
# TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF ENERGY TRANSITION OPTIONS

## Methodology and results

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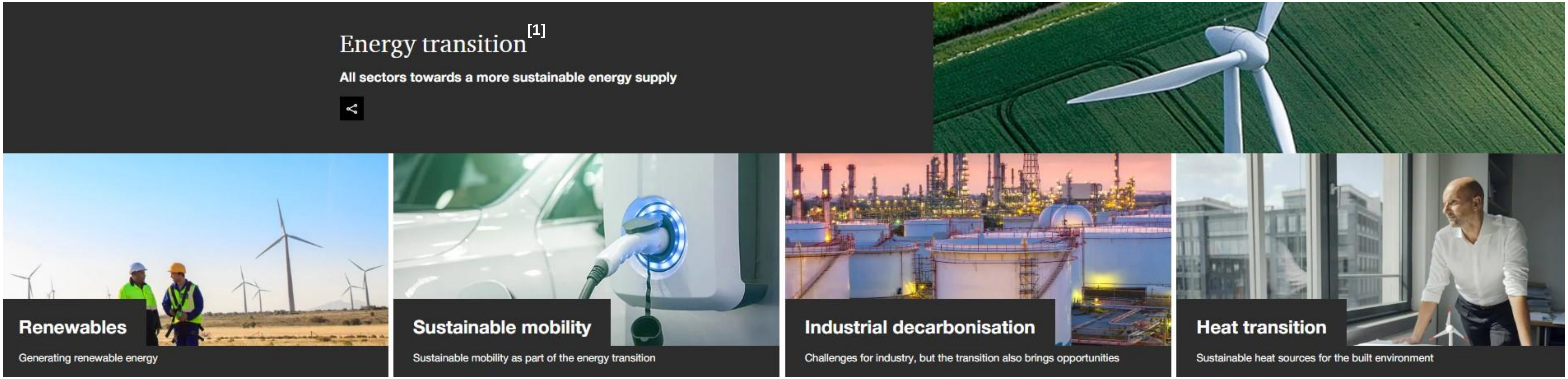
Yoga Rahmat, Julia Weyand, Ralph-Uwe Dietrich

DLR

# Energy transition demand – affecting the entire society

## Financial Accounting P.o.V. [1]

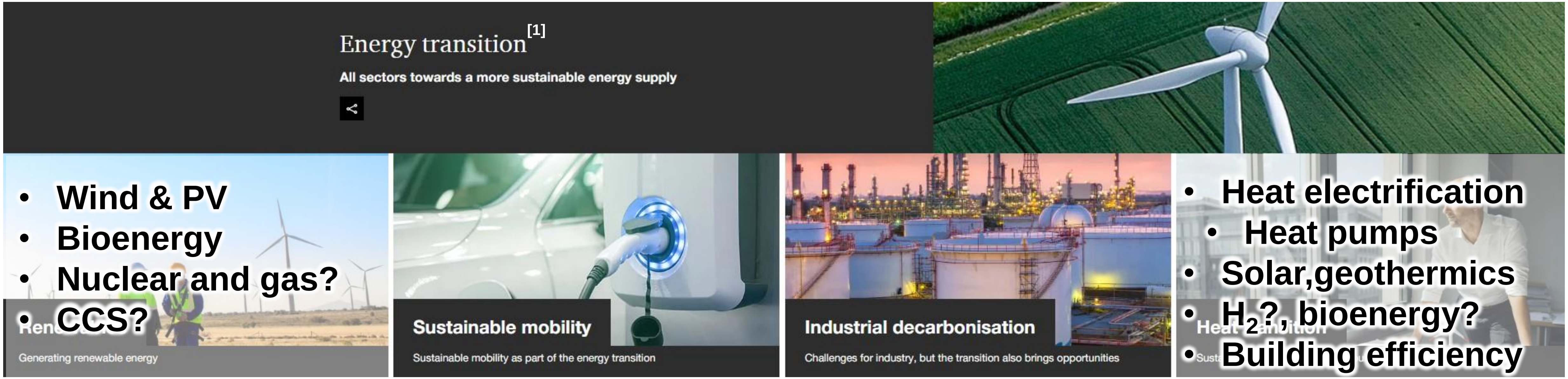



**Global Emissions 2016[2]: 49.4 $Gt_{CO2\text{-}eq.}$**

[1] https://www.pwc.nl/en/topics/sustainability/energy-transition.html

[2] https://ourworldindata.org/emissions-by-sector

# Energy transition demand – affecting the entire society
## Sectors with widely accepted response options




- **Wind & PV**
- **Bioenergy**
- **Nuclear and gas?**
- **CCS?**

- **Heat electrification**
  - **Heat pumps**
- **Solar,geothermics**
- **$H_2$?, bioenergy?**
- **Building efficiency**

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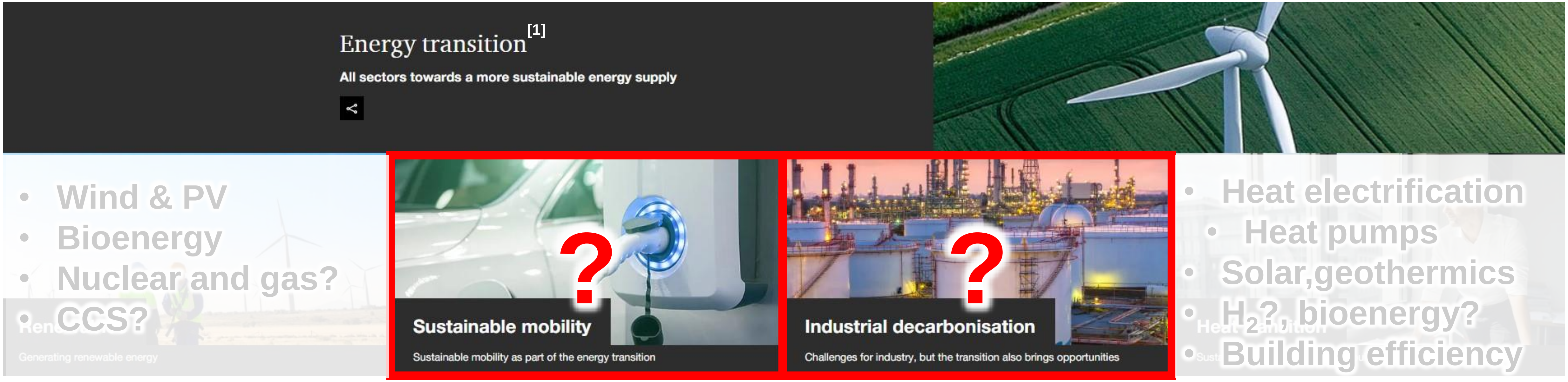
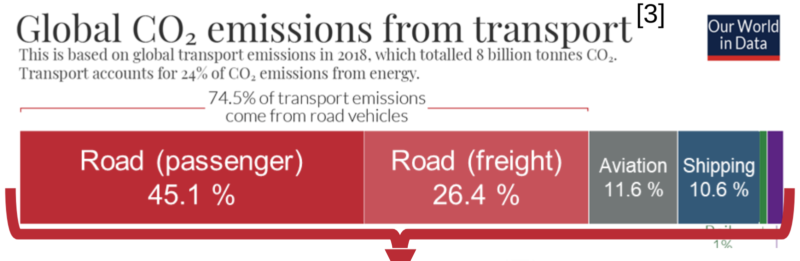
# Energy transition demand – affecting the entire society
## Sectors with manifold options, but no final solution




Transport Emissions 2016[1]: 8.0 $Gt_{CO2\text{-}eq.}$

**Global Emissions 2016[2]: 49.4 $Gt_{CO2\text{-}eq.}$**

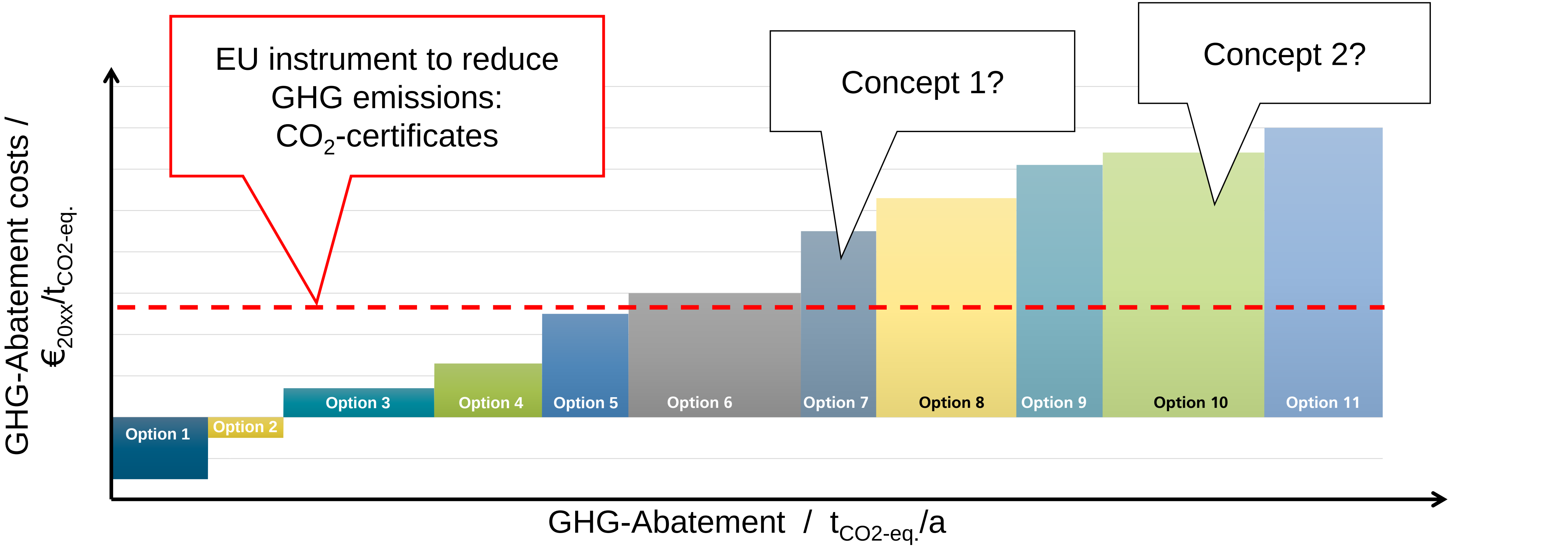
Energy use in industry (24.2 %)[2] 12.0 Gt

(5.2 %)[2] Direct Industrial Processes: 2.5 Gt

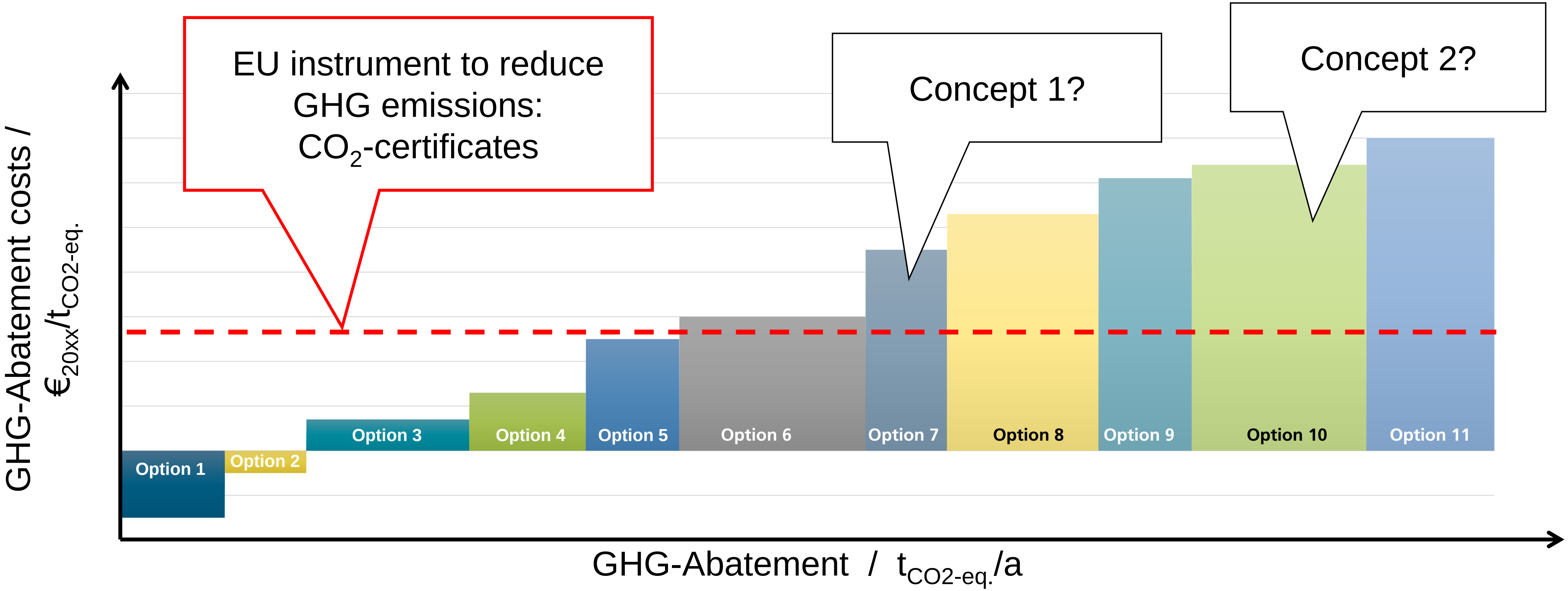
[1] https://www.pwc.nl/en/topics/sustainability/energy-transition.html
[3] https://ourworldindata.org/co2-emissions-from-transport

[2] https://ourworldindata.org/emissions-by-sector

# Assessment of renewable energy application concepts
## Merit-Order of GHG reduction technologies



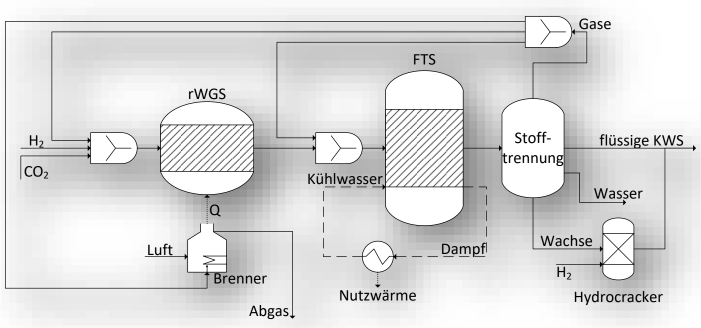
# Assessment of renewable energy application concepts …
## Merit-Order of GHG reduction technologies

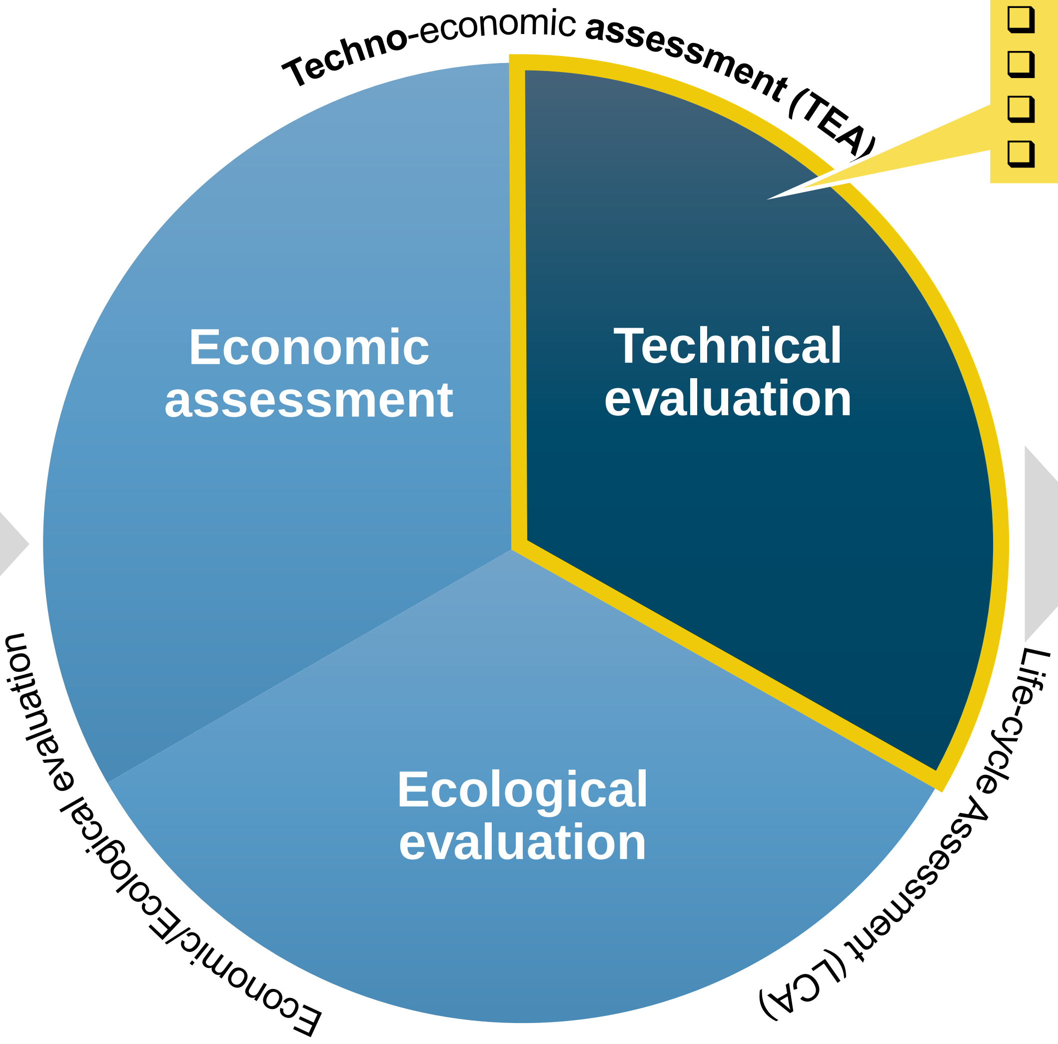



**Goal:** Maximal $CO_2$ reduction @ minimized GHG-Abatement cost, either by reducing GHG footprint or costs!

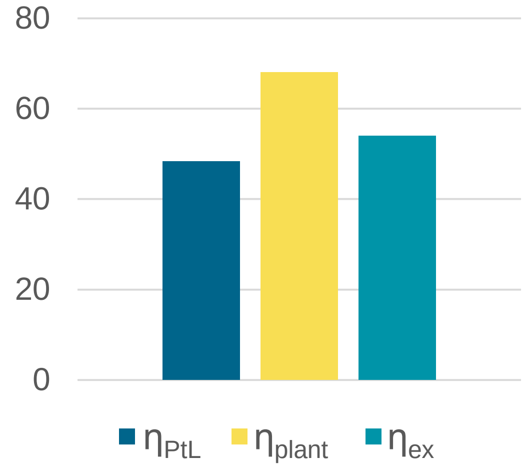
**→ Standardized methodology for LCA and TEA required!**

# Techno-Economic and ecological assessment (TEEA)




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



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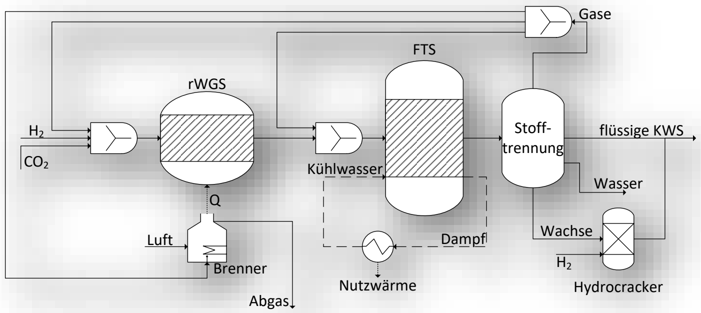


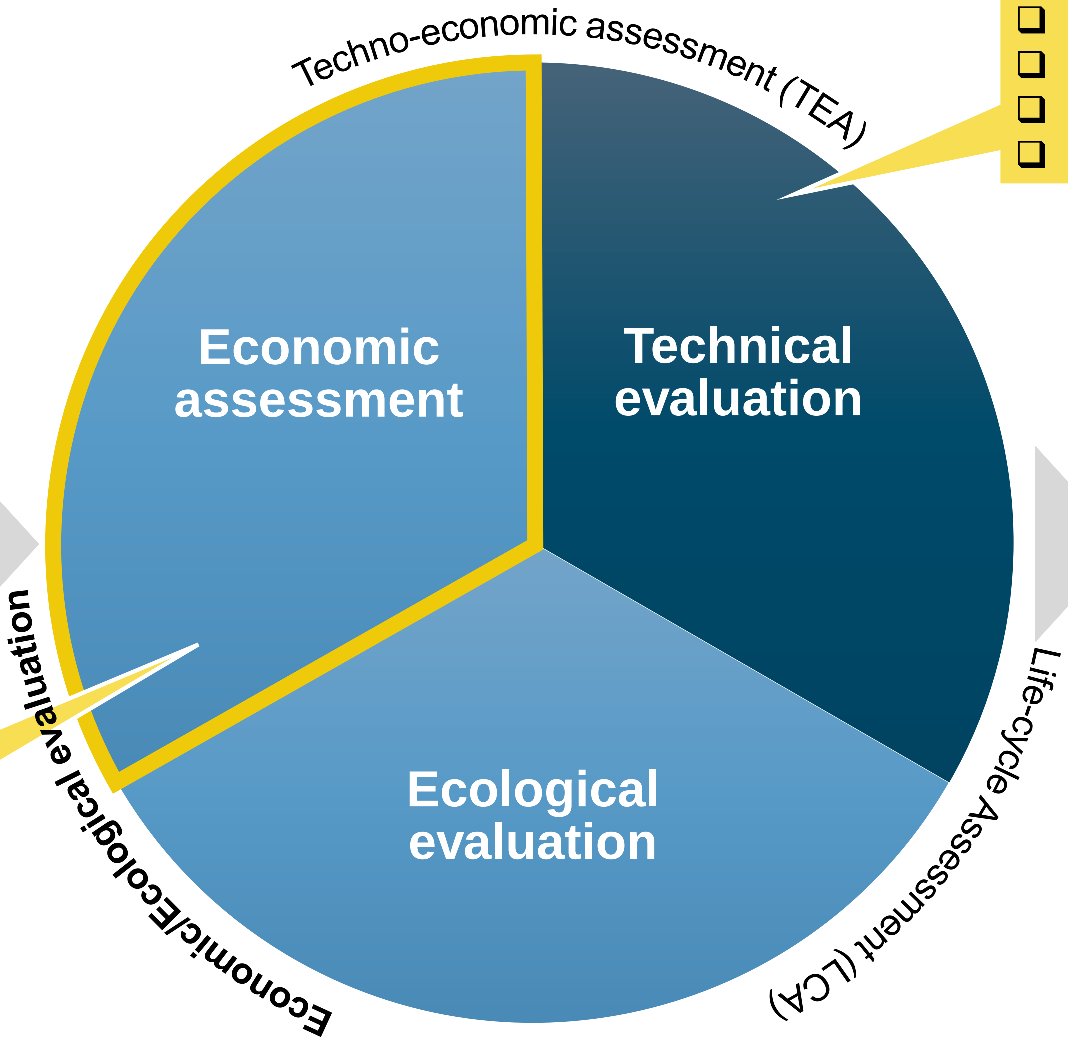


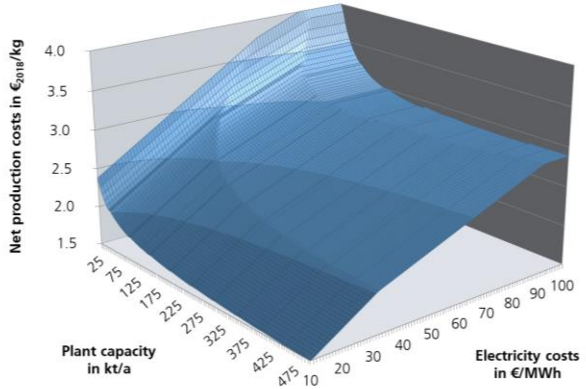


- ❑ CAPEX, OPEX, NPC
- ❑ Sensitivity analysis
- ❑ Identification of most economic feasible process design

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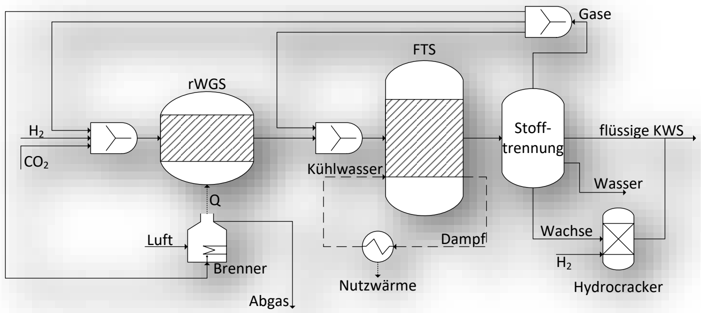


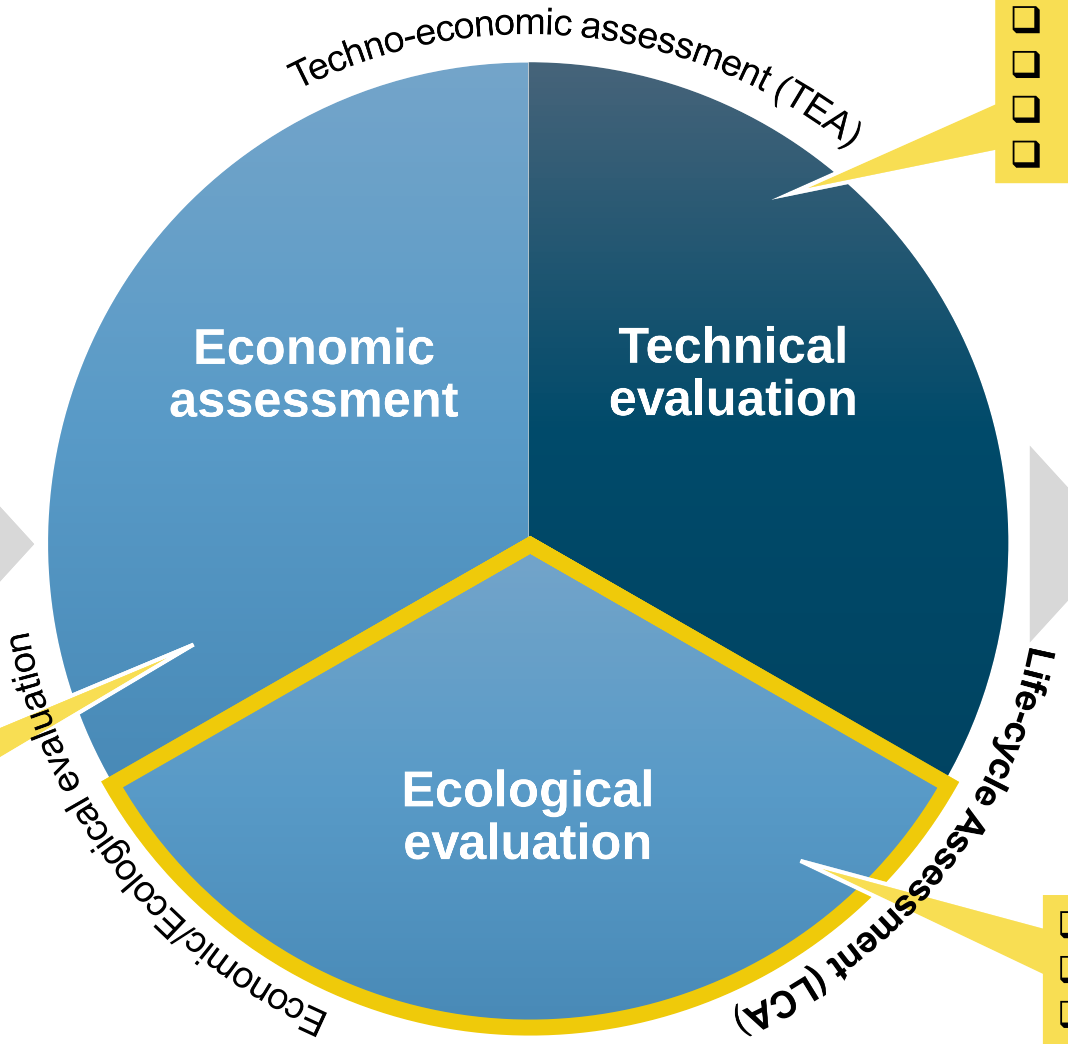


- ❑ CAPEX, OPEX, NPC
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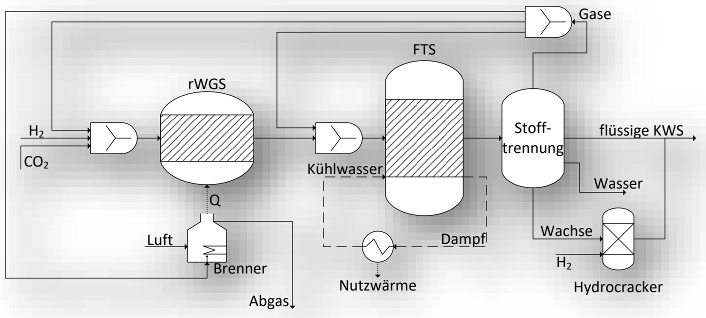
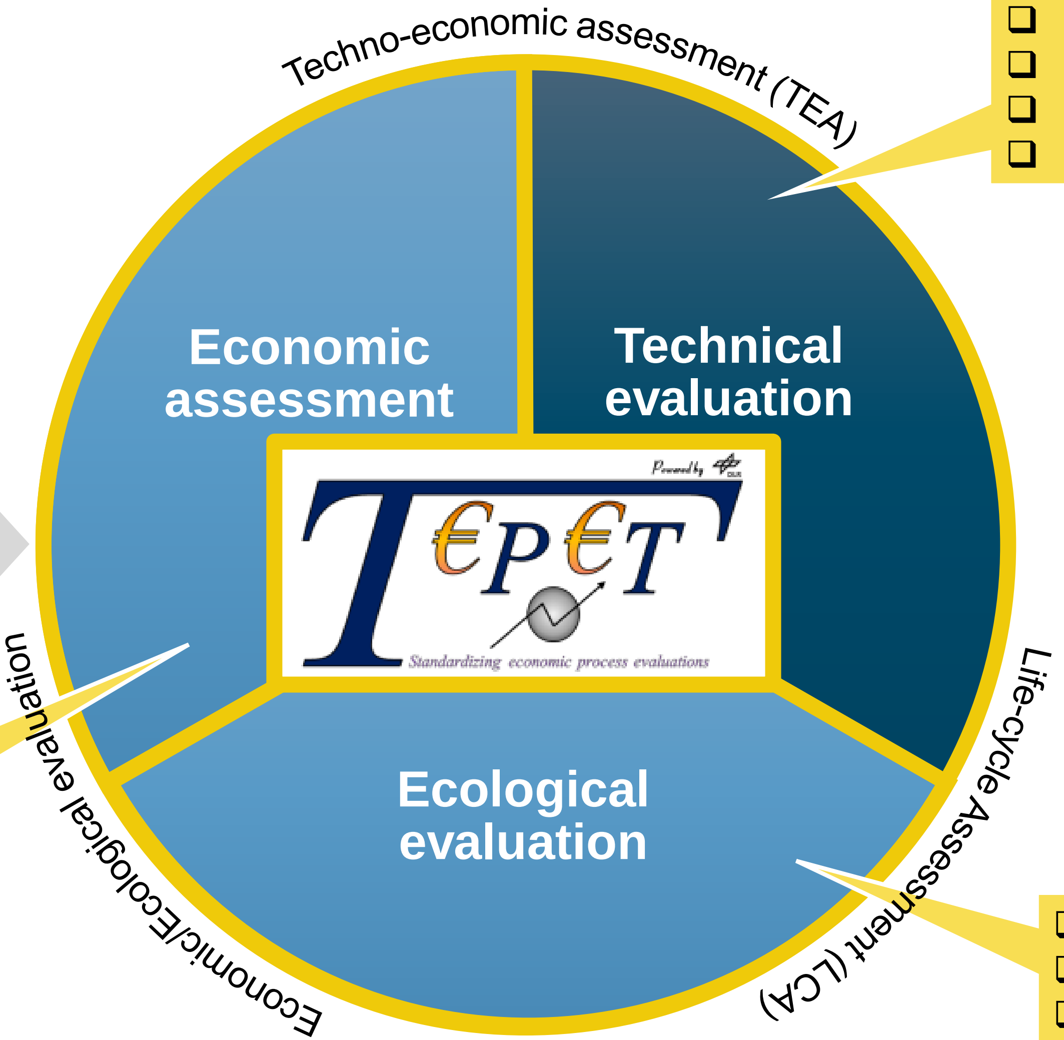
- ❑ GWP
- ❑ Other impact categories
- ❑ Identification of impact drivers

# Techno-Economic and ecological assessment (TEEA)

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# Techno-Economic and ecological assessment (TEEA) @DLR

DLR

1. Step

Literature survey

Exchange with project partners

**Simulation**

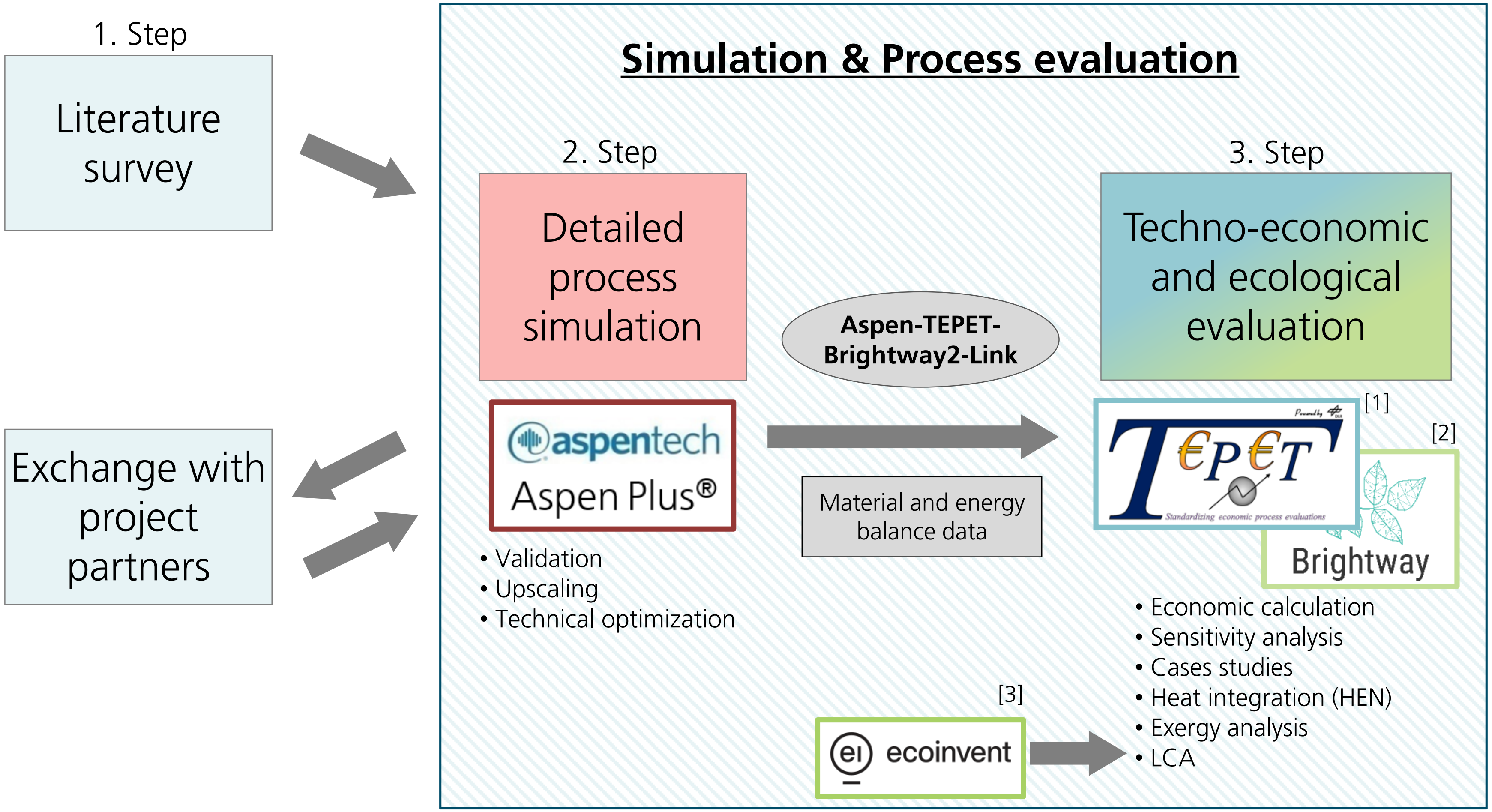
2. Step

Detailed process simulation

aspentech
Aspen Plus®

- Validation
- Upscaling
- Technical optimization

# Techno-Economic and ecological assessment (TEEA) @DLR




[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526
[2] Mutel (2017) - Brightway: An open source framework for Life Cycle Assessment, Journal of Open Source Software, 2(12): 236
[3] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.

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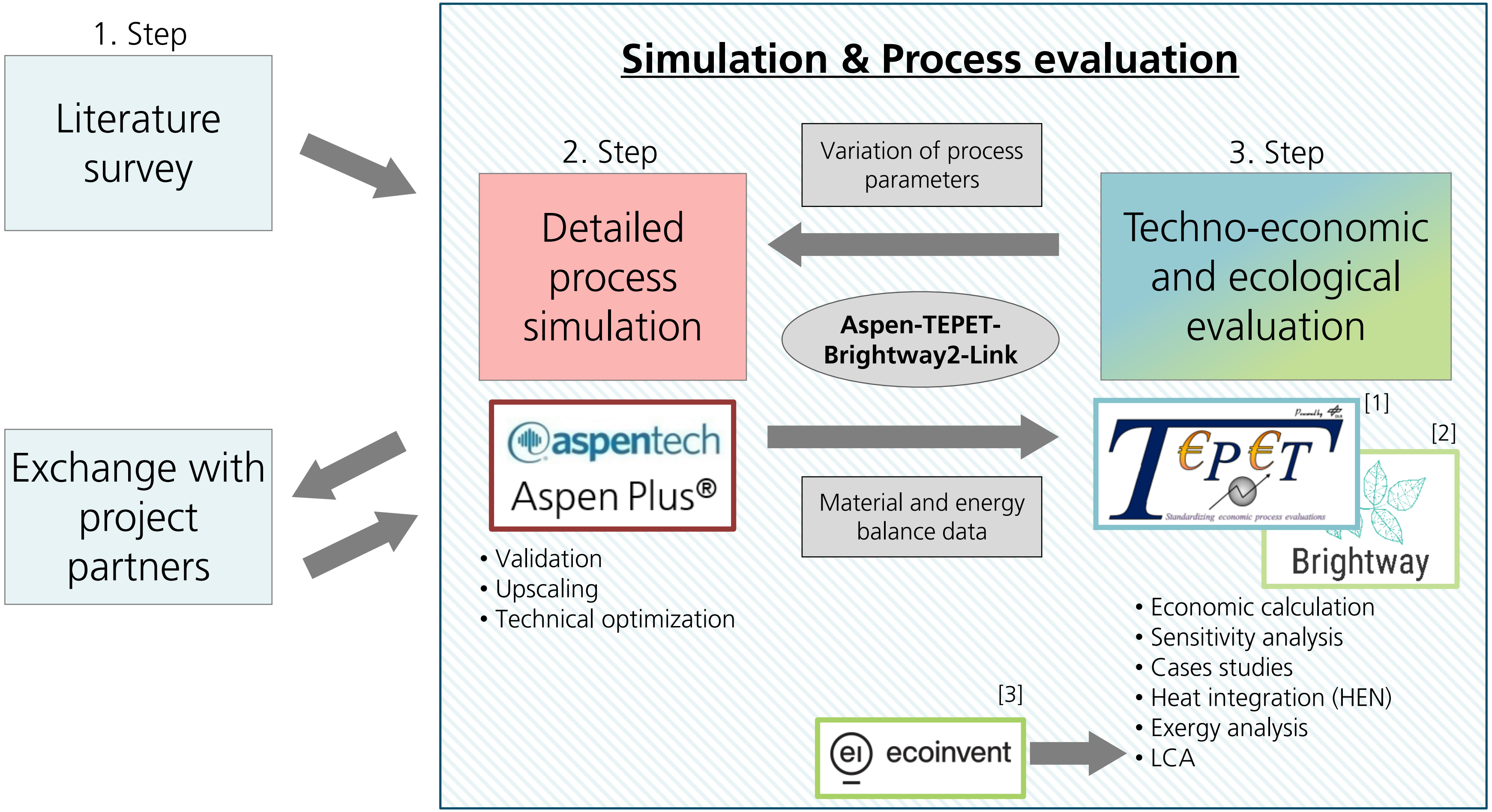


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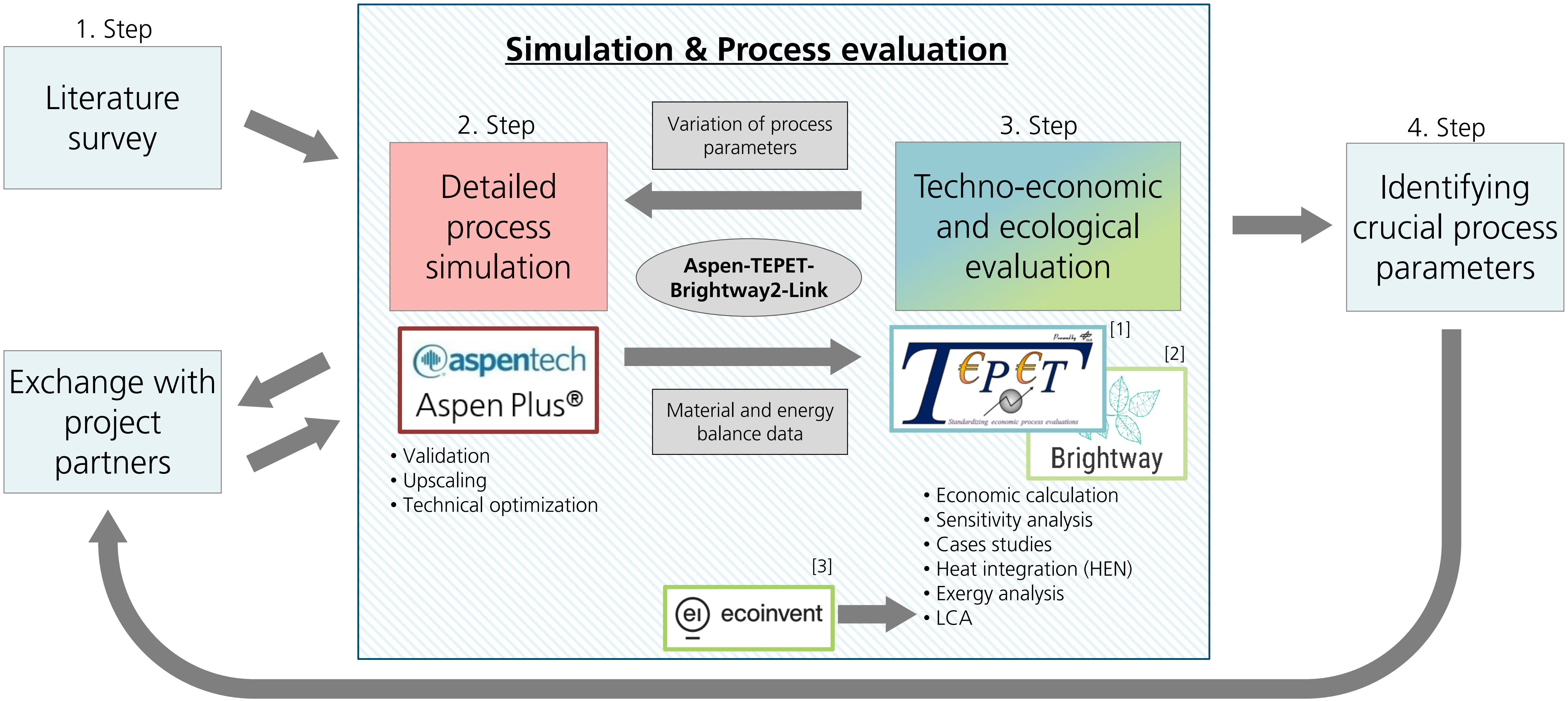


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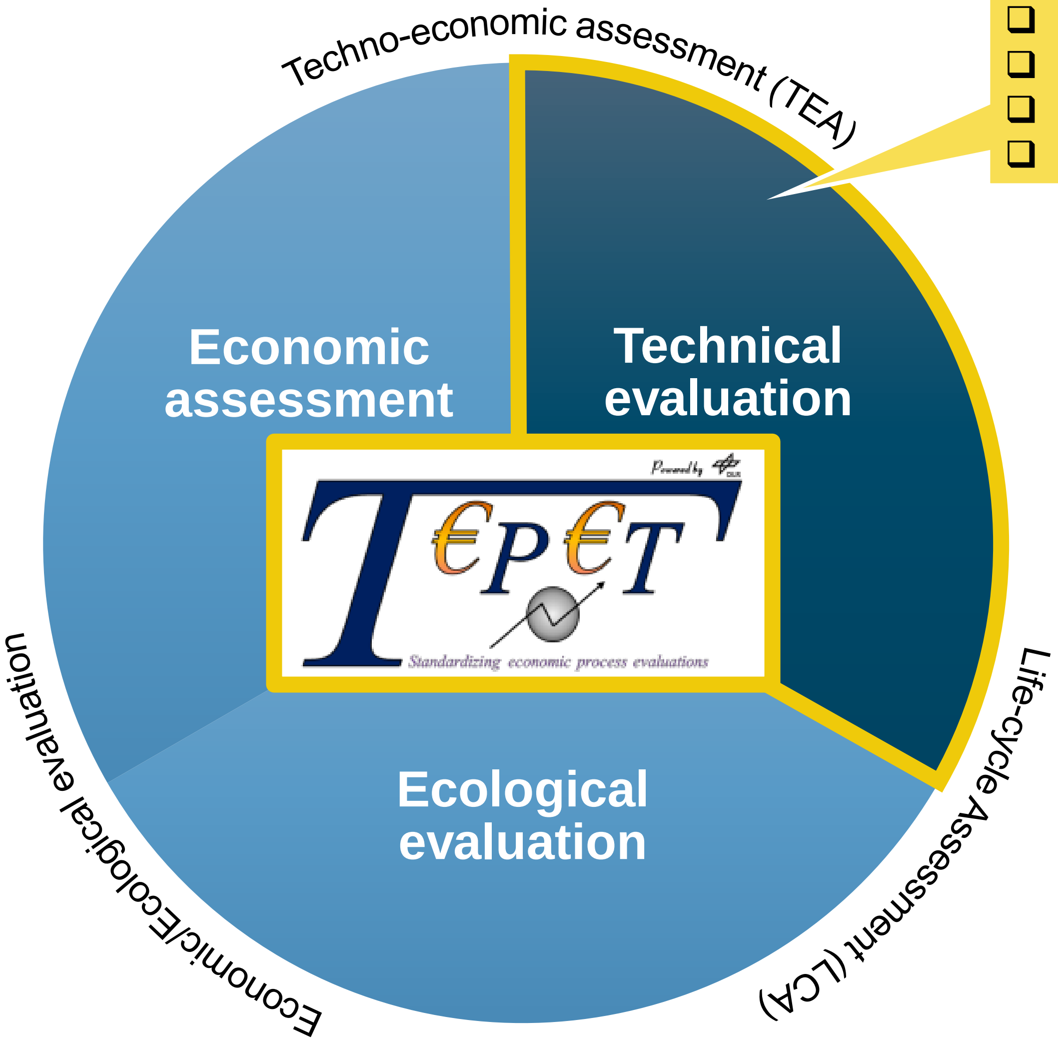
# Chapter Technical Evaluation




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

# Example: Evaluation of biofuels production

DLR

## DFB Pilot plant / VTT

## Mobile synthesis unit / INERATEC

5 $m^3$/h SLIP-STREAM TO SYNTHESIS

Straw / Bark → DFB gasifier → Filter → Reformer → Ultracleaning steps → Fischer-Tropsch synthesis →

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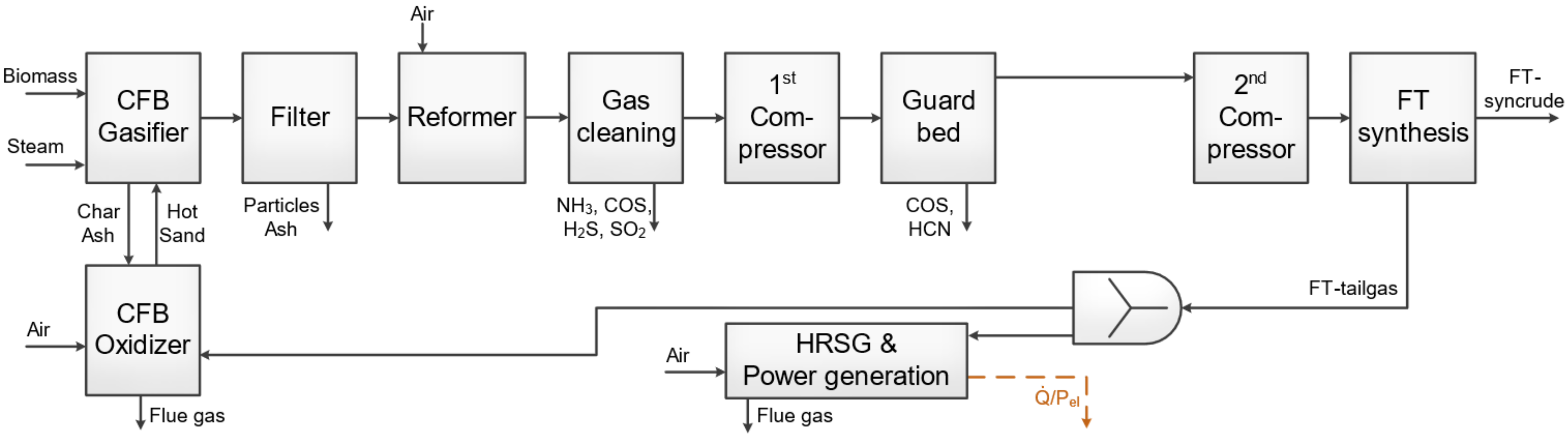
# Example: Evaluation of biofuels production options [1]




## Case 1

- Base case
- Autothermal reforming with air

[1] Maier et al., Techno-economically-driven identification of i … ase study for Central-Europe, 2021.

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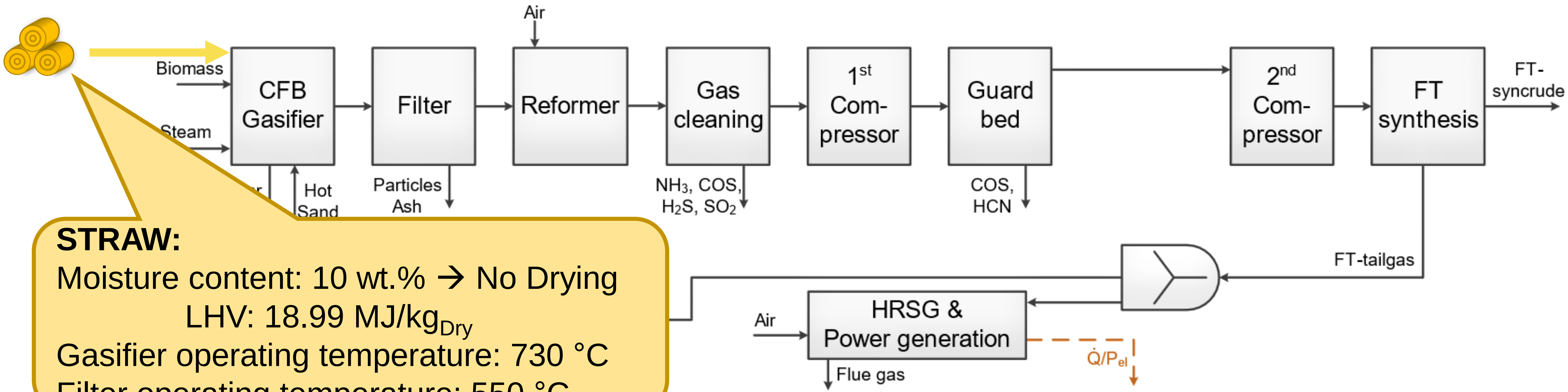


**STRAW:**
Moisture content: 10 wt.% → No Drying
LHV: 18.99 $MJ/kg_{Dry}$
Gasifier operating temperature: 730 °C
Filter operating temperature: 550 °C

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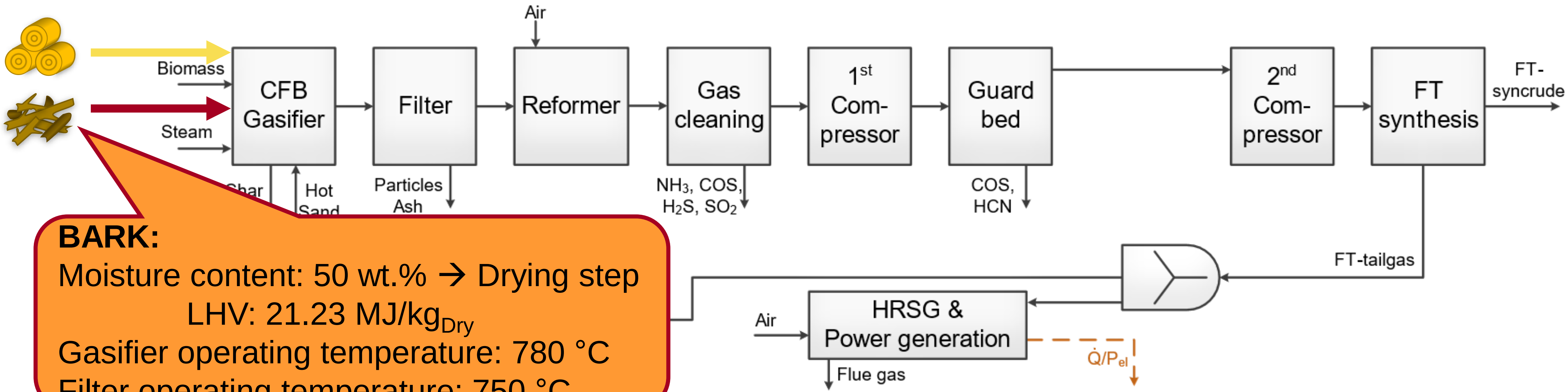


**BARK:**
Moisture content: 50 wt.% → Drying step
LHV: 21.23 MJ/kg$_{Dry}$
Gasifier operating temperature: 780 °C
Filter operating temperature: 750 °C

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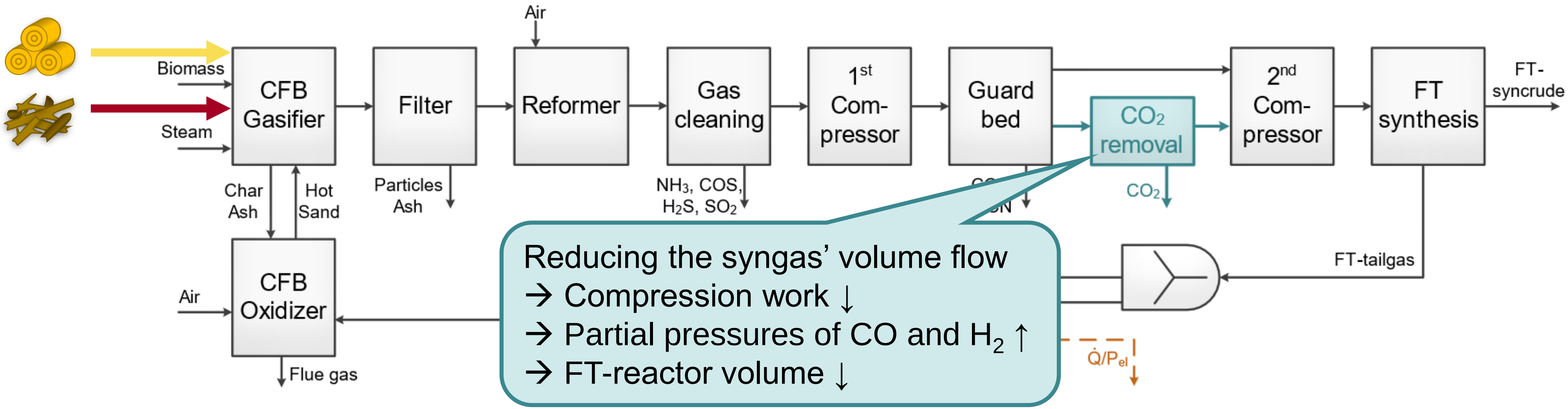


| Case 1 | Case 2 |
|---|---|
| • Base case<br>• Autothermal reforming with air | • Autothermal reforming with air<br>• **$CO_2$ removal** after guard bed<br>➢ Operating at 5 bar<br>➢ 80 % $CO_2$ is removed |

[1] Maier et al., Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – A case study for Central-Europe, 2021.

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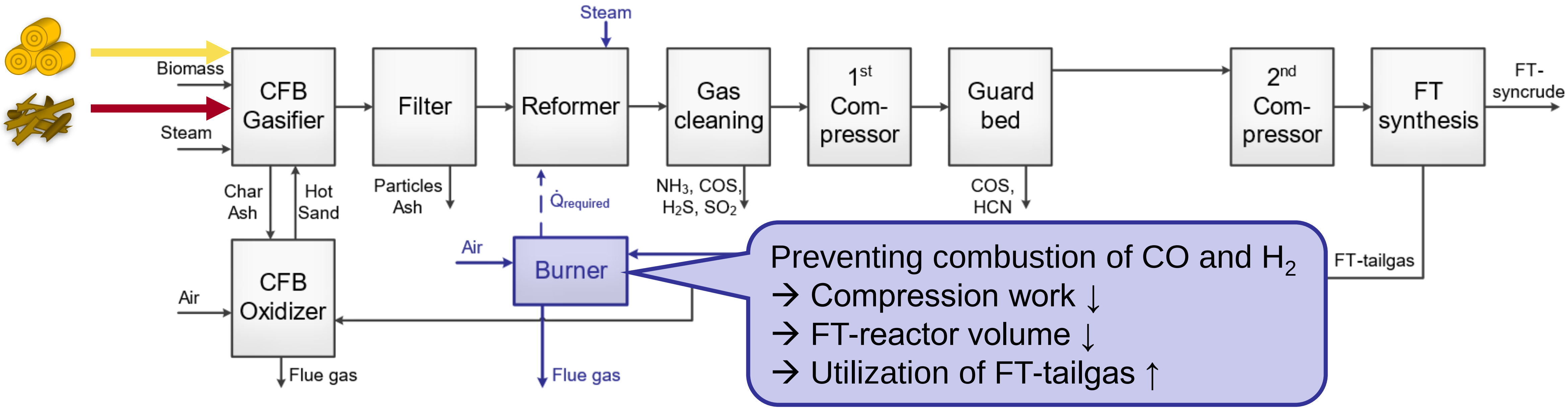


| Case 1 | Case 2 | Case 3 |
|---|---|---|
| • Base case<br>• Autothermal reforming with air | • Autothermal reforming with air<br>• **$CO_2$ removal** after guard bed<br>➢ Operating at 5 bar<br>➢ 80 % $CO_2$ is removed | • **Allothermal** steam reforming<br>➢ Required heat is provided by an additional burner<br>➢ Steam is led into the reformer |

[1] Maier et al., Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – A case study for Central-Europe, 2021.

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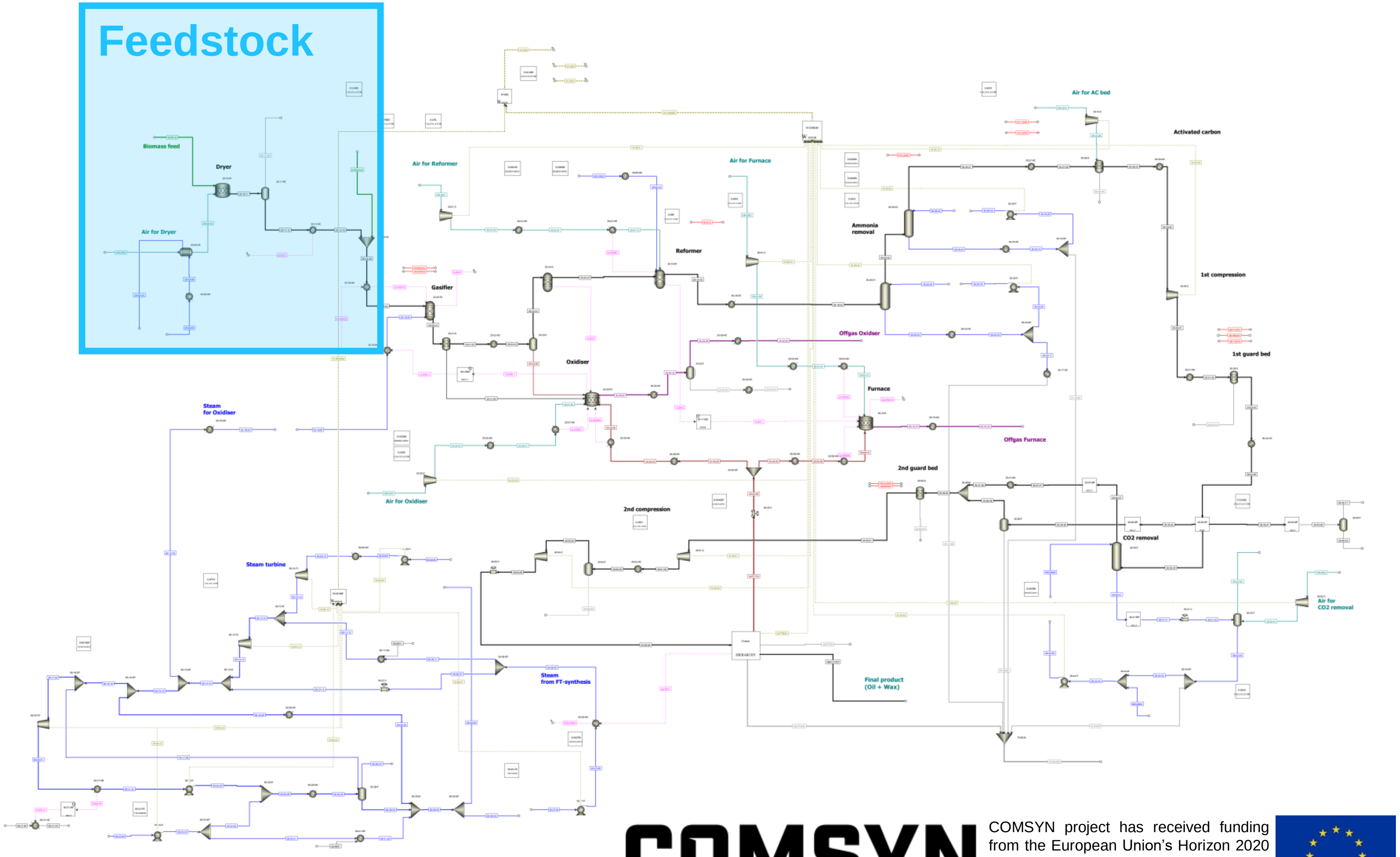
# Example: Evaluation of biofuels production

- Validated process flow diagram
  - Component list
  - VLE method

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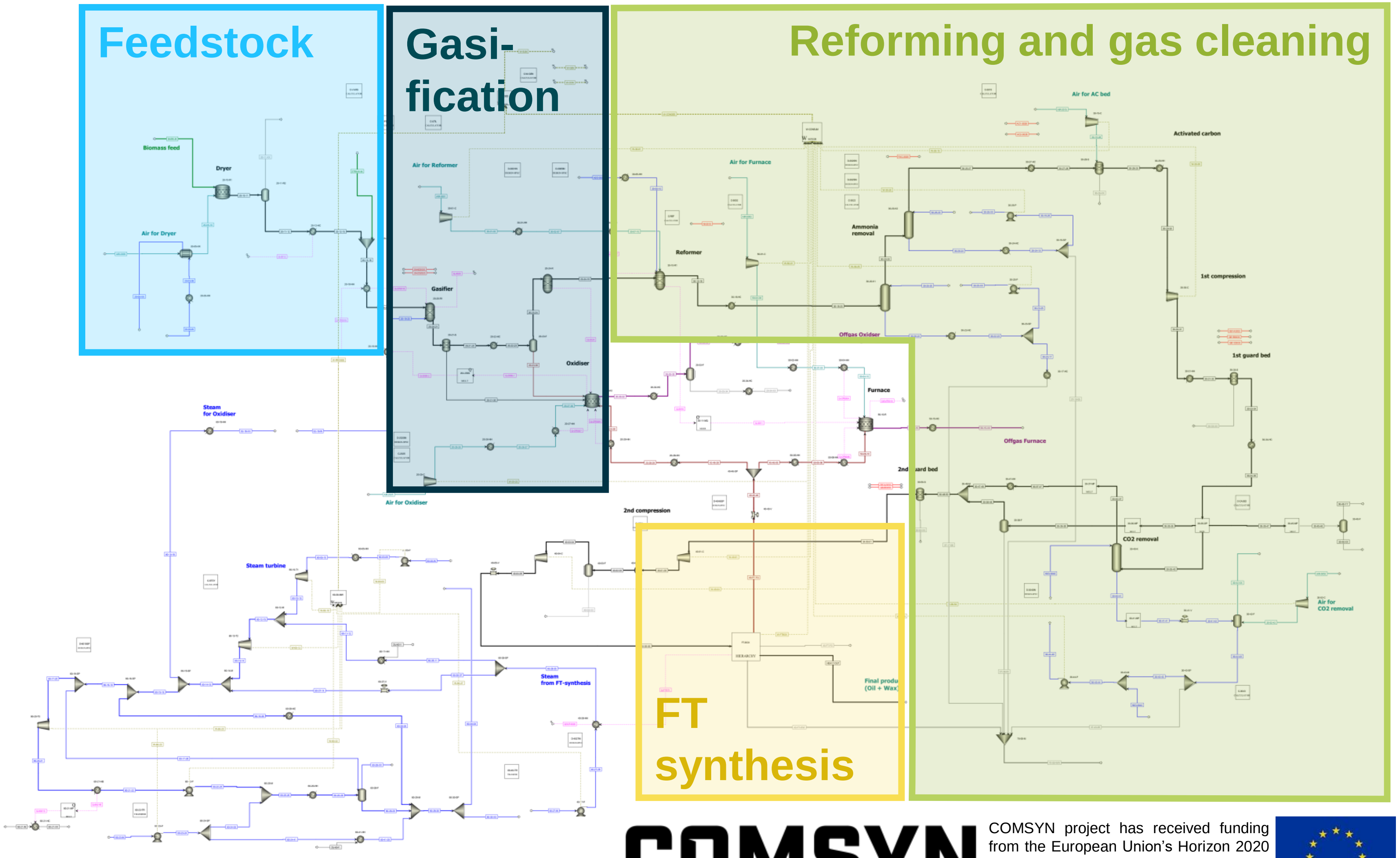
# Example: Evaluation of biofuels production

DLR

- Validated process flow diagram
  - Component list
  - VLE method
  - Reaction kinetic, unit performance
  - Realistic press. drop

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# Example: Evaluation of biofuels production

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- Validated process flow diagram
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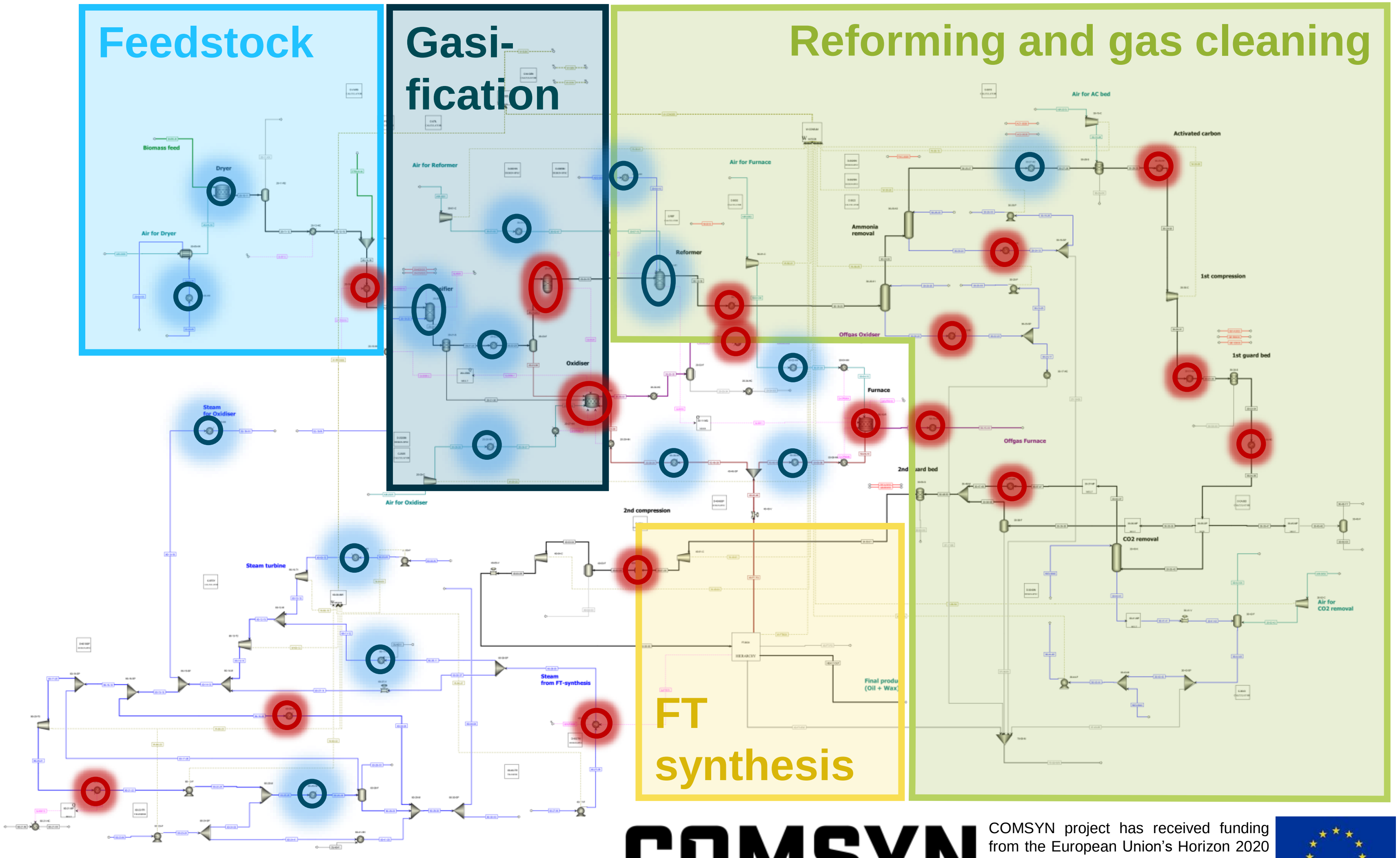
  - Reaction kinetic, unit performance
  - Realistic press. drop
  - Optimal heat integration

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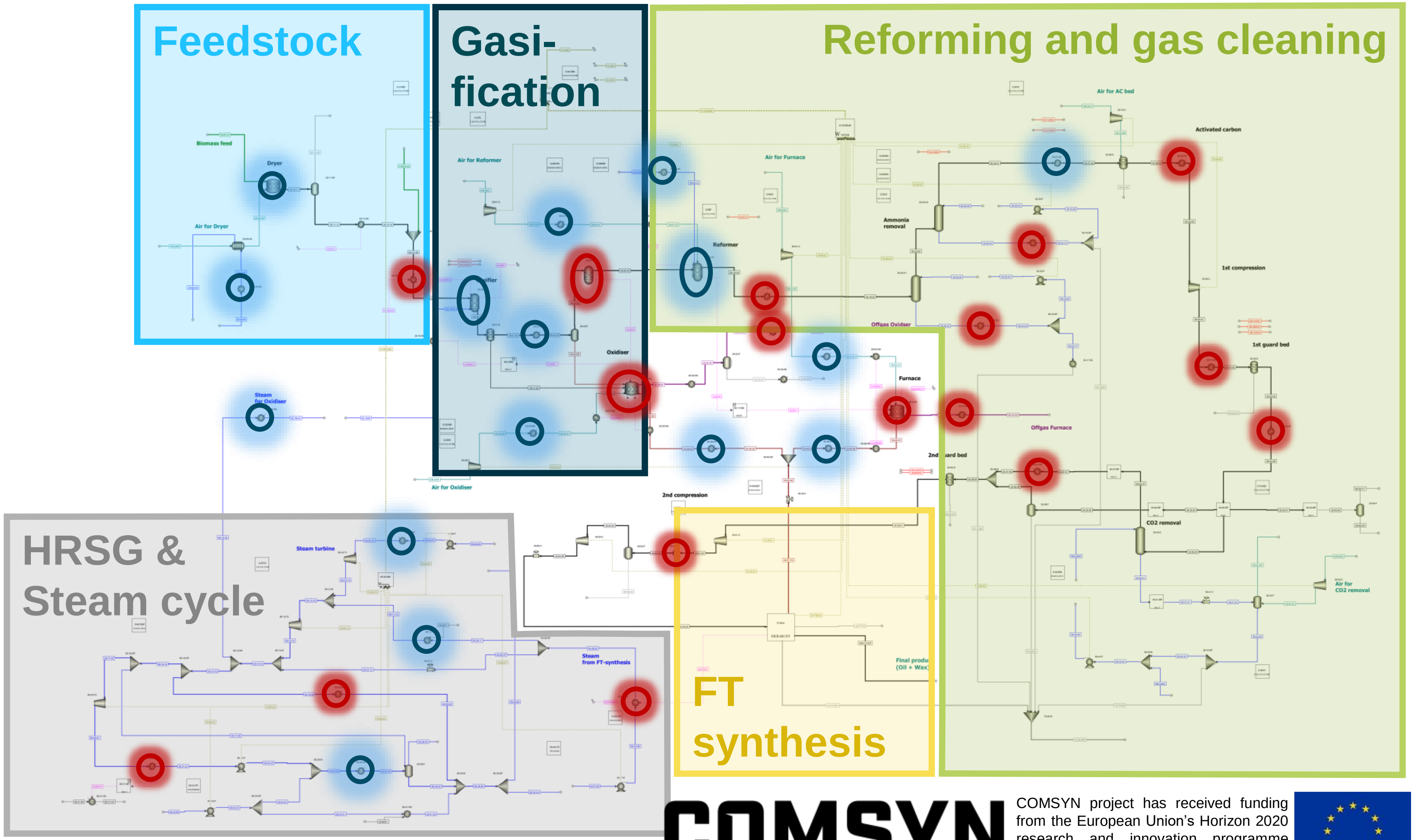
# Example: Evaluation of biofuels production

- Validated process flow diagram
  - Component list
  - VLE method
  - Reaction kinetic, unit performance
  - Realistic press. drop
  - Optimal heat integration
- Additional process ideas
  - Steam cycle integration
- Converged without errors/warnings?

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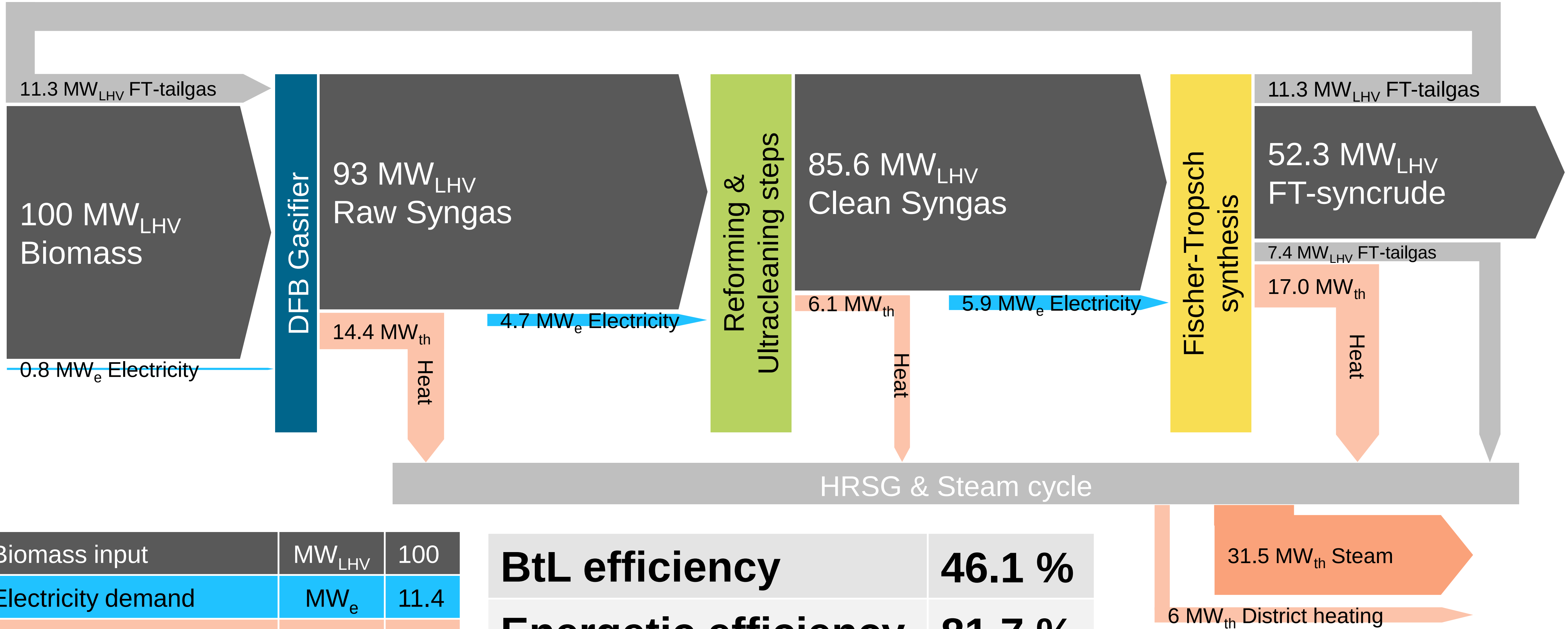
# Example results: Evaluation of biofuels production
## Sankey diagram of COMSYN BtL process energy flows




| Biomass input | $MW_{LHV}$ | 100 |
|---|---|---|
| Electricity demand | $MW_e$ | 11.4 |
| Steam + Distr. heating | $MW_{th}$ | 37.5 |

| **BtL efficiency** | **46.1 %** |
|---|---|
| **Energetic efficiency** | **81.7 %** |

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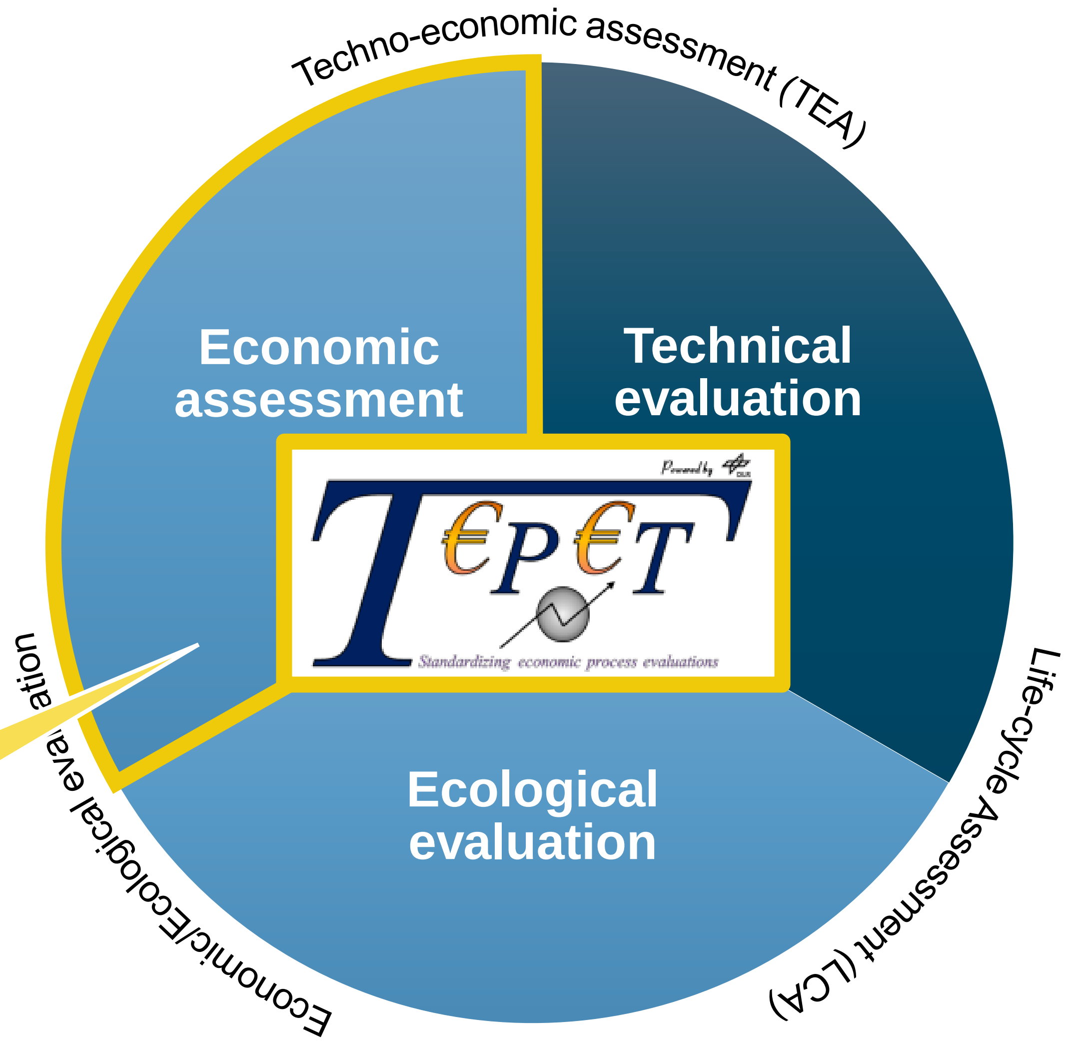
# Chapter Economic Assessment

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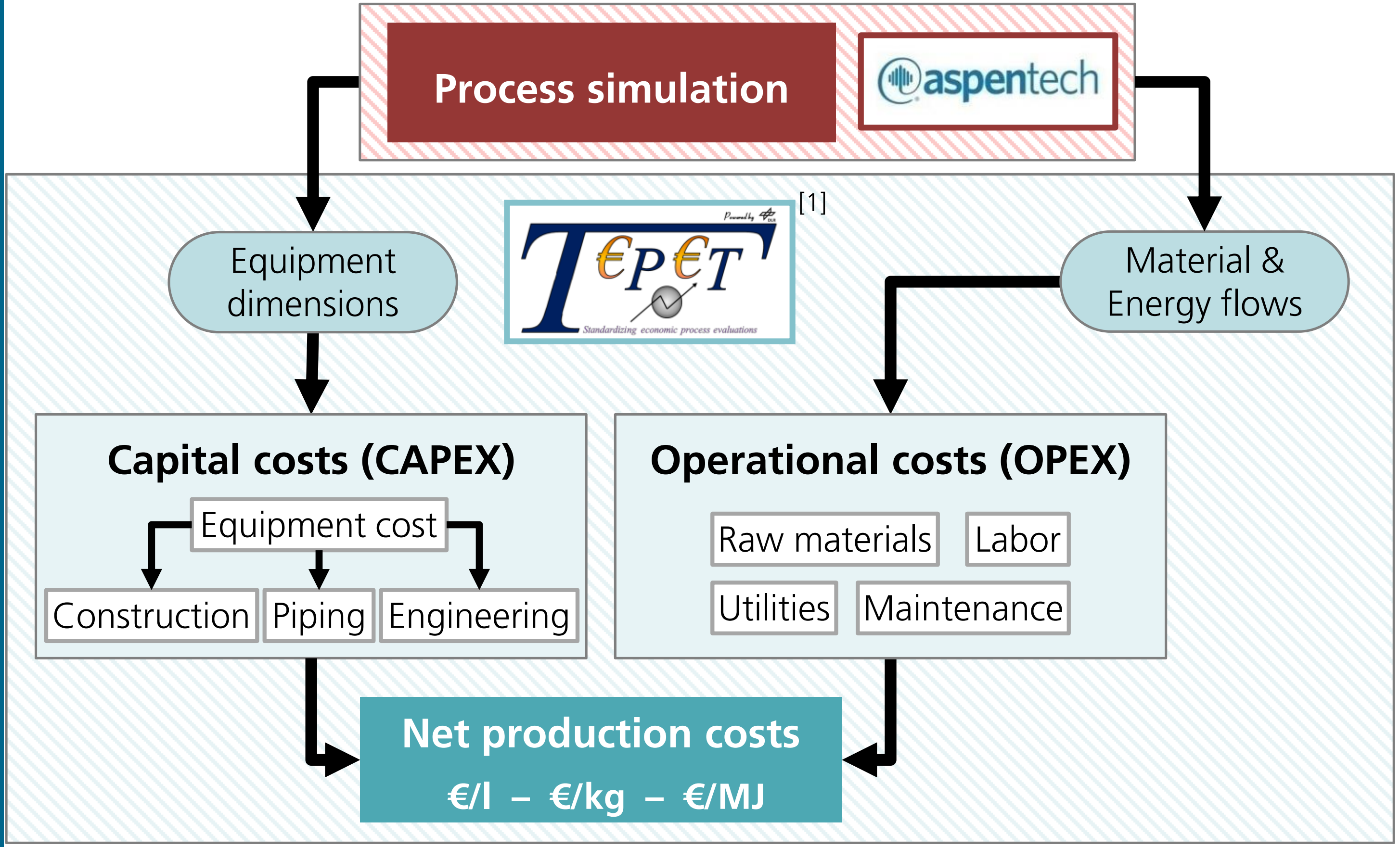
# TEEA tool TEPET @ DLR (part 1)




- 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, heating networks, …**
- Easy sensitivity studies for **each** parameter
- Learning curves, economy of scale, …

[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526

# Example results: Economic evaluation of BtL production[1]
## COMSYN general assumptions and OPEX cost data

| General assumptions | | | |
|---|---|---|---|
| Base year | - | 2019 | |
| Max. plant size ($C_{plant,max}$) | $MW_{th}$ | 200 | |
| Interest rate (IR) | % | 10 | |
| Full load hours (flh) | h/a | 8260 | |
| Plant lifetime (PL) | a | 20 | |
| **Site-specific costs** | | **DE** | **Ref.** |
| Electricity costs/revenue ($c_{EL}$) | €/MWh | 92.8 | [2] |
| Natural gas price ($r_{Gas}$) | €/GJ | 6.2 | [3] |
| Biomass costs (bark) ($c_{Bio,b}$) | €/GJ | 5.8 | [4] |
| Biomass costs (straw) ($c_{Bio,s}$) | €/GJ | 4.5 | [4] |
| Biomass transport costs ($c_{TrBio}$) | €/km/t | 0.45 | [4] |
| District heating revenue ($r_{DH}$) | €/MWh | 31.7 | [6] |
| Process steam revenue ($r_{PS}$) | €/MWh | 33.7 | [6] |
| Labor costs ($c_L$) | €/h | 30.9 | [5] |

[1] Maier et al., Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – A case study for Central-Europe, 2021.
[2] Union, E., *Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) [NRG_PC_205]*, in *Electricity prices for non-household consumers*. 2019, European Union.
[3] OECD. *Crude oil import prices (indicator)*. 2021 08 January 2021.
[4] Pablo Ruiz, A.S., Wouter Nijs,, et al., *The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries*. 2015. p. 176.
[5] Commission, E., *Labour cost, wages and salaries, direct remuneration (excluding apprentices) by NACE Rev. 2 activity ) - LCS surveys 2008, 2012 and 2016*. 2021.
[6] Ulrich, G.D. and P.T. Vasudevan, *How To Estimate Utility Costs.* Engineering Practice, 2006.

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# Example results: Economic evaluation of BtL production[1]
## COMSYN feedstock and process design cases assessment

| General assumptions | | | |
|---|---|---|---|
| Base year | - | 2019 | |
| Max. plant size ($C_{plant,max}$) | $MW_{th}$ | 200 | |
| Interest rate (IR) | % | 10 | |
| Full load hours (flh) | h/a | 8260 | |
| Plant lifetime (PL) | a | 20 | |
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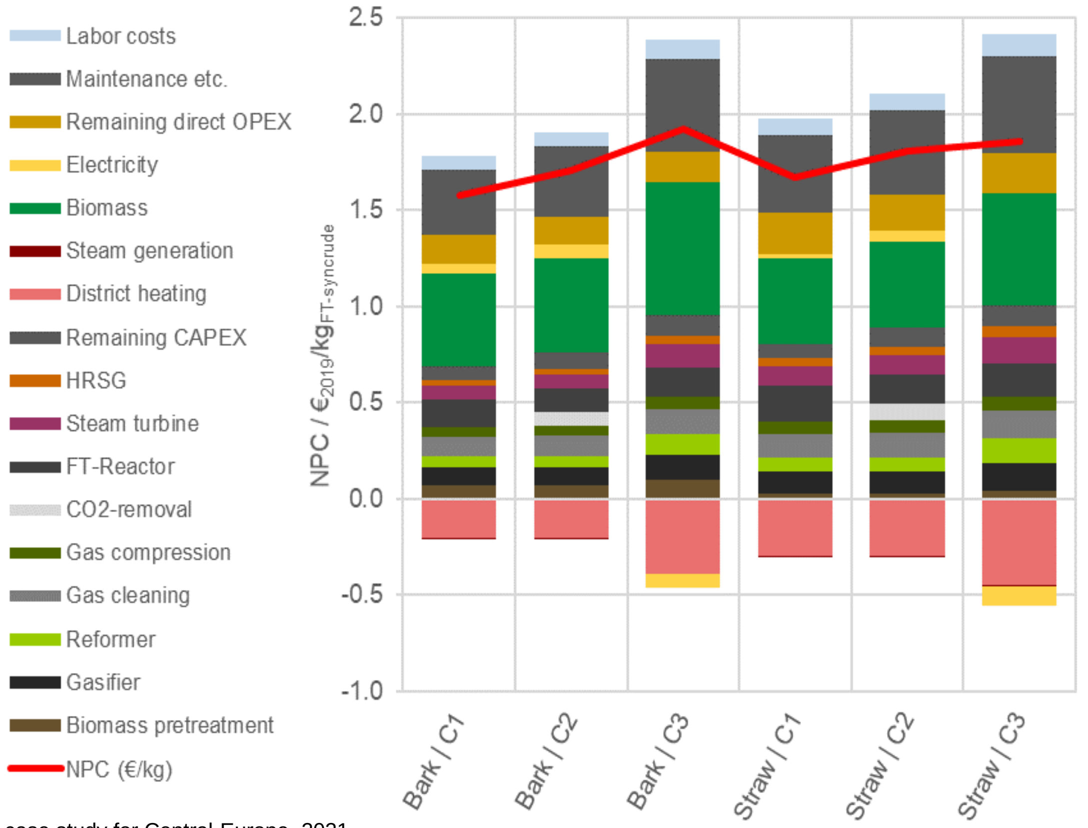


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# Example results: Economic evaluation of BtL production[1]
## COMSYN OPEX cost data extension

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|---|---|---|---|---|---|---|---|---|
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| Interest rate (IR) | % | 10 | | | | | | |
| Full load hours (flh) | h/a | 8260 | | | | | | |
| Plant lifetime (PL) | a | 20 | | | | | | |
| **Site-specific costs** | | **DE** | **Ref.** | **AT** | **CZ** | **HU** | **PL** | **SK** |
| Electricity costs/revenue ($c_{EL}$) | €/MWh | 92.8 | [2] | 78.4 | 70.5 | 79.6 | 76.3 | 98.9 |
| Natural gas price ($r_{Gas}$) | €/GJ | 6.2 | [3] | 6.9 | 6.9 | 6.4 | 6.3 | 7.0 |
| Biomass costs (bark) ($c_{Bio,b}$) | €/GJ | 5.8 | [4] | 5.6 | 5.4 | 2.6 | 3.3 | 2.8 |
| Biomass costs (straw) ($c_{Bio,s}$) | €/GJ | 4.5 | [4] | 6.9 | 4.5 | 3.7 | 2.9 | 4.9 |
| Biomass transport costs ($c_{TrBio}$) | €/km/t | 0.45 | [4] | 0.45 | 0.29 | 0.24 | 0.27 | 0.27 |
| District heating revenue ($r_{DH}$) | €/MWh | 31.7 | [6] | 37.0 | 33.8 | 27.2 | 27.7 | 29.4 |
| Process steam revenue ($r_{PS}$) | €/MWh | 33.7 | [6] | 39.3 | 35.9 | 28.9 | 29.5 | 31.3 |
| Labor costs ($c_L$) | €/h | 30.9 | [5] | 27.2 | 7.5 | 6.4 | 6.8 | 7.8 |

[1] Maier et al., Techno-economically-driven identification of ideal plant configurations for a new biomass-to-liquid process – A case study for Central-Europe, 2021.

[2] Union, E., *Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) [NRG_PC_205]*, in *Electricity prices for non-household consumers*. 2019, European Union.

[3] OECD. *Crude oil import prices (indicator)*. 2021 08 January 2021.

[4] Pablo Ruiz, A.S., Wouter Nijs,, et al., *The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries*. 2015. p. 176.

[5] Commission, E., *Labour cost, wages and salaries, direct remuneration (excluding apprentices) by NACE Rev. 2 activity ) - LCS surveys 2008, 2012 and 2016*. 2021.

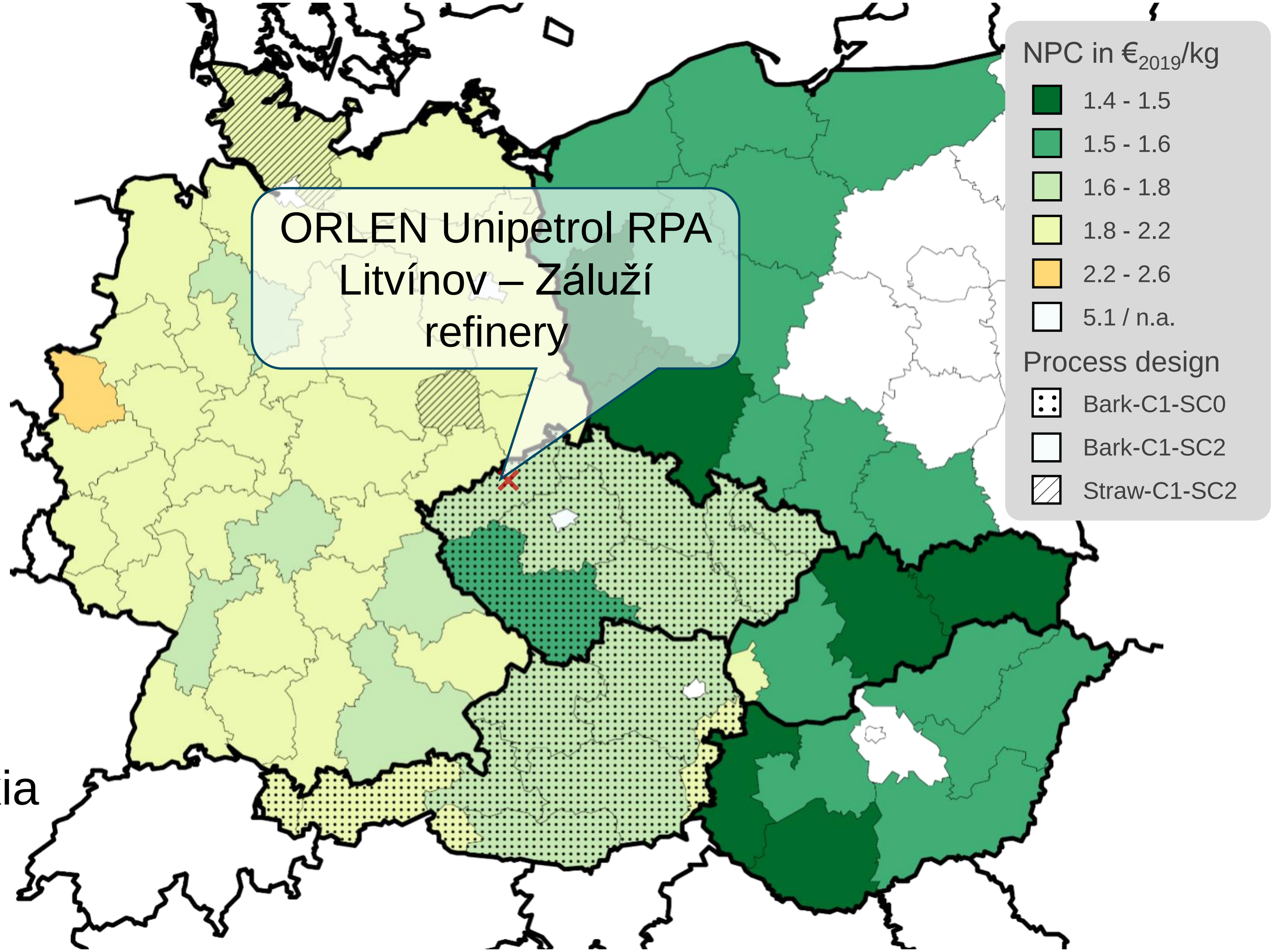
[6] Ulrich, G.D. and P.T. Vasudevan, *How To Estimate Utility Costs.* Engineering Practice, 2006.

COMSYN

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

# Example results: Economic evaluation of BtL production
## Central European map of COMSYN roll out

- Identification of regional sweet spots shown on a map for Central-Europe.
- Net production costs and the favorable process design for each region.
- Automated selection of the optimal feedstock, process design, plant size and heat / electricity utilization.
- Refinery Point of View preferences
- Net production costs < 1.12 $€_{2019}/l_{biofuel}$ regions in Hungary, Poland, and Slovakia

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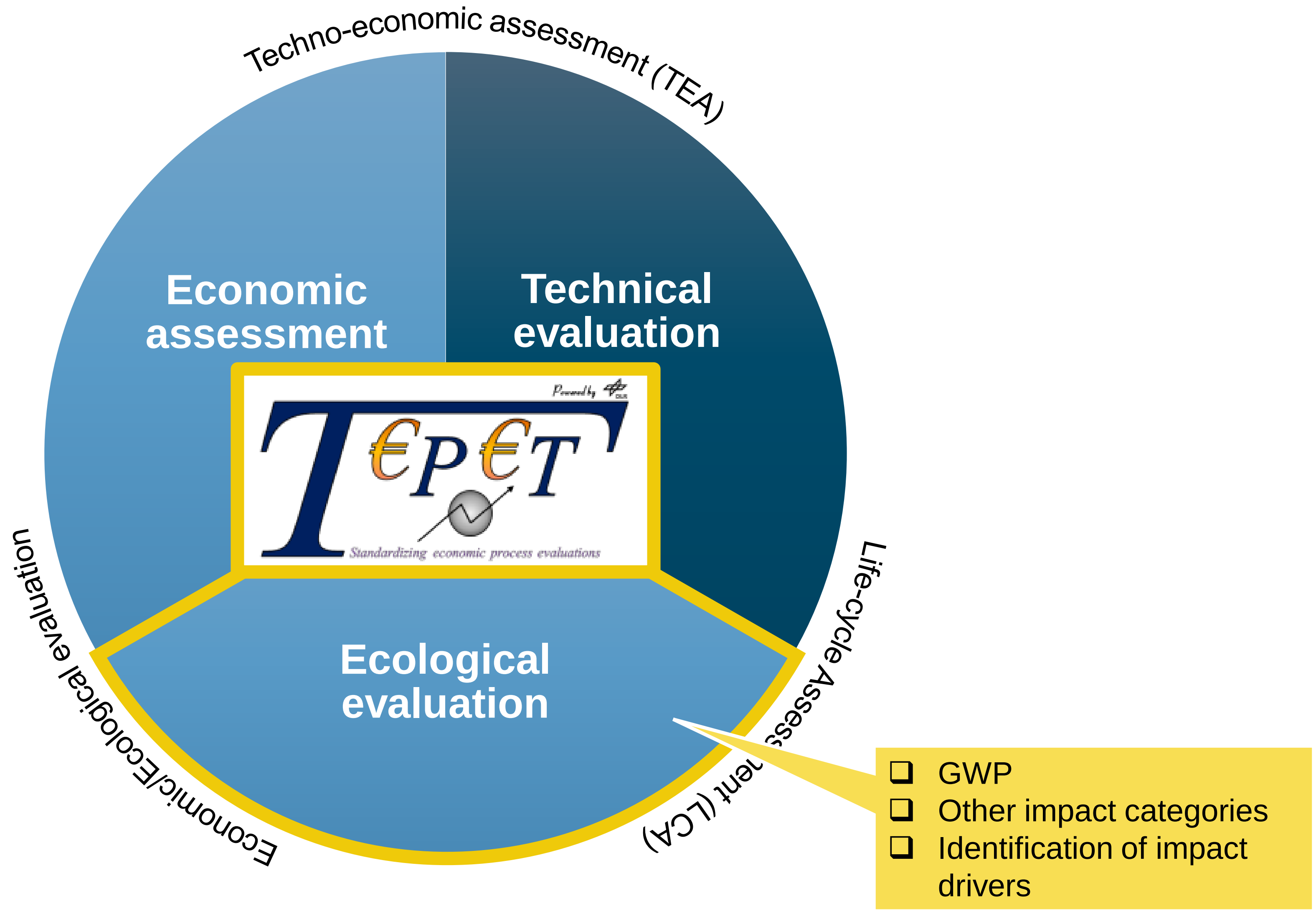
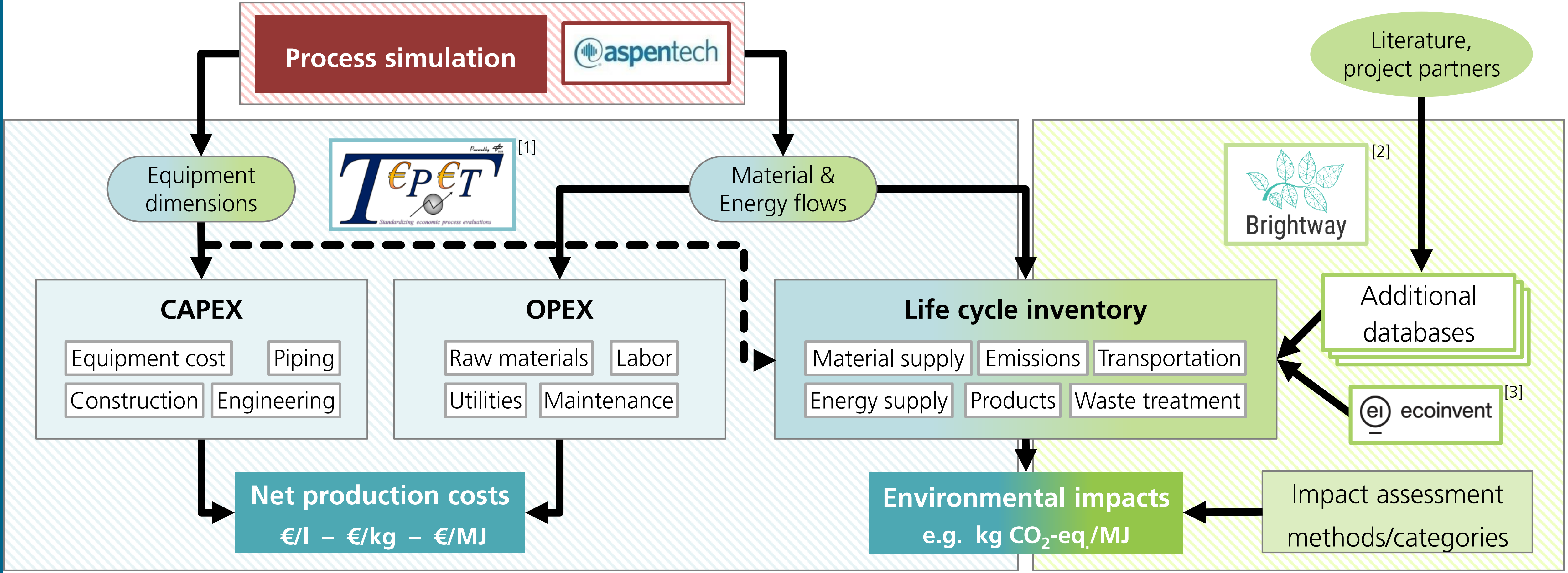
# Chapter Ecological Assessment

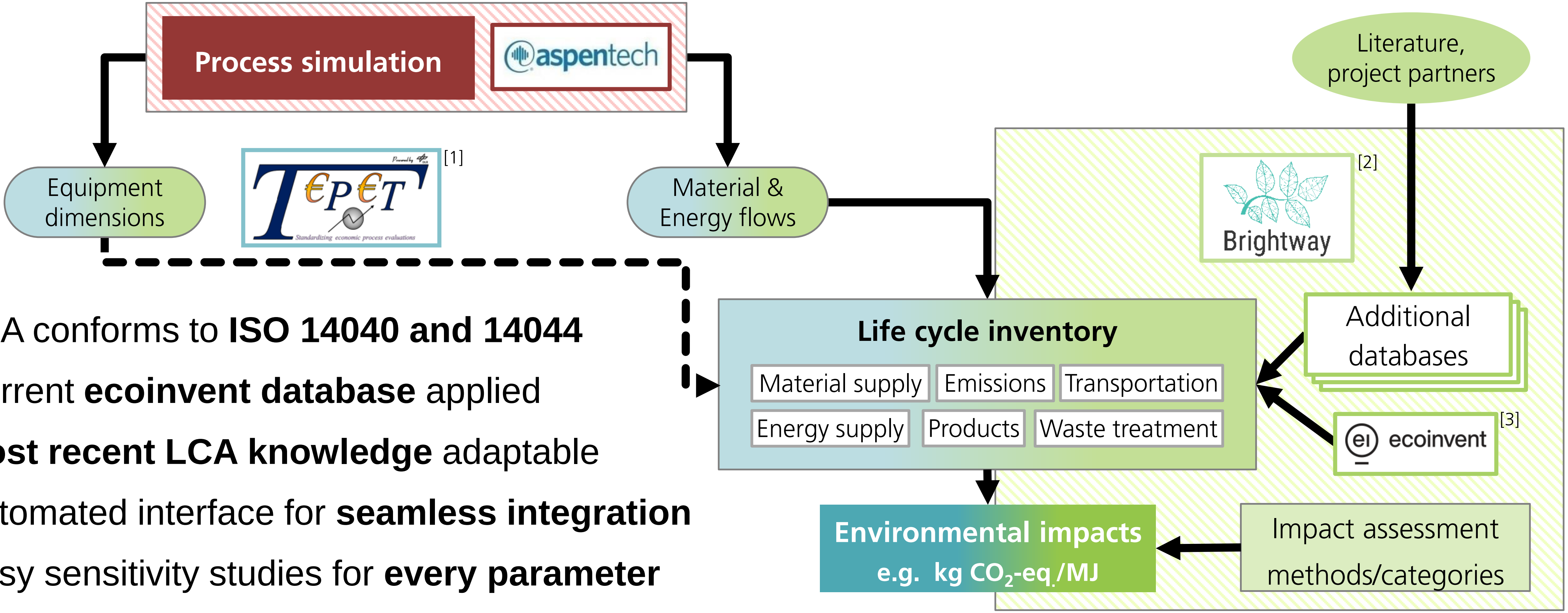


# TEEA tool TEPET @ DLR (part 2)




[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526
[2] Mutel (2017) - Brightway: An open source framework for Life Cycle Assessment, Journal of Open Source Software, 2(12): 236
[3] Wernet, G et al. (2016) – The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9): 1218–1230.

# TEEA tool TEPET @ DLR (part 2)




- LCA conforms to **ISO 14040 and 14044**
- Current **ecoinvent database** applied
- **Most recent LCA knowledge** adaptable
- Automated interface for **seamless integration**
- Easy sensitivity studies for **every parameter**


[1] Albrecht et al. (2016) - A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel, 194: 511-526
[2] Mutel (2017) - Brightway: An open source framework for Life Cycle Assessment, Journal of Open Source Software, 2(12): 236
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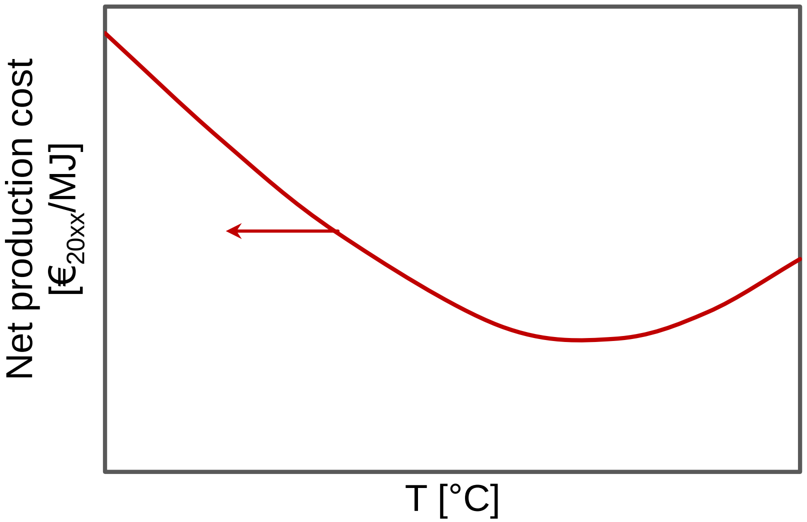
# Example results: Ecological evaluation of BtL production
## LCA impact category variety

- Extending from just one economic parameter

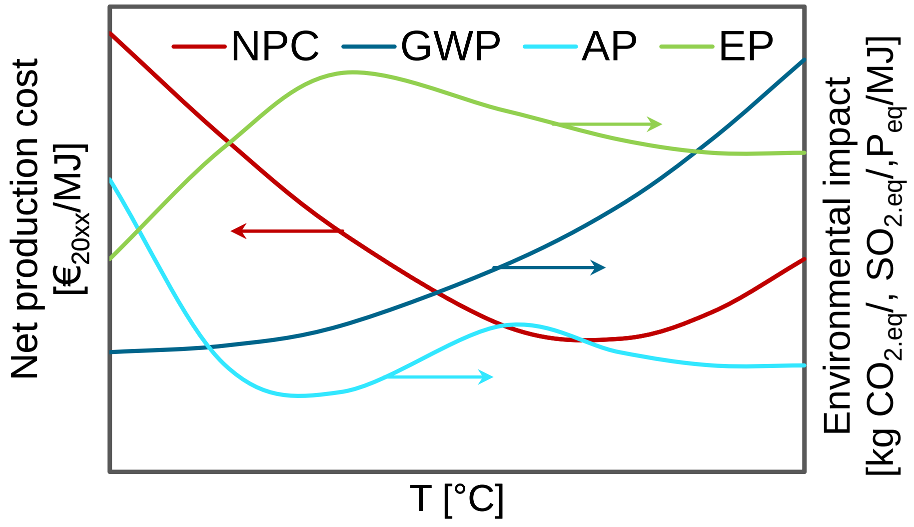



Schematic net production cost (NPC) dependency of a particular process parameter (e.g. gasifier, reformer temperature etc.)

# Example results: Ecological evaluation of BtL production
## LCA impact category variety

- Various impact categories determine LCA

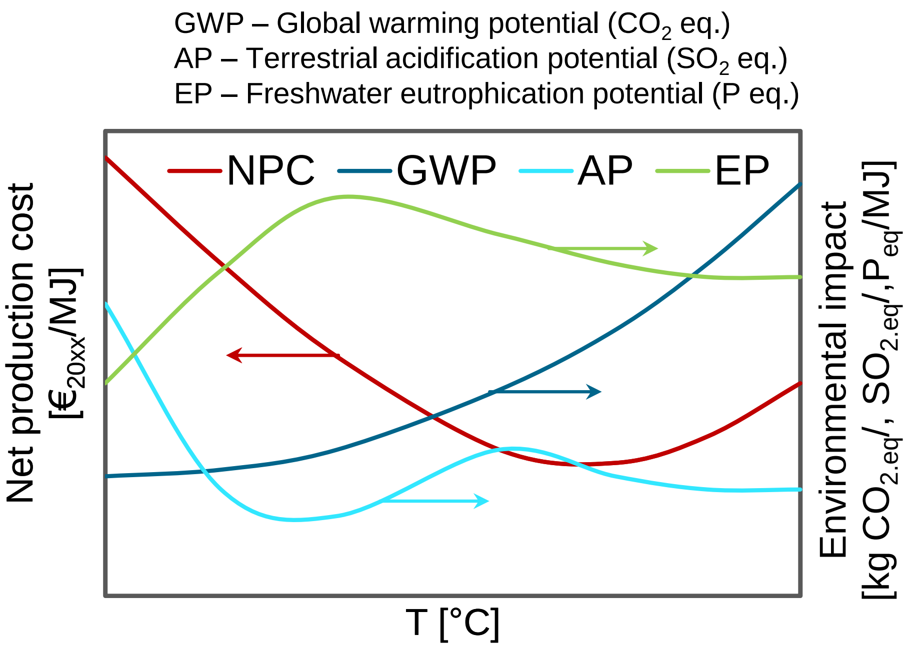
GWP – Global warming potential ($CO_2$ eq.)
AP – Terrestrial acidification potential ($SO_2$ eq.)
EP – Freshwater eutrophication potential (P eq.)




Schematic net production cost (NPC) and environmental impacts dependency of a particular process parameter (e.g. gasifier, reformer temperature, etc.)

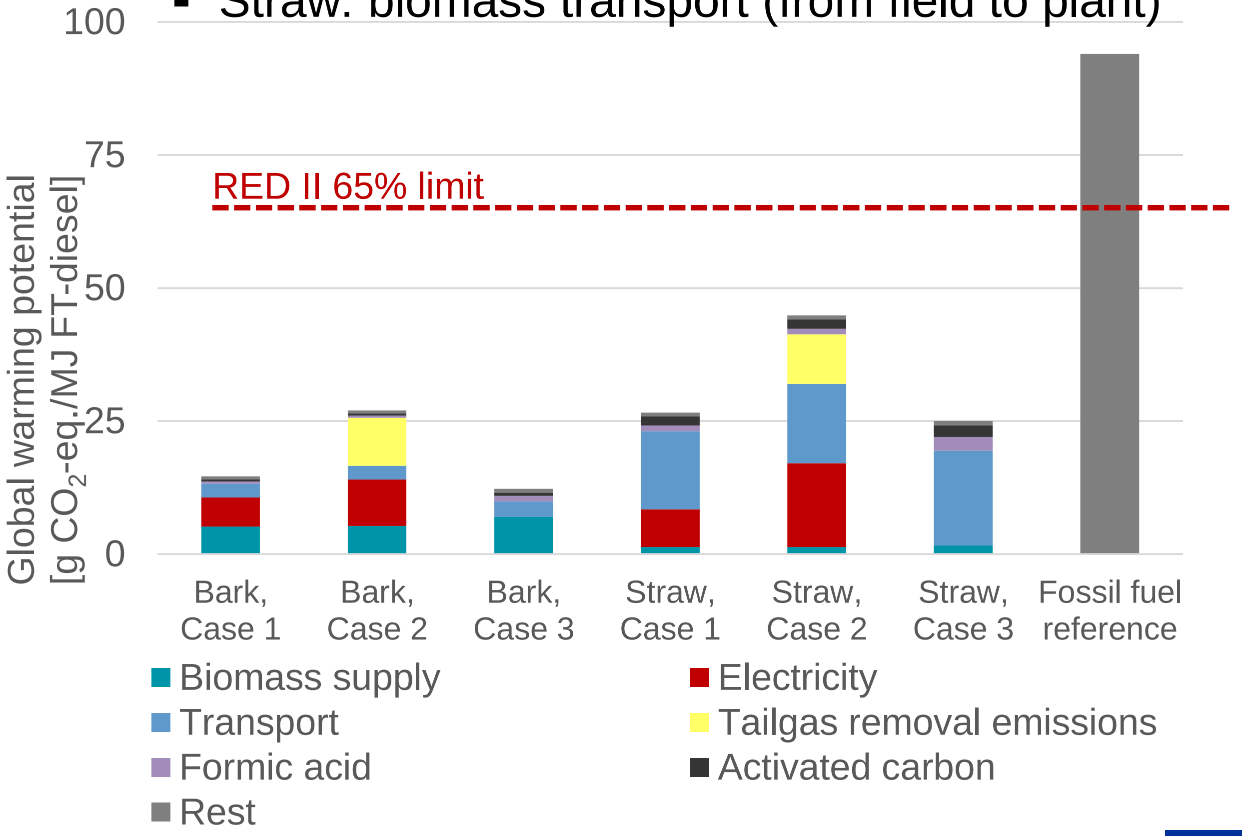
# Example results: Ecological evaluation of BtL production
## GWP assessment of feedstocks and process design cases

- Various impact categories determine LCA




Schematic net production cost (NPC) and environmental impacts dependency of a particular process parameter (e.g. gasifier, reformer temperature, etc.)

- Different major impact drivers
  - Bark: biomass supply (harvesting)
  - Straw: biomass transport (from field to plant)




COMSYN

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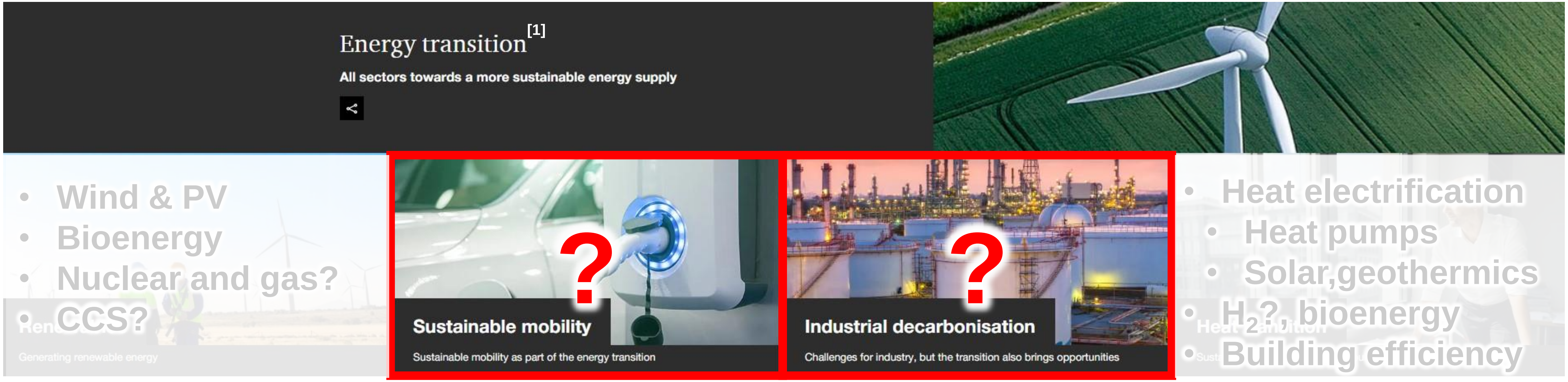
# Energy transition demand – affecting the entire society
## Assessing energy transition options, opportunities, challenges




- Wind & PV
- Bioenergy
- Nuclear and gas?
- CCS?

- Heat electrification
  - Heat pumps
  - Solar,geothermics
- $H_2$?, bioenergy
- Building efficiency

**→Standardized methodology for LCA and TEA**

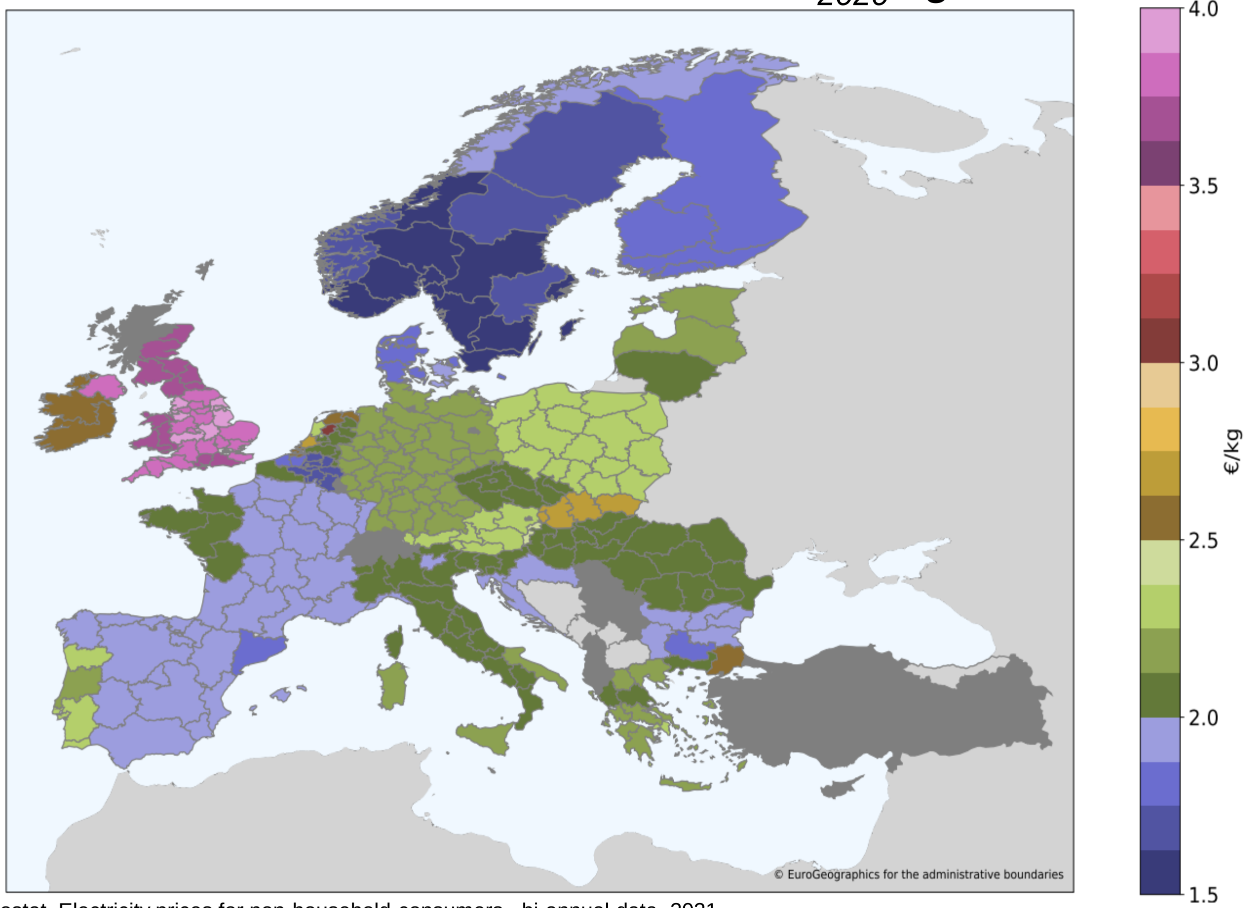
**Support of various energy transition options**

[1] https://www.pwc.nl/en/topics/sustainability/energy-transition.html

# TEEA results supporting Energy transition options
## Sustainable Aviation Fuels for Europe

### PBtL kerosene roll out costs

*Net Production Costs of PBtL SAF / €$_{2020}$/kg:*




**Northern EU's inexpensive electricity: Lowest NPC**

- National electricity prices from [1]
- Biomass prices from [2]
- Transport distance as a function of biomass density
- Nation-specific transport and labor costs



[1] Eurostat, Electricity prices for non-household consumers - bi-annual data. 2021.
[2] Ruiz, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., ... & Thrän, D. (2019). ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Reviews*, *26*, 100379.

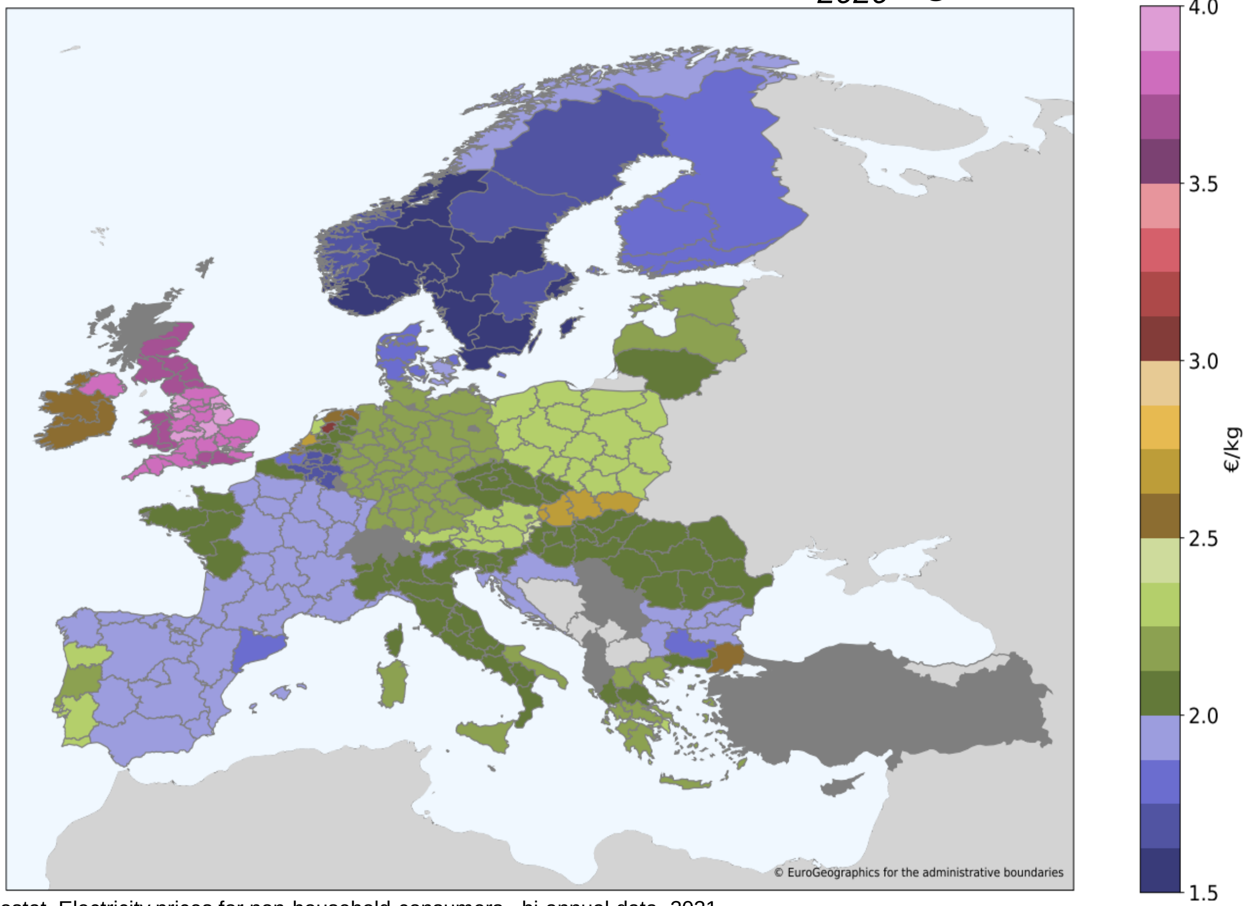
# TEEA results supporting Energy transition options

## Sustainable Aviation Fuels for Europe

Felix Habermeyer @ processnet:
Energy Transition IV, Room K 3
Power and Biomass to Liquid – An option for Europe's sustainable and independent aviation fuel production

### PBtL kerosene roll out costs

*Net Production Costs of PBtL SAF / €$_{2020}$/kg:*

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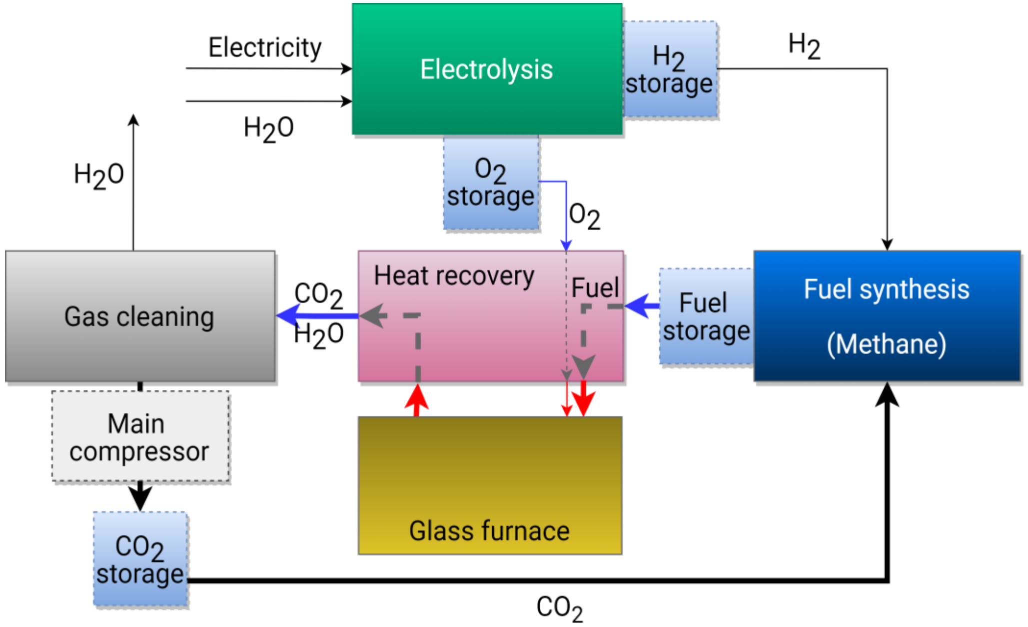
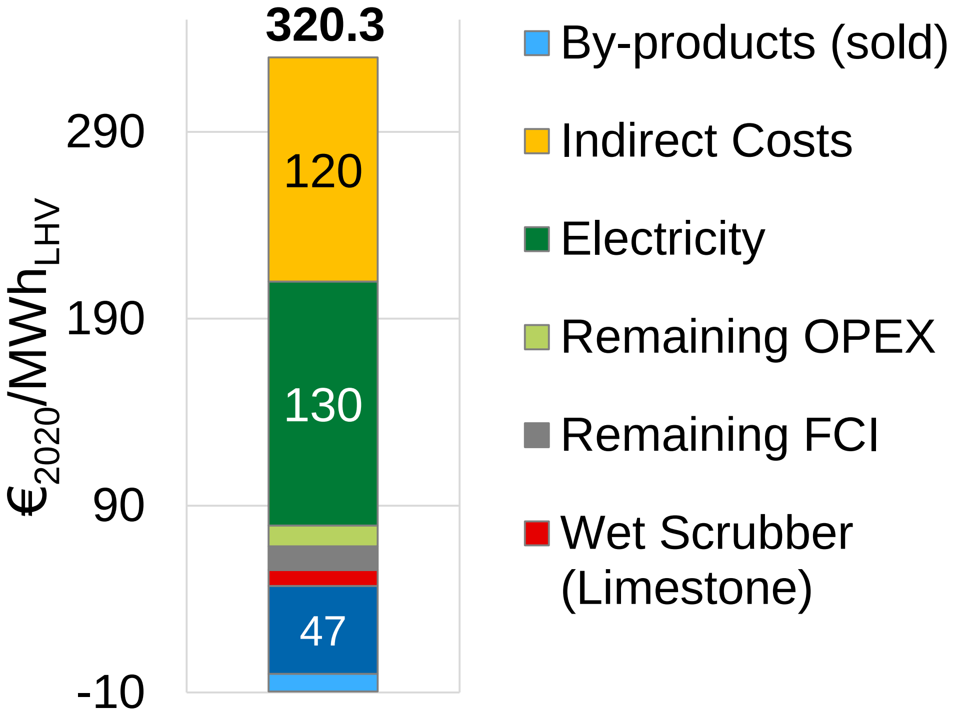
# TEEA results supporting Energy transition options
## Decarbonization of glass furnace

### Glas-$CO_2$ (Methane)




Ref.: F. Drünert (HVG), F. Moser (DLR) - Closed CO2 cycle in the container glass production

Breakdown of NPC




- CCU of an **oxyfuel** glass furnace (container glass)

$CH_4$ ➔ $CO_2$ ➔ $CH_4$

- Surplus of $CO_2$ from carbonates also converted

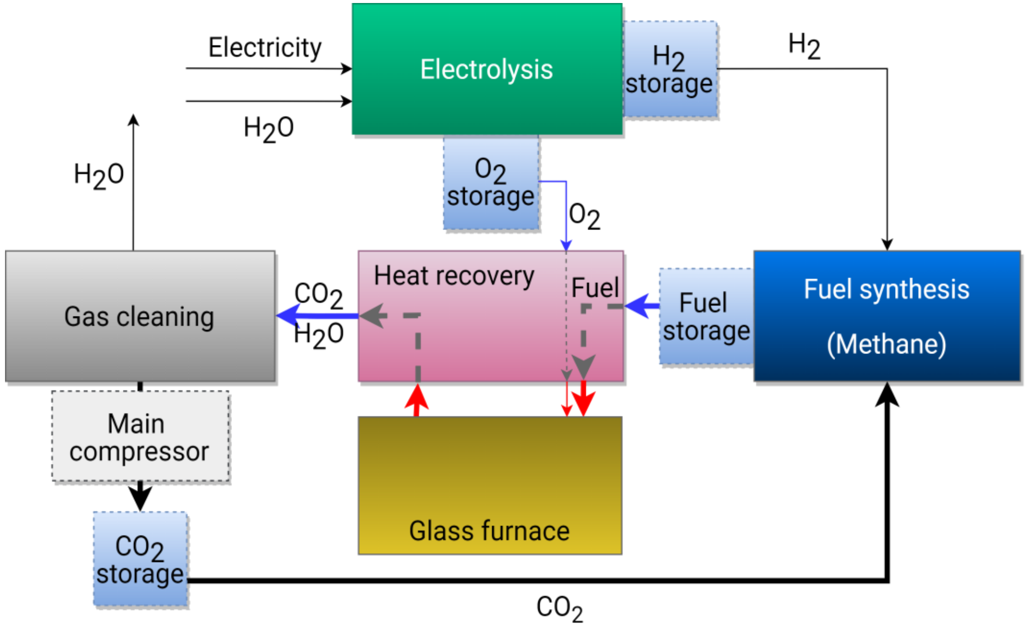
# TEEA results supporting Energy transition options

## Decarbonization of glass furnace

Francisco Moser @ processnet: Energy Transition IV, Room K 3

Closed CO2 cycles in the glass production – A techno-economic evaluation

### Glas-$CO_2$ (Methane)

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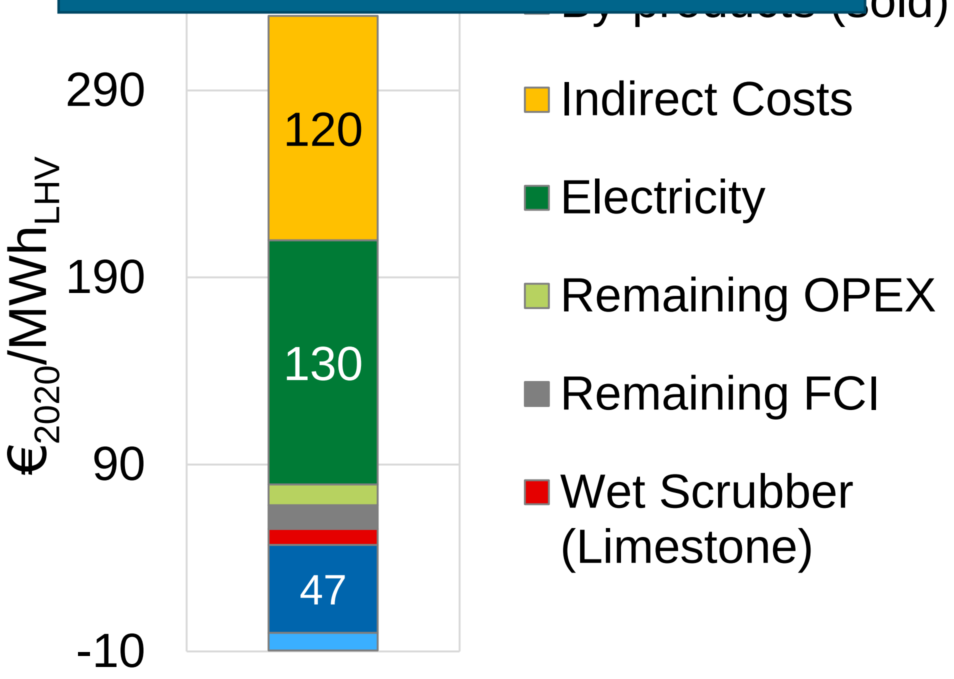



- CCU of an **oxyfuel** glass furnace (container glass)

$CH_4$ ➔ $CO_2$ ➔ $CH_4$

- Surplus of $CO_2$ from carbonates also converted

NPC: 320 $[€_{2020}/MWh]$ ↔ 0.40 $[€_{2020}/kg_{Glass}]$

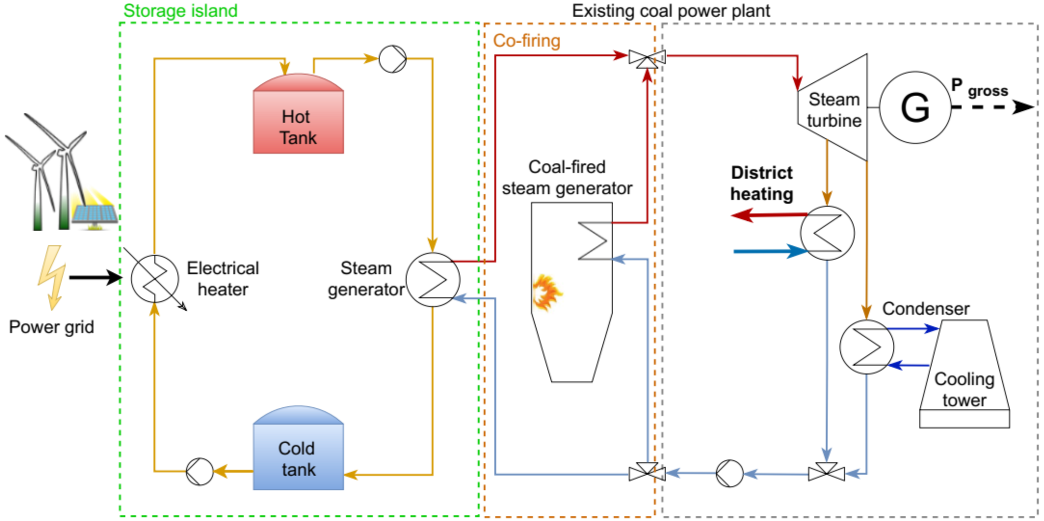
Fossil: 8.9 $[€_{2020}/MWh]$[1] ☛ 305 $[€_{2022}/MWh]$[2]

[1] Tradingeconomics (2022) https://tradingeconomics.com/commodity/eu-natural-gas
[2] www.bundesnetzagentur.de/.../220826_gaslage.pdf, 26.08.22

# TEEA results supporting Energy transition options
## $2^{nd}$ life coal power plants

### Revamp costs / benefits

Heat-storage power plant (HSPP), option for global power supply transition




- Turn RE into demand driven base load
- Round-trip efficiency ~40%
- District heating can also be provided

# TEEA results supporting Energy transition options

## 2nd life coal power plants

### Revamp costs / benefits

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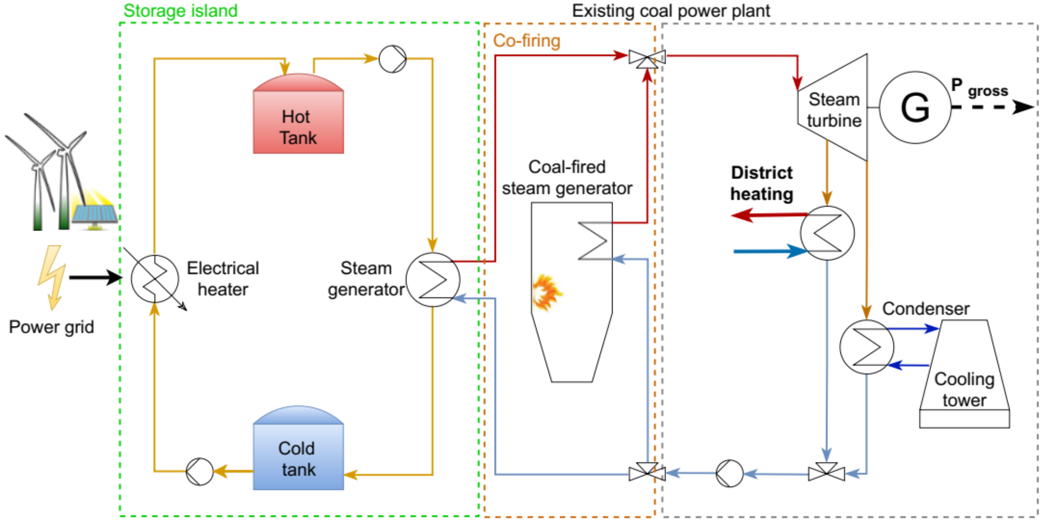
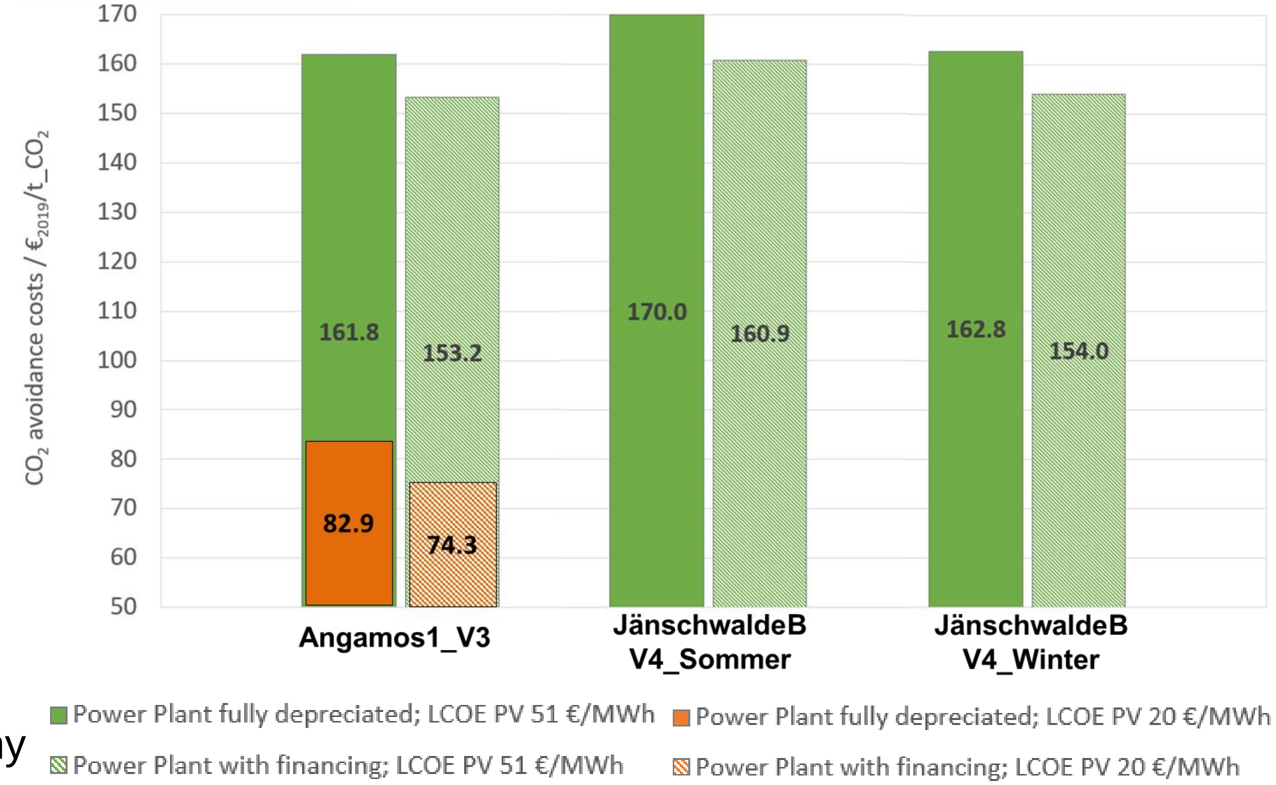



- Turn RE into demand driven base load
- Round-trip efficiency ~40%
- District heating can also be provided
- **$CO_2$ avoidance costs** for 2000+ coal power plant sites
  - Examples: Angamos, Chile & Jänschwalde, Germany
  - Angamos: **better PV potential** than Jänschwalde



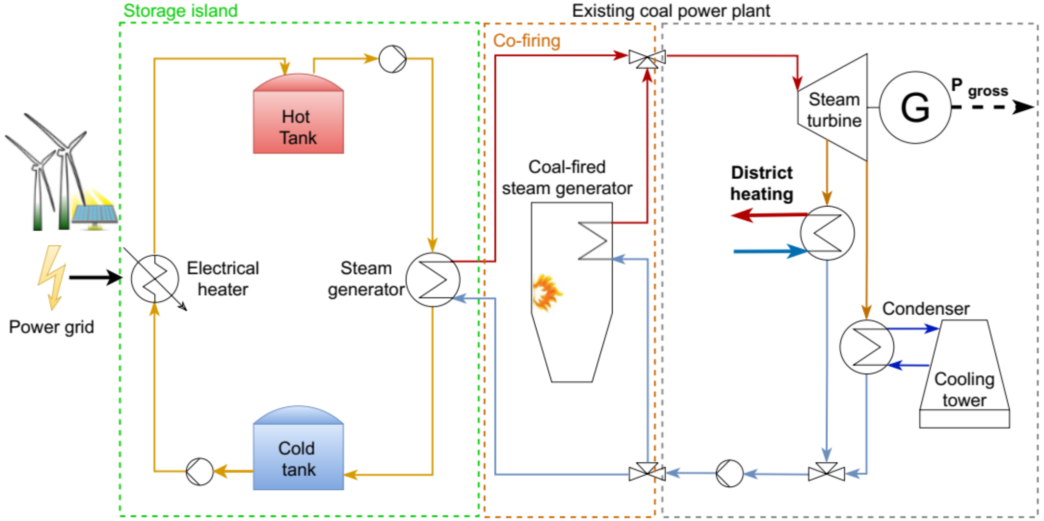
# TEEA results supporting Energy transition options

## 2nd life coal power plants

Yoga Rahmat @ processnet:
Energy Transition XYZ
Next conference?

### Revamp costs / benefits

Heat-storage power plant (HSPP), option for global power supply transition

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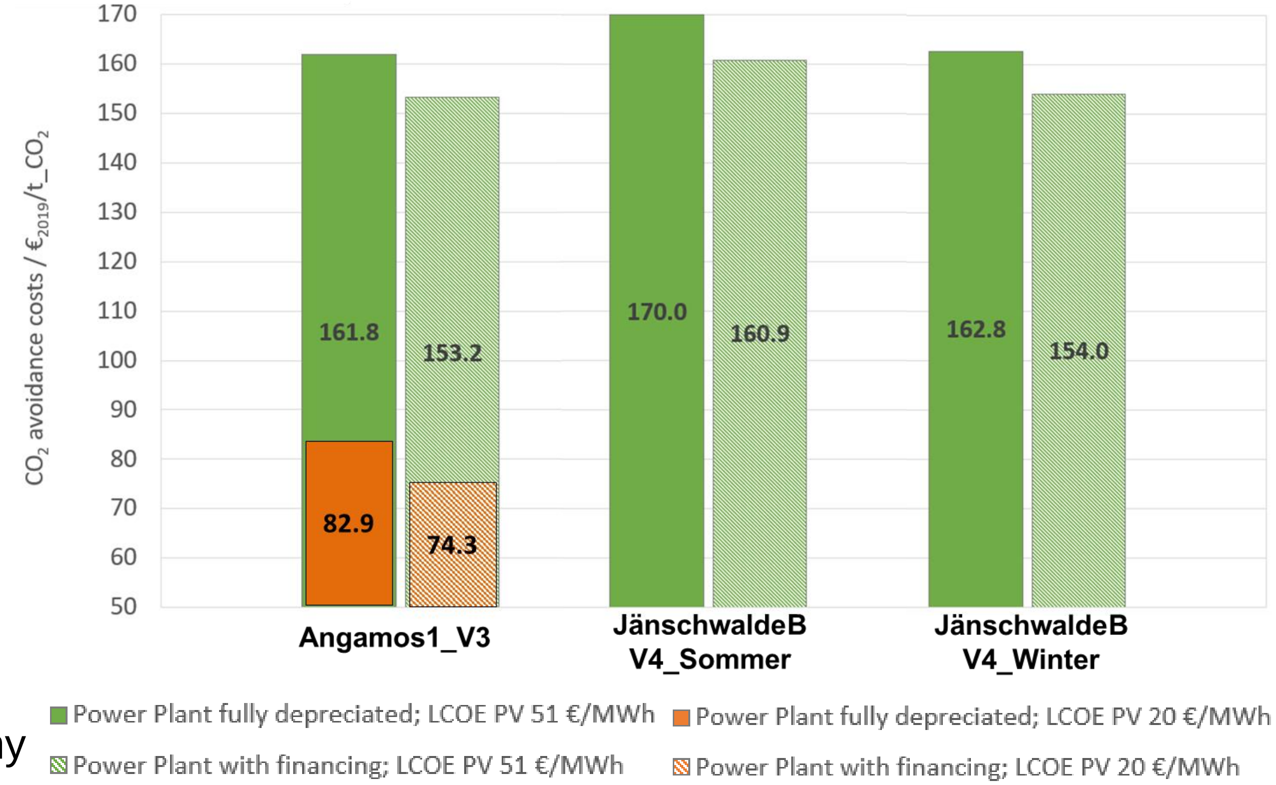


# TEEA results supporting Energy transition options

## Summary

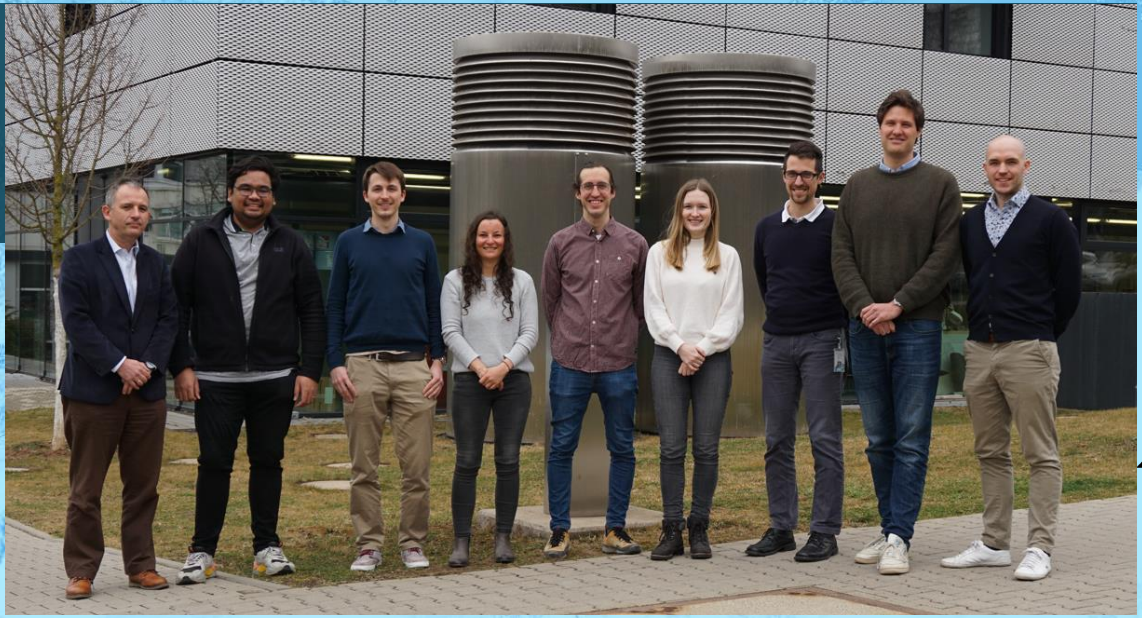
- Transparent, standardized techno-economic and environmental assessment of renewable energy applications is key for societal acceptance
  - Renewables often not competitive to fossil energy ➔ subsidies, regulation?

- Valid process simulation is the basic requirement for valid assessment
- All assumptions and boundary conditions must be disclosed
- Most process equipment have viable rough cost data, new equipment needs adaptation

- DLR methodology is widely accepted for different questions regarding energy transition
  - Examples are presented in detail e.g. at the ProcessNet
- Energy transition includes energy usage (transport, industry, …) – partners requires


# TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT OF ENERGY TRANSITION OPTIONS

**Thanks to the team.**
**Thank you for your attention.**
**Questions?**



Sandra Adelung, Felix Habermeyer, Nathanael Heimann; Simon Maier, Francisco Moser, Moritz Raab, Yoga Rahmat, Julia Weyand, <u>Ralph-Uwe Dietrich</u>

DLR