6th International Conference on

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1013rd Conference

June 29-30, 2017 Madrid, Spain

Synthetic jet fuel from renewable energy sources for sustainable aviation

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German Aerospace Center (DLR e.V.)
Petroleum Engineering 2017
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DLR


Knowledge for Tomorrow

Agenda

1. **Current developments within the Aviation sector**
    - Growth rates
    - CO_2-reduction targets (IATA)
    - Expected future demand on alternative fuels

2. **“Green” jet fuel options**
    - Certified fuels by ASTM
    - Potential fuel yields for Germany/Europe
    - Introduction to Fischer-Tropsch fuels

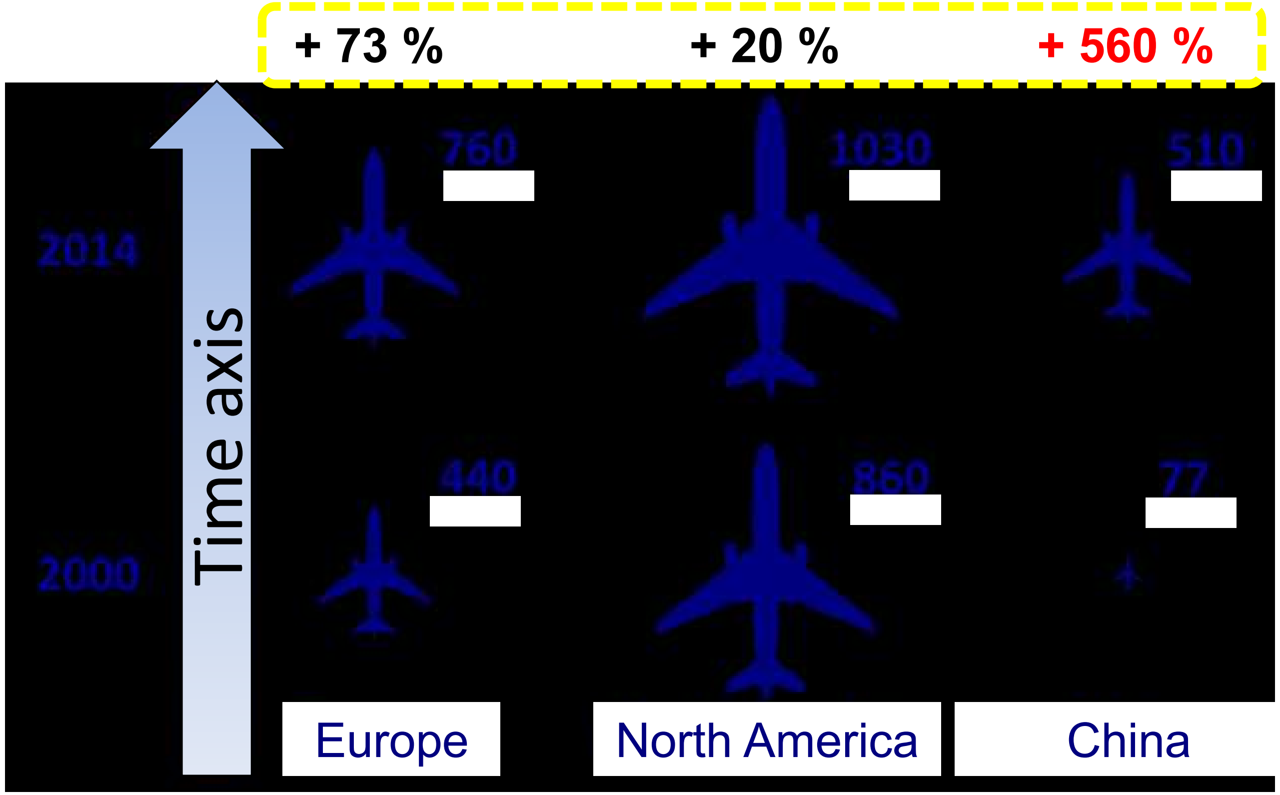
3. **Case study on green Fischer-Tropsch fuels**
    - Techno-economic evaluation
    - CO_2-Abatement costs

4. **Summary and outlook**

Growth sector aviation


Fuel for sustainable aviation

Aviation mileage within three world regions



(in billion passenger kilometers /a)

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

Political paradigm shift rises the pressure

COP21: 12.12.2015, Paris

COP21 Main agreements

- Hold global temperature increase below 2 °C
- De-carbonization of global economy in this century

Main targets: EU Roadmap 2050 – White paper

- 40% use of sustainable low carbon fuels in aviation

What does this mean for the aviation sector?

IATA Technology Roadmap

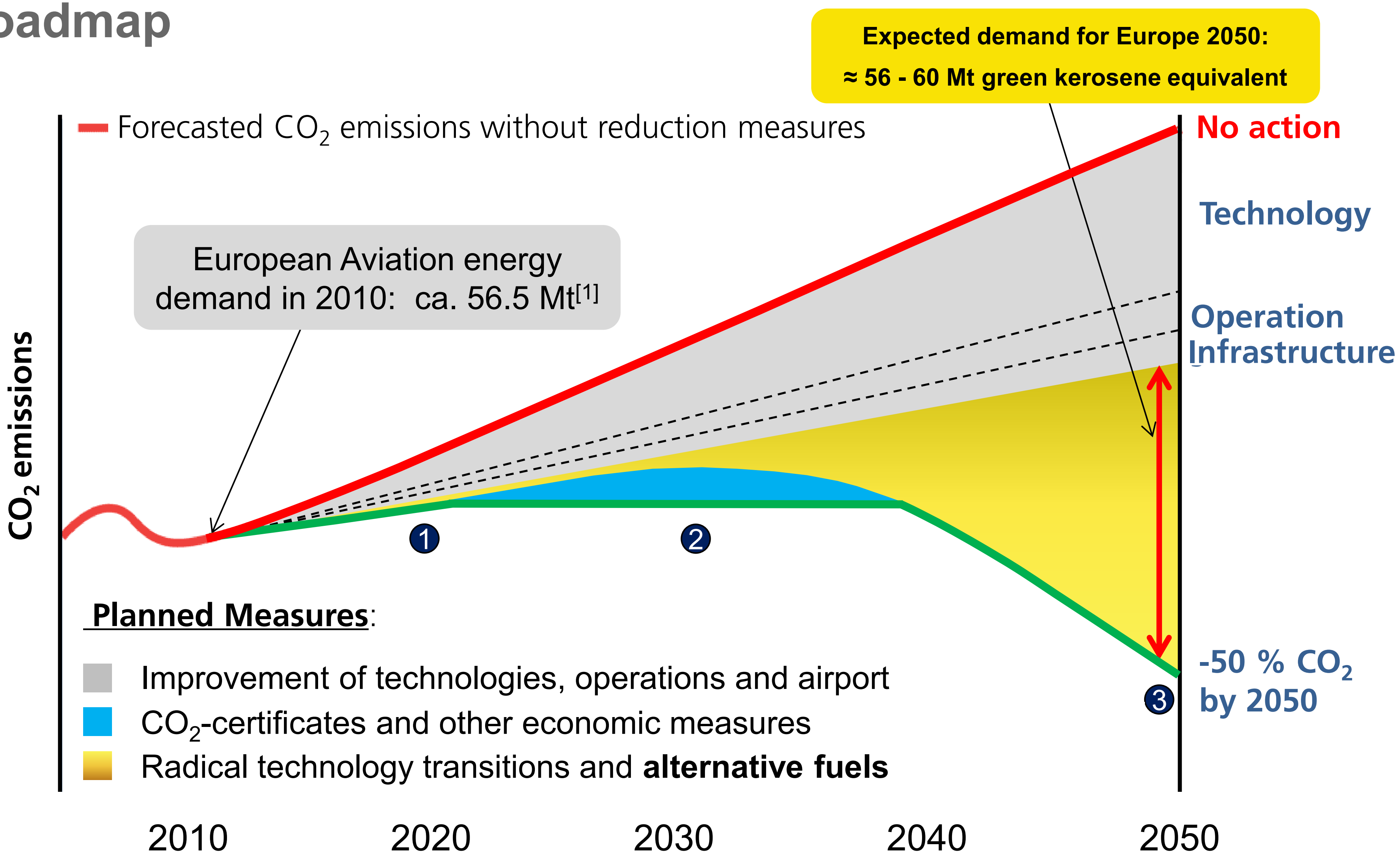
4. Edition, June 2013

Main aims:

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



Expected demand for Europe 2050:
≈ 56 - 60 Mt green kerosene equivalent

European Aviation energy demand in 2010: ca. 56.5 Mt[1]

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[1] FuelsEurope "Statistical Report" 2010

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

- AtJ in Europe (EU28)? – For example wheat

  - Wheat area$_{2014}$[2]: **26.7 Mio.ha** ➔ Ethanol yield: **2.2 t/ha**[3] (range -30 % European yield average[])
    Conversion to fuel[4]: **0.56 $t_{kerosene}/t_{ethanol}$**
    Kerosene wheat based: **23.0** to **32.9 Mt/a** (≈ 40.1 – 58.2 % of the aviation demand)

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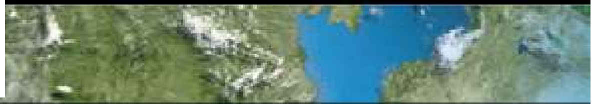
[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015
[2] Eurostat „Crop statistics“ 2014
[3] Specialist agency renewable raw materials e. V., „Introduction of fuel ethanol”, 2016
[4] NREL, „Review of Biojet Fuel Conversion Technologies”, Golden, 2016



Certified sustainable jet fuels: ASTM D7566 – 14c [1]

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- DSHC in Europe (EU28)? – For example sugar beets
  - Sugar beet area$_{2014}$[2]: **1.6 Mio.ha** ➔ sugar beet yield: **131 Mt**[2] ➔ sugar content$_{average}$ ≈ **18 %**[3]
    Conversion to fuel[4]: **0.168 $t_{kerosene}/t_{sugar}$**
    Kerosene sugar based: **3.96 Mt/a** (≈ 7.0 % of the Aviation demand)

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

Fuels for a sustanable aviation sector

Synthetic jet fuels (ASTM D7566 – 14c)[1]

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- HEFA in Europe (EU28)? – For example rape oil
  - Rapeseed area$_{2014}$[2]: **12.9 Mio.ha** ➔ rape yield: **24.1 Mio.t** ➔ oil content$_{average}$ ≈ **42 %**[3]
    Conversion to fuel[4]: **0.49 t$_{kerosene}$/t$_{rape\ oil}$**
    Kerosene sugar based: **7.3 Mio.t/a** (≈ 12.9 % of the Aviation demand)

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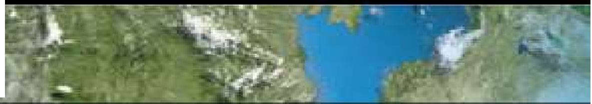
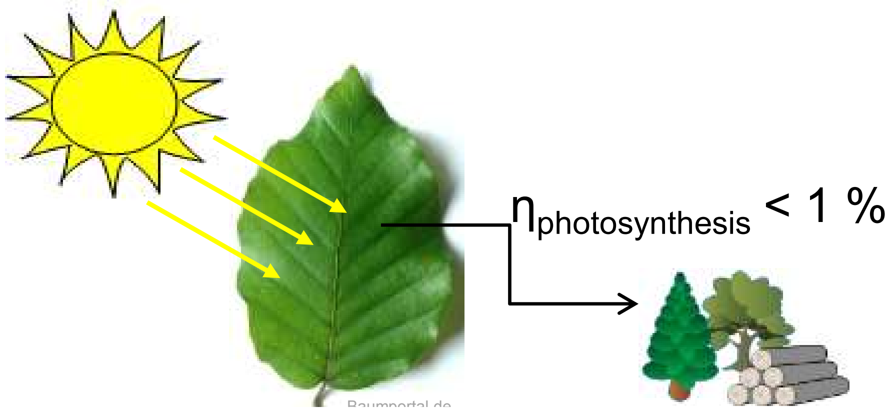
[1] ASTM International, „ASTM D7566 - 14C: Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons“, 2015
[2] Eurostat „Crop statistics“ 2014
[3] UFOP “Rapeseed the Power Plant“ 2017
[4] DBFZ, „Abschlussbericht Projekt BurnFAIR”, 2014



Biomass potential from agricultural products in Europe

Kerosene from	Production [Mt/a]	[%]	Cultivation area [Mha]	EU28 [%]
Wheat	23.0 – 32.9	40.1 – 58.2	26.7[1]	30.2
Sugar	3.9	7.0	1.6[1]	1.8
Rapeseed	7.3	12.9	12.9[1]	13.3
Σ	34.3 – 44.2	60.7 – 78.2	39.9	45.2

- Direct competition to food markets
- Ineffective conversion of sun light to biomass



$\eta_{photosynthesis} < 1\ \%$

Baumportal.de

[1] Eurostat „Crop statistics“ 2014

Fuels for a sustanable aviation sector

Synthetic jet fuels (ASTM D7566 – 14c)[1]

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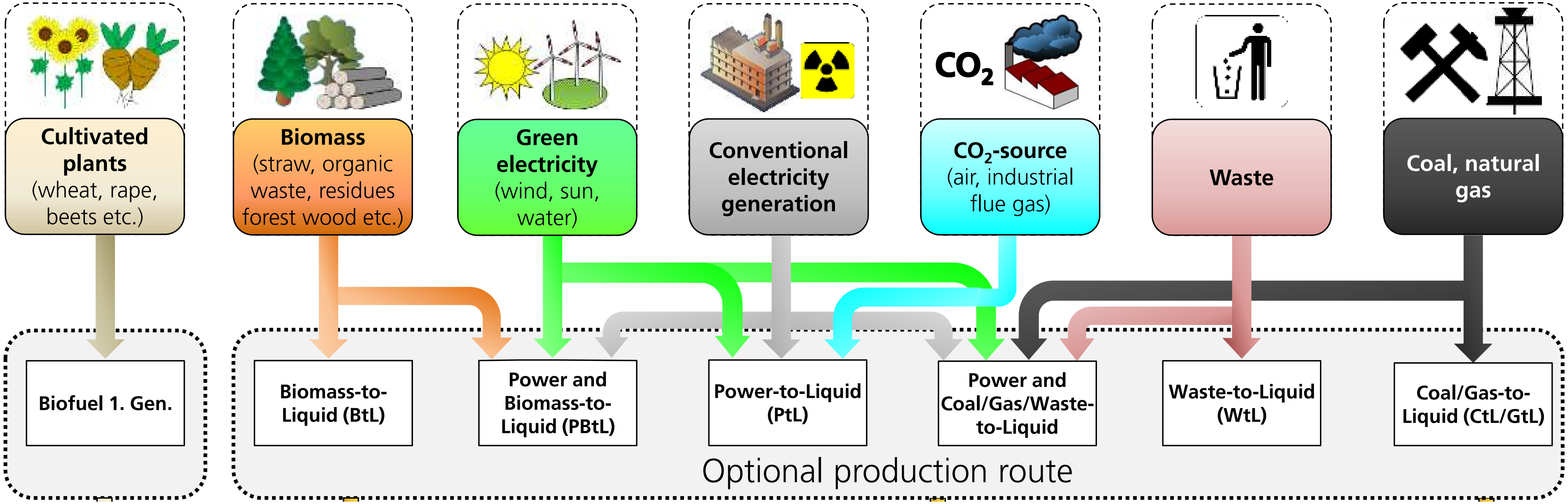
Fischer-Tropsch synthesis

- Large scale, commercial technology
- Based on synthesis gas, which can be produced from almost any carbon and hydrogen source
- Fully synthetic kerosene achievable[2]

[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.

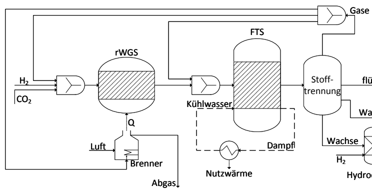
Production routs of alternative Kerosene

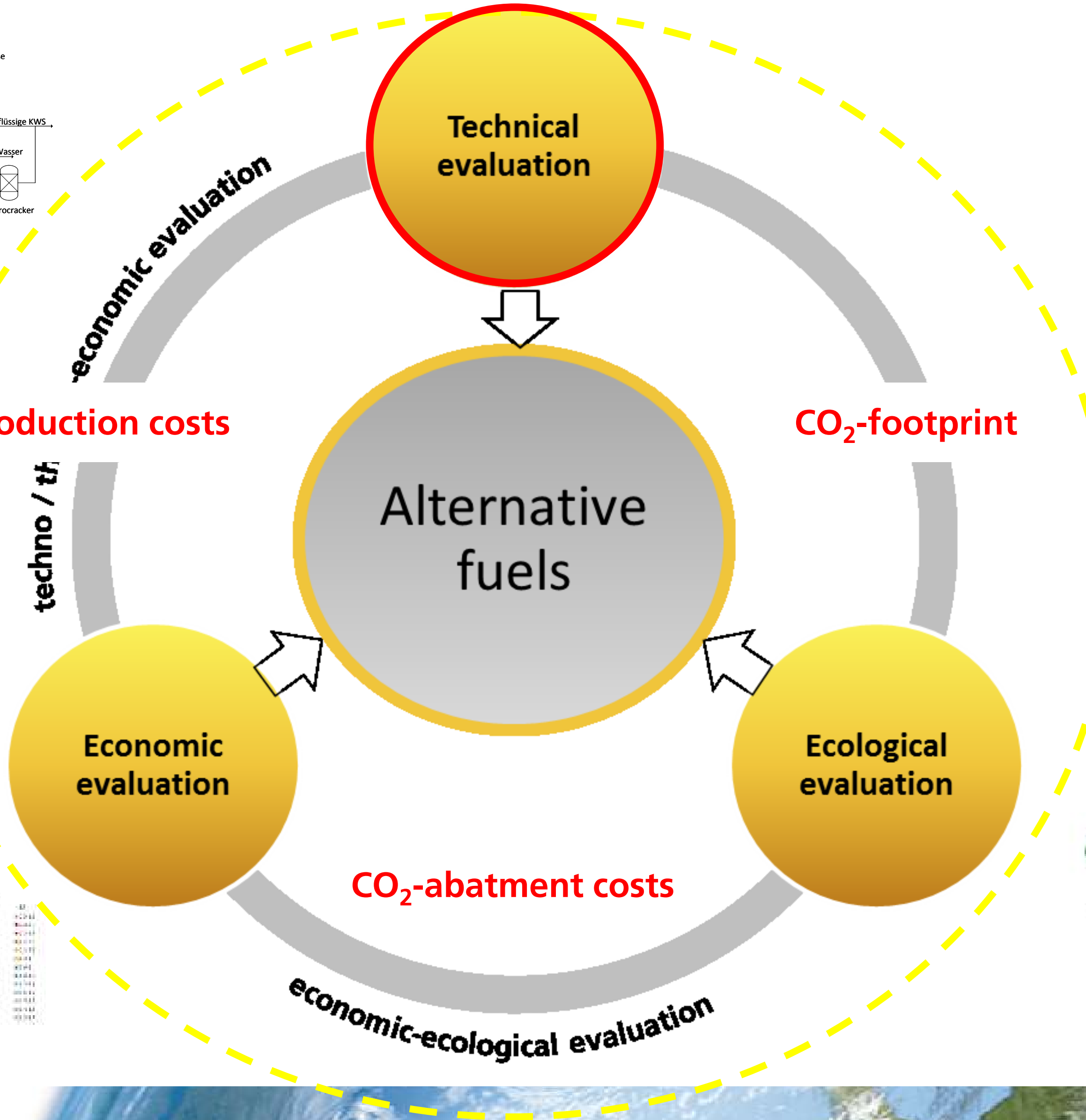
- Low CO$_2$ footprint
- Too large raw material potential



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

2. Applied methodology for fuel evaluation

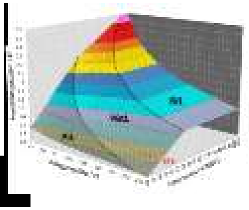




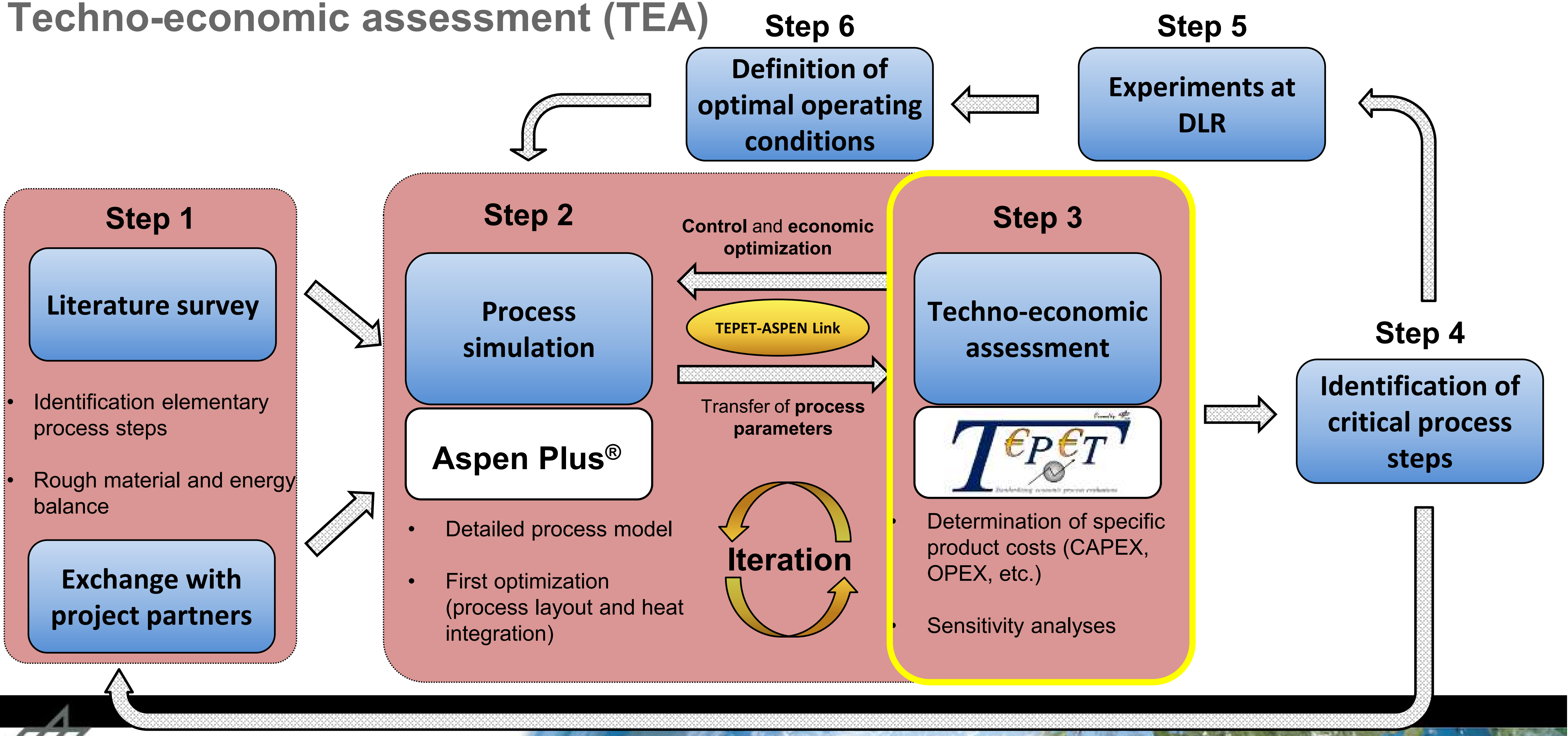
DLR-Sfotwaretool:

TEPET
Powered by DLR
Standardizing economic process evaluations

Results calculated with TEPET:



Techno-economic assessment (TEA)



Step 1

Literature survey

- Identification elementary process steps
- Rough material and energy balance

Exchange with project partners

Step 2

Process simulation

Aspen Plus®

- Detailed process model
- First optimization (process layout and heat integration)

Control and **economic optimization**

TEPET-ASPEN Link

Transfer of **process parameters**

Iteration

Step 3

Techno-economic assessment

- Determination of specific product costs (CAPEX, OPEX, etc.)
- Sensitivity analyses

Step 4

Identification of critical process steps

Step 5

Experiments at DLR

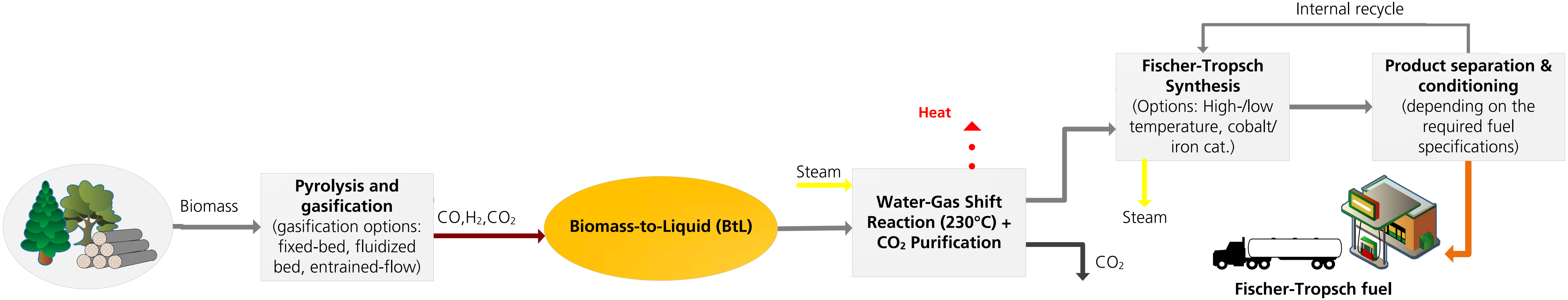
Step 6

Definition of optimal operating conditions

Investigated Fischer-Tropsch concepts

-From biomass (Biomass-to-Liquid, BtL)

Syngas supply | **Syngas conditioning** | **Fuel synthesis**



Internal recycle

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.)

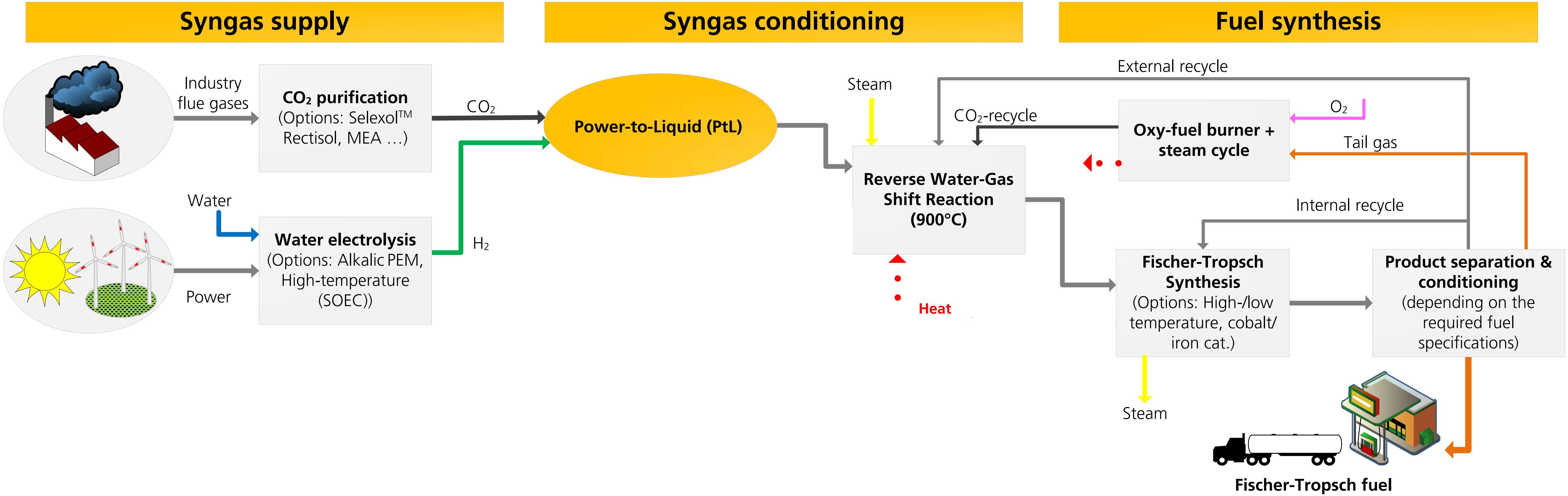
Steam

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

Fischer-Tropsch fuel

Investigated Fischer-Tropsch concepts

-From power and CO_2 (Power-to-Liquid, BtL)



Syngas supply

Syngas conditioning

Fuel synthesis

Industry flue gases

CO_2 purification
(Options: Selexol™ Rectisol, MEA …)

CO_2

Water

Power

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

H_2

Power-to-Liquid (PtL)

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.)

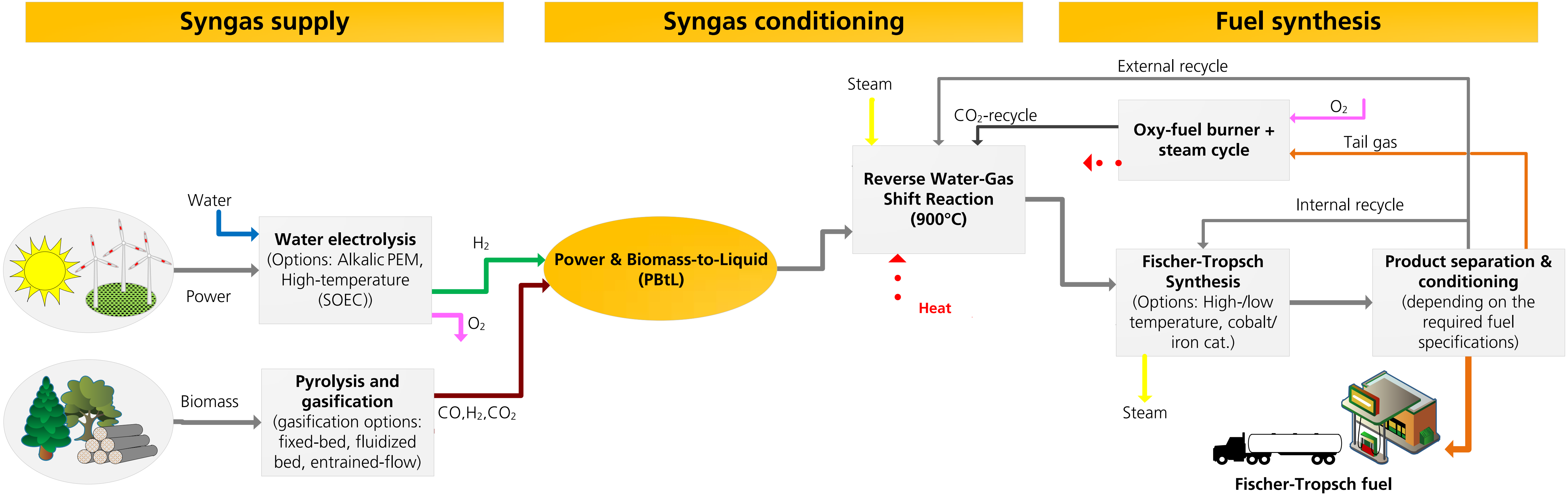
Steam

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

Fischer-Tropsch fuel

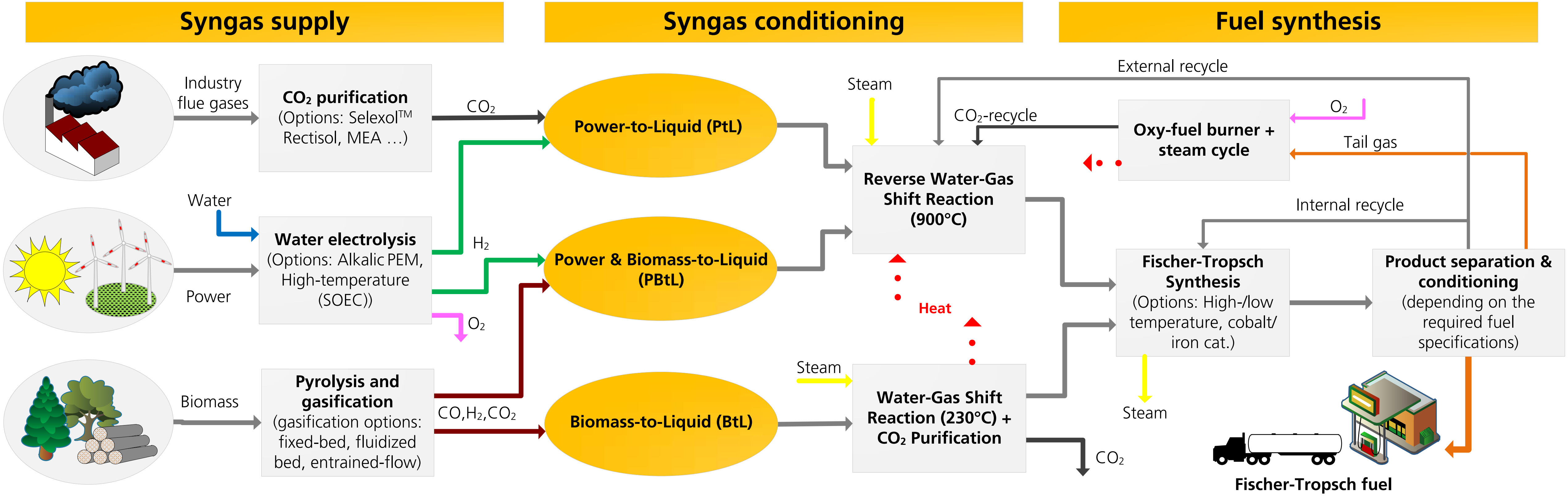
Investigated Fischer-Tropsch concepts

-From power and biomass (Power&Biomass-to-Liquid, BtL)



Investigated Fischer-Tropsch concepts

Overview of concepts



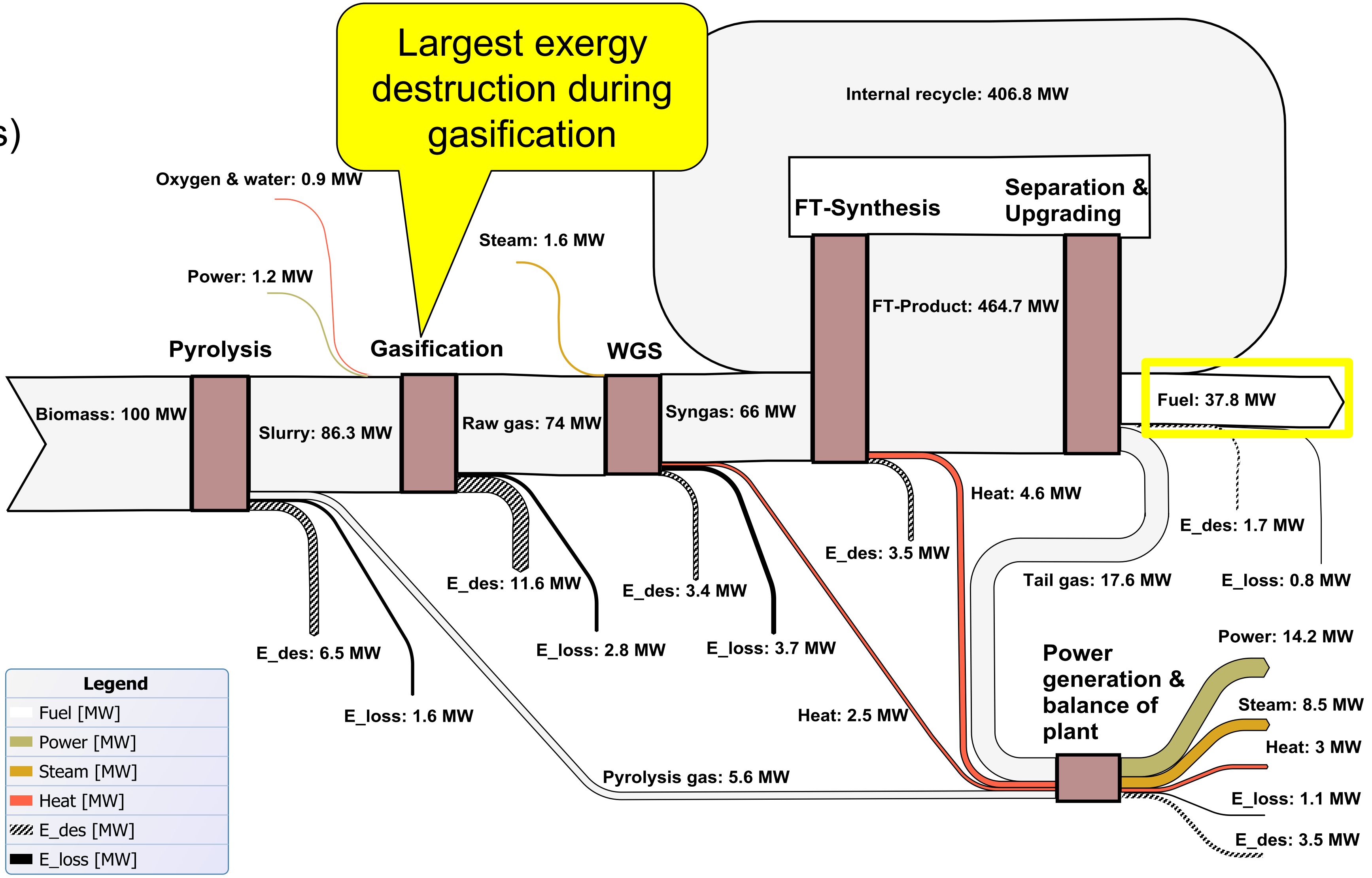
<u>More information available in recent publication:</u>

F. G. Albrecht, D. H. König, N. Baucks und R. U. Dietrich, „A standardized methodology for the techno-economic

Exergy flows - Biomass-to-Liquid

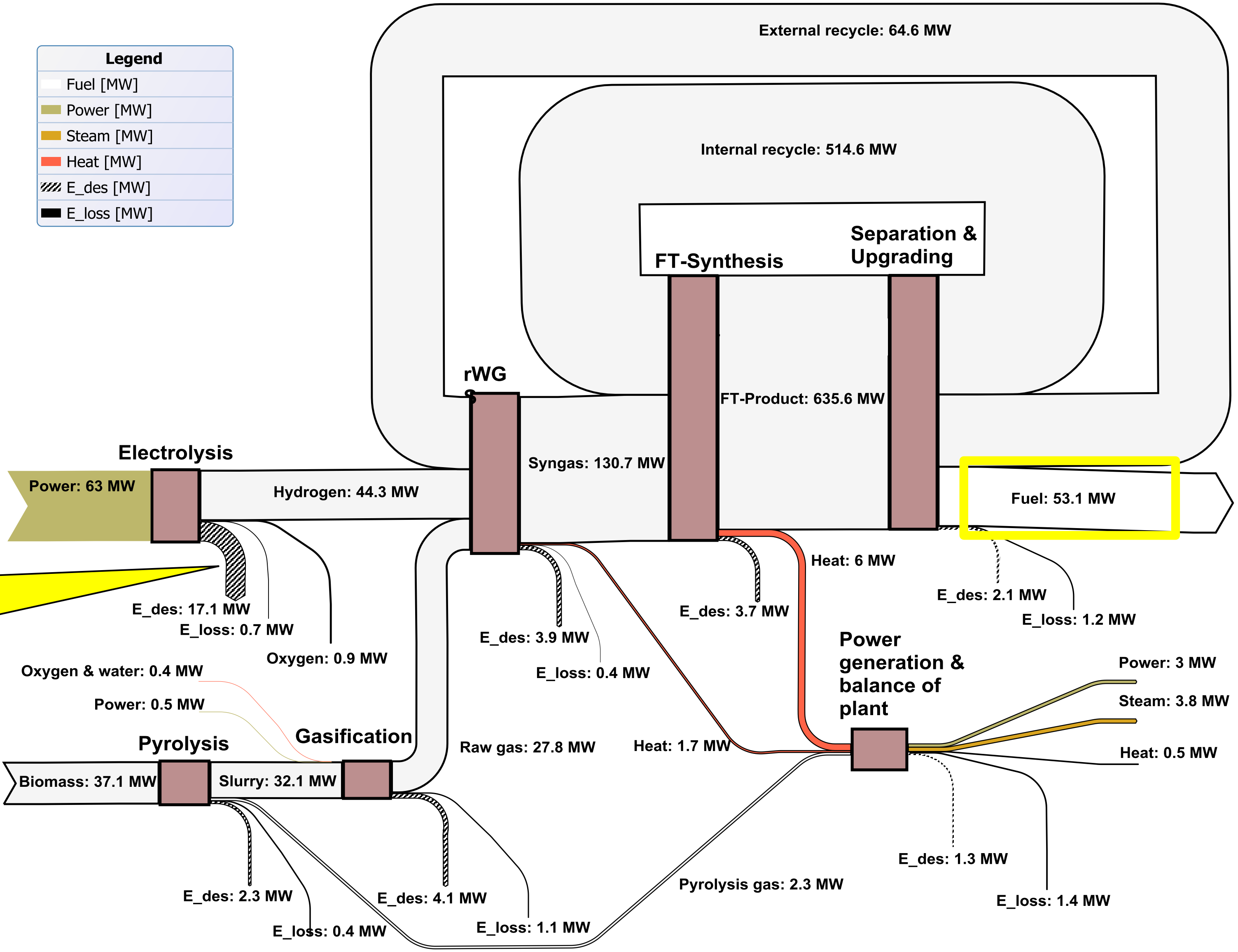
Exergy input:
100 MW (Biomass)

Largest exergy destruction during gasification



Exergy flows - PBtL

Exergy input:
37 MW (Biomass)
63 MW (Power)



Largest exergy destruction during electrolysis!

Technical process assessment

Case study equipment selection and assumptions:

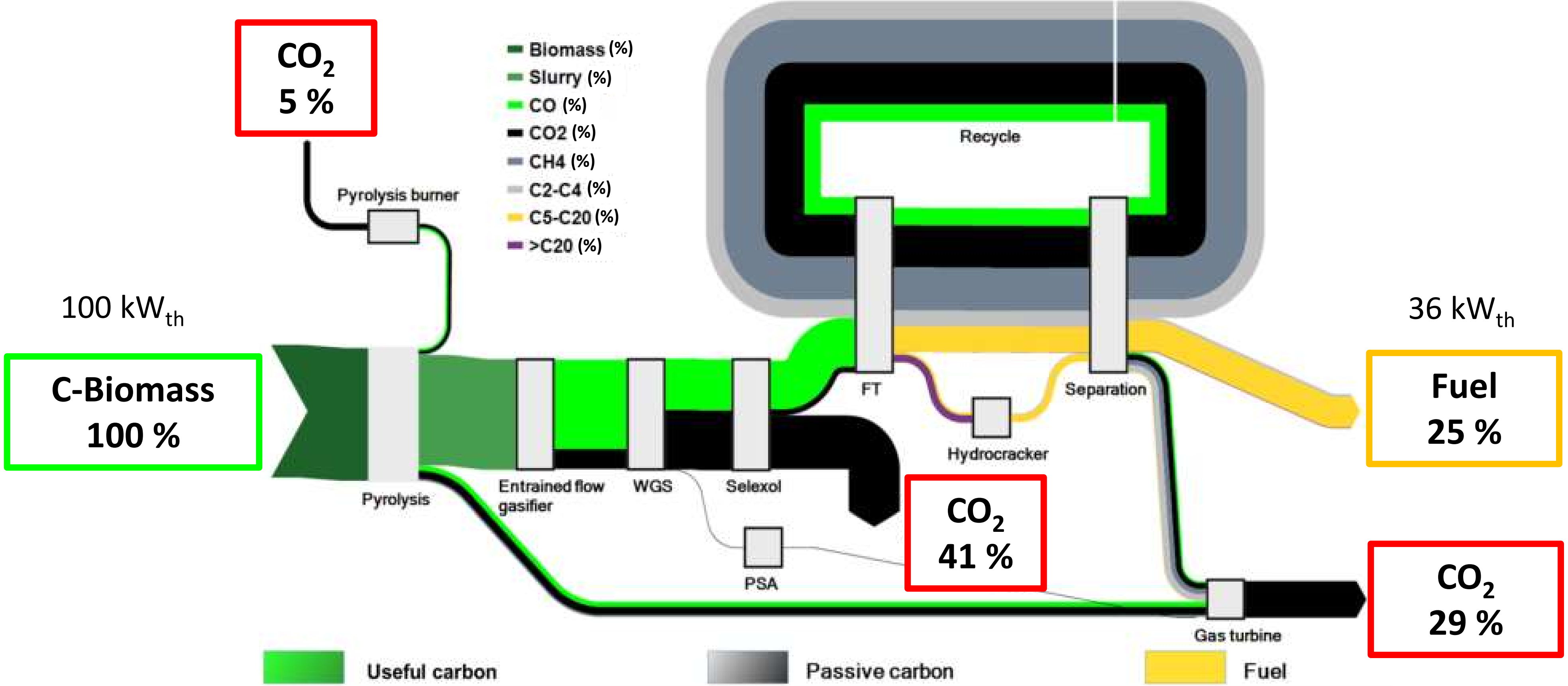
- Proton exchange membrane electrolyzer (PEM), η = 4.3 kWh/Nm³ [1]
- Entrained flow gasifier, T = 1200 °C, p = 30 bar, pure O_2 [2]
- Fischer-Tropsch synthesis, T = 225 °C, p = 25 bar, α = 0.85, X_{CO} = 40 % [3]

Process parameter	BTL	PBTL	PTL
Energy efficiency η_{XTL}	36.3 %	51.4 %	50.6 %
Power consumption	- 4.2 kWh/kg_{fuel}	15.8 kWh/kg_{fuel}	24.4 kWh/kg_{fuel}
Biomass/CO_2 demand	7.5 kg_{BM}/kg_{fuel}	2.0 kg_{BM}/kg_{fuel}	3.1 kg_{CO2}/kg_{fuel}
Carbon efficiency η_C	24.9 %	97.7 %	98.0 %

- BTL fuel yield can be increased **by the factor 3 – 4 by the PBTL** concept
- Approximately full carbon conversion for PBTL and PTL applying oxy-fuel combustion and recycle concept
- PBTL XTL-efficiency comparable high as for PTL with reduced power consumption

[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.

Biomass-to-Liquid – Carbon flow diagram



CO_2
5 %

100 kW_{th}

C-Biomass
100 %

CO_2
41 %

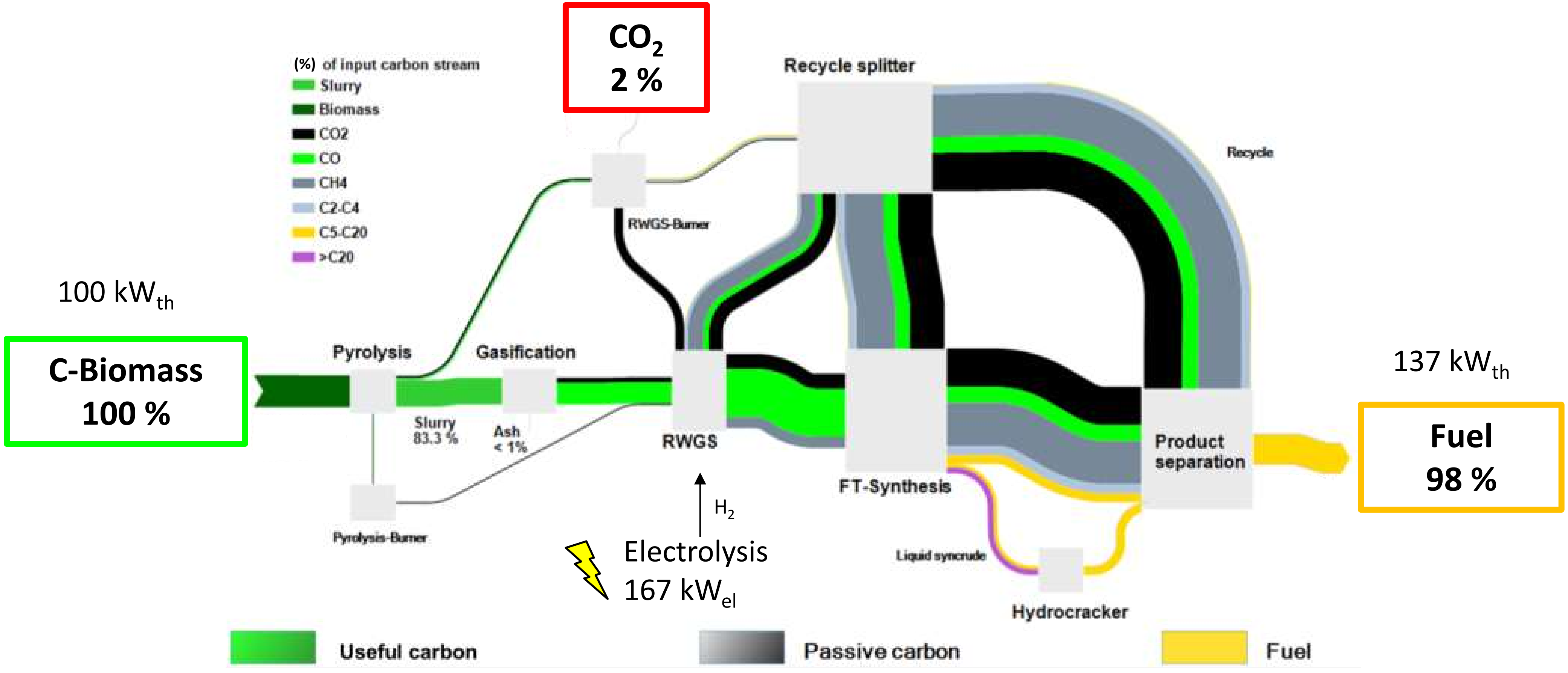
36 kW_{th}

Fuel
25 %

CO_2
29 %

75 % of biomass carbon lost as CO_2

Power&Biomass-to-Liquid – Carbon flow diagram



CO_2
2 %

100 kW_{th}

C-Biomass
100 %

137 kW_{th}

Fuel
98 %

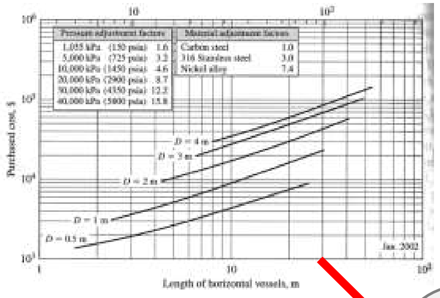
H_2

Electrolysis
167 kW_{el}

98 % of biomass carbon used in fuel

Methodology applied for TEA

Meets AACE class 3-4
Accuracy: **+/- 30 %**



Direct cost factors		
Installation factor	[illegible]	[illegible]
Instrumentation and control	[illegible]	[illegible]
Piping system	[illegible]	[illegible]
Electrical systems	[illegible]	[illegible]
Buildings	[illegible]	[illegible]
Yard improvements	[illegible]	[illegible]
Service facilities	[illegible]	[illegible]
Indirect cost factors		
Engineering and supervision	[illegible]	[illegible]
Construction expenses	[illegible]	[illegible]
Legal expenses	[illegible]	[illegible]
Contractor's fee	[illegible]	[illegible]
Contingency	[illegible]	[illegible]

Process simulation results

Plant and unit sizes

material and energy balance

Aspen Plus®

TEPET-ASPEN Link

Capital costs

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

Operational costs

- **Raw materials**
- **Operating materials**
- **Maintenance**
- **Wages …**

Production costs
€/l , €/kg , €/MJ

Assumptions dictate results of TEA

Plant size: **100 MW_{th} (Biomass input LHV)**

Investment costs:

PEM-Elektrolyszer:	**640** €/kW [1]	(installed capacity)
Entrained flow gasification:	**103.650** €/(kg_{Slurry}/h) [2]	(scale-factor 0.7)

Raw material prices:

Power:	**105** €/MWh [3]	(industrial consumer)
Biomass (35% moisture):	**97.4** €/t [4]	

General economic assumptions:

Reference year:	2014	*System operation:*	30 a
Operating hours:	8,260 h/year	*Capital interest:*	7 %

[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, Êlectricity prices for industrial consumer, 2014

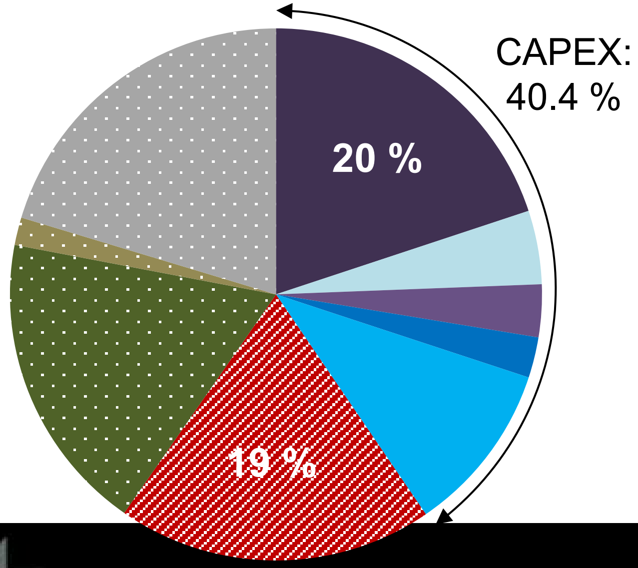
Comparison of Costs BTL / PBTL / PTL

Plant size: 100 MW_{th}

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

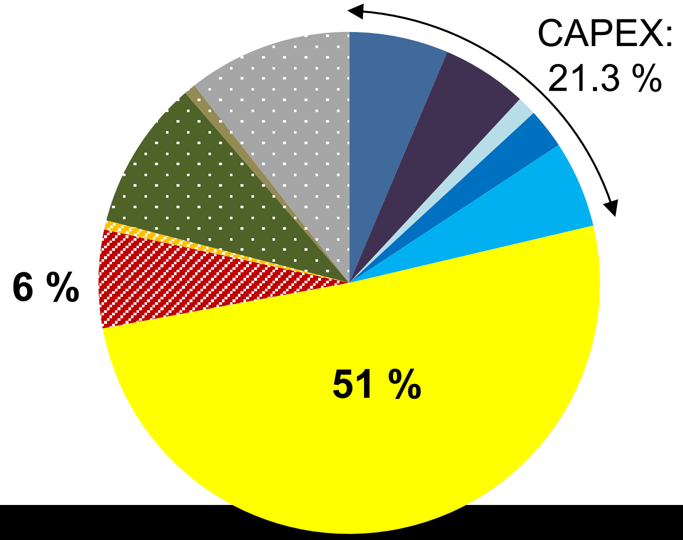
Biomass-to-Liquid (BTL)

Investment:	ca. 395.2 mio. €
Fuel production:	24.17 Mt
Fuel costs:	ca. **2.34 €/l**



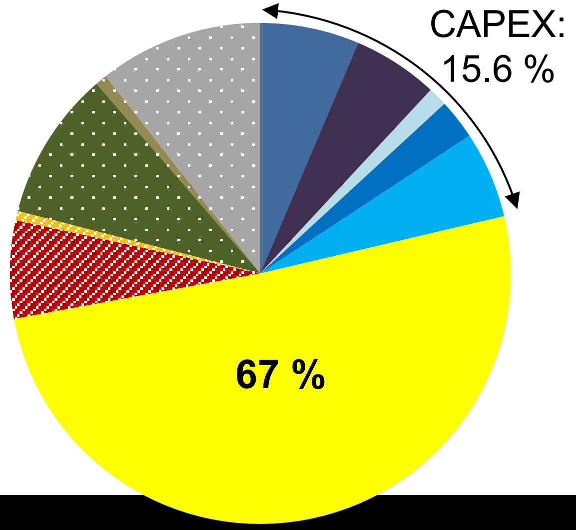
Power&Biomass-to-Liquid (PBTL)

Investment:	ca. 751 mio. €
Fuel production:	91.27 Mt
Fuel costs :	ca. **2.24 €/l**

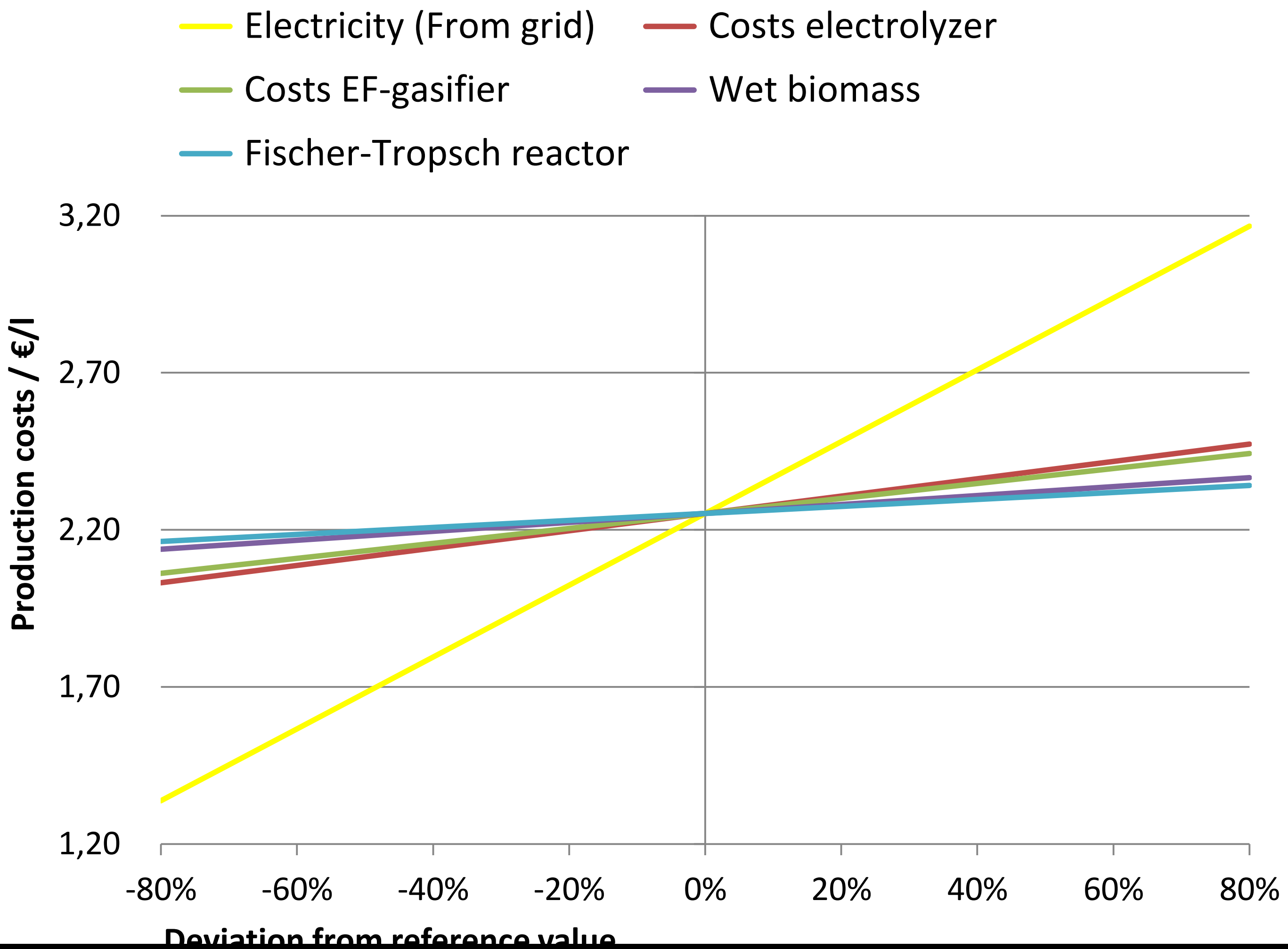


Power-to-Liquid (PTL)

Investment:	ca. 672.5 mio. €
Fuel production:	91.27 Mt
Fuel costs :	ca. **2.74 €/l**

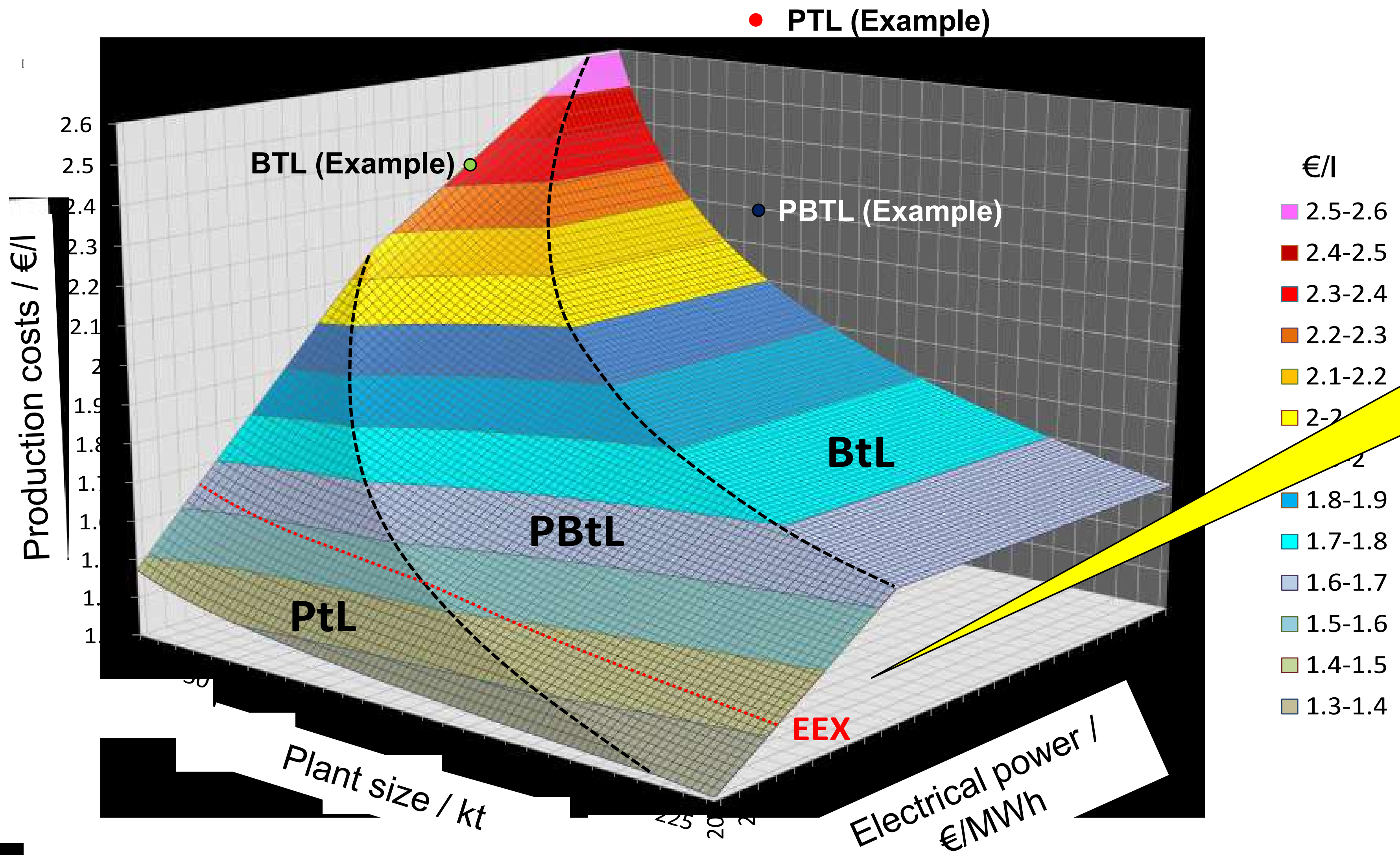


Sensitivity analysis for PBTL



- OPEX are the main cost driver for PBTL
- Power price mostly defines the net production costs
- Minor influence of CAPEX

Techno-economic assessment

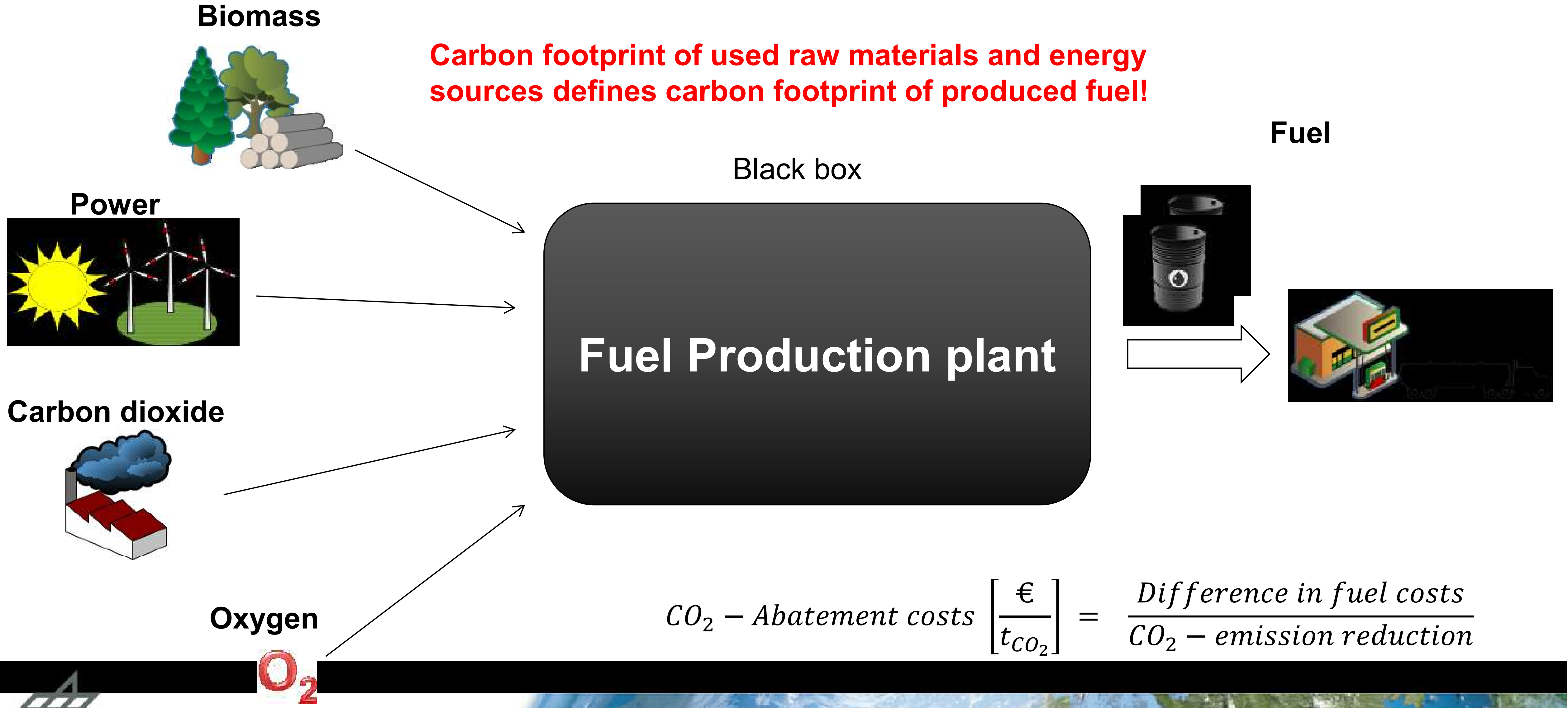


“optimal” production concept depends on boundary conditions!

- Cost-efficient fuel production depends mainly on the boundary conditions e.g. plant size and power price

CO_2-Footprint - Methodology

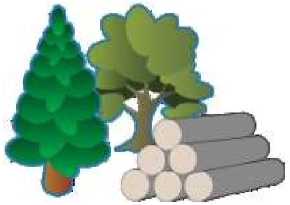
Carbon footprint of used raw materials and energy sources defines carbon footprint of produced fuel!



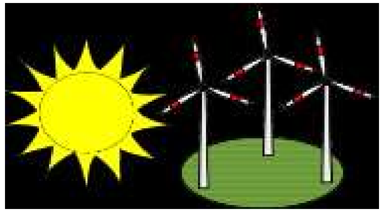
$$CO_2 - \text{Abatement costs}\left[\frac{€}{t_{CO_2}}\right] = \frac{\text{Difference in fuel costs}}{CO_2 - \text{emission reduction}}$$

CO_2 Footprint – Basics

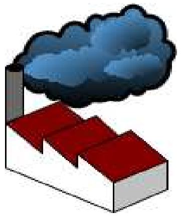
Biomass



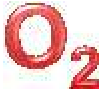
Power



Carbon dioxide



Oxygen



	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	10	5	10
Average	134.3	272.5	77.5	75
High boundary	255	535	150	140

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

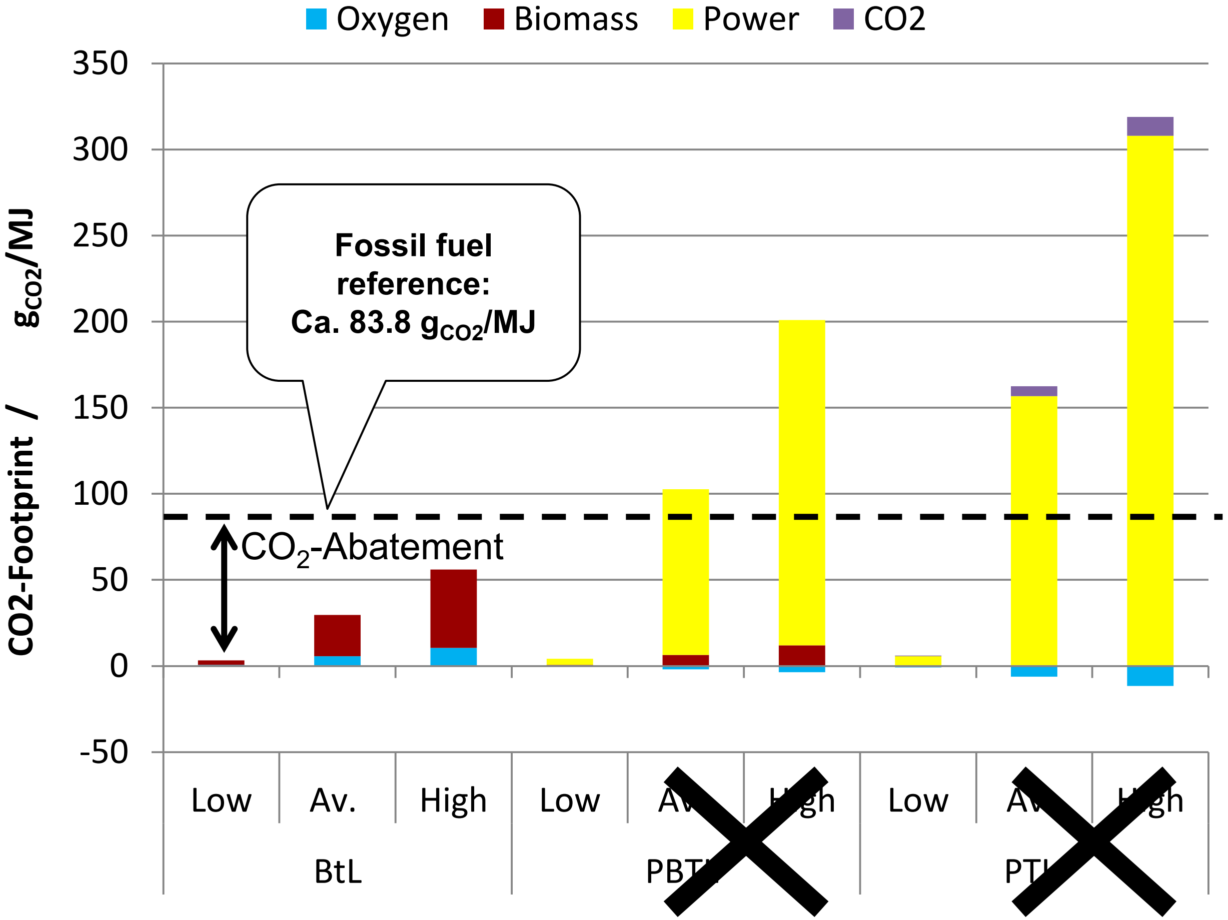
[b] Low boundary value for pure wind electricity taken from [1]. High value corresponds to the actual CO_2-footprint of the German electricity sector [2].

[c] Representing emissions arising from sequestration of CO_2 from flue gas (cement industry and coal fired power plants). The probably fossil nature of the flue gas was not taken into account. Low/high value: energy demand of CO_2-sequestration is covered with wind energy/German electricity mix.

[d] 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.

CO_2 Footprint – Calculation



PtL-concepts only viable when using renewable power!

CO_2-Abatement costs:

Case1:
Price of fossil kerosene: ca. 0.5 €/l
Power price: 105 €/MWh
Biomass price: 100 €/t

Case2:
Price of fossil kerosene: ca. 1 €/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	2756	631	827
2	406	605	1183	134	155

Current Price of CO_2 - European Emission Allowances:
ca 5 €/t

Required: Feedstock shift for sustainable aviation

- European jet fuel consumption (2010)
  ca. 56.5 Mt/a
- EU target (2050):
  40 % sustainable low carbon fuels
- Expected "green" jet fuel demand in 2050:
  55-60 Mt/a

Six fully "green" refineries!

Just for aviation!!

Raw materials and energy requirements for 60 Mt/a of green jet fuel:

Demand	Unit	BtL	PBtL	PtL
Power[a]	TWh	-	890	1450
CO_2[c]	Mt	-	-	186

To be compared with:

[a] Total produced renewable electricity in EU (2015): **930 TWh[1]**
Expected development potential wind: **≈ 40,000 TWh[2]**

[b] Total bioenergy consumption in EU (2014): **105.5 Mt[3]**
Expected wood potential (2030 EU): **146 Mt[4]**

[c] Total $CO_{2,eq.}$ emissions (2015 EU): **4,451.1 Mt[5]**

[1] Eurostat database, "online data codes: nrg_105a and tsdcc330," 2017
[2] EEA Technical report, "Europe's onshore and offshore wind energy potential", No 6/2009
[3] AEBIOM „Statistical Report 2016 - Key findings"
[4] European Commission, Agriculture and rural development, „Biomass potential"
[5] Eurostat „Total greenhouse gas emissions by countries"

Summary

- EU aviation emission targets ➔ large demand for green jet fuel
- Mass production of green jet fuel ➔ renewable power-based fuel production concepts (Fischer-Tropsch)
- Syncrude from Fischer-Tropsch synthesis has to be upgraded ➔ Update existing refinery infrastructure
- Alternative fuel costs are currently not competitive compared to fossil jet fuel ➔ political demand
  ➔ Identify the most viable fuel options in terms of fuel costs / CO_2-abatement costs
- Use the standardized DLR methodology for the evaluation of alterative jet fuels with respect to technical, economic and ecological key performance parameters
  (CAPEX, OPEX, net production costs, CO_2-Abatement costs)

Otherwise? – How about biking?

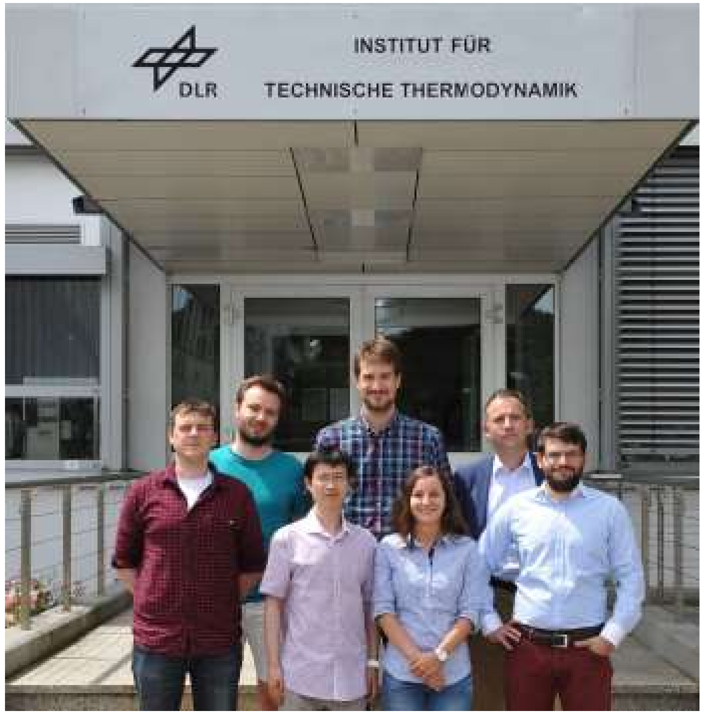
The Gossamer Albatross crossed the English Channel between Folkestone and Cap Gris-Nez

- Bryan Allen on June 12, 1979
- Distance: 35,8 km
- Travel time: 2:49 hours

This corresponds to:

- Flight from Frankfurt am Main (FRA)
  ➔ Madrid (MAD): 1.450 km
- Calculated flight time: **114 hours**

THANK YOU FOR YOUR ATTENTION!



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