GREENER
SKIES
AHEAD
GSA 2019

Mitigating the Impact on
Climate Change in Air Transport

Klimaschutz im Luftverkehr

Future
Large Scale Sustainable Aviation Fuels Production – Challenges and Opportunities

Sandra Adelung, Friedemann Albrecht, Ralph-Uwe Dietrich, Felix Habermeyer,
Simon Maier, Moritz Raab, Julia Weyand

German Aerospace Center (DLR)
Institute of Engineering Thermodynamics,
Stuttgart

Bonn,
19th November 2019

Knowledge for Tomorrow

Agenda

1. Motivation – Explaining the need for renewable jet fuel

- GHG emission reduction need
- Political framework conditions – Paris Agreement
- IATA reduction targets

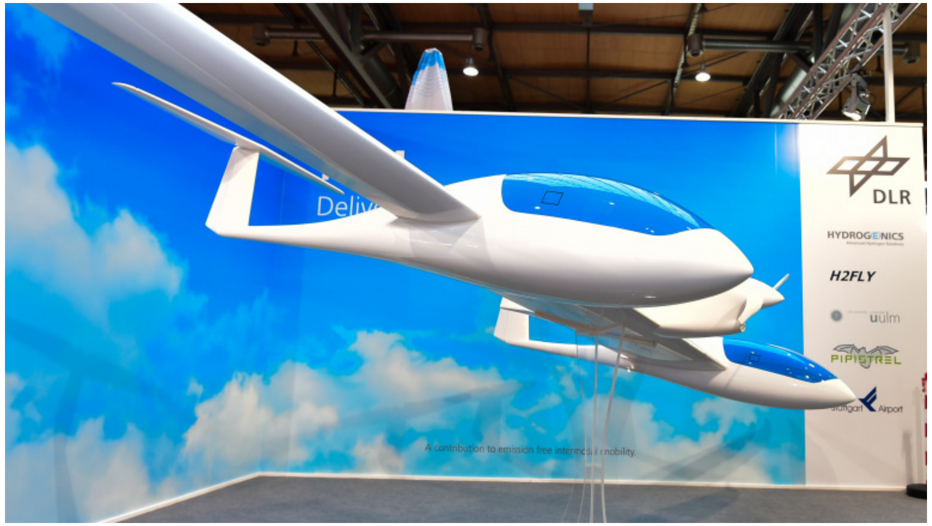
2. Renewable jet fuel options

- 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 CO_2

4. Summary and outlook



1. IATA Technology Roadmap

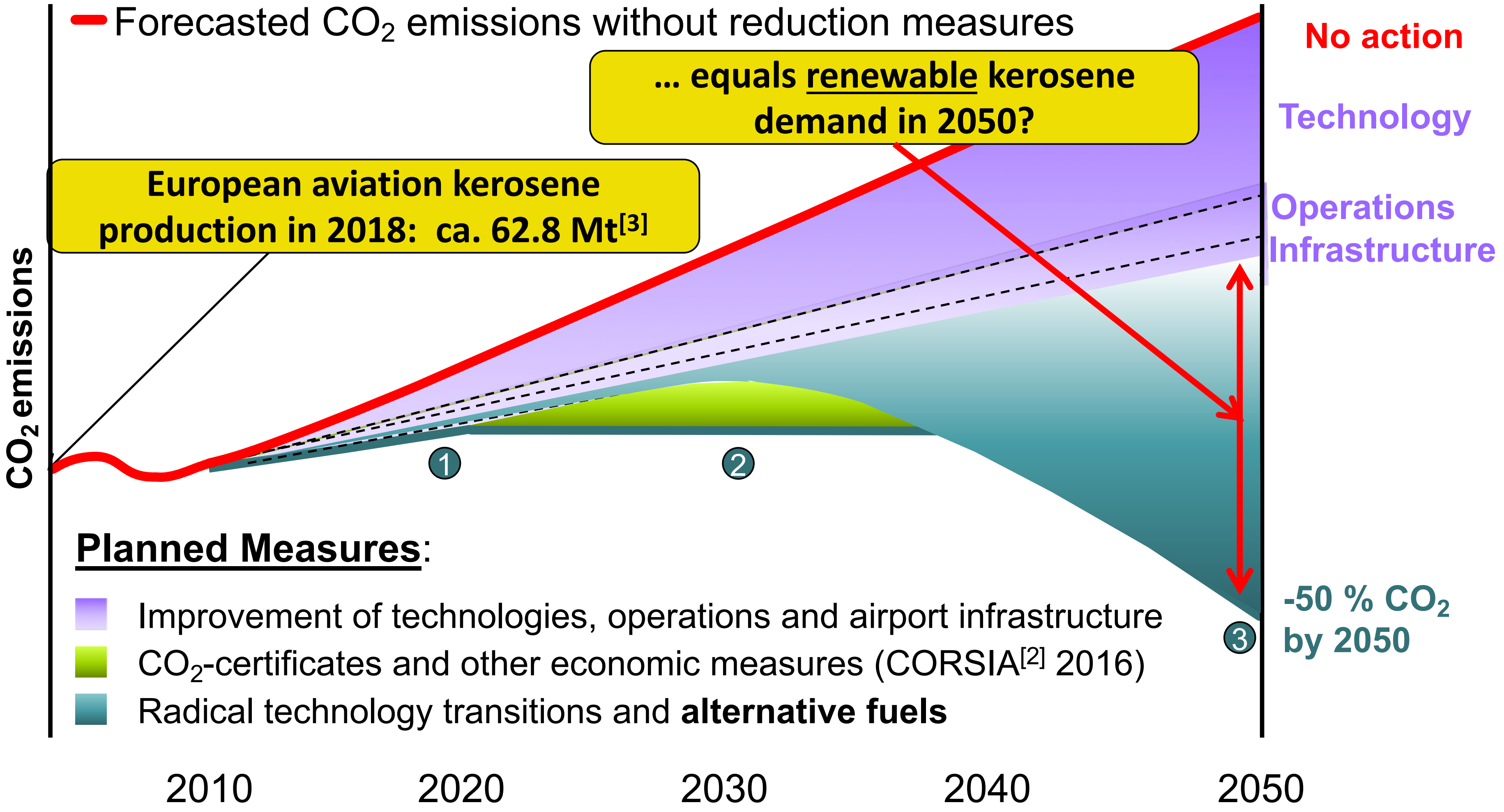
4. Edition, June 2013[1]

Main goals:

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

② Carbon-neutral growth from 2020

③ 50 % CO_2 emissions reductions by 2050



European aviation kerosene production in 2018: ca. 62.8 Mt[3]

… equals renewable kerosene demand in 2050?

Planned Measures:

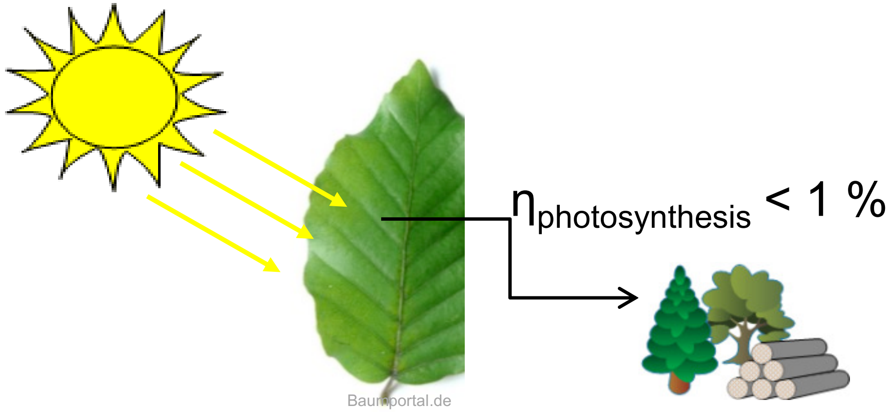
- 🟪 Improvement of technologies, operations and airport infrastructure
- 🟩 CO_2-certificates and other economic measures (CORSIA[2] 2016)
- 🟦 Radical technology transitions and **alternative fuels**

[1] iata.org, IATA Technology Roadmap 4. Edition, June 2013
[2] ICAO-Resolution A39-3: Carbon Offsetting and Reduction Scheme for International Aviation
[3] FuelsEurope “Statistical Report“ 2019

2. Jet fuel options: Certified sustainable jet fuels (ASTM D7566 – 14c [1])

Feedstock	Synthesis technology	Fuel
Coal, natural gas, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis	Synthetic paraffinic kerosene
Lipids from Biomass (e.g. algae, soya, jatropha)	Hydroprocessed esters and fatty acids (HEFA)	Synthetic paraffinic kerosene
Sugar from Biomass	Direct Sugars to Hydrocarbons (DSHC)	Synthetic iso-paraffins / Farnesane
Bioethanol (-propanol, -butanol)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK

Most certified jet fuels are currently made from energy crops!



Baumportal.de

---

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015

2. Jet fuel options: Certified sustainable jet fuels (ASTM D7566 – 14c)

Feedstock	Synthesis technology	Fuel
Coal, natural gas, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis	Synthetic paraffinic kerosene
Lipids from Biomass (e.g. algae, soya, jatropha)	Hydroprocessed esters and fatty acids (HEFA)	Synthetic paraffinic kerosene
Sugar from Biomass	Direct Sugars to Hydrocarbons (DSHC)	Synthetic iso-paraffins / Farnesane
Bioethanol (-propanol, -butanol)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK

Total technical potential of 1st generation sustainable jet fuel in Europe [2-6] :

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
- Low technical development potential

[2] Eurostat „Crop statistics“ 2018
[3] Specialist agency renewable raw materials e. V., „Introduction of fuel ethanol”, 2016
[4] NREL, „Review of Biojet Fuel Conversion Technologies”, Golden, 2016
[5] UFOP, „Rapeseed the Power Plant“ 2017
[6] DBFZ, „Abschlussbericht Projekt BurnFAIR”, 2014

2. Jet fuel options: Certified sustainable jet fuels (ASTM D7566 – 14c)

Feedstock	Synthesis technology	Fuel
Coal, natural gas, biomass, CO_2 & H_2	Fischer-Tropsch (FT) synthesis	Synthetic paraffinic kerosene
Lipids from Biomass (e.g. algae, soya, jatropha)	Hydroprocessed esters and fatty acids (HEFA)	Synthetic paraffinic kerosene
Sugar from Biomass	Direct Sugars to Hydrocarbons (DSHC)	Synthetic iso-paraffins / Farnesane
Bioethanol (-propanol, -butanol)	dehydration+oligomerization+hydration (Alcohol-to-Jet, AtJ)	AD-SPK

Fischer-Tropsch synthesis

- Large scale, commercial technology
- Based on synthesis gas (Produced from almost any carbon and hydrogen source possible)
- Fully synthetic kerosene achievable[1]

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

- Current jet fuel consumption: ≈ **62.8 Mt/a**[2]
- Power demand for exclusively power based kerosene in Europe: ≈ **1,600 TWh**
- European wind power potential[3]: **12,200 – 30,400 TWh** ≈ 8 - 20 times of power based kerosene demand!

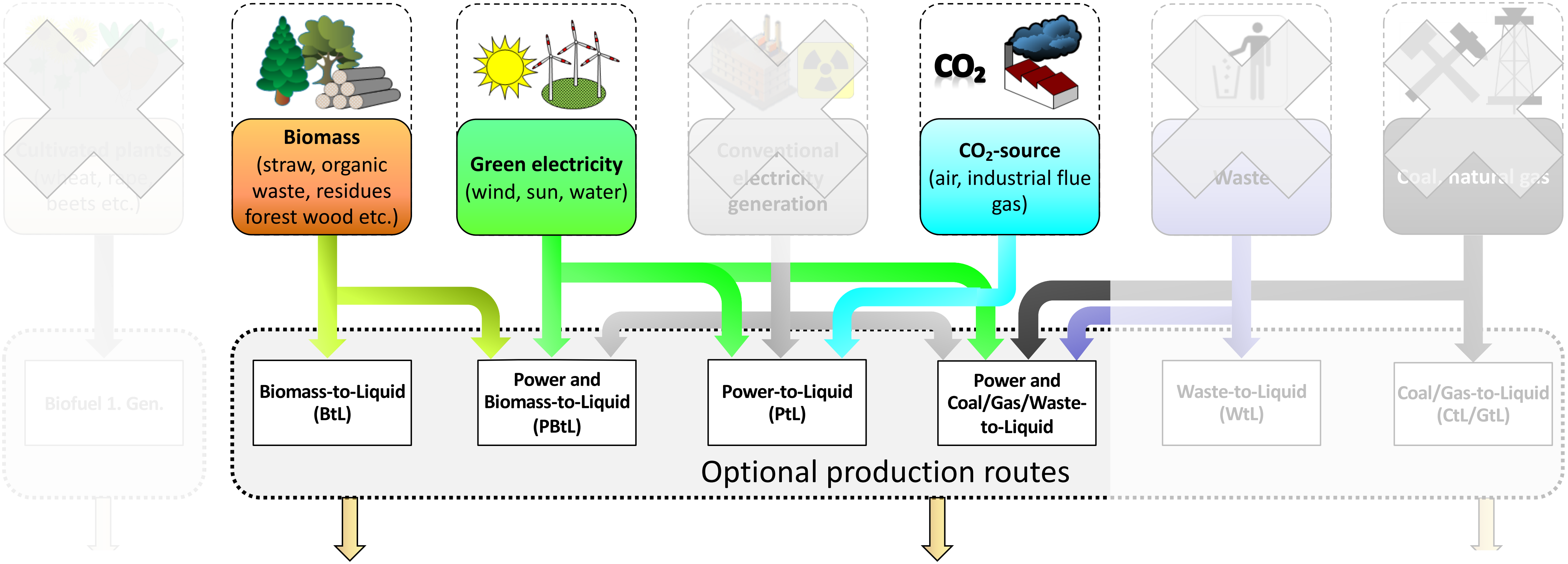
---

[1] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1“, UK Defense Standardization, 2011
[2] FuelsEurope “Statistical Report“ 2019
[3] European Environment Agency, “Europe's onshore and offshore wind energy potential,” 2009.

2. Mass production routes of alternative fuels

Small/unreliable feedstock potential

Too large CO$_2$ footprint



Cultivated plants (wheat, rape, beets etc.)

Biomass (straw, organic waste, residues forest wood etc.)

Green electricity (wind, sun, water)

Conventional electricity generation

CO$_2$-source (air, industrial flue gas)

Waste

Coal, natural gas

Biofuel 1. Gen.

Biomass-to-Liquid (BtL)

Power and Biomass-to-Liquid (PBtL)

Power-to-Liquid (PtL)

Power and Coal/Gas/Waste-to-Liquid

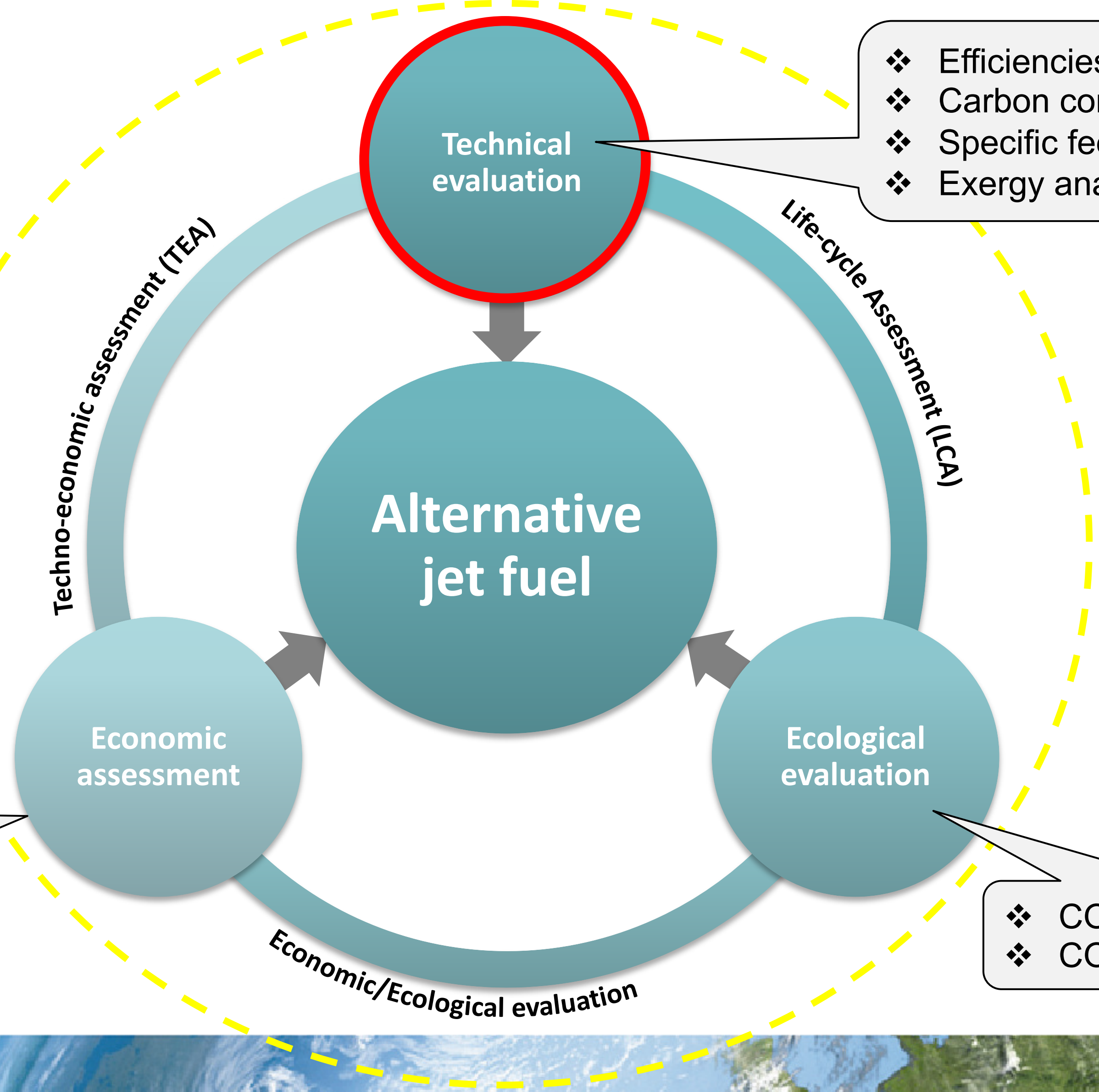
Waste-to-Liquid (WtL)

Coal/Gas-to-Liquid (CtL/GtL)

Optional production routes

The supply of large quantities of alternative kerosene within low GHG emissions is possible by coupling the sectors electricity generation and sustainable biomass *(without biomass imports).*

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



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

DLR-evaluation and optimization tool

Powered by DLR
TEPET
Standardizing economic process evaluations

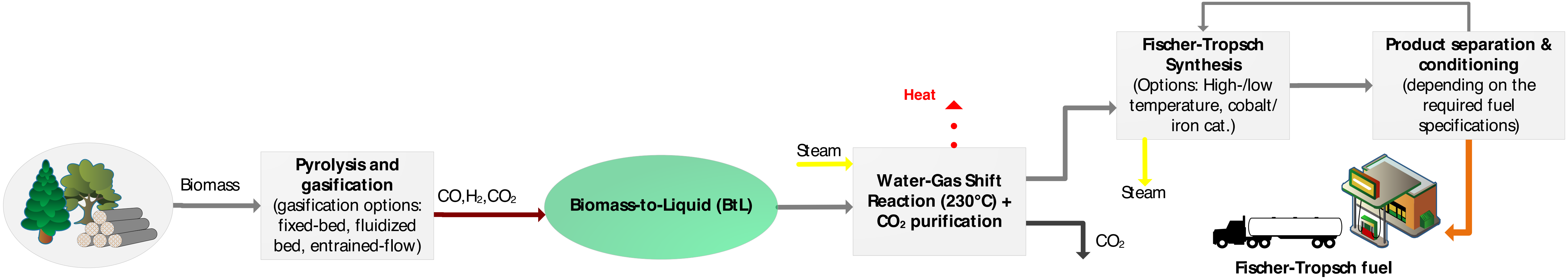
- ❖ CAPEX, OPEX, NPC
- ❖ Sensitivity analysis
- ❖ Identification of most economic feasible process design

- ❖ CO_2-footprint
- ❖ CO_2-abatement costs

3. Investigated Fischer-Tropsch concepts

Syngas from biomass (Biomass-to-Liquid, BtL)

Syngas supply	Syngas conditioning	Fuel synthesis



Biomass

Pyrolysis and gasification (gasification options: fixed-bed, fluidized bed, entrained-flow)

CO, H_2, CO_2

Biomass-to-Liquid (BtL)

Steam

Heat

Water-Gas Shift Reaction (230°C) + CO_2 purification

CO_2

Fischer-Tropsch Synthesis (Options: High-/low temperature, cobalt/ iron cat.)

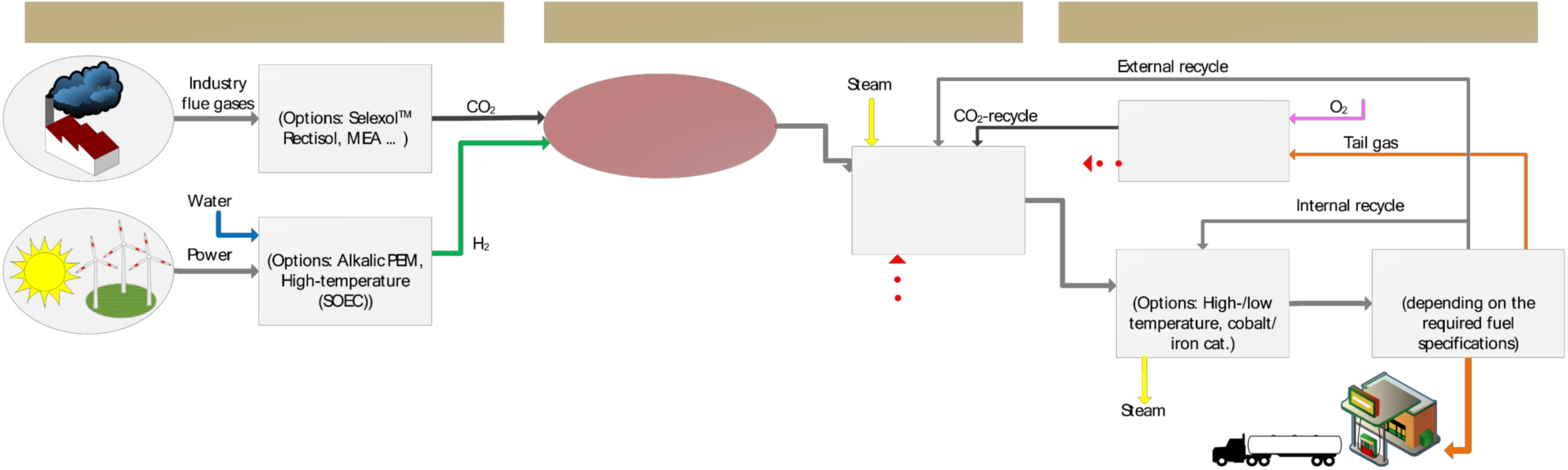
Steam

Product separation & conditioning (depending on the required fuel specifications)

Fischer-Tropsch fuel

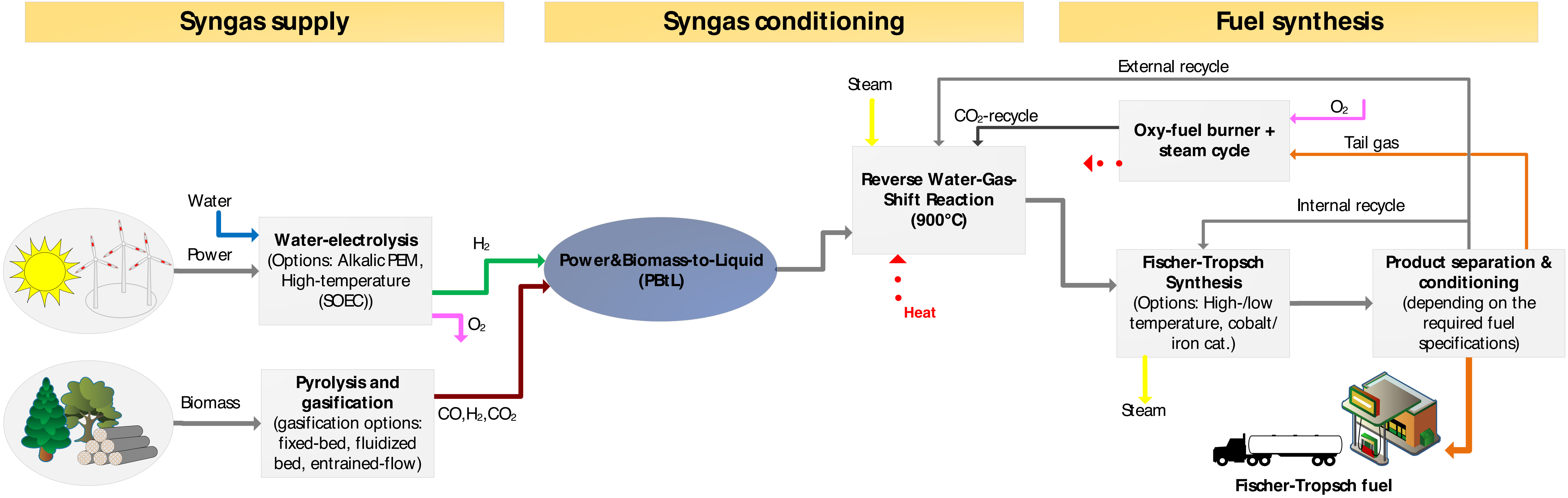
3. Investigated Fischer-Tropsch concepts

Syngas from power and CO_2 (Power-to-Liquid, PtL)



3. Investigated Fischer-Tropsch concepts

Syngas from power and biomass ()



Syngas supply

Syngas conditioning

Fuel synthesis

Water

Power

Water-electrolysis
(Options: Alkalic PEM, High-temperature (SOEC))

H_2

O_2

Biomass

Pyrolysis and gasification
(gasification options: fixed-bed, fluidized bed, entrained-flow)

CO, H_2, CO_2

Power&Biomass-to-Liquid (PBtL)

Steam

Reverse Water-Gas-Shift Reaction (900°C)

Heat

External recycle

CO_2-recycle

Oxy-fuel burner + steam cycle

O_2

Tail gas

Internal recycle

Fischer-Tropsch Synthesis
(Options: High-/low temperature, cobalt/ iron cat.)

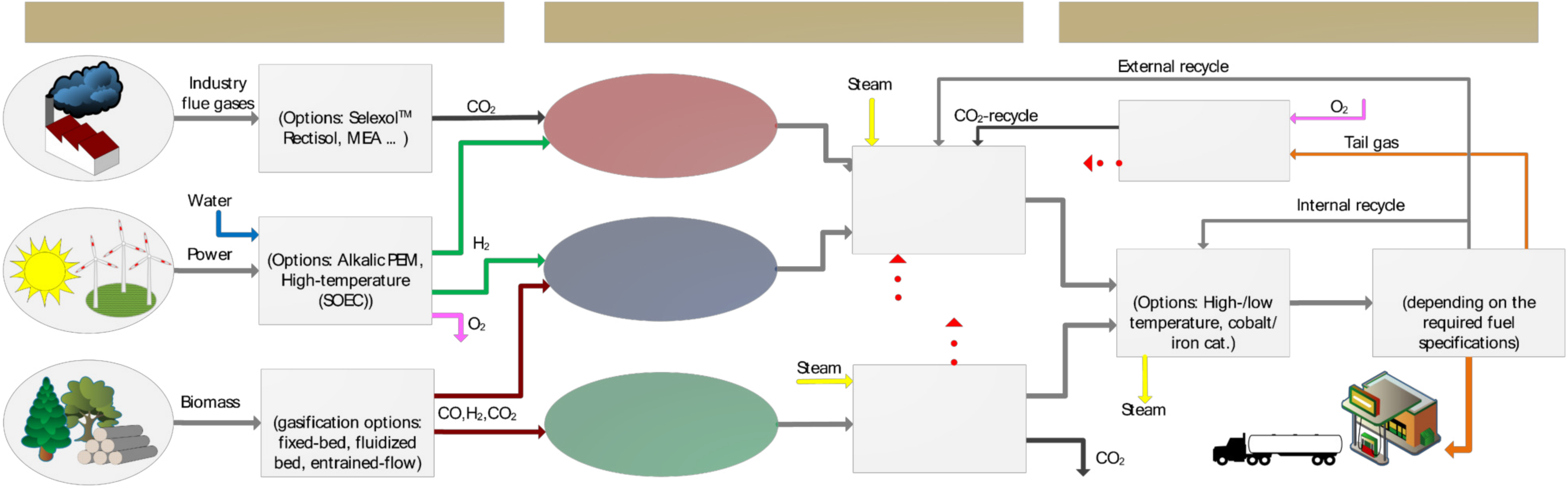
Steam

Product separation & conditioning
(depending on the required fuel specifications)

Fischer-Tropsch fuel

3. Investigated Fischer-Tropsch concepts

Three concepts to compare: Power-to-Liquid, PtL – Power&Biomass-to-Liquid – Biomass-to-Liquid



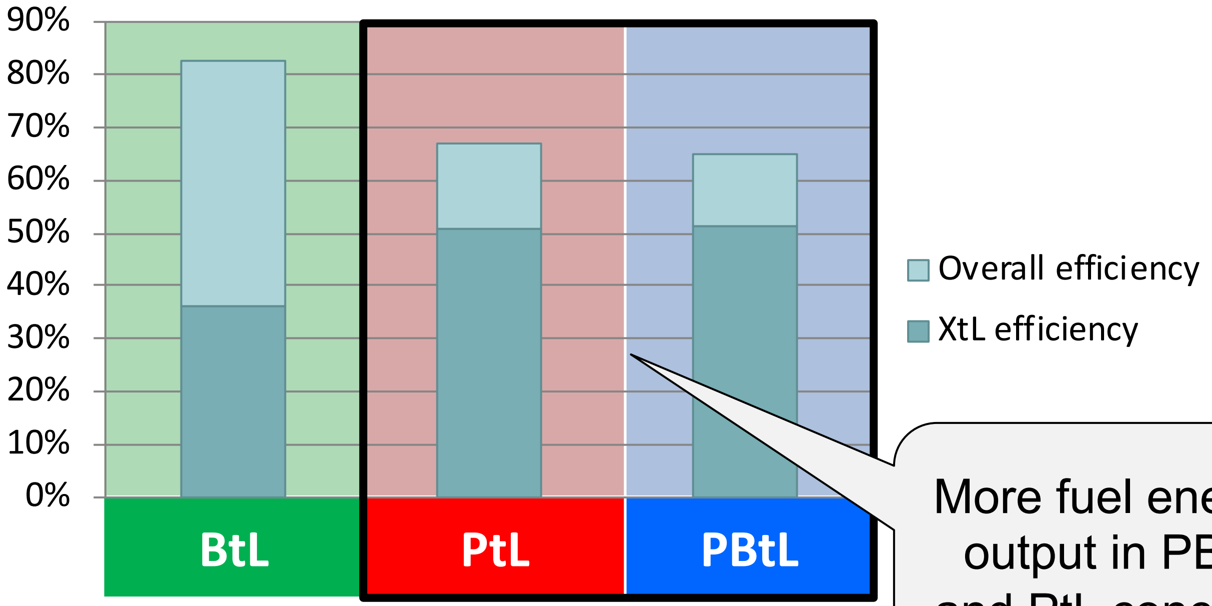
Source: F. G. Albrecht, D. H. König, N. Baucks und R. U. Dietrich, „A standardized methodology for the techno-economic evaluation of 1 alternative fuels,“ *Fuel,* Bd. 194, pp. 511-526, 2017.

3. Technical results: Yield, Efficiency

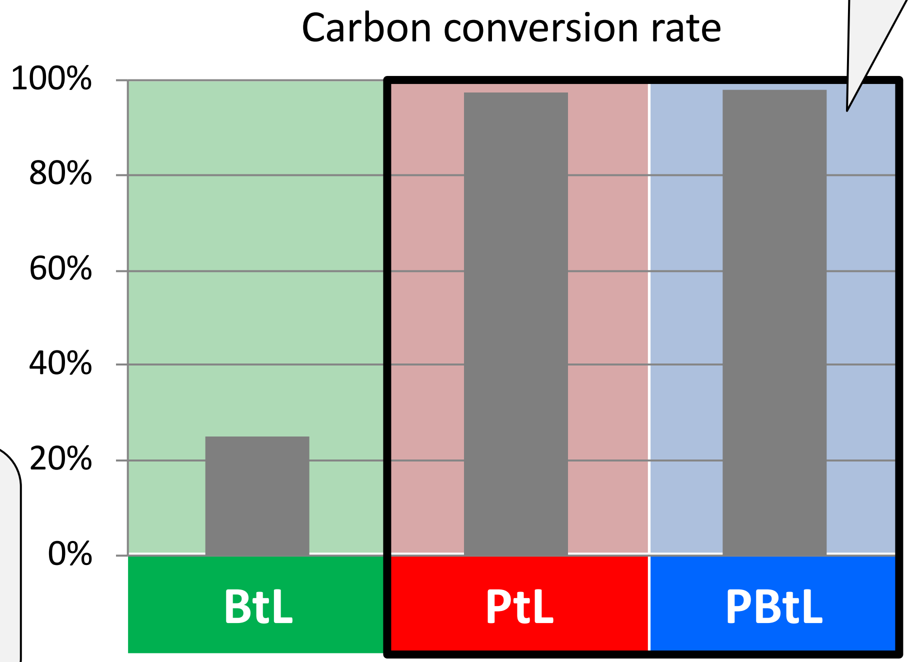
Case study equipment selection and assumptions:

- PEM, η_{LHV}= 67 % [1]
- Entrained flow gasifier, T = 1,200 ℃, p = 30 bar, pure O_2 [2]
- Fischer-Tropsch synthesis, T = 225 ℃, p = 25 bar, α = 0.85, X_{CO} = 40 % [3]

Technical evaluation results:



More fuel energy output in PBtL and PtL concept!



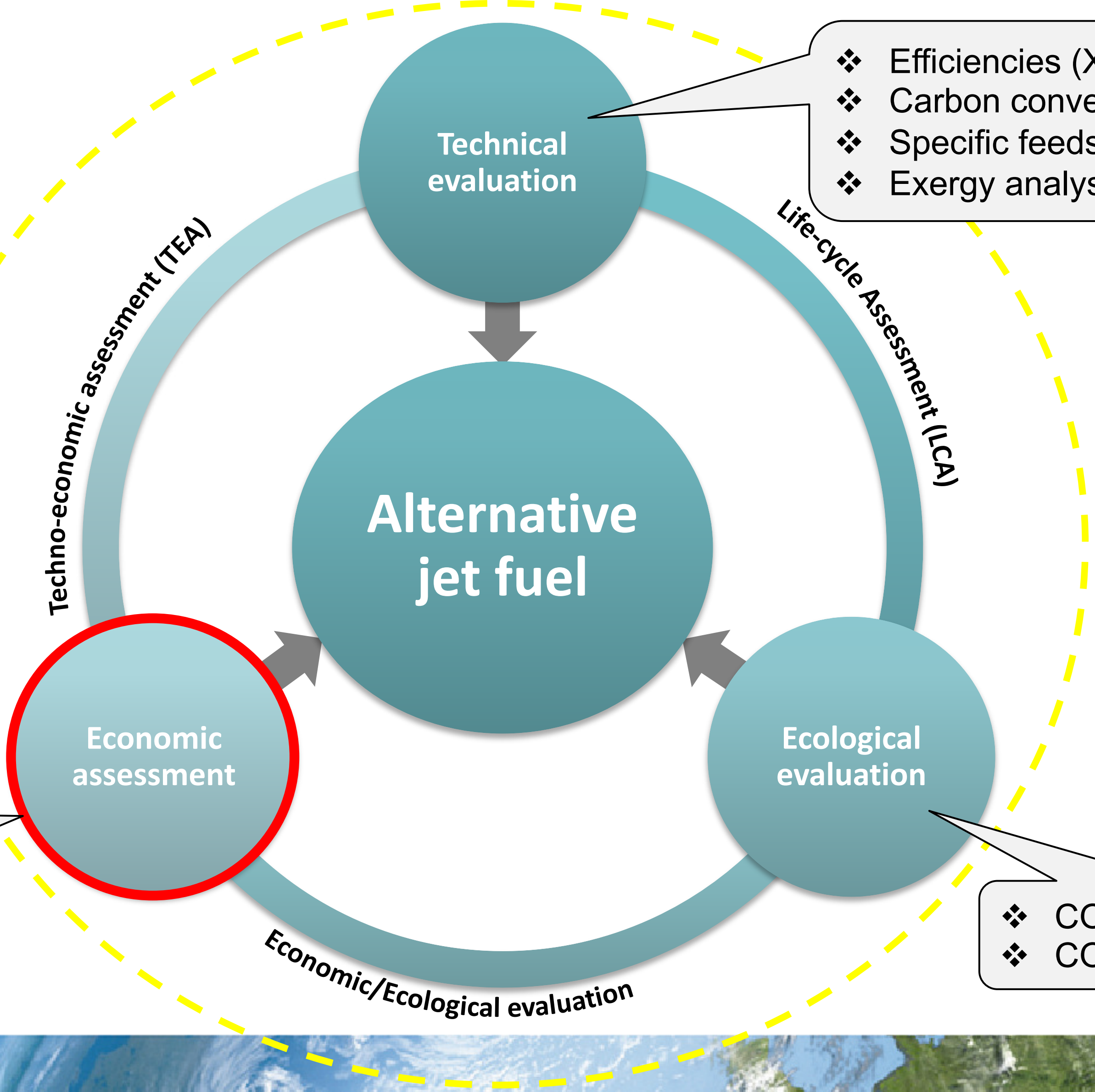
Higher carbon utilization in PBtL and PtL concept!

[1] T. Smolinka, M. Günther and J. Garche, „Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien," NOW GmbH, 2011, in German

[2] K. Qin, „Entrianed Flow Gasification of Biomass, Ph. D. thesis," Technical University of Denmark (DTU), Kgs. Lyngby, 2012.

[3] P. Kaiser, F. Pöhlmann and A. Jess, "Intrinsic and effective kinetics of cobalt-catalyzed Fischer-Tropsch synthesis in view of a Power-to-Liquid process based on renewable energy," *Chemical Engineering Technology,* vol. 37, pp. 964-972, 2014.

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



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

DLR-evaluation and optimization tool

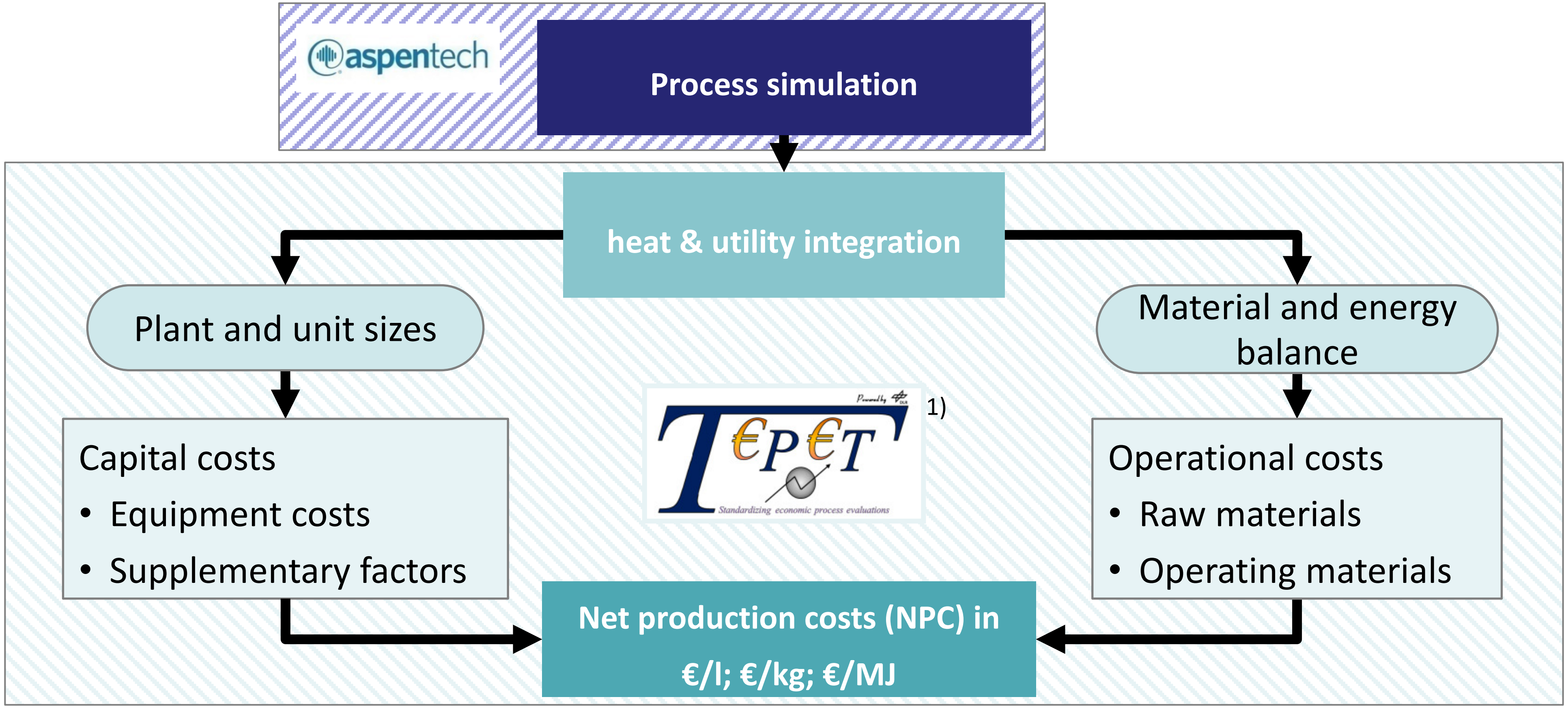
TEPET
Powered by DLR
Standardizing economic process evaluations

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

- ❖ CO_2-footprint
- ❖ CO_2-abatement costs

3. TEEA – Methodology

- adapted from **best-practice chem. eng. methodology**
- Meets AACE class 3-4, Accuracy: **+/- 30 %**
- **Year specific** using annual CEPCI Index
- Automated interface for **seamless integration**
- Easy sensitivity studies for **every** parameter
- Learning curves, economy of scale, …



---

[1] Albrecht et al. (2017), A standardized methodology for the techno-economic evaluation of alternative fuels.

3. TEEA: Base Case definition for Germany, 2018

Plant capacities:

BtL:

- 100 MW_{LHV} biomass
- **Fuel production: 24.2 kt/a**

PBtL:

- 100 MW_{LHV} biomass
- 165 MW power
- **Fuel production: 91.3 kt/a**

PtL:

- 267 MW power
- **Fuel production: 91.3 kt/a**

Investment costs:

PEM-Electrolyzer (stack):	**850**	€/kW [1]	
PEM-Electrolyzer (system):	**1,370**	€/kW	(TEPET, incl. supplementary factors)
Fischer-Tropsch reactor:	**17.44**	Mio.€/($kmol_{syngas}$/s) [2]	

Raw materials and utility costs

Electricity:	**89.4**	€/MWh [3]
CO_2:	**12.5**	€/t [4]
Oxygen (export):	**24.3**	€/t [5]
Steam (export):	**19.8**	€/t [6]

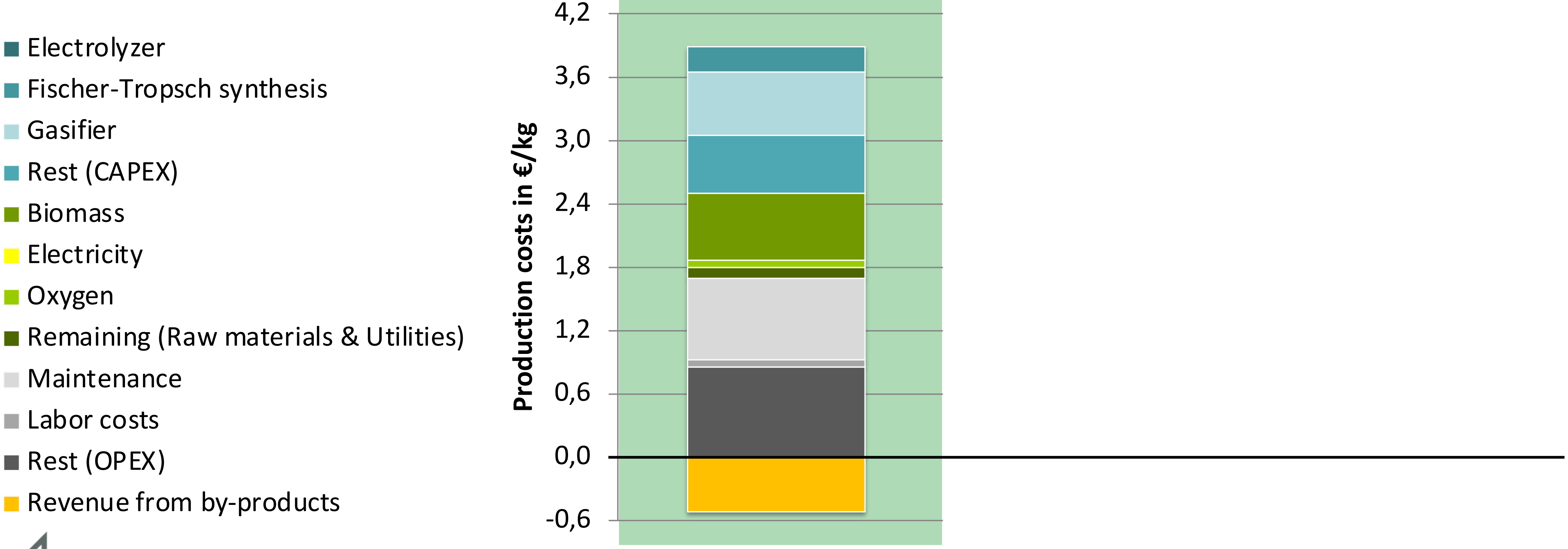
General economic assumptions:

Year:	2018	*Plant lifetime:*	30 years
Full load hours:	8,260 h/a	*Interest rate:*	5 %

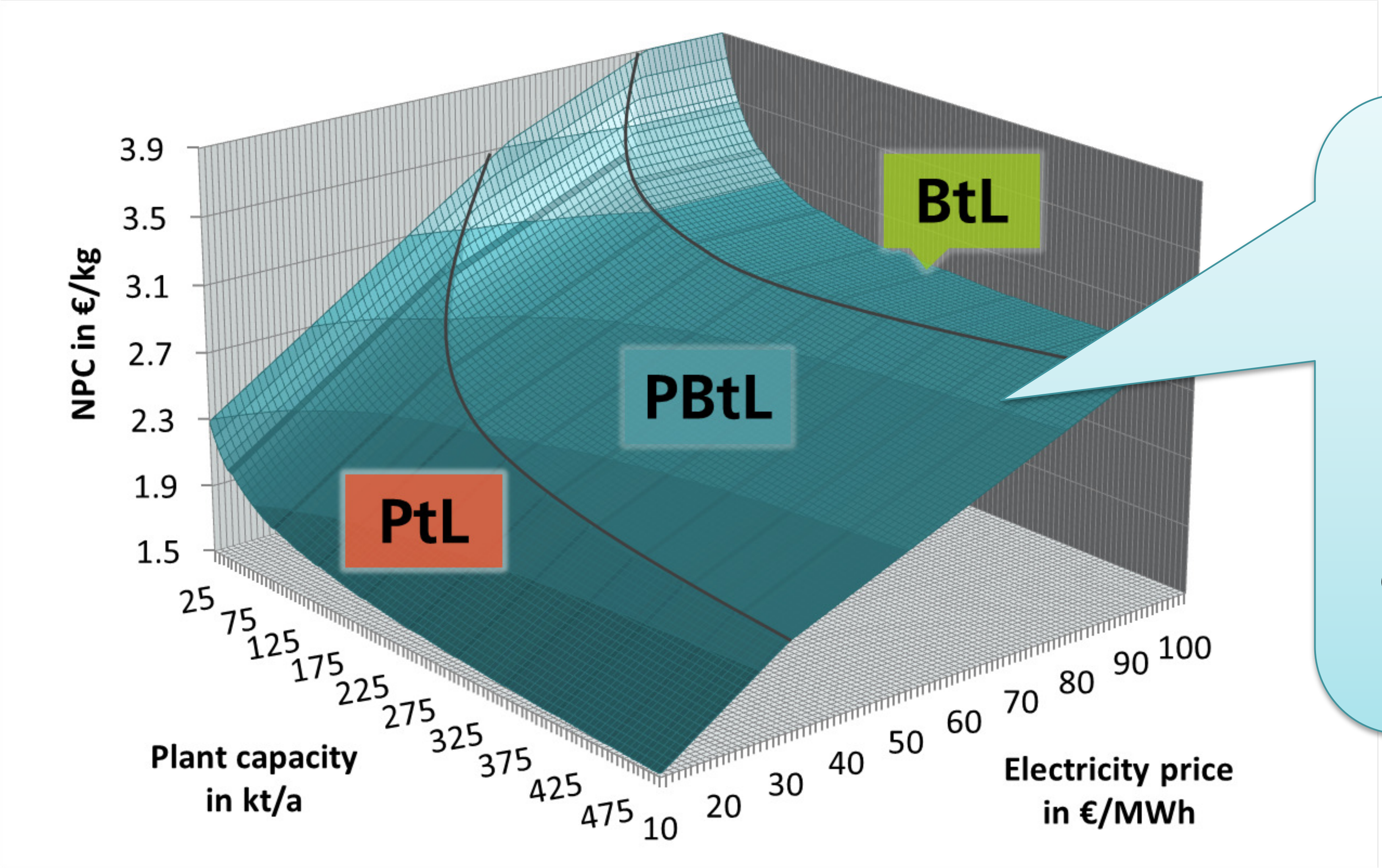
[1] G. Saur, Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study, Technical Report NREL, 2008
[2] I. Hannula and E. Kurkela, Liquid transportation fuels via large-scale fluidised-bed gasification of lignocellulosic biomass, VTT, Finland, 2013
[3] Eurostat, Preise Elektrizität für Industrieabnehmer in Deutschland, 2018
[4] S. D. Phillips, „Gasoline from wood via integrated gasification, synthesis, and methanol-to-gasoline technologies," NREL, 2011
[5] NREL,"Appendix B: Carbon Dioxide Capture Technology Sheets - Oxygen Production," US Department of Energy, 2013
[6] Own calculations based on natural gas price from Eurostat database

3. TEEA: Results for Germany, 2018

	BtL (24.2 kt/a)
Fixed Capital Investment:	473 m€$_{2018}$
Net production costs:	3.33 €/kg



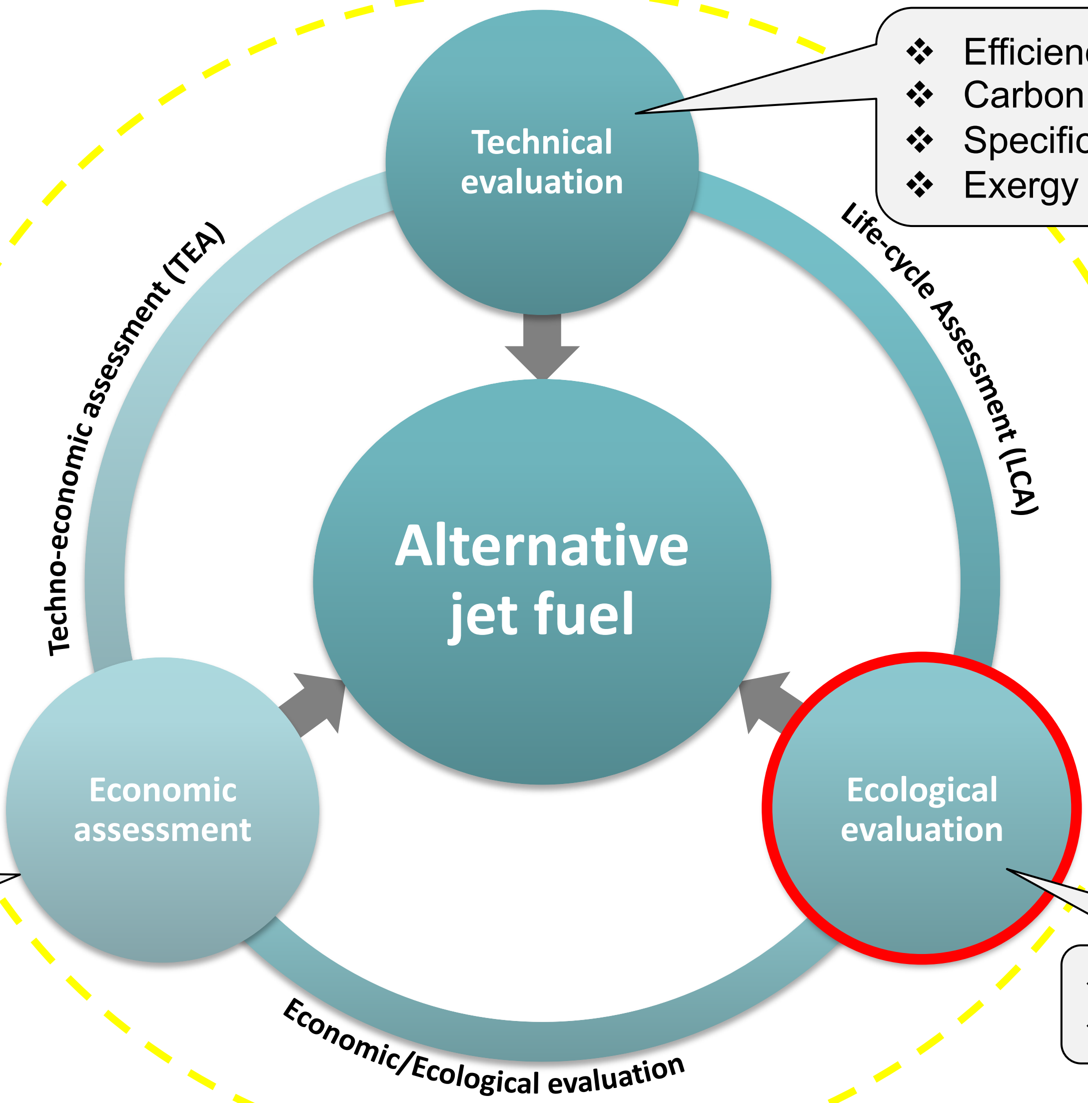
3. Sensitivity analysis – Economy of scale and Power Price



Applicable to each country, location, feedstock price, individual site specifics

'Optimal' production concept depends on local feedstock availability/costs!

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



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

DLR-evaluation and optimization tool

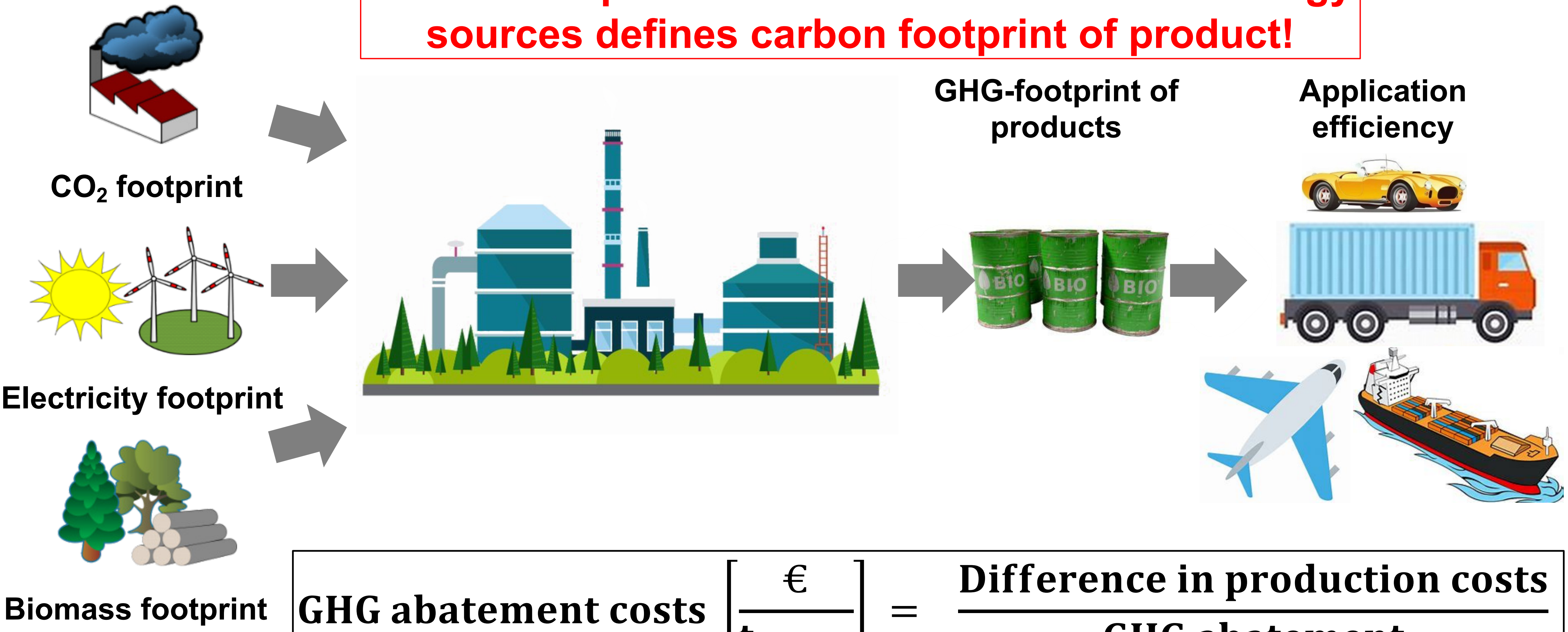
TEPET
Powered by DLR
Standardizing economic process evaluations

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

- CO_2-footprint
- CO_2-abatement costs

3. CO_2-Footprint calculation – Approach

Carbon footprint of used raw materials and energy sources defines carbon footprint of product!



CO_2 footprint

Electricity footprint

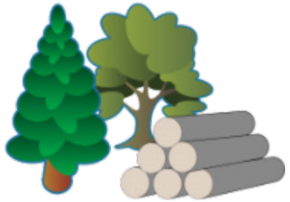
Biomass footprint

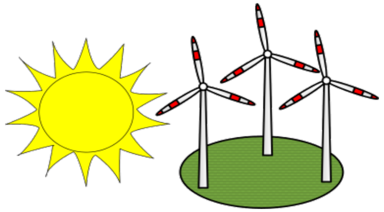
GHG-footprint of products

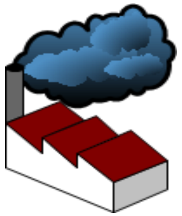
Application efficiency

$$\text{GHG abatement costs}\left[\frac{\text{€}}{t_{CO_2\,eq.}}\right] = \frac{\text{Difference in production costs}}{\text{GHG abatement}}$$

3. CO_2-Footprint calculation – Bounderies







O_2

	Biomass	**Power**	**Carbon dioxide**	**Oxygen**
Functional unit	$[kg_{CO2eq}/t]$[a]	$[kg_{CO2eq}/MWh]$[b]	$[kg_{CO2eq}/t]$[c]	$[kg_{CO2eq}/t]$[d]
Low boundary	13.6	25	5	100
Average	134	270	78	250
High boundary	255	515	150	400

[a] Based on own calculations taking into account biomass type (forest residues, straw etc.) and transport distances. CO_2-emissions during cultivation and harvesting are accounted for.

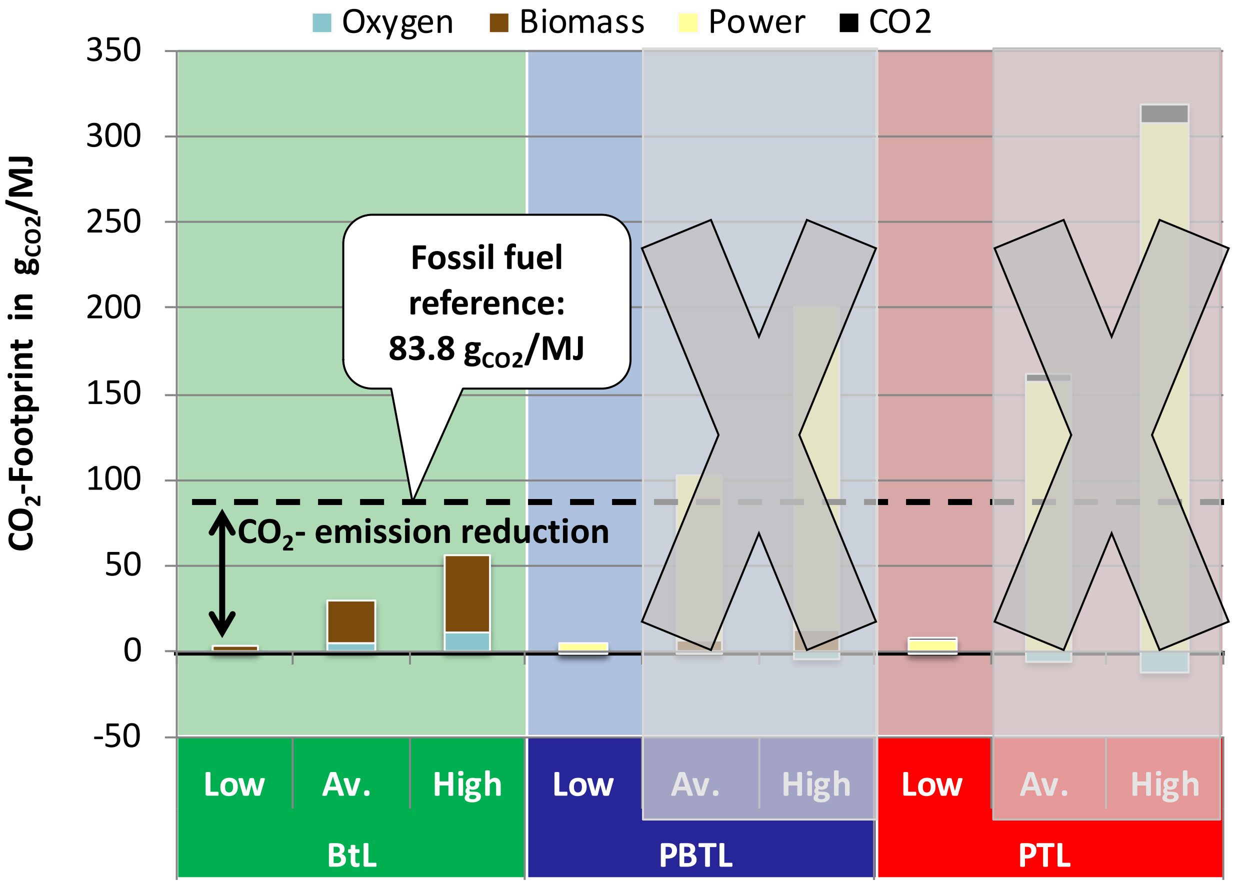
[b] Low boundary value for pure wind electricity taken from[1]. High value corresponds to the actual CO_2-footprint of the German electricity sector [2].

[c] Based on own calculations. The carbon footprint represents emissions arising from sequestration of CO_2 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.

[1] Umweltbundesamt, “Prozessorientierte Basisdaten für Umweltmanagementsysteme,” http://www.probas.umweltbundesamt.de/php/index.php.
[2] Umweltbundesamt, “Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 – 2016,“ Dessau-Roßlau,2017.

3. CO$_2$-Footprint calculation – Results



P(B)tL-concepts only viable when using renewable power!

$$CO_2 - Abatement\ costs\left[\frac{€}{t_{CO_2}}\right] = \frac{Difference\ in\ fuel/heat/H_2\ costs}{CO_2 - emission\ reduction}$$

Case 1 – Current state:		
Price of fossil kerosene:	ca. 0.5	€/l
Grid power price:	89.4	€/MWh
Plant capacity:	100	kt/a
Case 2 – Pressure on fossil fuels:		
Price of fossil kerosene:	1	€/l
Renewable power price:	30	€/MWh
Plant capacity:	1,000	kt/a

CO$_2$-Abatement costs in €/t$_{CO2eq}$

Case	BtL-Low	BtL-Av.	BtL-High	PBtL-Low	PtL-Low
1	**557**	**841**	**1,651**	**712**	**974**

Current CO$_2$ Price of EU Emissions Trading System:
ca. 20-30 €/t$_{CO2eq}$

4. Conclusions

- Large quantities of renewable jet fuel with low carbon footprint are required to reduce GHG emissions in the growing aviation sector
- Technical potential of 1st generation jet fuel from energy crops is very limited – power based jet fuel have less potential restriction but tremendous renewable electricity demand
- DLR e.V. has developed a standardized and transparent methodology to evaluate production routes for alterative fuels, including: CAPEX, OPEX, net production costs, CO_2-Abatement costs

Results of case study:

- Economic boundary conditions dictate fuel production costs
- Most sensitive cost factors in investigated Fischer-Tropsch concepts:
  renewable power price, biomass gasifier invest., economy of scale

4. Outlook: New concept(s) evaluation

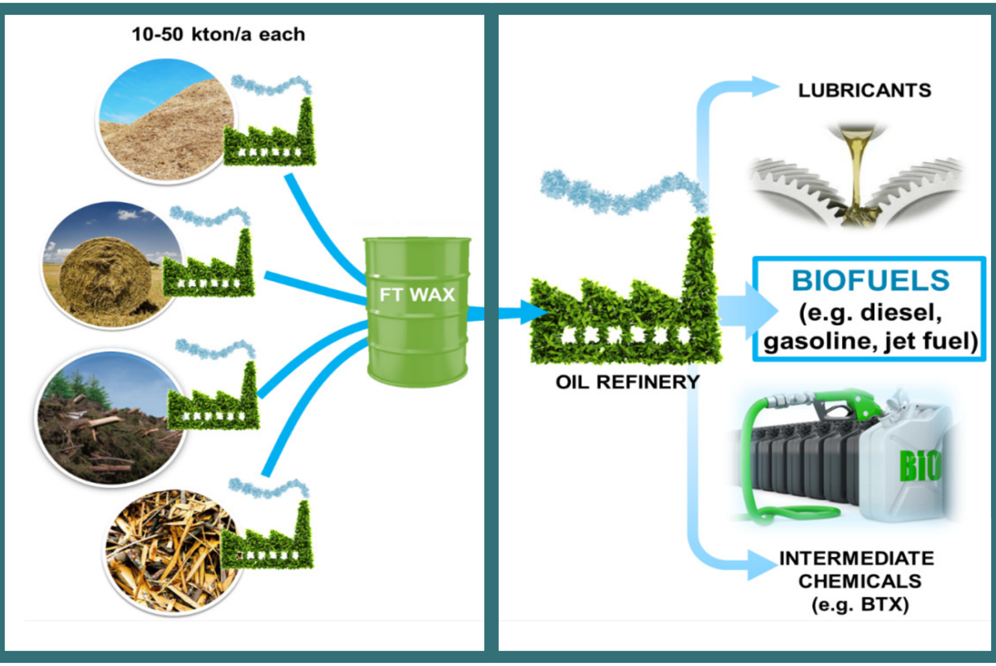
COMSYN

COMSYN project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727476

New decentralized BTL production concept with biofuel production **cost reduction** up to 35 % compared to alternative routes (< 1.10 €/kg production cost for diesel) [1]

PRIMARY CONVERSION

Decentralized FT wax production at **small-to-medium scale** units at biomass sites (50-150 MW_{th} input) + locally utilized excess heat for η_{total} > 80 %



PRODUCT UPGRADING

Centralized FT product refining to high quality drop-in liquid fuels at existing oil refineries

---

[1] Special thanks to the contribution of: P. Simell, J. Kihlman, S. Tuomi, E. Kurkela, C. Frilund, V. Kivelä (VTT), T. Böltken, M. Selinsek (INERATEC), H. Balzer (GKN), J. Hajek (UniCRE), V. Tota (Wood), V. Hankalin (ÅF Consult)

4. Outlook: COMSYN project challenges

COMSYN

COMSYN project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727476

DFB PILOT @ VTT

DFB Gasifier
- Biomass fee

Hot gas filtration
- Intermediate cooling/reh eliminated
- Filtration at high tempera with simultaneous decor

GKN SINTER METALS

Ultracleaning concept:
- Specifically for biomass-based gasification gas
- Wet scrubbing acid gas process (Rectisol, Selexol) replaced by:
  - Simpler dry bed desulphurization
  - Partial CO_2 removal in simple pressure water scrubbing to 5 vol-% content

VTT

MOBILE SYNTHESIS UNIT

croreactor*:
ular design

Product upgrading
- Co-processesing of FT-waxes or
- Stand-alone treatment

UniCRE

DFB GASIFIER → FILTER → REFORMER → ULTRACLEANING STEPS → FISCHER-TROPSCH SYNTHESIS → Product Upgrading

4. Outlook: COMSYN project challenges

COMSYN

COMSYN project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727476

Market survey:
- Questionaire
- Market studi
- Site specific b

DFB GASIFIE

UNIT

essment:

optimization

wood.

Product Upgrading

Open Questions / Development Tasks

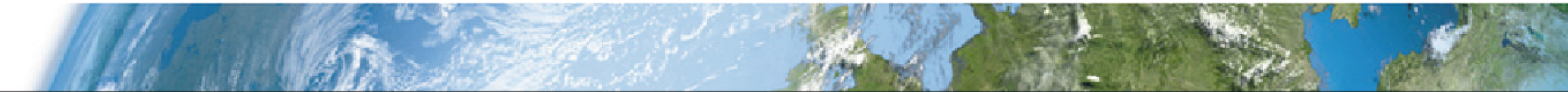
Within COMSYN:
- Technical Validation
- Fuel Flexibility
- Techno-economic assessment
- Ecological impact
- Business cases for different European regions

Beyond COMSYN:
- No. of European sites for decentralized fuels production
- Logistic to interconnect multiple decentralized sites
- Mass manufacturing of decentralized fuel plants

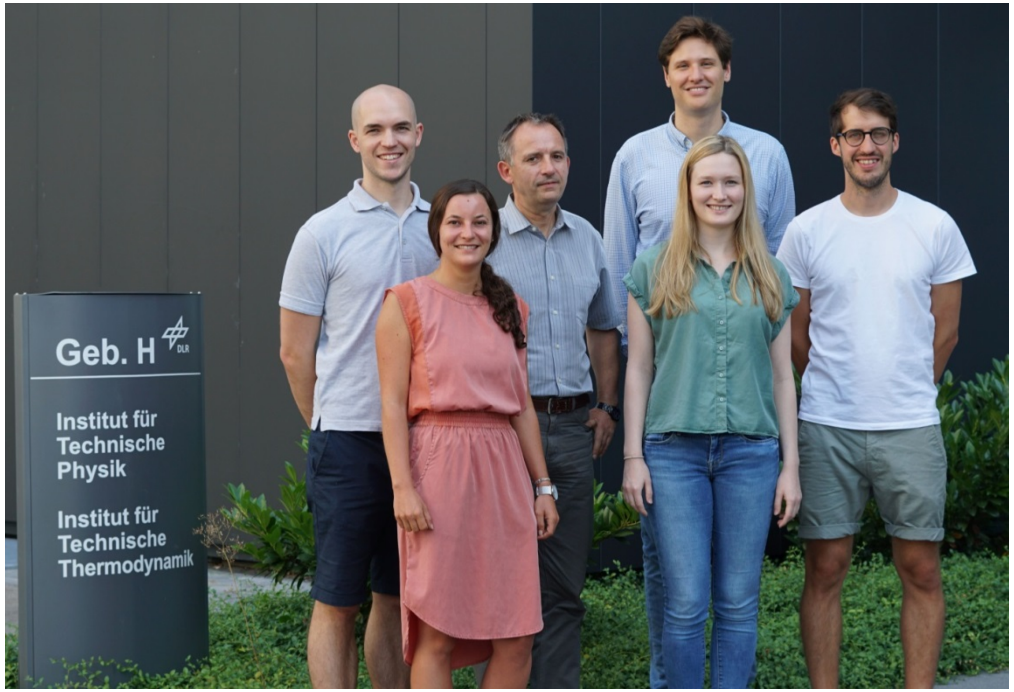
Validation of decentralized sustainable fuel production for large scale defossilization of aviation!

4. Outlook: European Renewable Aviation Roadmap

How to replace about
60 Mt/a fossil jet fuel consumption
in EU 28?
Who? Where? When?



THANK YOU FOR YOUR ATTENTION!



ERTC

German Aerospace Center (DLR)
Institute of Engineering Thermodynamics
Research Area Techno Economic Assessment

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

DLR