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

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Athens 15.11.2017

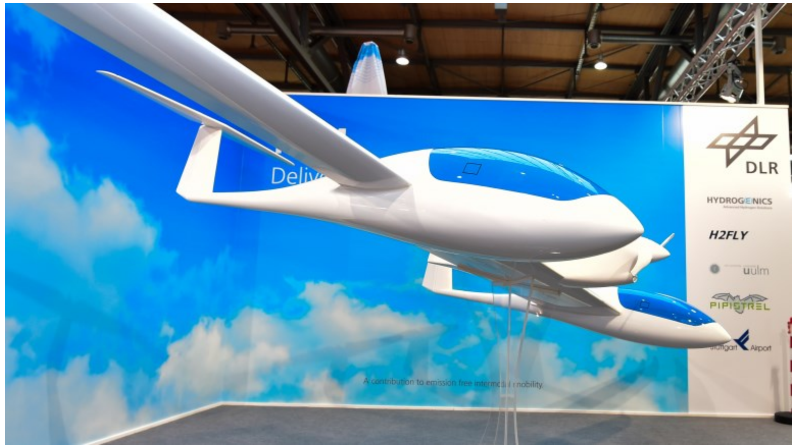
Agenda

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



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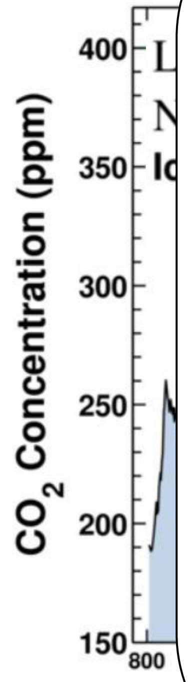
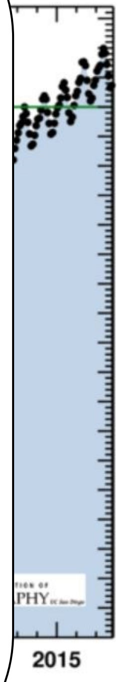
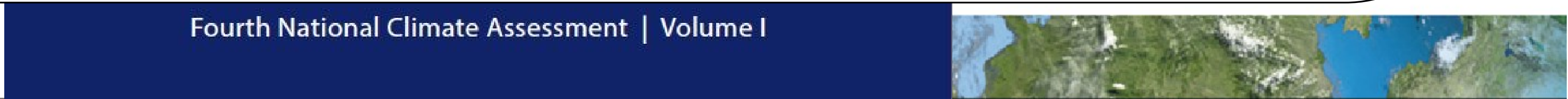
1. Climate Change –

USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp.



- 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)**

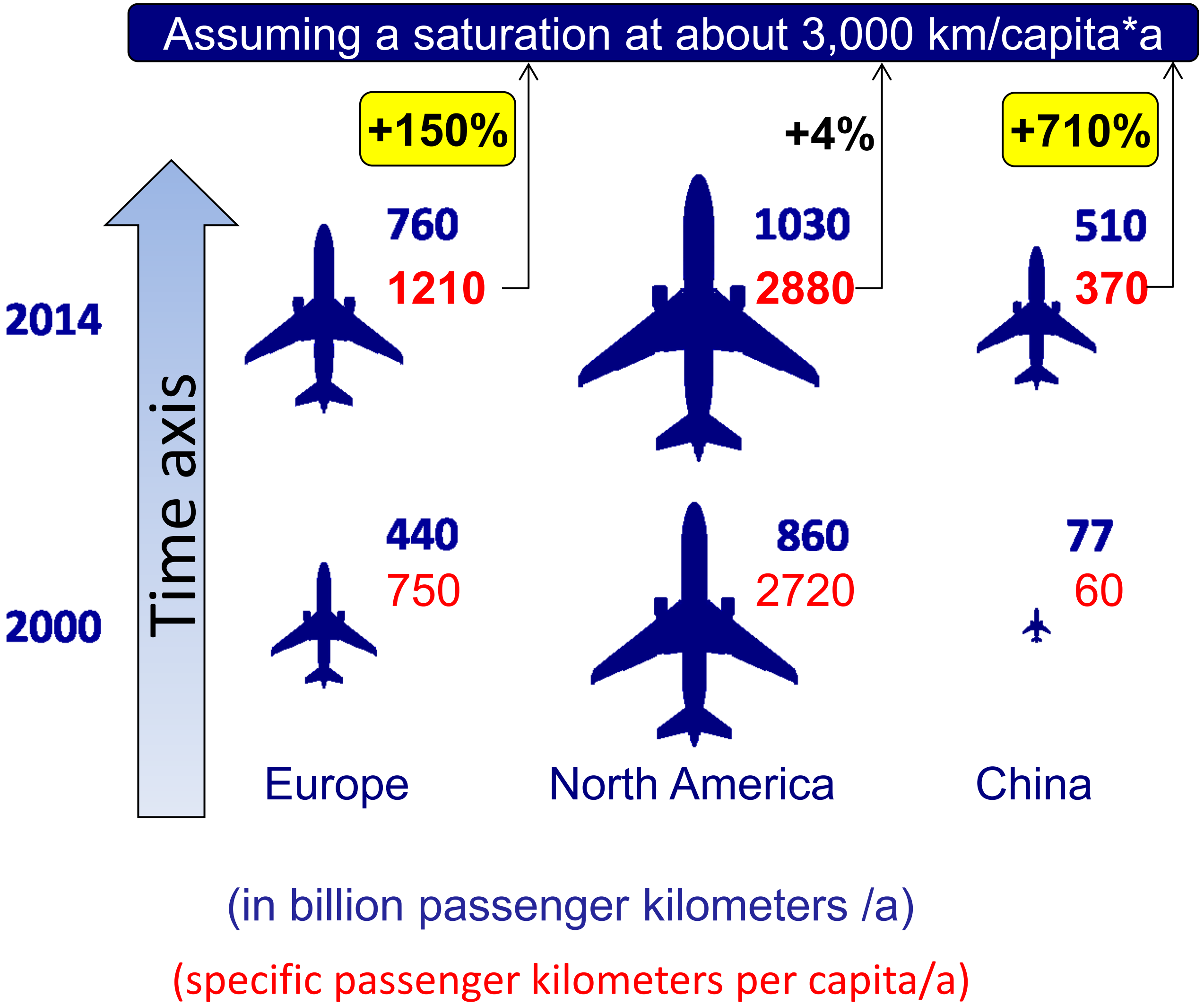
❖ **27 % increase of renewable energies in primary energy consumption**

❖ **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



Source: Thess et al., DGLR-Mitgliedermagazin „Luft- und Raumfahrt" edition 2/2016, p.20

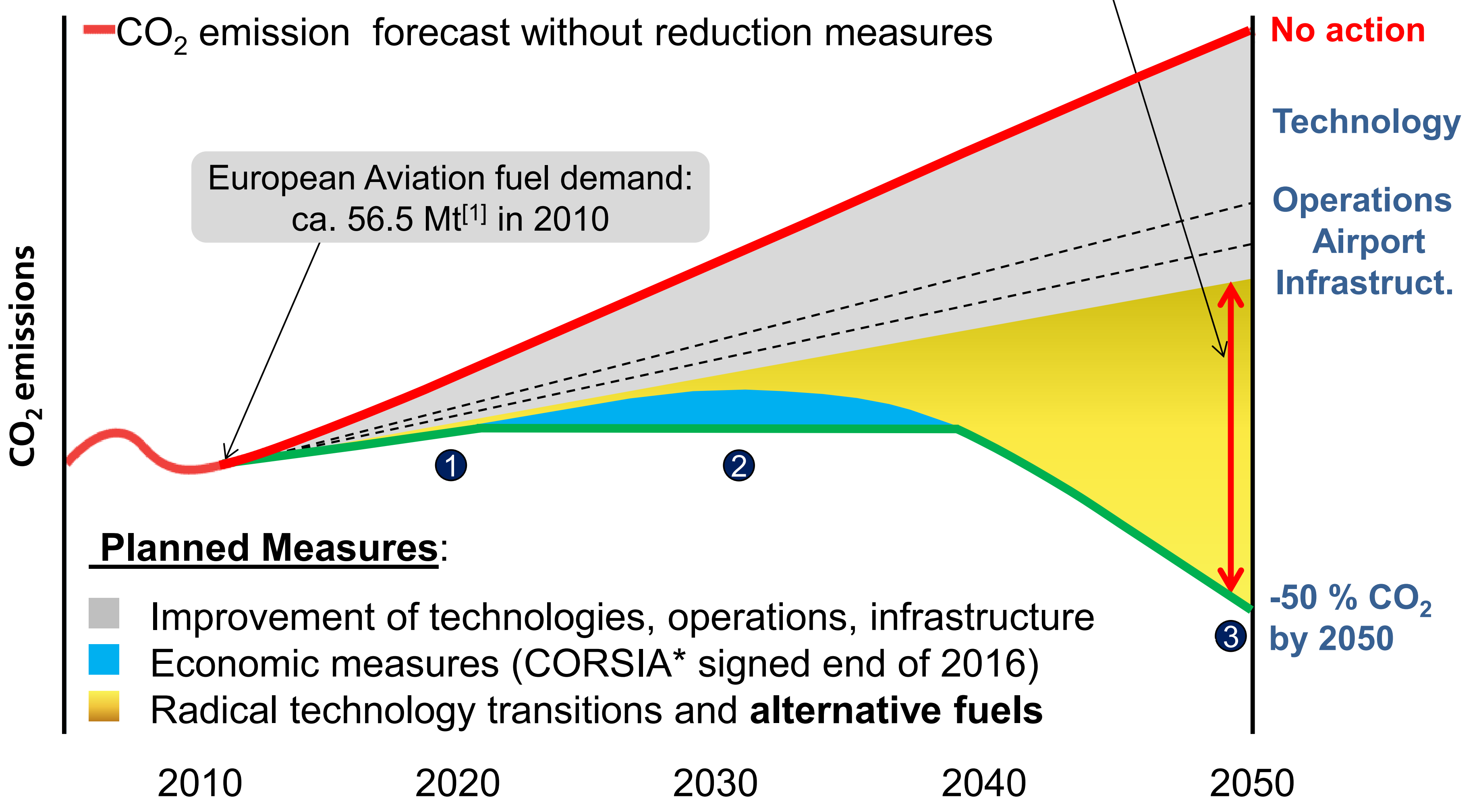
1. IATA Technology Roadmap

4. Edition, June 2013

2050 demand forecast:
≈ 56 - 60 Mt „ CO_2-neutral“ kerosene equivalent

Aviation Self-commitments:

1. Improvement of fuel efficiency ≈ 1,5 % p.a. until 2020
2. Carbon-neutral growth from 2020
3. Potential CO_2 emissions reductions by 2050



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

Source: iata.org

[1] FuelsEurope “Statistical Report“ 2010

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
Li...		...ne
Su...		
Bi...		

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] :

Feedstock	Kerosene yield from total EU crop production [Mt/a]	Share of EU kerosene consumption$_{2014}$ [%]	Share of total cultivation area in EU [%]
Wheat	23.0 – 32.9	41.8 – 59.8	30.2
Sugar	3.9	7.1	1.8
Rapeseed	7.3	13.3	13.3
Σ	**34.3 – 44.2**	**62.4 – 80.4**	**45.2**

[2] Eurostat „Crop statistics“ 2014
[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

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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

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: ≈ **56 Mt/a**[3]
- Power demand for exclusively power based kerosene in Europe: ≈ **1,410 TWh**
- European wind power potential[4]: **12,200 – 30,400 TWh** ≈ 8.6 - 22 times of power based kerosene demand!

[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015
[2] UK Ministry of Defense, „DEF STAN 91-91: Turbine Fuel, Kerosene Type, Jet A-1“, UK Defense Standardization, 2011
[3] Eurostat database, 2015
[4] European Environment Agency, “Europe's onshore and offshore wind energy potential,” 2009.

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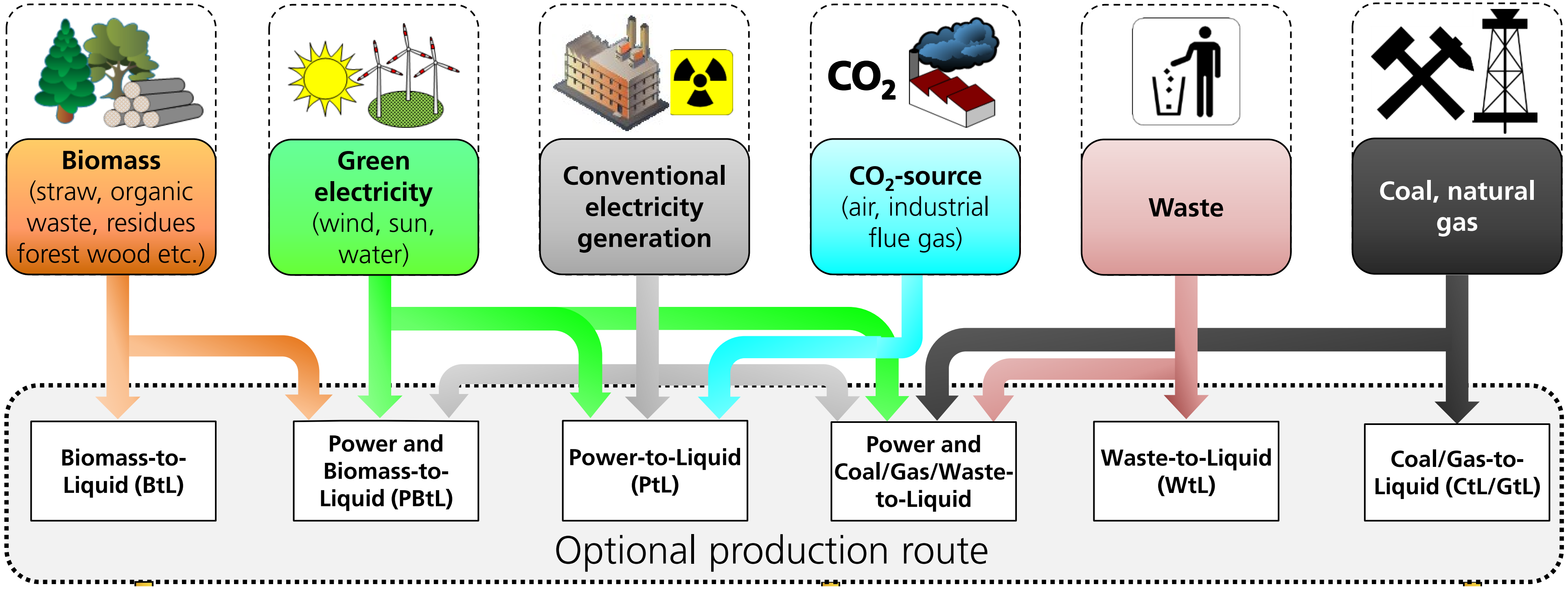
2. Production routes of alternative FT-Kerosene

- Low large CO_2 footprint potential



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).*

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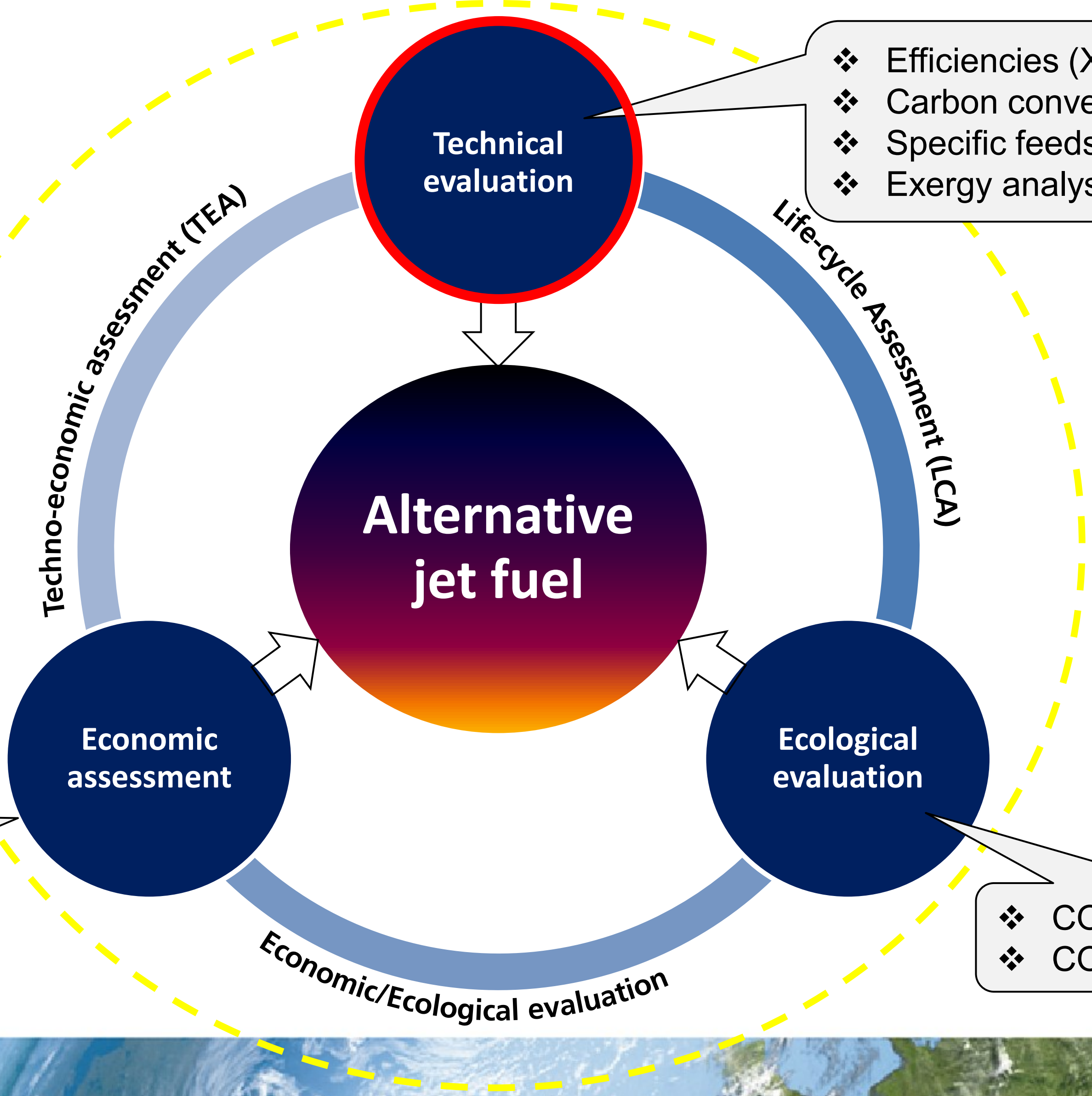
3. Techno-Economic and ecological assessment (TEA) of renewable jet fuel

DLR's Techno economic process evaluation tool

TEPET – Powered by DLR – Standardizing economic process evaluations



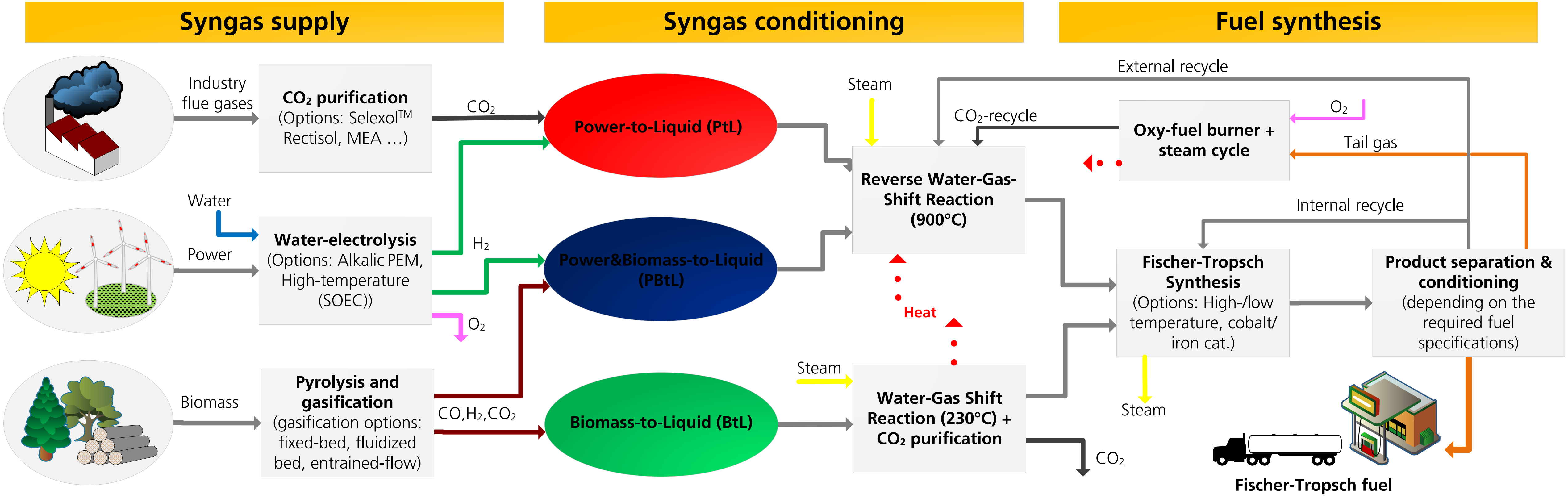
- Efficiencies (X-to-Liquid, Overall)
- Carbon conversion
- Specific feedstock demand
- Exergy analysis

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

- CO_2-footprint
- CO_2-abatement costs

3. Investigated Fischer-Tropsch concepts

Three concepts to compare



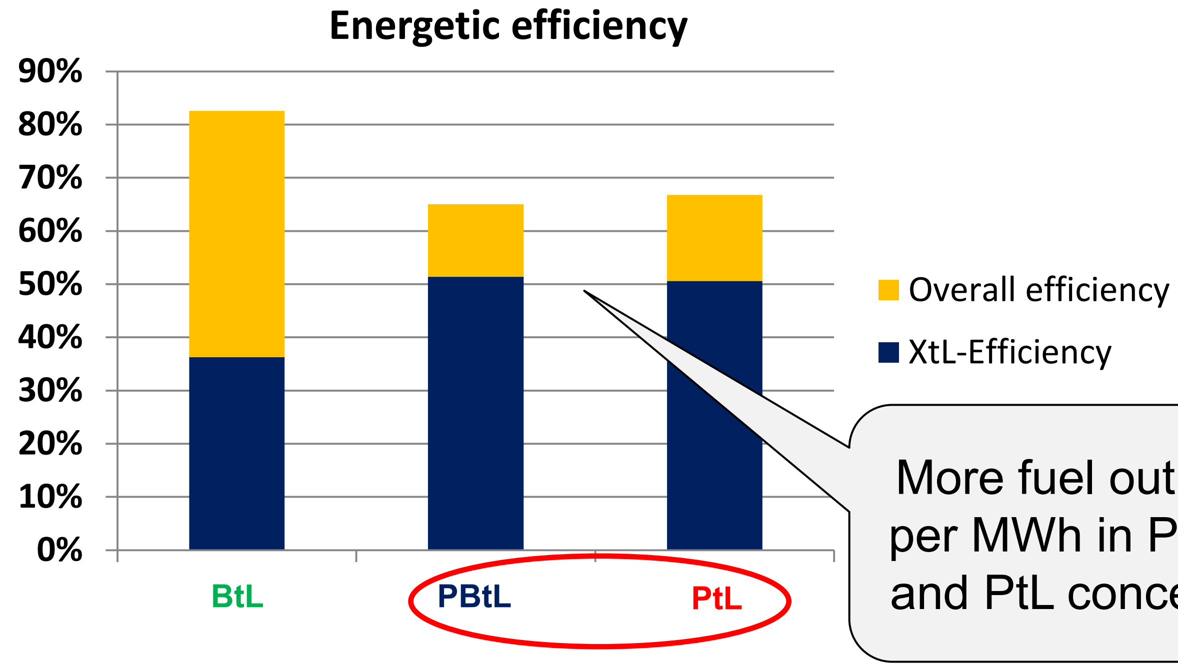
Source: F. G. Albrecht, D. H. König, N. Baucks und R. U. Dietrich, „A standardized methodology for the techno-economic evaluation of 1 alternative fuels," *Fuel,* Bd. 194, pp. 511-526, 2017.

3. Technical results: Yield, Efficiency

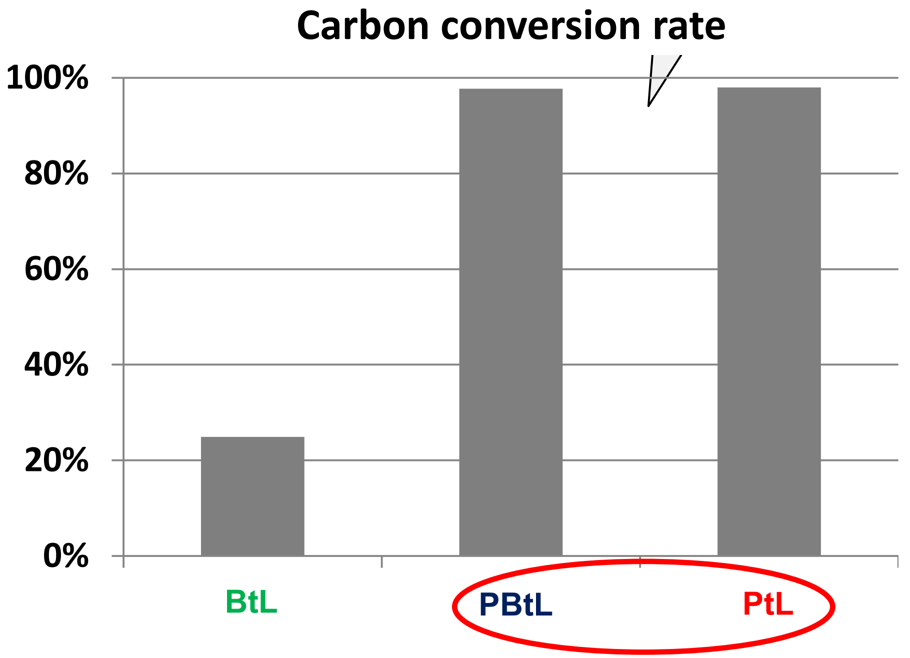
Case study equipment selection and assumptions:

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

Technical evaluation results:



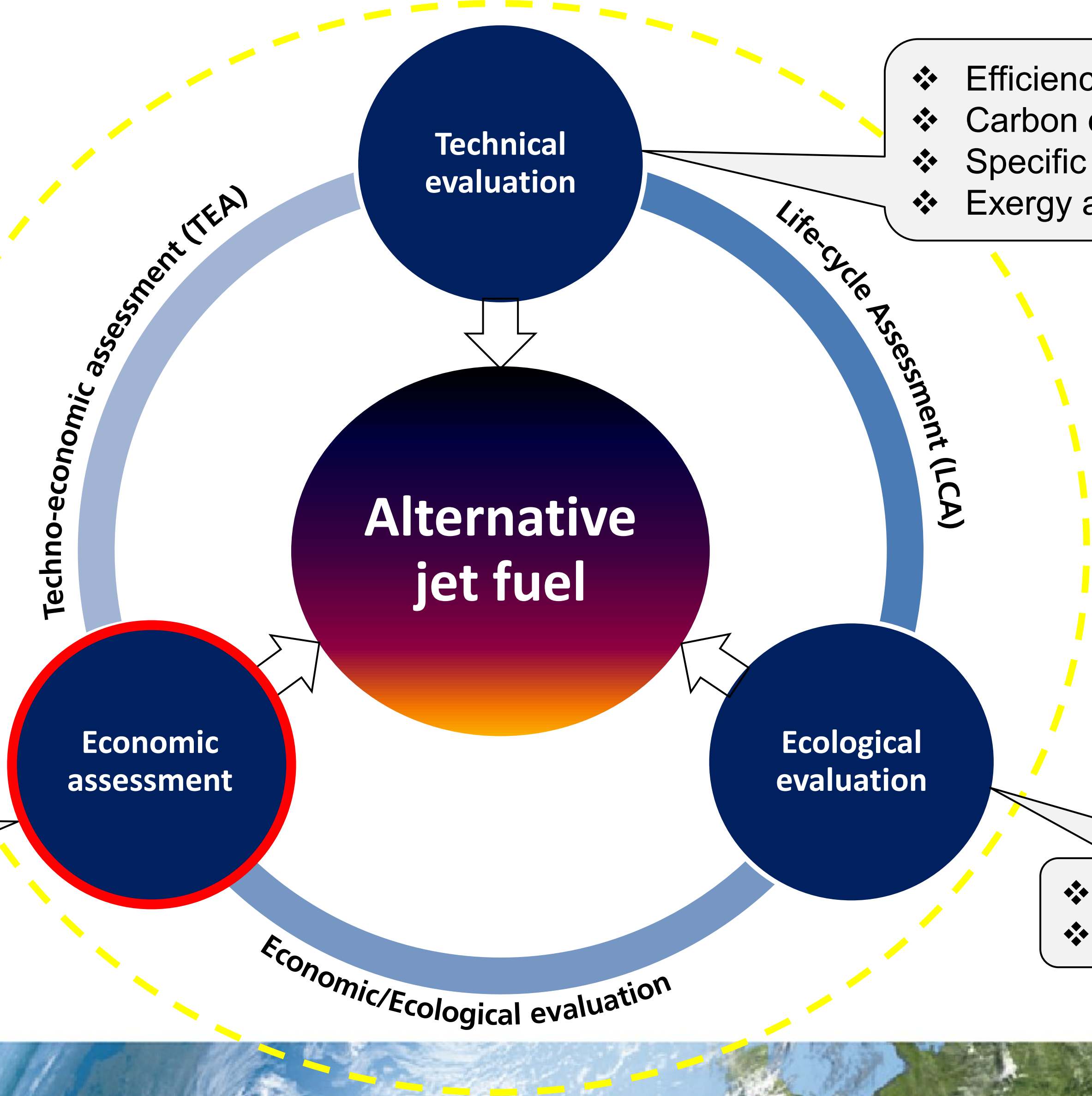
More fuel output per MWh in PBtL and PtL concept!



More fuel output per carbon unit 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. Techno-Economic and ecological assessment (TEA) of renewable jet fuel



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

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TEPET – Standardizing economic process evaluations

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

- ❖ CO_2-footprint
- ❖ CO_2-abatement costs

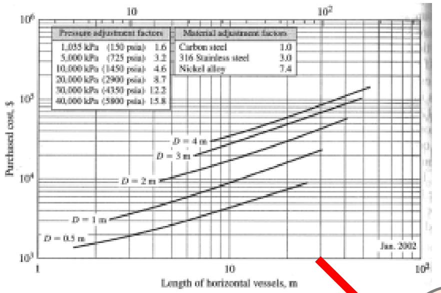
3. Methodology applied for TEA

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

Process simulation results

Plant and unit sizes

Material and energy balance



Capital costs

- Equipment costs
- Piping & installation
- Factory buildings
- Engineering services …

Direct cost factors		
Installation factor:	0.25	x Equip. cost
Instrumentation and control:	0.22	x Equip. cost
Piping system:	0.05	x Equip. cost
Electrical systems:	0.1	x Equip. cost
Buildings:	0	x Equip. cost
Yard improvments:	0	x Equip. cost
Service facilities:	0	x Equip. cost
Indirect cost factors		
Engineering and supervision:	0	x Equip. cost
Construction expenses:	0	x Equip. cost
Legal expenses:	0	x Equip. cost
Contractor's fee:	0	x D+I
Contingency:	0.1	x D+I

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TEPET – Standardizing economic process evaluations

Operational costs

- Raw materials
- Operating materials
- Maintenance
- Wages …

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Production costs
€/l , €/kg , €/MJ

3. TEA: Base Case definition

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:	**723 €/kW** [1]	(installed capacity)
Fischer-Tropsch reactor:	**95,650 €/(m³)**[2]	(Scale-factor 1)

Raw material & by-products market prices:

Electricity:	**83.7 €/MWh** [3]
CO_2:	**12.1 €/t** [4]
Oxygen (export):	**23.7 €/t** [5]
Steam (export):	**14.7 €/t** [6]

Other economic assumptions:

Base year:	2016	*Plant lifetime:*	30 years
Operating hours:	8,260 h/a	*Interest rate:*	5 %

[1] G. Saur, Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study, Technical Report NREL, 2008
[2] P. Kerdoncuff, Modellierung und Bewertung von Prozessketten zur Herstellung von Biokraftstoffen der zweiten Generation, Dissertation, KIT, Karlsruhe, 2008
[3] Eurostat, Preise Elektrizität für Industrieabnehmer in Deutschland, 2016
[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

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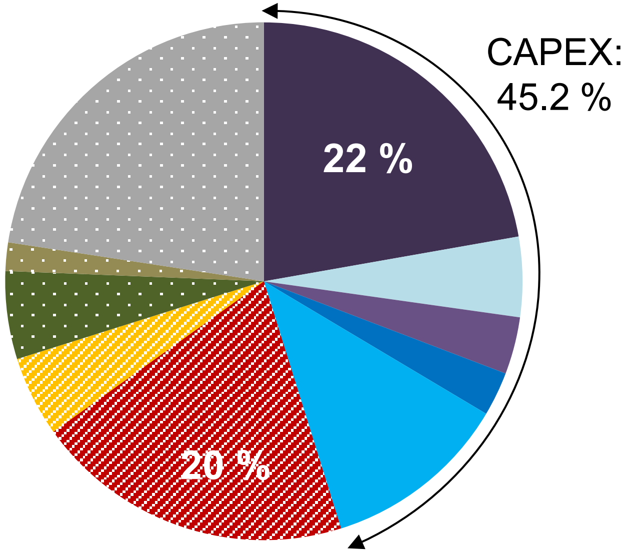
3. Results of TEA

- Electrolyzer
- Entrained flow gasification
- Pyrolysis
- Fischer-Tropsch
- Selexol
- Remaining (CAPEX)
- Power[3]
- Biomass[4]
- Remaining (Utilities)
- Maintenance
- Labor costs
- Remaining (OPEX)

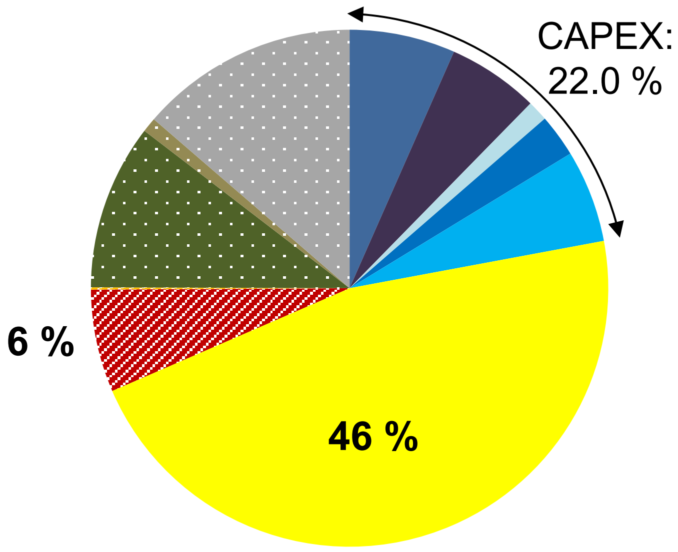
Biomass-to-Liquid (BTL)

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



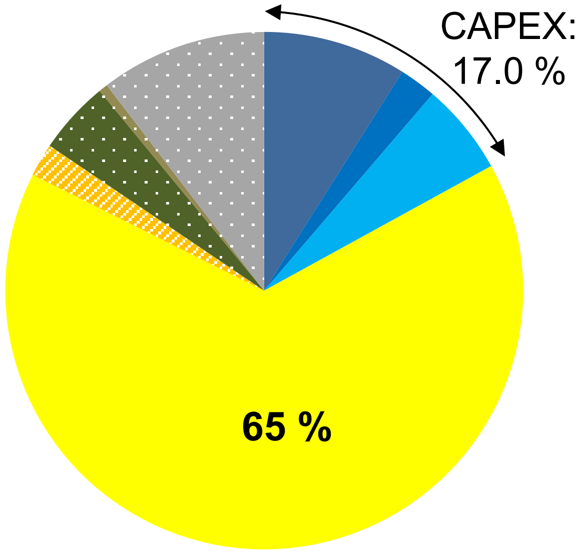
Power&Biomass-to-Liquid (PBTL)

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

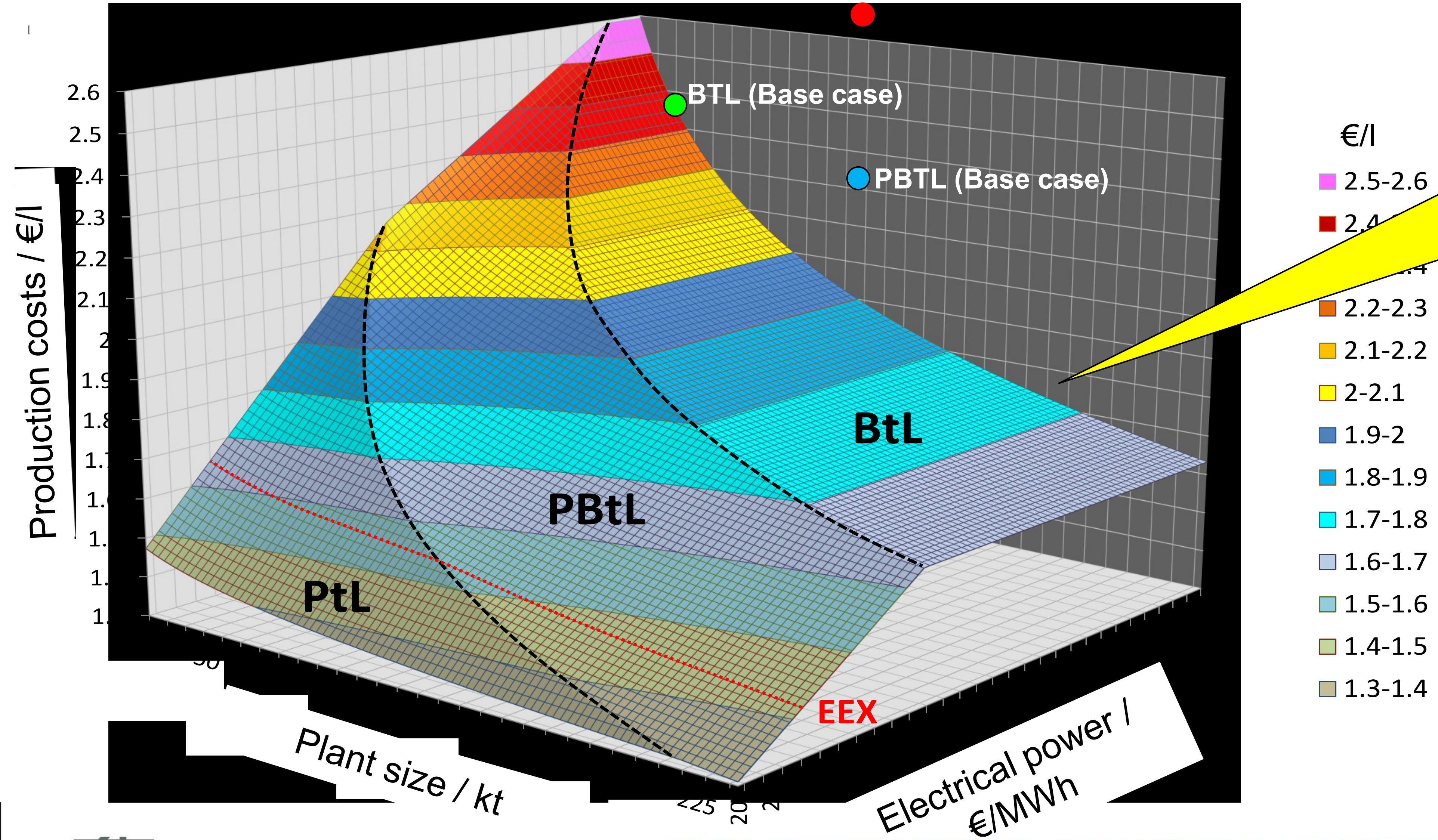


Power-to-Liquid (PTL)

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



3. Sensitivity analysis – Economy of scale and Power Price



“optimal” production concept depends on local feedstock availability/costs!

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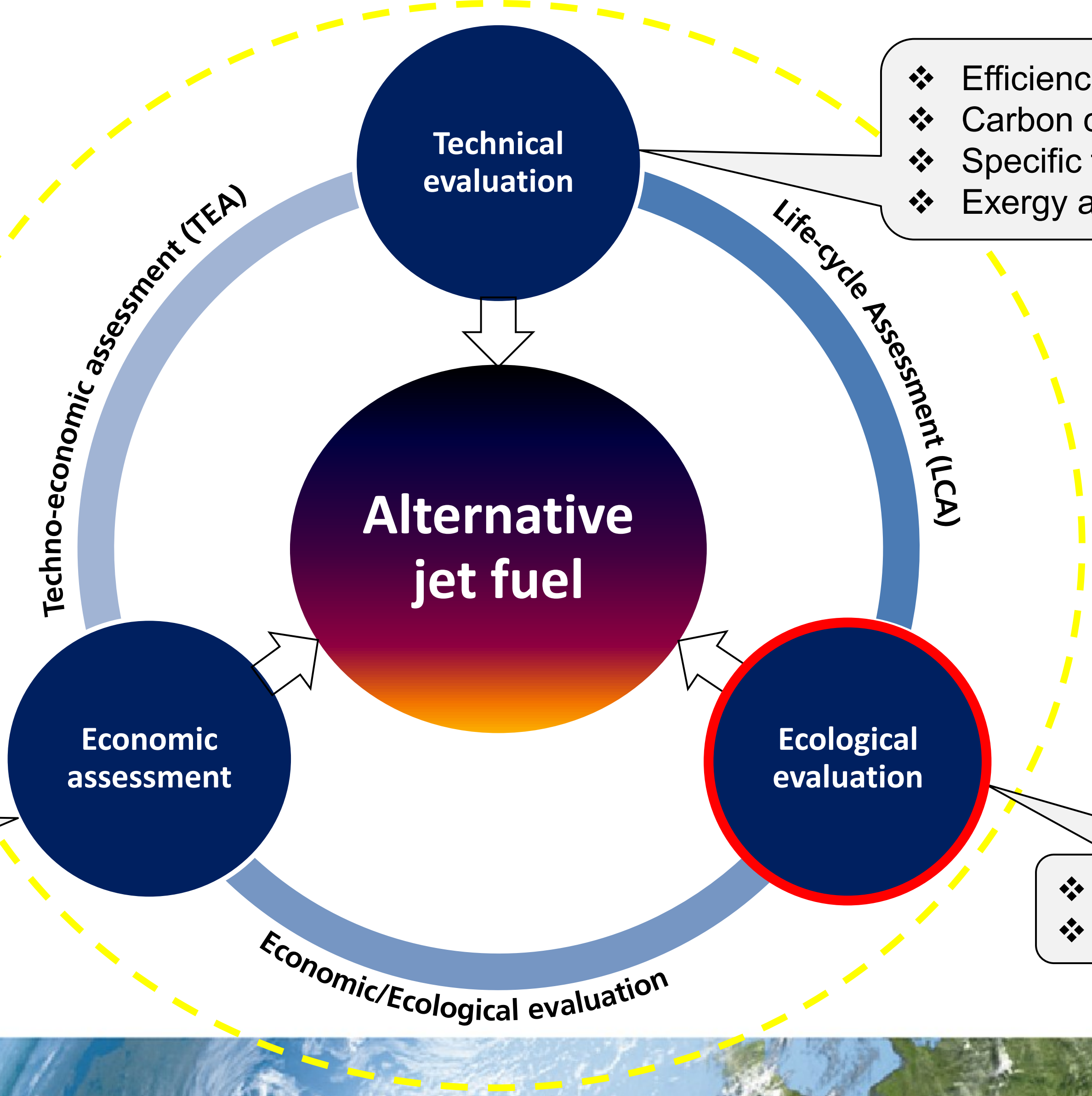

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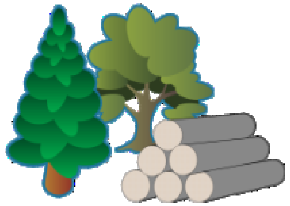
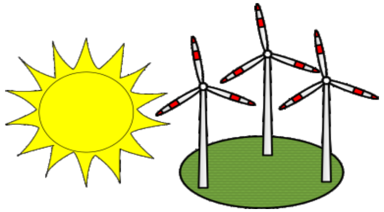
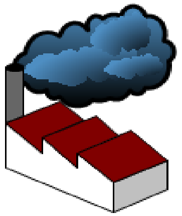
3. CO_2-Abatement Cost – Footprint of Feedstocks

	Biomass	Power	Carbon dioxide	Oxygen
				O_2
Functional unit	$[kg_{CO2eq}/t]$[a]	$[kg_{CO2eq}/MWh]$[b]	$[kg_{CO2eq}/t]$[c]	$[kg_{CO2eq}/t]$[d]
Low boundary	13.6	10	5	100
Average	134.3	272.5	77.5	250
High boundary	255	535	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.

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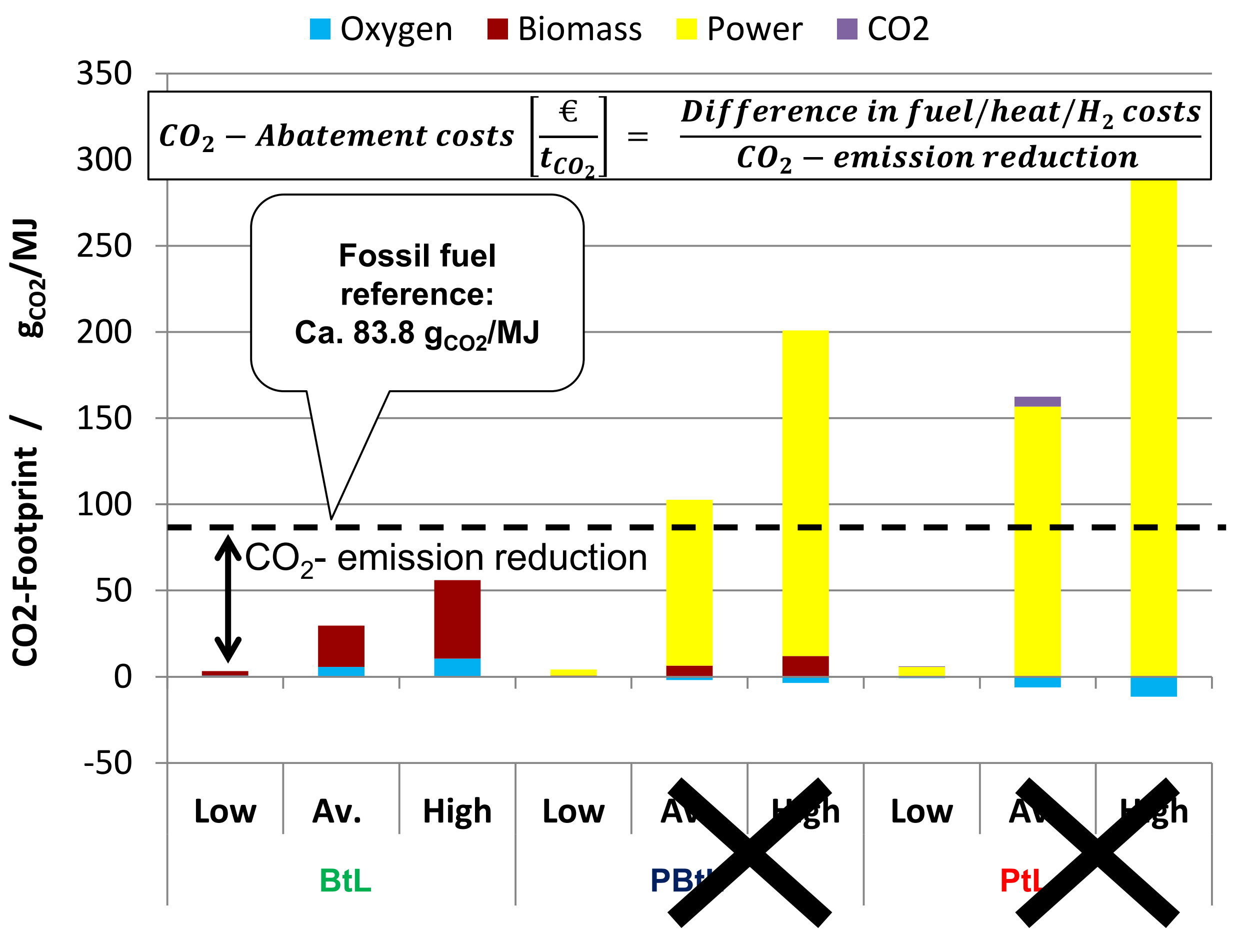
3. CO_2-Abatement Cost – Results



PtL-concepts only viable using CO_2-neutral power!

Cost comparison:

Case1 – Status Quo:

Price of fossil kerosene: ca. 0.5 €/l
Power price: 105 €/MWh
Biomass price: 100 €/t

Case2 – Pressure on Fossil Energy:

Price of fossil kerosene: ca. 1.0 €/l
Power price: 30 €/MWh
Biomass price: 60 €/t

CO_2-Abatement costs $€ / t_{CO_2}$					
Case	BtL-Low	BtL-Av.	BtL-High	PBtL-Low	PtL-Low
1	662	985	2,756	631	827
2	406	605	1,183	134	155

Current CO_2 Price of EU-ETS: **5-7 €/$t_{CO2.eq}$**

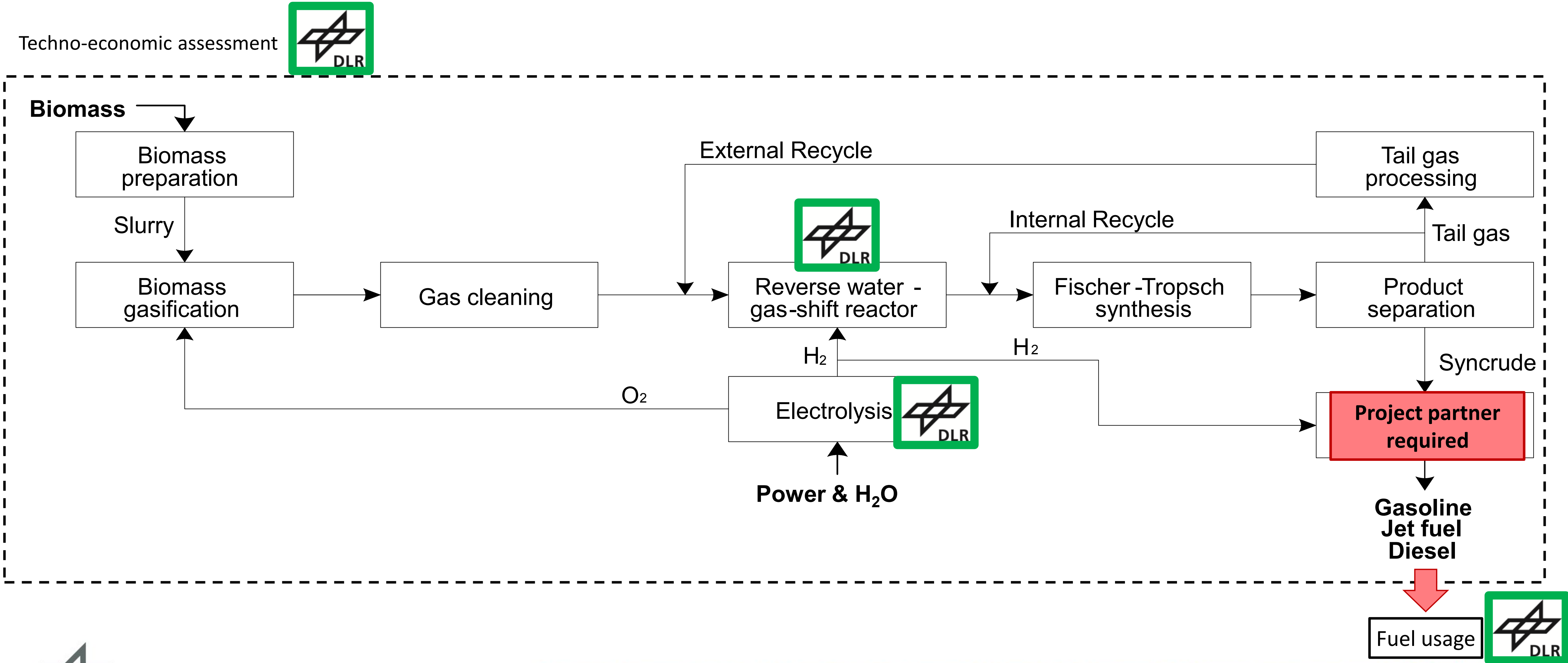
Conclusions

- 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 alterative 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



THANK YOU FOR YOUR ATTENTION!

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- Replication maintains standardisation
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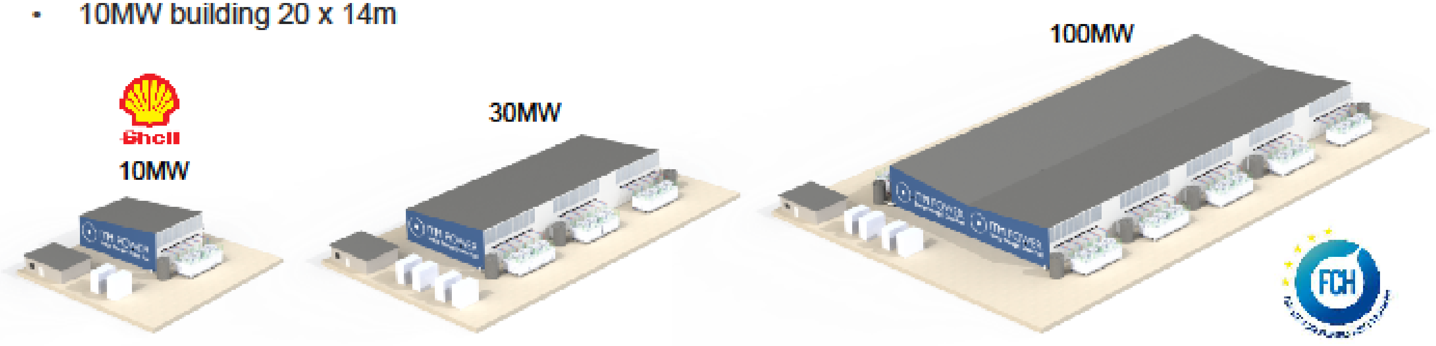

ELECTROLYSER SCALE-UP

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