13th Concawe Symposium 2019, Antwerp
Session 3: ’’Low-carbon pathways & Refining Technologies (I)’’

Challenges & opportunities for sustainable aviation
Technical, economic and ecologic fuel evaluation from aviation point of view

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Moritz Raab
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Agenda

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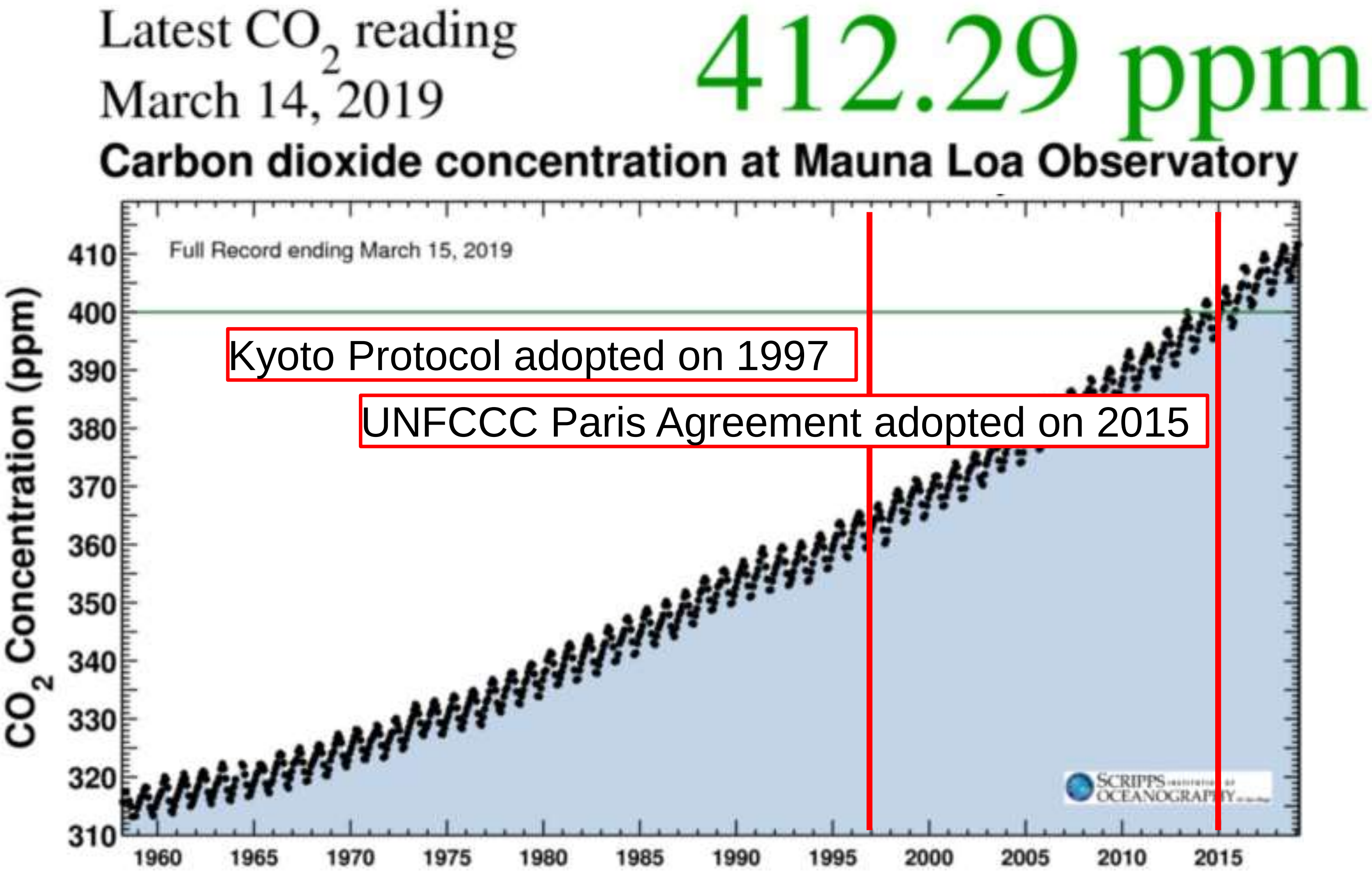
Session 3: "Low-carbon pathways & Refining Technologies (I)"

Motivation



Source: https://www.co2.earth/daily-co2?noaa-mauna-loa-co2-data.html

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Motivation

London

Davos


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Climate change
'Our house is on fire': Greta Thunberg, 16, urges leaders to act on climate
Greta Thunberg
Swedish school strike activist demands economists tackle runaway global warming. Read her Davos speech here

Our house is on fire. I am here to say, our house is on fire.

Washington, DC

Paris

Brussels

Sydney

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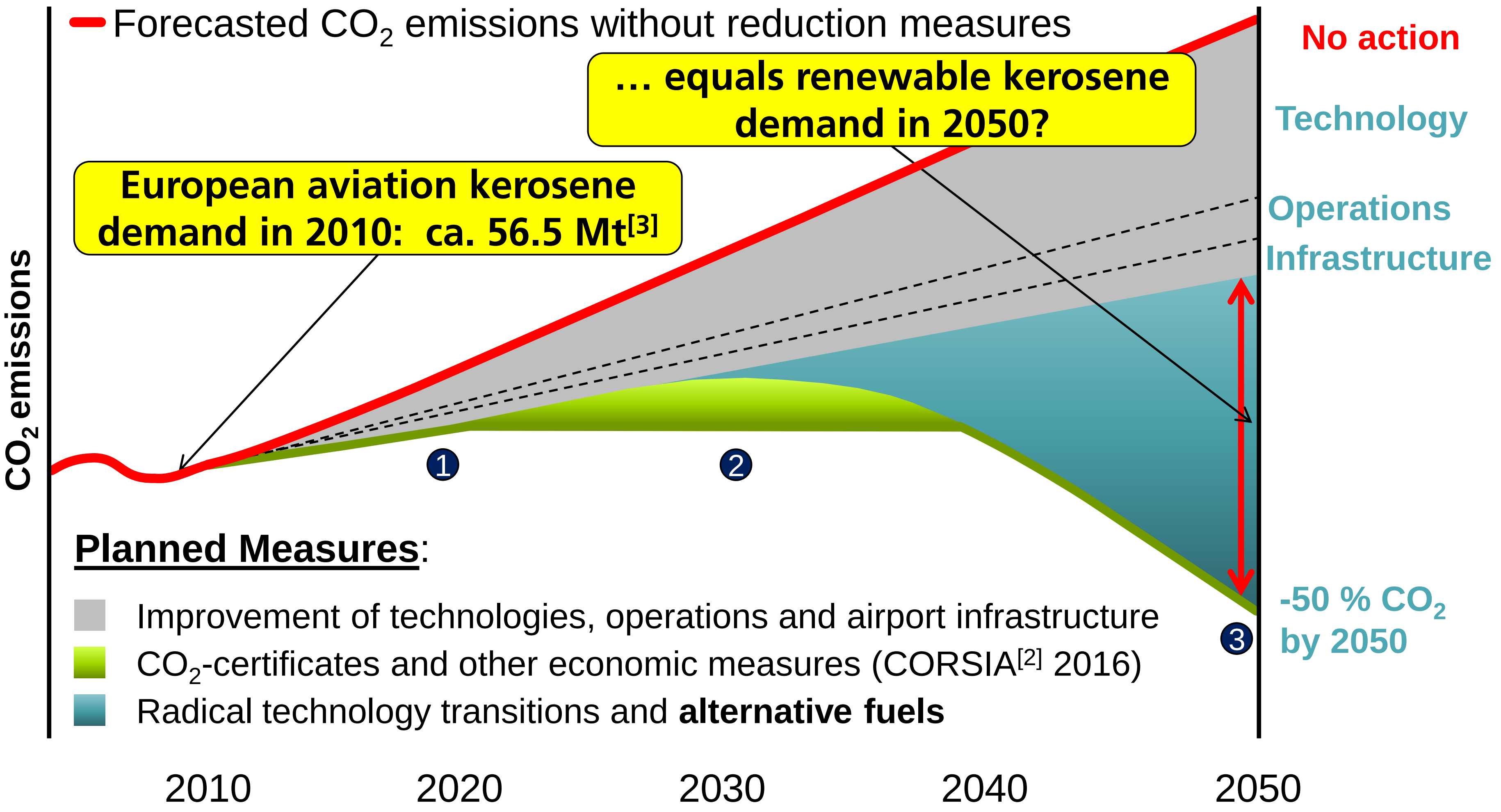
Aviation Industry Response: IATA Technology Roadmap [1]

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



[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" 2010

Certified alternative 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

European AtJ? – feedstock example wheat:

Wheat cultivated area$_{2017}$[2]: **25.9 mio. ha** ➔ Ethanol per area: **2.2 t/ha**[3]

Conversion to fuel [4]: **0.56 $t_{Kerosene}/t_{Ethanol}$**

European kerosene production based on wheat: **31.9 Mt/a** (≈ 56 % of demand)

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2015
[2] Eurostat 2019, Crop production in EU standard humidity by NUTS 2 regions
[3] Fachagentur Nachwachsende Rohstoffe, „Steckbrief Ethanol-Kraftstoff", 2016
[4] NREL, „Review of Biojet Fuel Conversion Technologies", Golden, 2016

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European DSHC? – feedstock example sugar beet:

Sugar beet cultivated area$_{2017}$[2]: **1.8 mio. ha** ➔ Sugar per area: **11.6 t/ha**[3]

Conversion to fuel [4]: **0. 168 $t_{Kerosene}/t_{Sugar}$**

European kerosene production based on sugar: **3.4 Mt/a** (≈ 6 % of demand)

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2015
[2] Eurostat 2019, Crop production in EU standard humidity by NUTS 2 regions
[3] Fachagentur Nachwachsende Rohstoffe, „Steckbrief Ethanol-Kraftstoff", 2016
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European HEFA? – feedstock example rapeseed & soya:

Apeseed/Soya cultivated area$_{2017}$[2]: **11.6 mio. ha** ➔ Rapeoil/Soyaoil per area: **2.6 t/ha**[3]

Conversion to fuel [4]: **0. 49 $t_{Kerosene}/t_{Biooil}$**

European kerosene production based on HEFA: **14.7 Mt/a** (≈ 26 % of demand)

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015
[2] Eurostat 2019, Crop production in EU standard humidity by NUTS 2 regions
[3] Fachagentur Nachwachsende Rohstoffe, „Steckbrief Ethanol-Kraftstoff”, 2016
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European **BtL** Fischer-Tropsch kerosene? – feedstock forestry and municipal waste:

Forest residues, municipal waste potential[2]: **≈ 8 EJ_{LHV}/a**

Conversion to fuel[3]: **0.363 $P_{LHV,Kerosene}/P_{LHV,Biomass}$**

European kerosene production based on BtL: **68.4 Mt/a (121 %** of demand)

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons", 2015
[2] Pablo Ruiz, „The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries", Table 38-43, 2015
[3] Albrecht, "A standardized methodology for the techno-economic evaluation of alternaitve fuels – a case study", 2016

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European **PtL** Fischer-Tropsch kerosene? – feedstock renewable electricity:

European wind power potential[2]: **44 – 109 EJ_e/a** (2018: 1.3 EJ_e/a[3])

Conversion to fuel[4]: **0.506 $P_{LHV,Kerosene}/P_e$**

European kerosene production based on PtL: **56.5 Mt/a (5 - 10 % of wind potential)**

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015
[2] European Environment Agency, "Europe's onshore and offshore wind energy potential," 2009
[3] Komusanac et al, "Wind energy in Europe in 2018", 2019
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Wind capacity increase 17 GW/a required until 2050 !!! ($wind_{2018}$: 11.7 GW[3])

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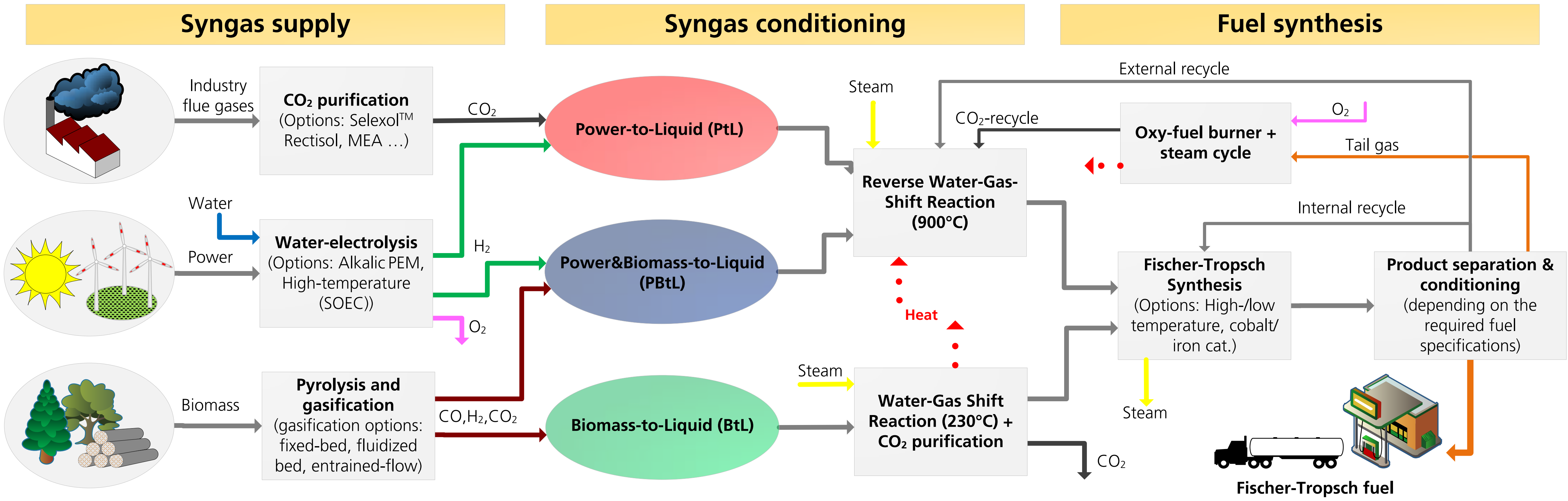
Overview: Fischer-Tropsch Kerosene Concepts [1]



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

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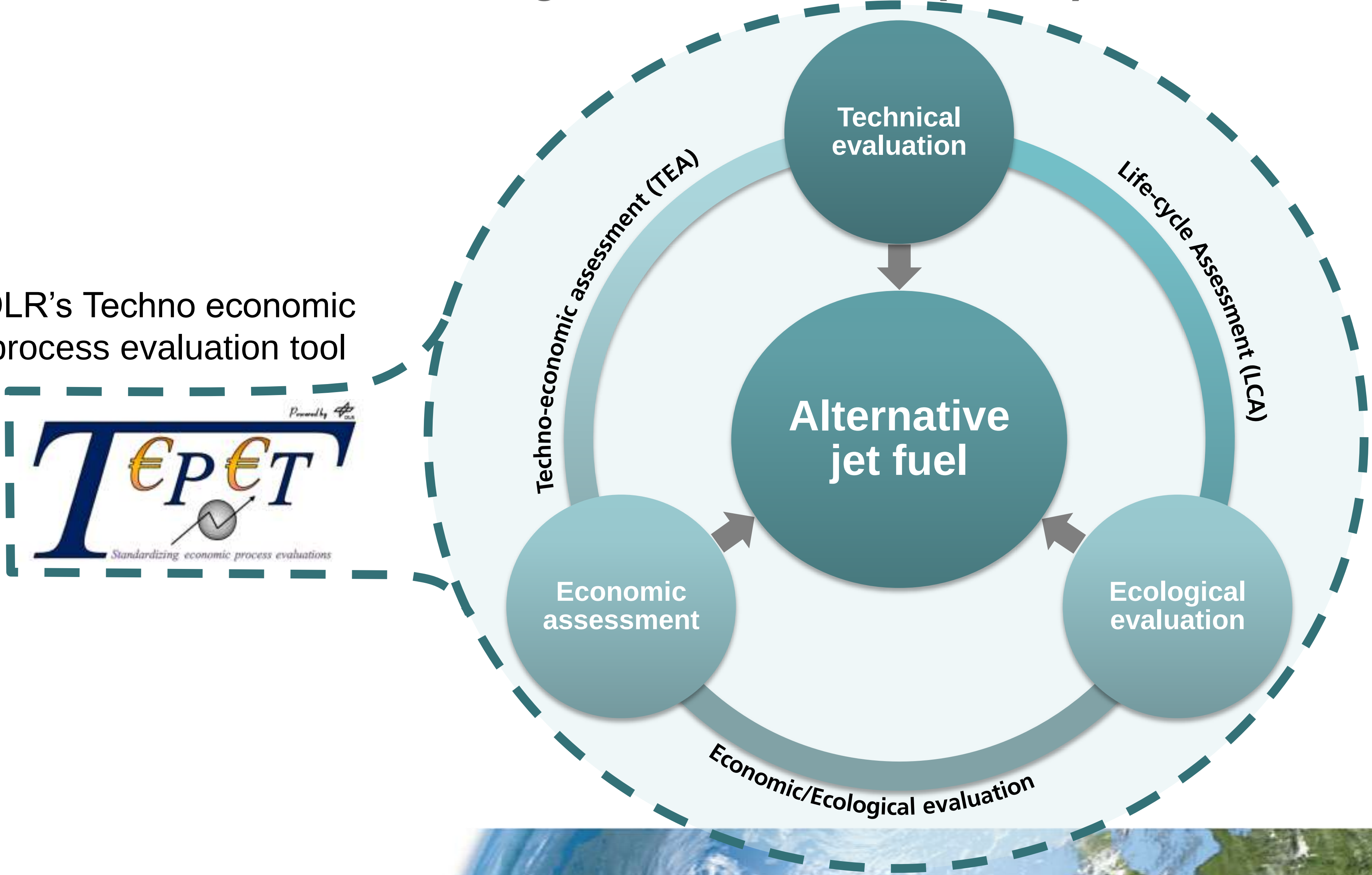
Techno-Economic and ecological assessment (TEEA)

DLR's Techno economic process evaluation tool



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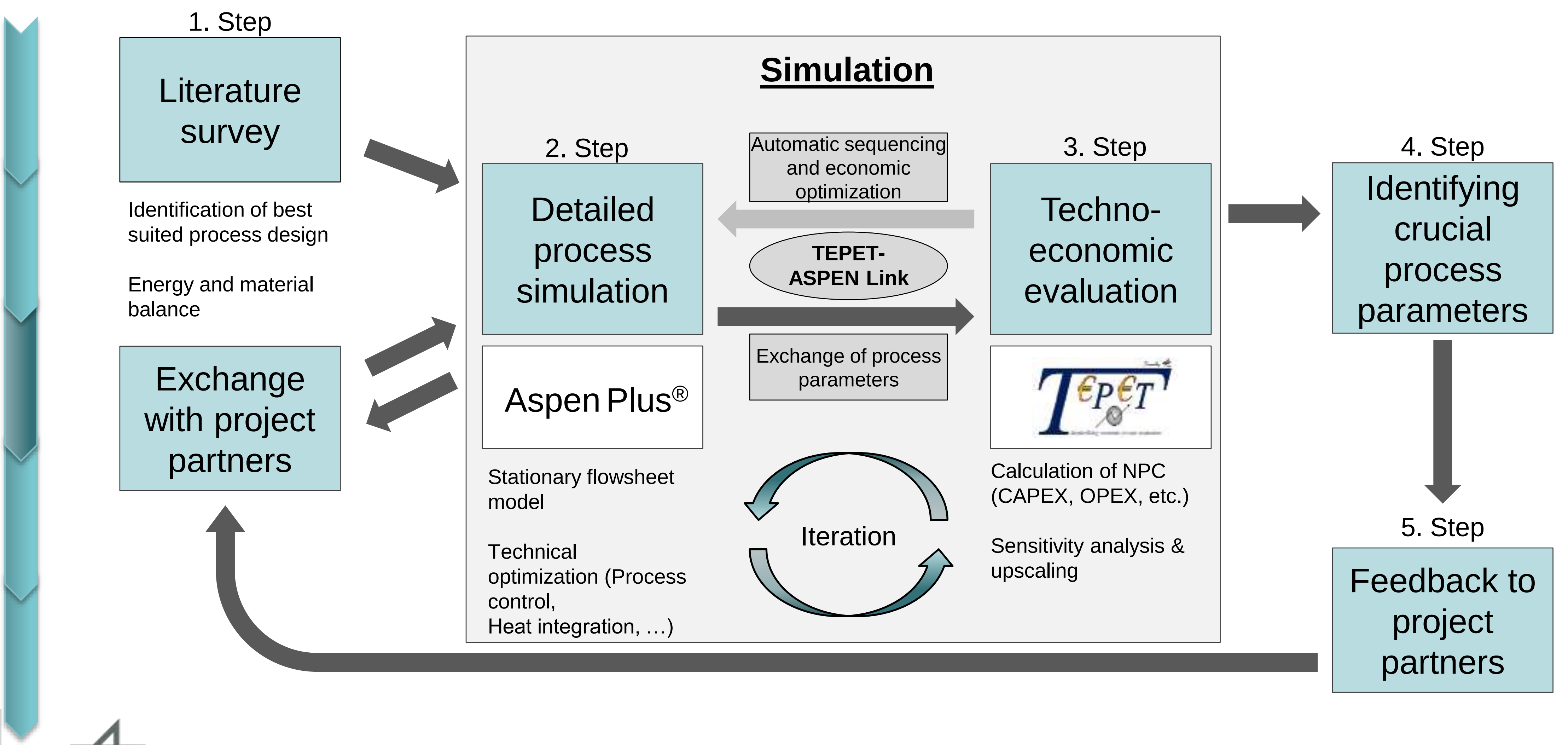
TEEA approach @ DLR



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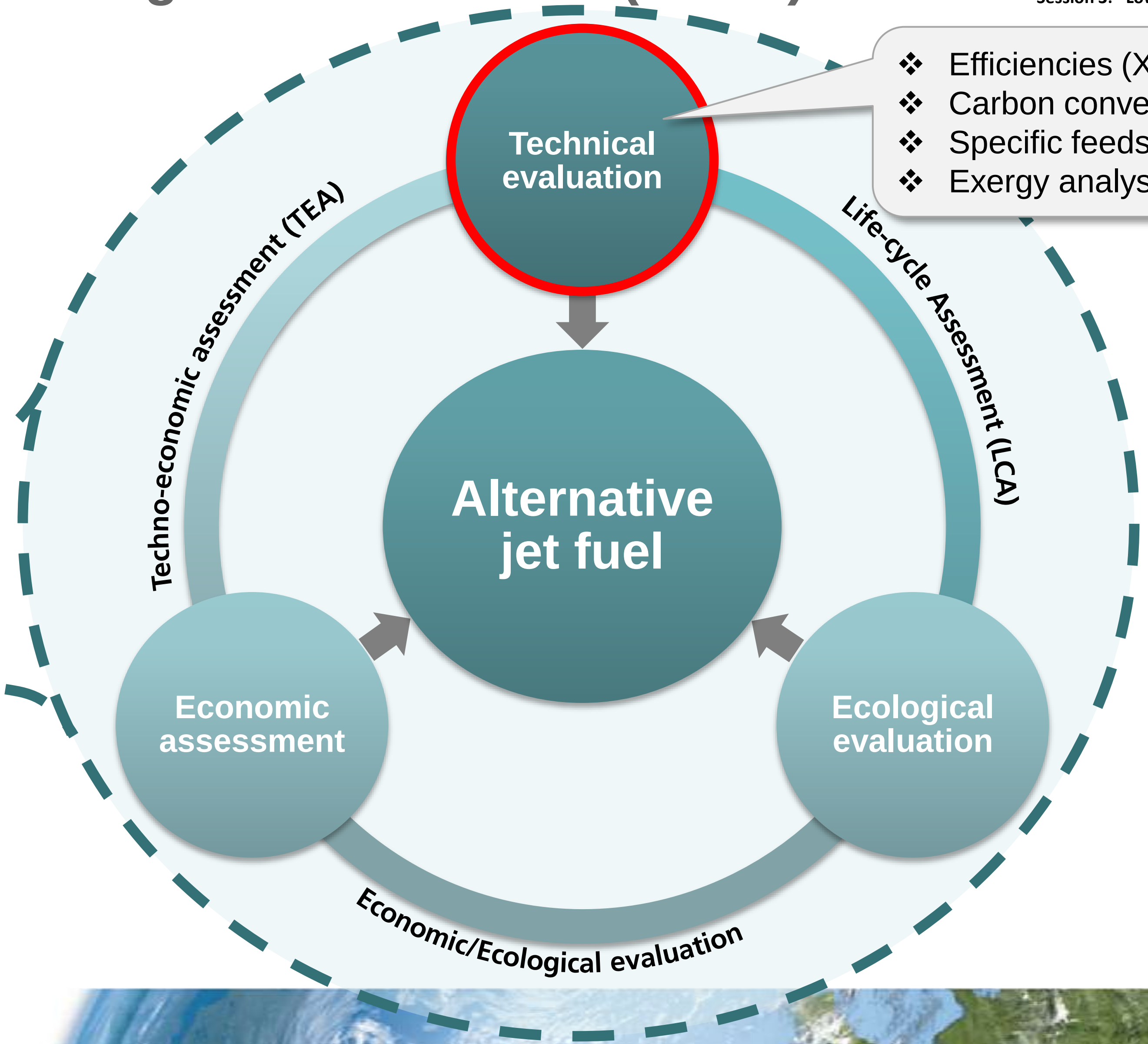
TEPET – Powered by DLR – Standardizing economic process evaluations



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

Technical evaluation of renewable jet fuel options [1]

Comparison	Biomass-to-Liquid	Power/Biomass-to-Liquid	Power-to-Liquid
X-to-Liquid efficiency	36.3 %	51.4 %	50.6 %
Energy efficiency	82.6 %	65.0 %	66.8 %
Carbon conversion	24.9 %	97.7 %	98 %

$$\eta_{XtL} = \frac{\dot{Q}_{keroesene-LHV}}{P_e + \dot{Q}_{Biomass-LHV}}$$

$$\eta_e = \frac{\dot{Q}_{keroesene-LHV} + \dot{Q}_{steam}}{P_e + \dot{Q}_{Biomass-LHV}}$$

$$\eta_c = \frac{\dot{n}_{C-keroesene}}{\dot{n}_{C-Feedstock}}$$

[1] Albrecht, “A standardized methodology for the techno-economic evaluation of alternaitve fuels – a case study”, 2016

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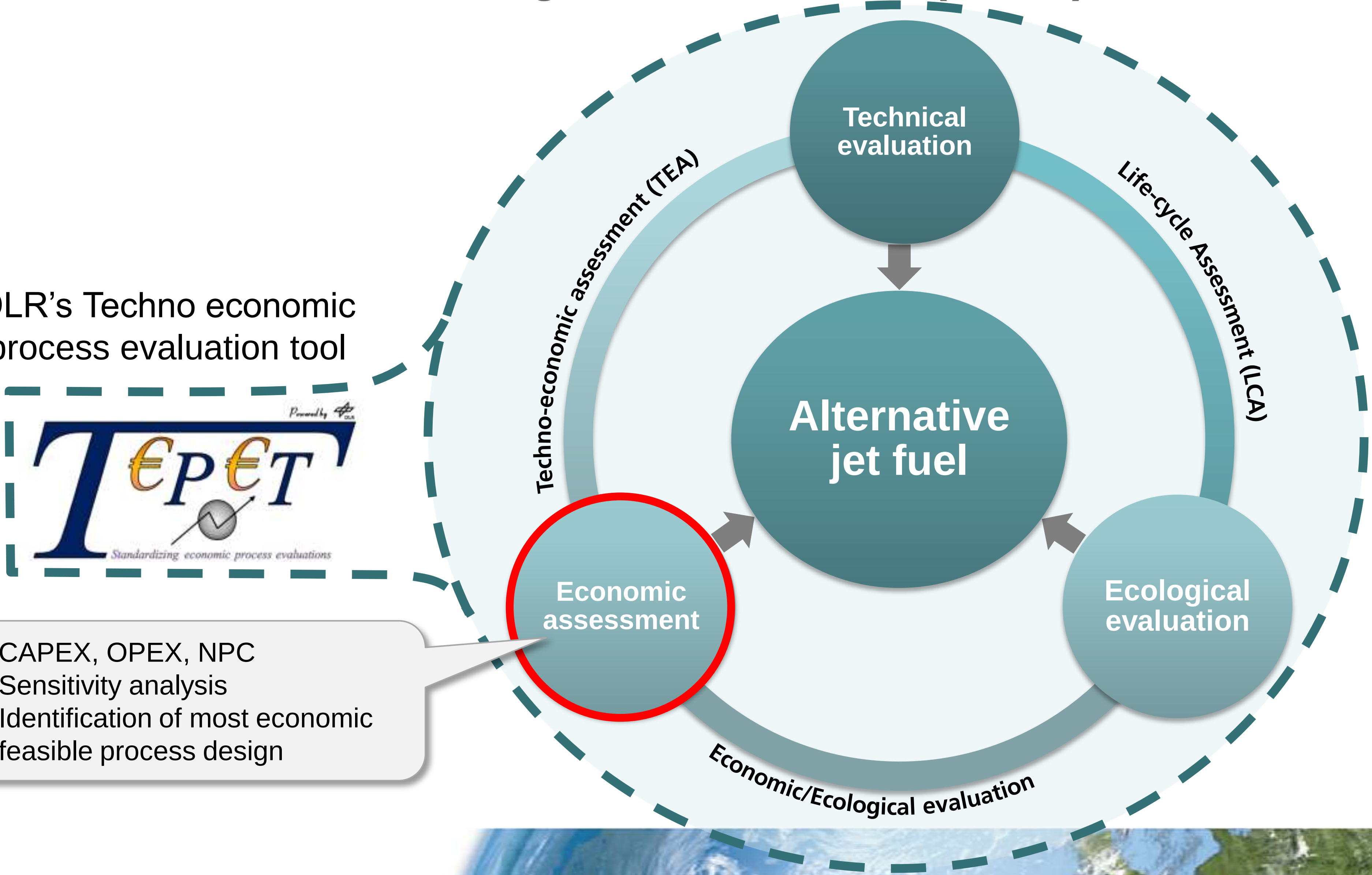
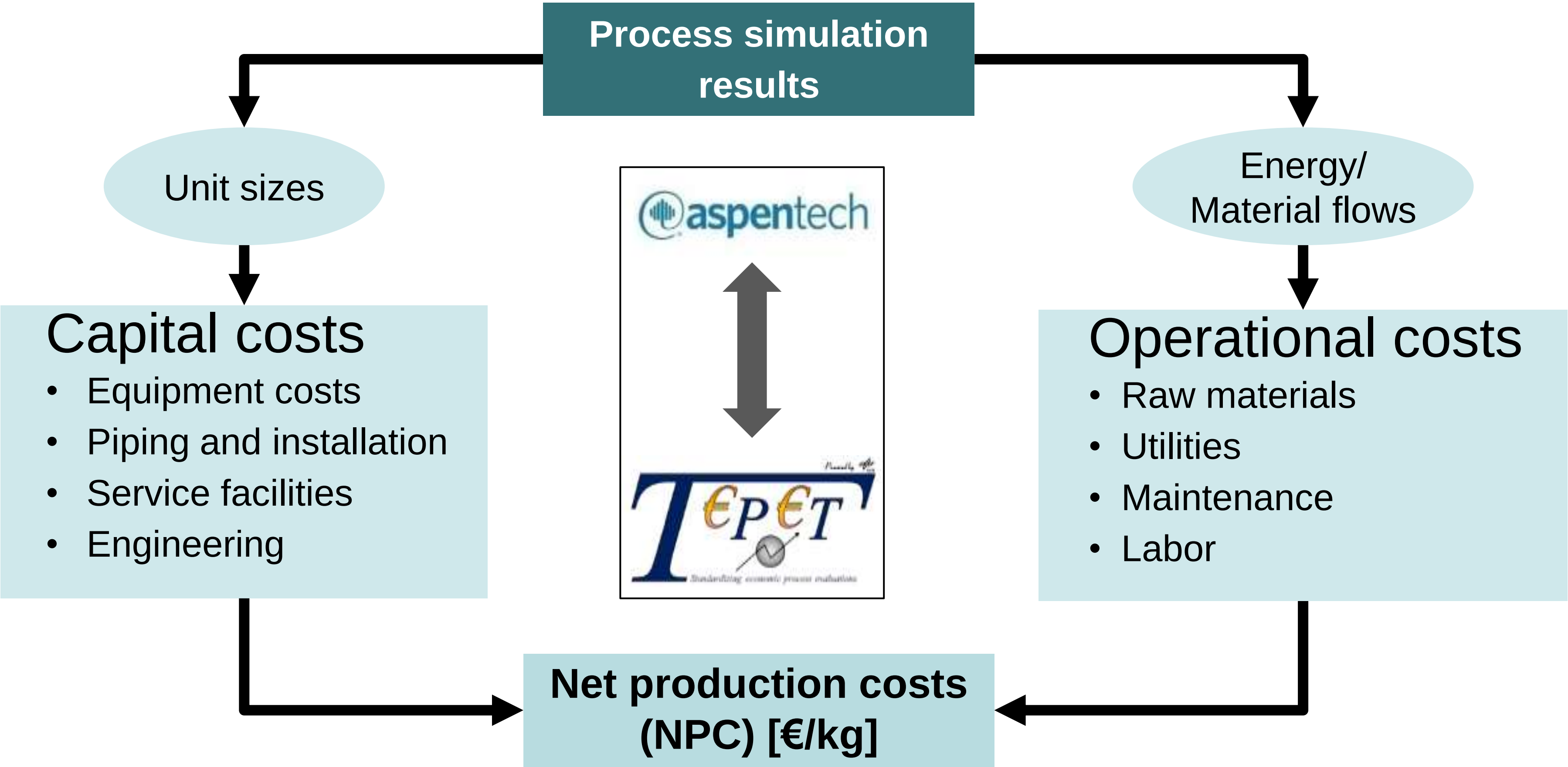


- CAPEX, OPEX, NPC
- Sensitivity analysis
- Identification of most economic feasible process design

TEEA tool TEPET @ DLR

- 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, …



Example: TEEA of sustainable Jet fuel production

Plant capacity: 550 kt/a (1 % of European jet fuel consumption)

Investment costs:

PEM-Electrolyzer (stack):	**850**	€/kW [1]	(scale factor: 1)
PEM-Electrolyzer (system):	**1,370**	€/kW	(TEPET, incl. supplementary factors)
Fischer-Tropsch reactor:	**17.44**	Mio.€/(kmol$_{feed}$/s) [2]	(scale factor: 0.67)

Raw materials and utility costs

Electricity:	**99.6**	€/MWh [3]	
Biomass:	**80.1**	€/t [4]	
District heating	**0.027**	€/kWh [5,7]	Byproduct
Steam (export):	**19.8**	€/t [6]	Byproduct

General economic assumptions:

Year:	2017	*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, 2016
[4] C.A.R.M.E.N. – Preisentwicklung bei Waldhackschnitzel (Energieholz-Index), 2017
[5] Energieeffizienzverband für Wärme, Kälte und KWK e.V., Heizkostenvergleich nach VDI 2067-Musterrechnung, 2014
[6] Own calculations based on natural gas price from Eurostat database 2017
[7] http://www.rogersrawmaterials.com/home.asp (accessed 02/2018)

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Example: TEEA of sustainable Jet fuel production

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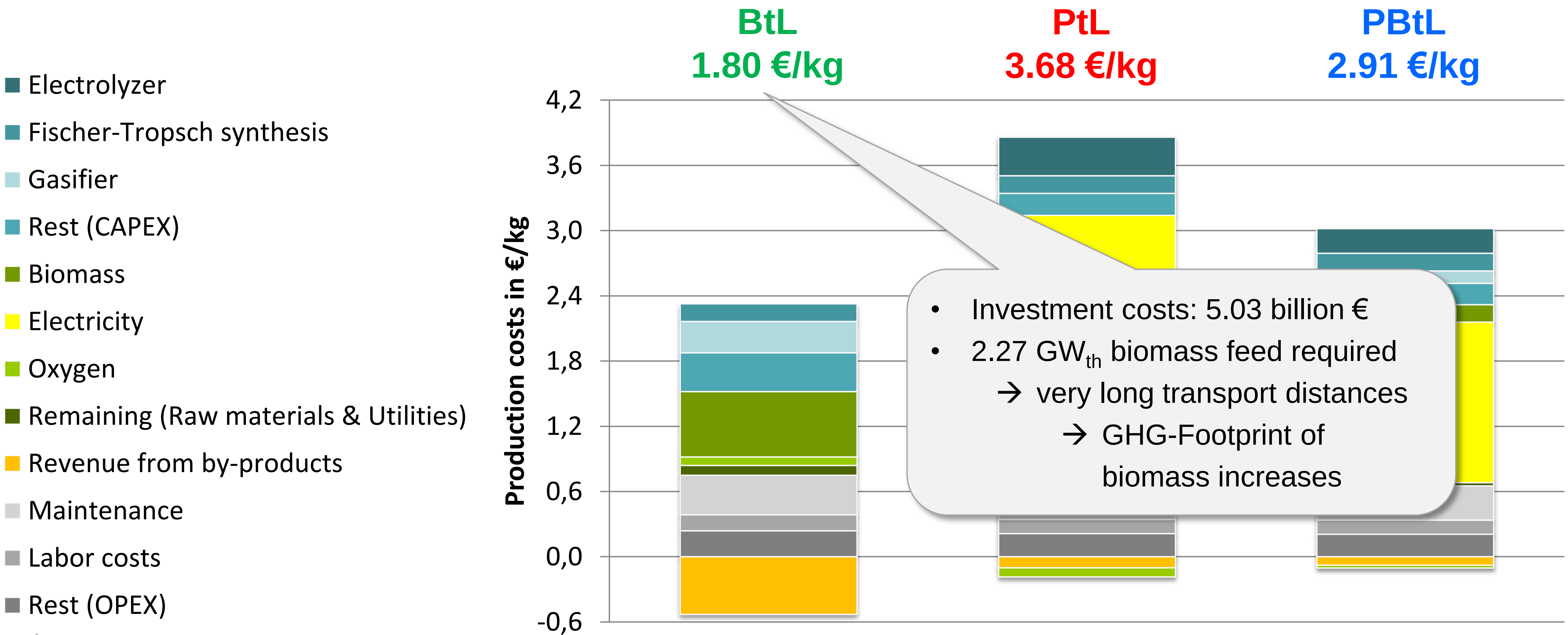

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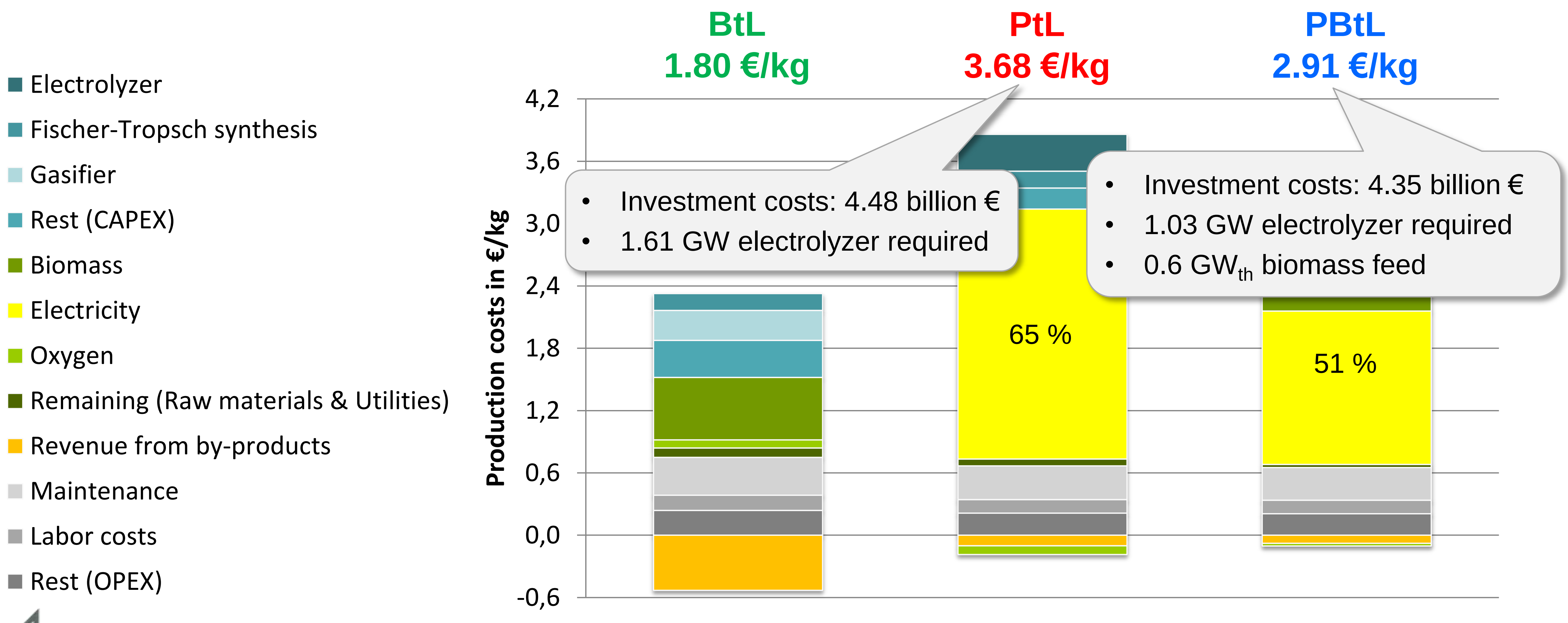

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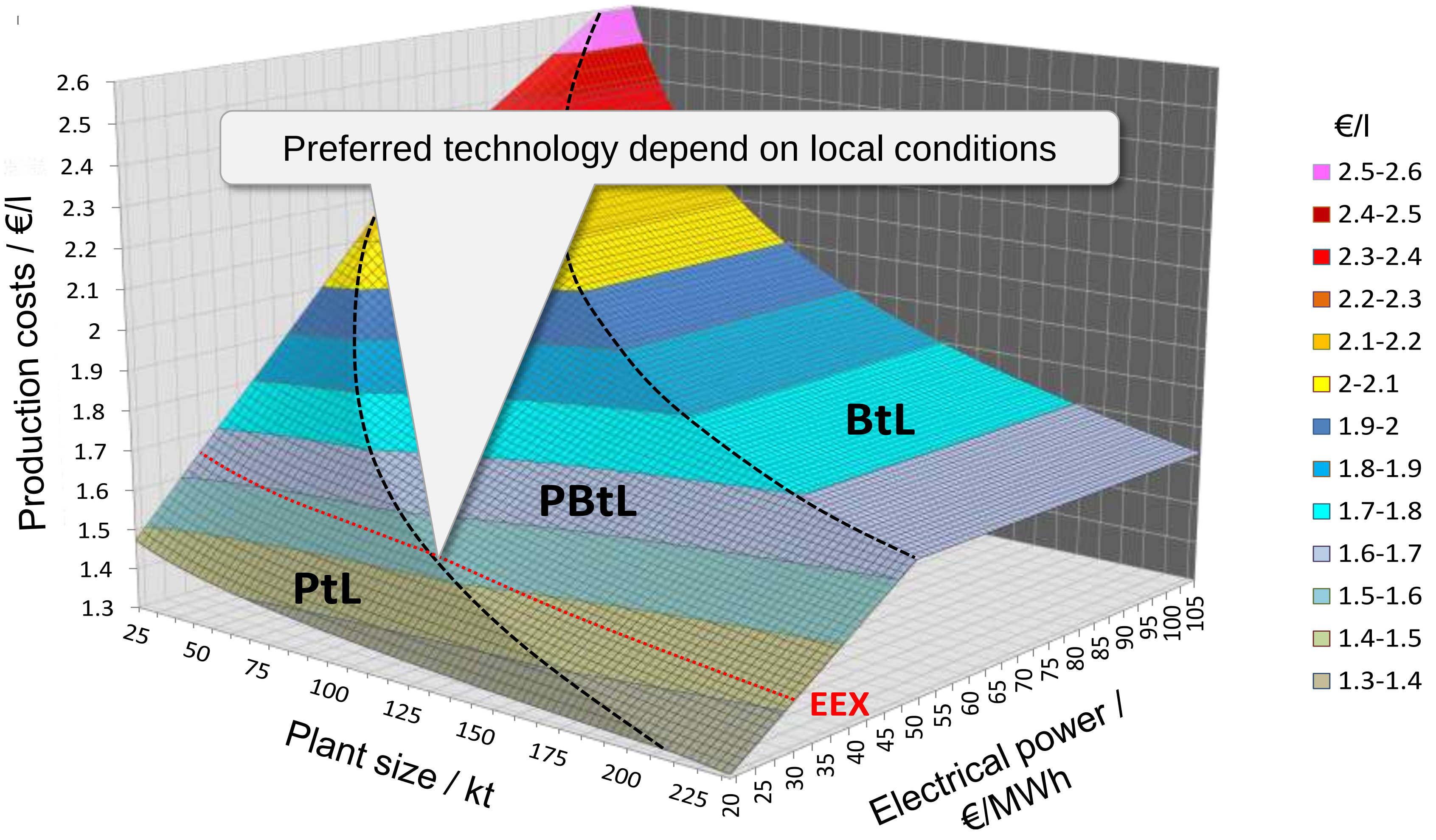
Example: TEEA sensitivity of PBtL

Plant capacity: 550 kt/a (1 % of European jet fuel consumption) – Base year: 2017



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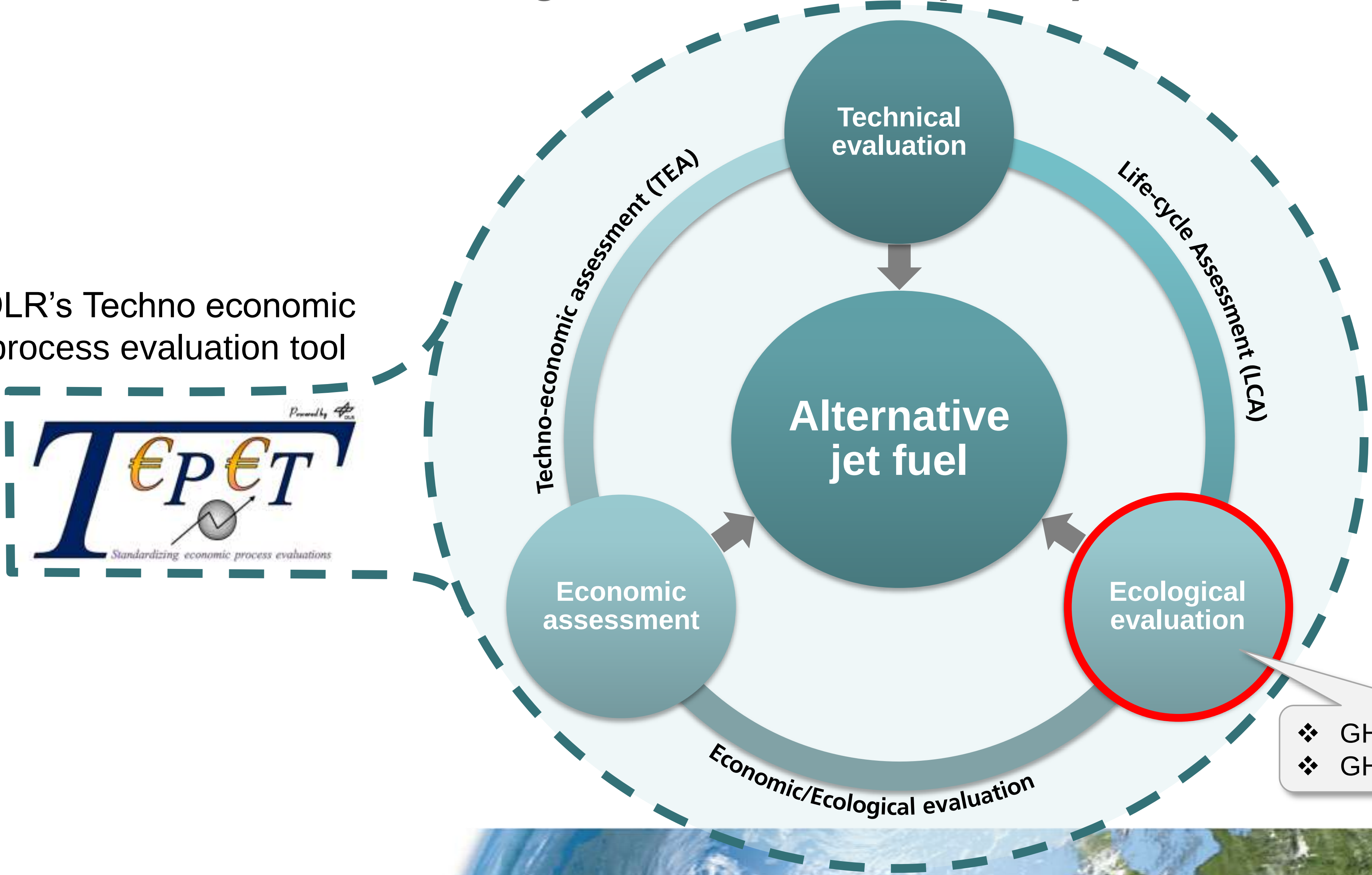

- GHG-footprint
- GHG-abatement costs

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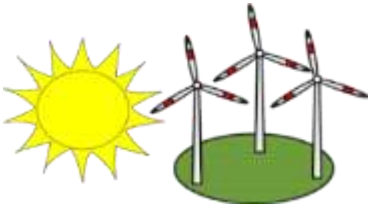
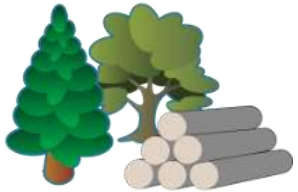
Example: Fischer-Tropsch Jet fuel GHG-Footprint

CO_2 footprint



Electricity footprint



Biomass footprint

P&BtX - Concept

- Systemintegration
- Efficiency
- Plant emissions
- Crediting of by-products (steam, electricity, …)

GHG-footprint of products

Application efficiency

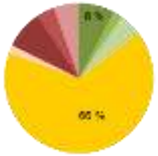
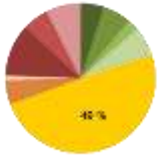
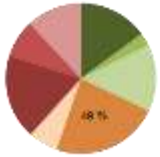
$$\text{GHG abatement costs}\left[\frac{€}{t_{CO_2 eq.}}\right] = \frac{\text{Difference in production costs}}{\text{GHG abatement}}$$

Example: Fischer-Tropsch Jet fuel GHG-Footprint

$$\text{GHG abatement costs}\left[\frac{€}{t_{CO_2eq.}}\right] = \frac{\text{Difference in production costs}}{\text{GHG abatement}}$$

- Calculation of production costs (550 kt/a):

PtL	PBtL	BtL
3.68 €/kg	2.91 €/kg	1.80 €/kg

vs.

conv. Kerosene
0.63 €/kg [1]

- Calculation of GHG-emissions in $kg_{CO2eq.}/kg_{fuel}$:

Electricity origin	PtL	PBtL	BtL
Electricity mix (VEU-2015 scenario)	13.97	9.11	- 3.59
100 % wind energy	- 1.61	- 0.37	- 0.89

No CO_2-reduction with current German electricity mix!

vs.

conv. Kerosene
3.11 $kg_{CO2eq.}/kg$ [2]
+
0.64 $kg_{CO2eq.}/kg$ [3]

[1] U.S. energy information administration (05.09.2018) http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm
[2] Eigene Berechnung: CO_2-Ausstoß bei der Verbrennung von 1 kg Kerosin Jet-A1
[3] Bouvart et al. (2013), „Well-To-Tank" carbon impact of fossil fuels

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Example: Fischer-Tropsch Jet fuel GHG-Footprint

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

Production route:	PtL	PBtL	BtL
Production costs [€/kg$_{kerosene}$]	3.68	2.91	1.80
Electricity mix (VEU-2015 reg. change)	x	x	159
100 % wind energy	569	553	252

- Future feedstock cost reduction?

Electricity & biomass prices -70 %:	1.45 €/kg	1.29 €/kg	1.00 €/kg
Electricity mix (VEU-2015 reg. change)	x	x	50
100 % wind energy	152	160	80

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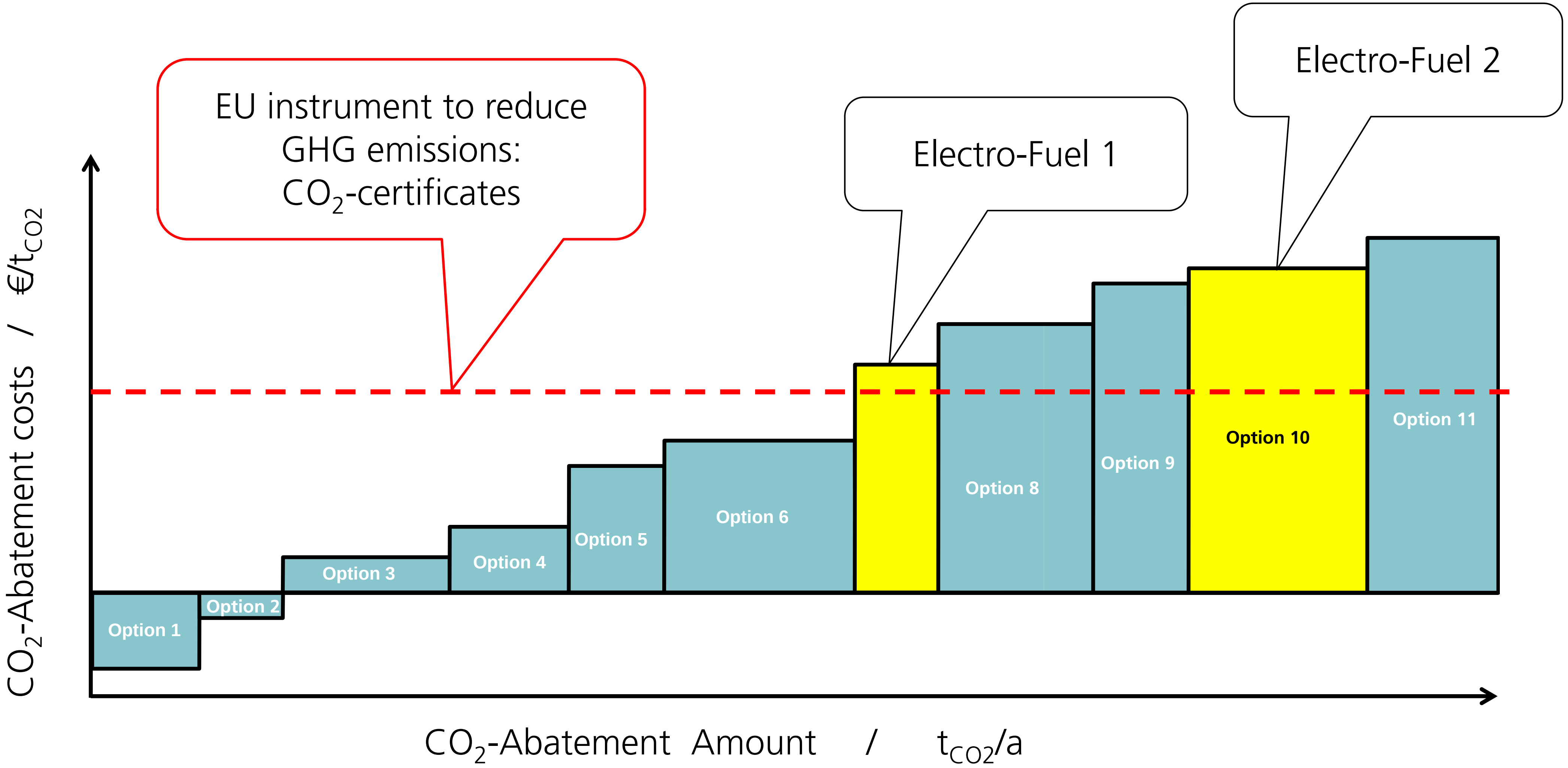
TEEA – long term goal

Merit order of GHG abatement



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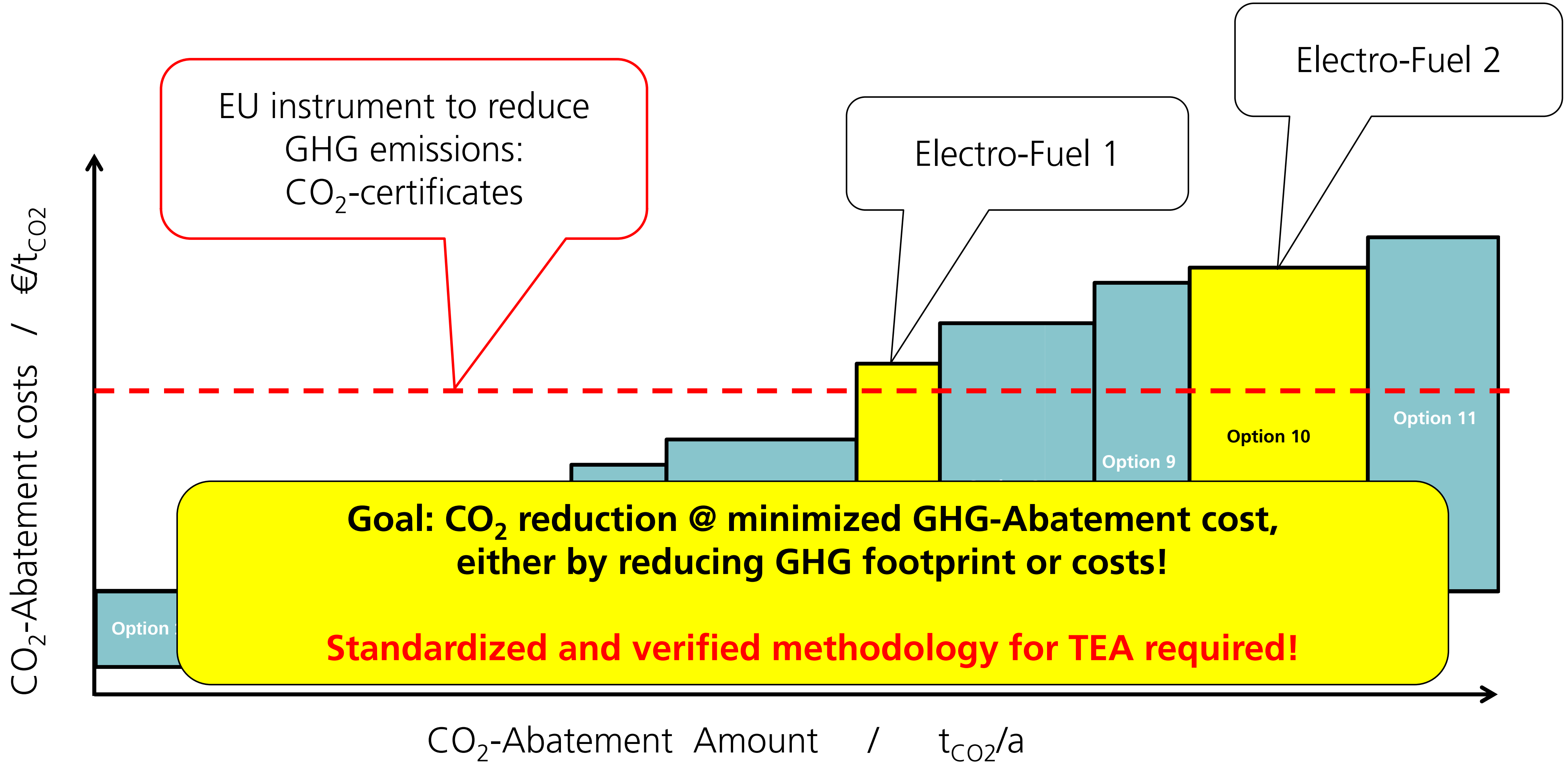

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Summary (part 1)

- Renewable fuels are required to achieve the aviation climate change mitigation goals
- "Silver bullet" technology not decided yet
- Large scale Fischer-Tropsch synthesis: highest feedstock flexibility (syngas) and highest technical maturity
  Downscale towards renewable power and/or biomass supply?
- GHG abatement cost should be the key decision criterion for any climate change mitigation roadmap
- Transparent and standardized DLR methodology for cost estimation and GHG-footprint offers a valid starting point for technology assessment and future global transport roadmap
- Renewable kerosene technology development, scale up and market introduction ➔ outlook

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Decentralized Approach: EU project COMSYN[1]

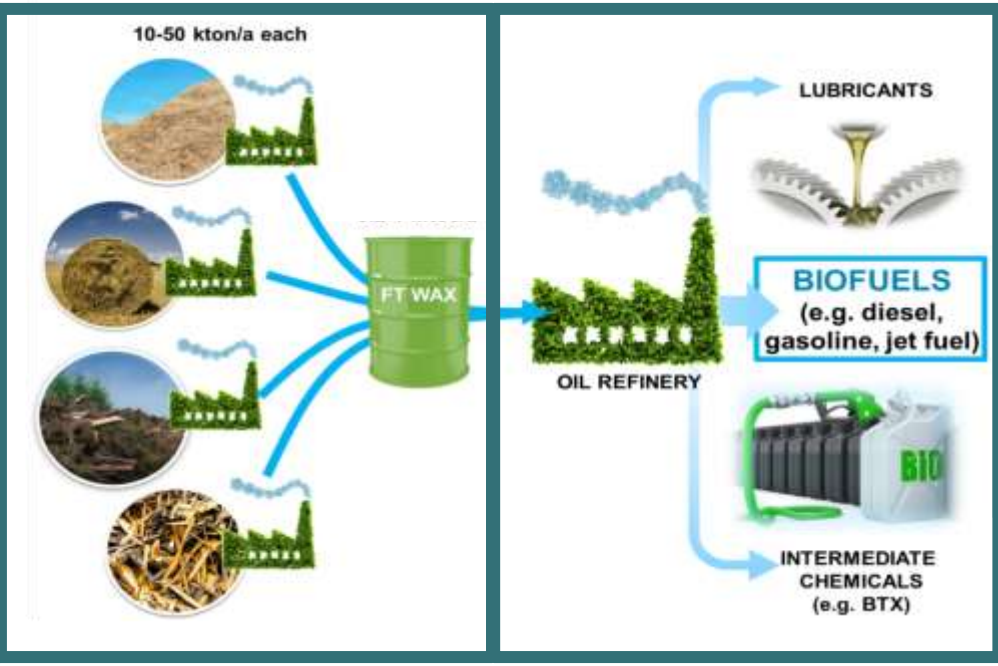
www.comsynproject.eu – EU No. 727476

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)

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)

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Decentralized Approach: EU project COMSYN

Project concept details

COMSYN

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DFB PILOT @ VTT

5 m^3/h SLIP-STREAM TO SYNTHESIS

MOBILE SYNTHESIS UNIT

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

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Project concept details

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

- Finalized: 2015
- Biomass feed: ca. 50 kg/h
- Gasifier temperature: 750 – 820 °C
- Oxidizer temperature: ca. 900 °C
- Bed material: Dolomite/sand mixture

5 m³/h SLIP-STREAM TO SYNTHESIS

MOBILE SYNTHESIS UNIT

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

Concawe

13th Concawe Symposium 2019, Antwerp
Session 3: "Low-carbon pathways & Refining Technologies (I)"

Decentralized Approach: EU project COMSYN
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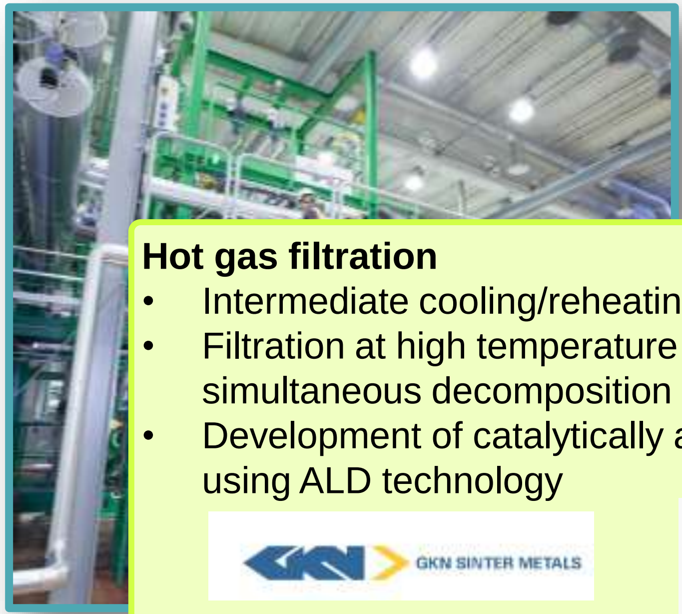

Hot gas filtration
- Intermediate cooling/reheating steps eliminated
- Filtration at high temperature (ca. 800 °C) with simultaneous decomposition of tars
- Development of catalytically activated filters using ALD technology

GKN SINTER METALS

VTT

/h
EAM TO
ESIS

MOBILE SYNTHESIS UNIT

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MOBILE SYNTHESIS UNIT

Catalytic reforming

- Development of an oxygen-permeable membrane reactor to enable better control of reaction temperature in the reformer (hot spots)
- Catalyst development: ALD coating to increase the activity as well as sulphur and coke tolerance of the catalyst

VTT

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

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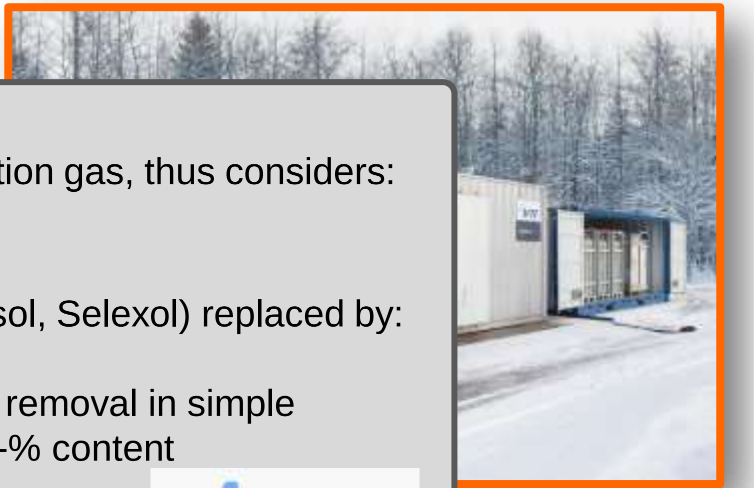

Ultracleaning concept:

- Specifically for biomass-based gasification gas, thus considers:
  - Low to medium sulphur content
  - Residual hydrocarbons (tars)
- Wet scrubbing acid gas process (Rectisol, Selexol) replaced by:
  - Simpler dry bed desulphurization
  - No removal of CO_2 or partial CO_2 removal in simple pressure water scrubbing to 5 vol-% content

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

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5 m^3/h SLIP-STREAM TO SYNTHESIS

MOBILE SYNTHESIS UNIT

Fischer-Tropsch microreactor:
- Compact and modular design
- High efficiencies
- Load flexible

INERATEC

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

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5 m³/h SLIP-STREAM TO SYNTHESIS

MOBILE SYNTHESIS UNIT

Product upgrading

- Co-processesing of FT-waxes or
- Stand-alone treatment (incl. a new hydroisomerisation unit)

UniCRE

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

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Product Upgrading

Open Questions / Development Tasks

Within COMSYN:
- Technical Validation
- Fuel Flexibility
- Techno-economic assessments
- 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 decarbonization of aviation!

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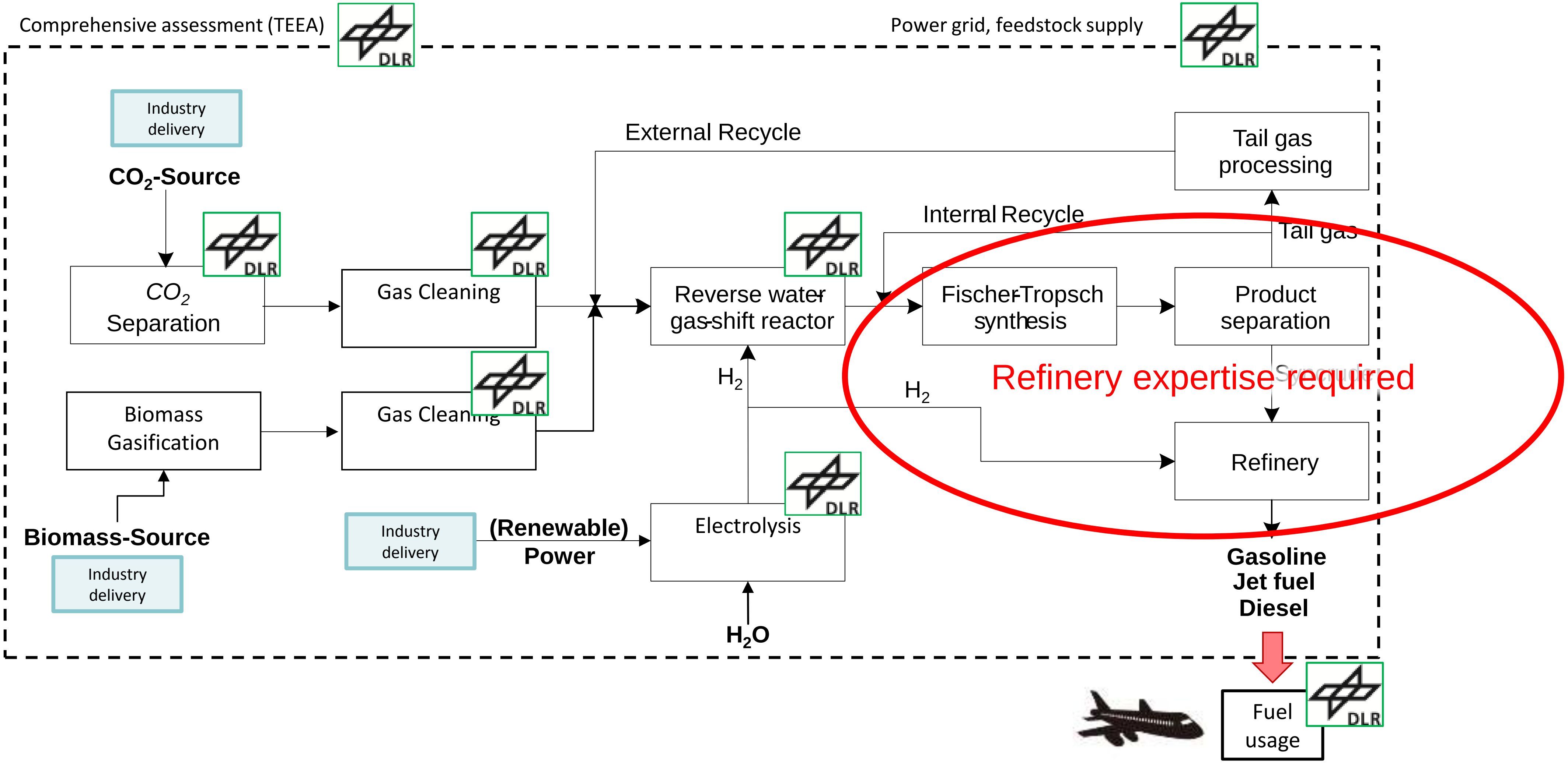
DLR contribution to renewable kerosene research



Outlook

- Renewable aviation fuels development requires strong refinery commitment
- European GHG abatement will change global fossil energy market ➔ leading countries, other stakeholders?
- Upcoming CO_2 regulation will need techno economic guidance ➔ GHG abatement costs
- DLR supports every promising technology towards renewable aviation ➔ HORIZON 2020 calls available
- Technology demonstration not sufficient for future renewable aviation ➔ market introduction
- Find a serious response to ensure next generations living conditions – now!

13th Concawe Symposium 2019, Antwerp
Session 3: ''Low-carbon pathways & Refining Technologies (I)''

Thank you for your attention!

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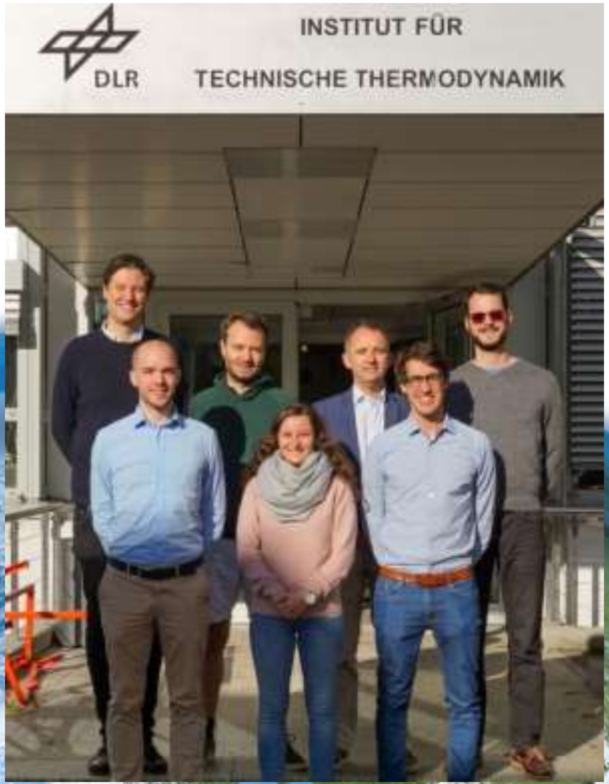

Knowledge for Tomorrow

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