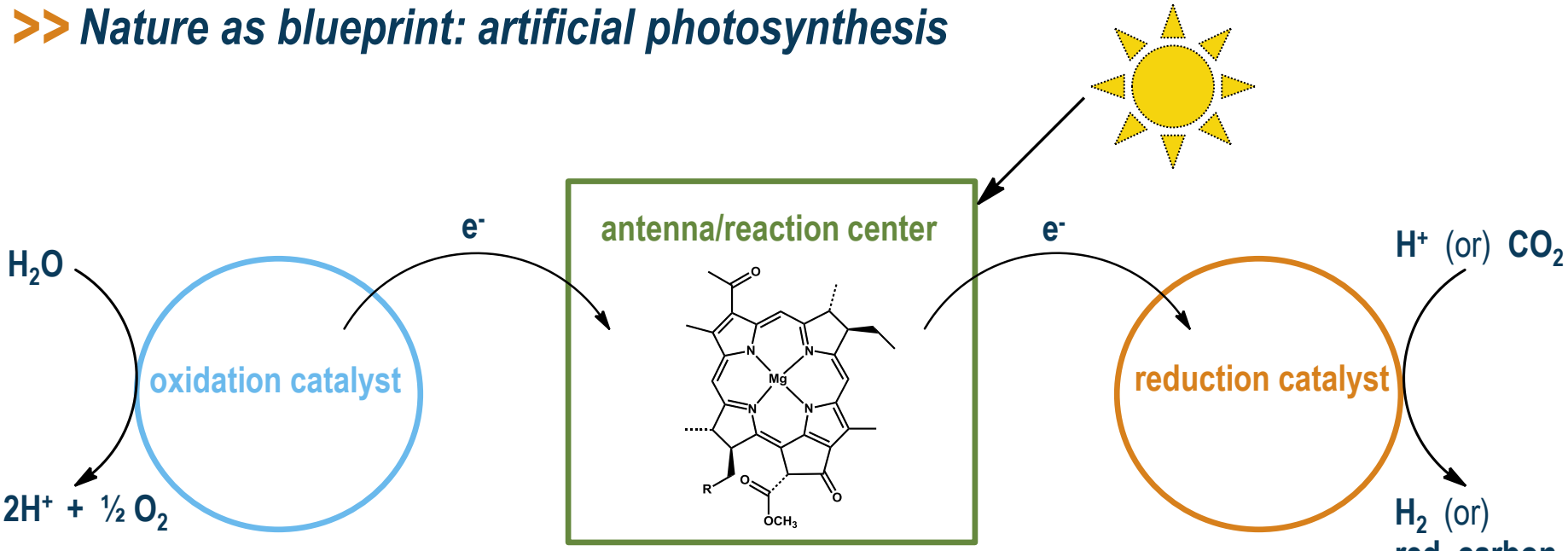
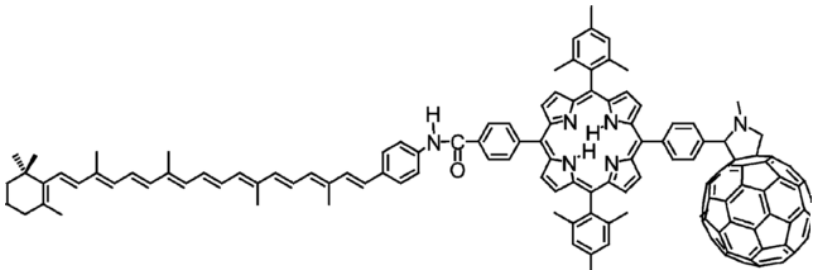
>> Nature as blueprint: artificial photosynthesis





synthetic reaction center

Electrofuels

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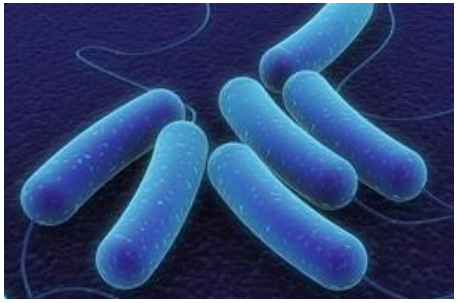
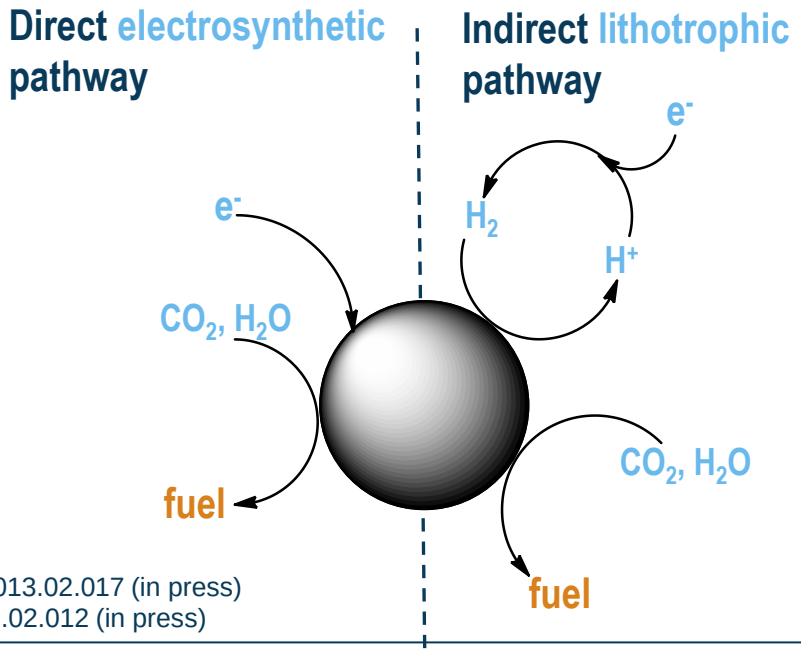
>> *CO_2 assimilation through utilization of electric energy by non-photosynthetic, autotrophic microbes*



>> *Novel technology!*

- > low TRL
- > Efficiency?
- > Technically viable? Extensive genetic engineering required!
- > Scalable?
- > Economics?



A. S. Hawkins *et al*., *Current Opinion in Biotechnology* **2013**, doi 10.1016/j.copbio.2013.02.017 (in press)
D. R. Lovly *et al*., *Current Opinion in Biotechnology* **2013**, doi 10.1016/j.copbio.2013.02.012 (in press)

Dropping the „drop-in“ requirement?

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>> *Critical issues of „drop-in“ capable alternatives*

> Complex mixtures of complex organic molecules

> Multi-step synthesis required

> Disadvantageous w.r.t. overall efficiency, costs, GHG emissions etc.

>> *Long-term option: „Non-drop-in“ alternatives*

> Disruptive technologies!

>> *Examples:*

>> *Liquid carbon-based gases (e.g., CH_4)*

>> *Hydrogen (H_2)*

> Combustion

> Fuel cell (electric flying)

Electromobility in aviation?

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>> *Exergy (useable energy):*

The energy density is insufficient as feasibility assessment criterion

Electromobility in aviation?

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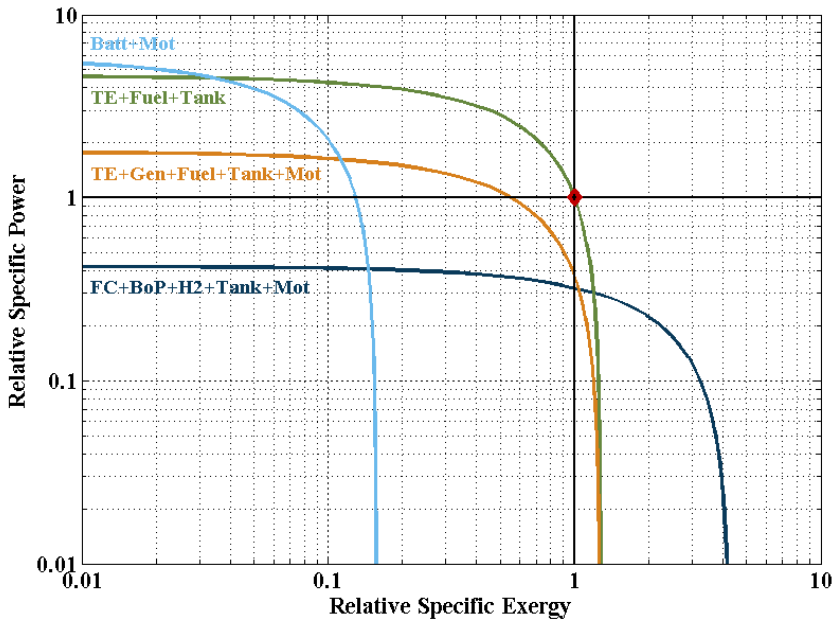
>> Exergy (useable energy):

The energy density is insufficient as feasibility assessment criterion

>> Ragone metrics:

Exergy and power densities are the key indicators for electric aircraft feasibility in the comparison of alternative power sources



References:
[1] A. Sizmann, Fuelling the Climate 2010, Hamburg, 18.07.2010
[2] H. Kuhn et al., CEAS, Venice, 24.10.2011
[3] H. Kuhn et al., ICAS, Brisbane, 2012

Electromobility in aviation?

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>> Exergy (useable energy):

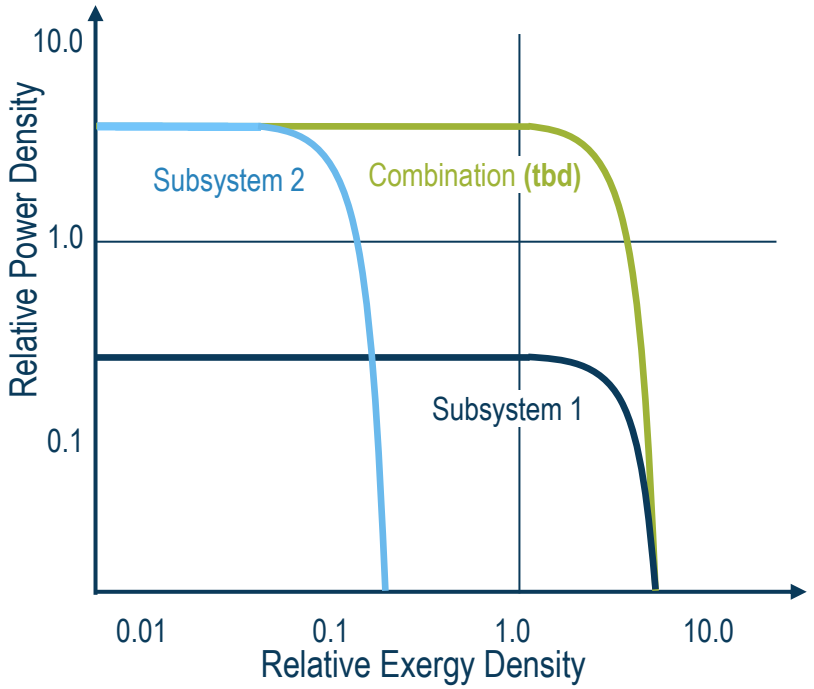
The energy density is insufficient as feasibility assessment criterion

>> Ragone metrics:

Exergy and power densities are the key indicators for electric aircraft feasibility in the comparison of alternative power sources

>> Hybridization:

energy storage devices each inadequate may be an enabling energy system in combination



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Conclusions and outlook

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>> *Alternative (i.e., synthetic) jet fuel:Various pathways existent or conceivable*

>> *From long-term perspective: No alternative yet developed to fully meet all of the main criteria suitability, scalability and sustainability*

>> *Critical issue of „drop-in“ solutions: Complex product, requiring complex and costly production procedures*

>> *Good reasons to*

> continue and increase efforts toward development of novel renewable alternatives, *e.g.*, pathways beyond biofuels

> seriously pursue R&D on „non-drop-in“ options for long-term application