Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Solar hydrogen and fuels production with concentrated solar energy

European Hydrogen Energy Conference

EHEC 2022 – 18-20 May 2022 Madrid, Spain

A. Rosenstiel, N. Monnerie, M. Roeb and C. Sattler

German Aerospace Center (DLR), Institute of Future Fuels

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Outline

- Introduction
- Overview of concepts for solar fuel production
- Simulation and results
  - Concept 1
  - Concept 2
- Summary and Outlook

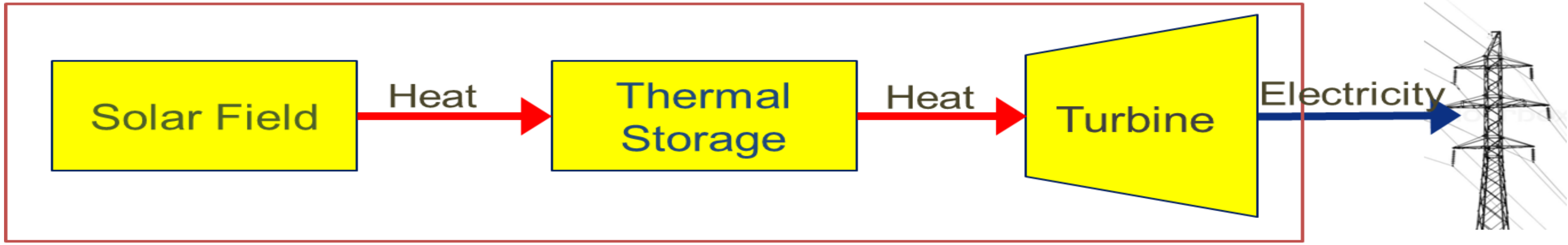
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Introduction









Carbon dioxide (CO_2)

Water (H_2O)

Synthesis gas

(H_2 + CO)

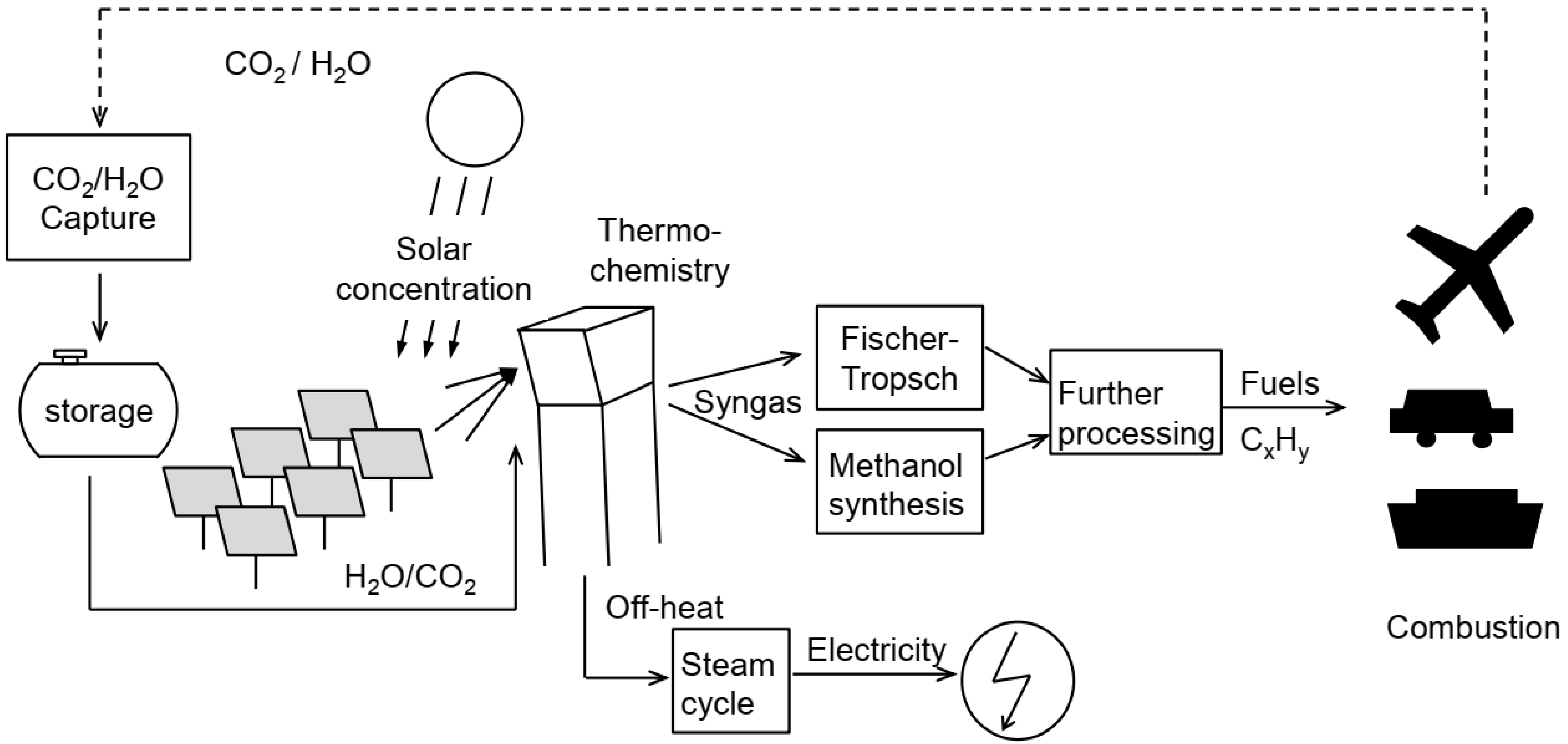

Future Fuels…

e.g. Fischer-Tropsch-Plant

-> high energy density makes liquid fuels vital for the energy and transportation sectors in the near future, especially for long transport with truck or by aviation sector

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

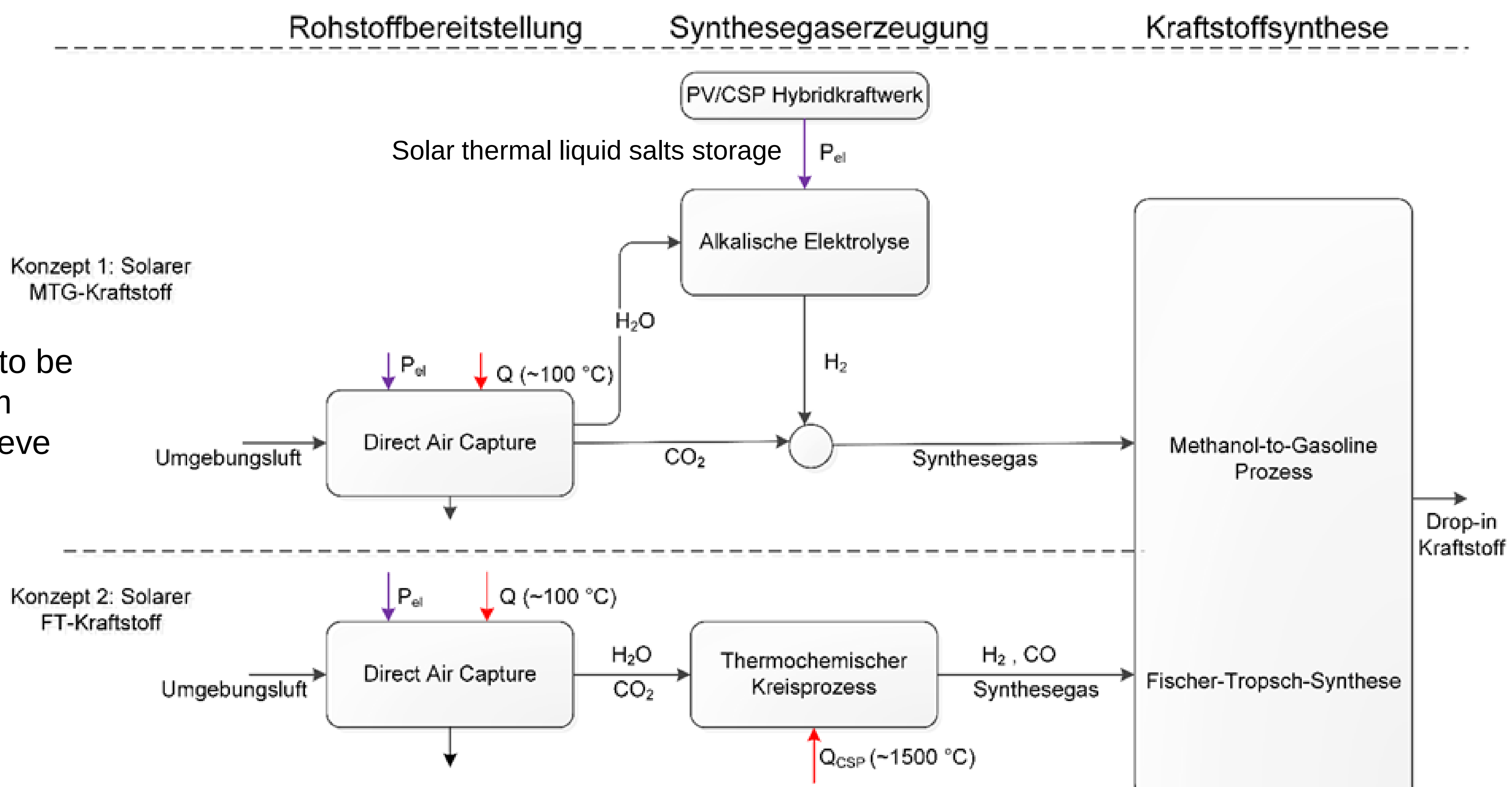
Motivation



Identify promising production pathways for solar hydrogen and other solar fuels

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Overview of concepts for solar synthesis gas production



DAC: potential to be useful long term solution to achieve net0 emission

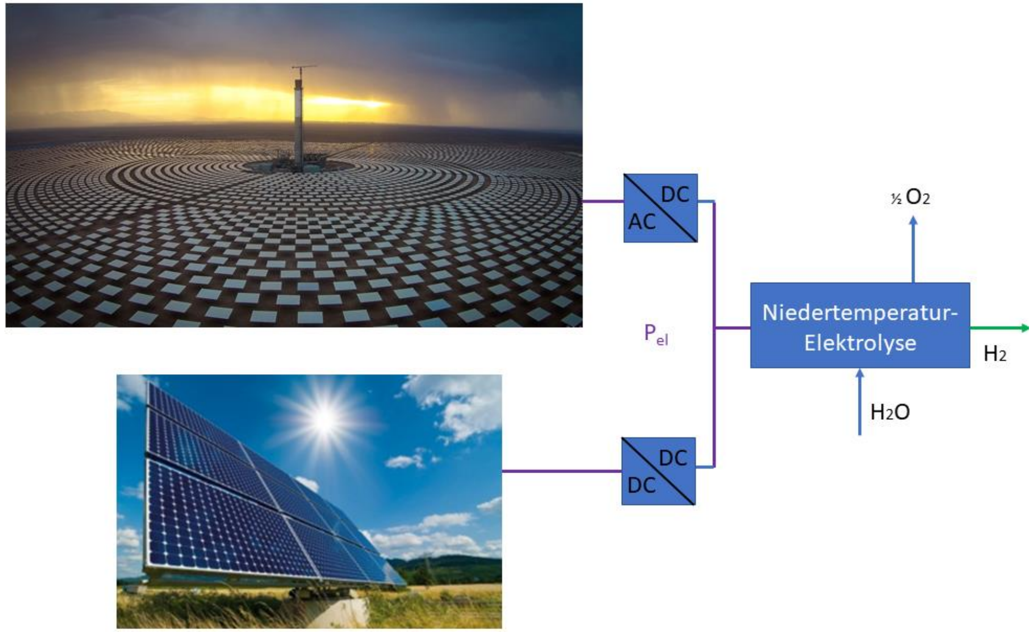
-> Process simulation modeling have been developed

-> Entire process chain of solar-produced fuels has been evaluated

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results

Concept 1 - PV/CSP hybrid power plant and low-temperature electrolysis



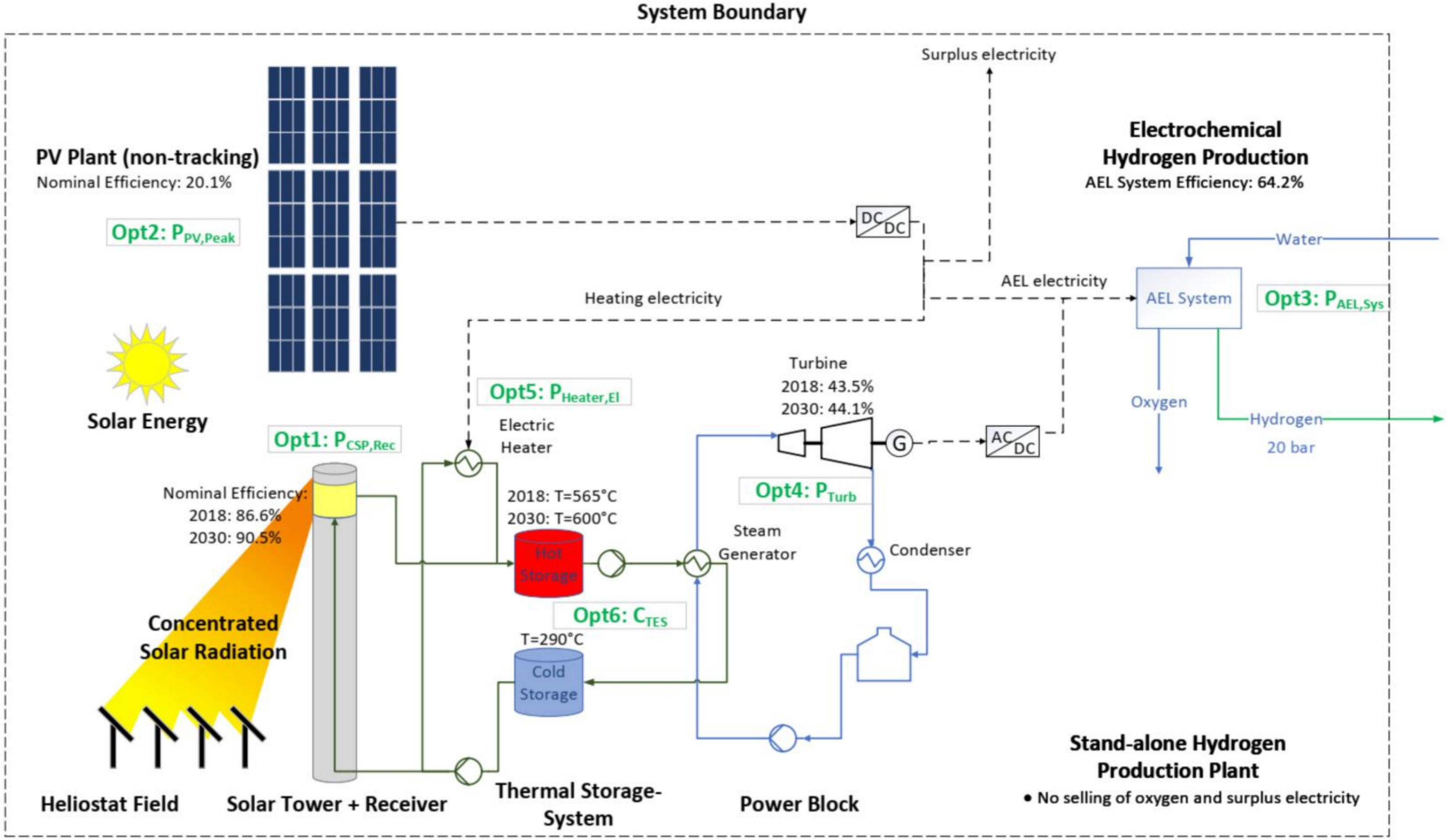
- By coupling: combination of advantages of both technologies:
- Low PV electricity generation costs
- Low costs for thermal liquid salt storage
- High full load hours with low electricity generation costs

- Direct synthesis of methanol from CO_2 and hydrogen
- H_2/CO_2 in a molar ratio of 3:1
- Electricity demand for CO_2 supply also covered by PV/CSP hybrid power plant

Combination of CSP with thermal liquid salt storage with PV power plant
-> Achievment of a relatively continuous power supply for AEL and other process units

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

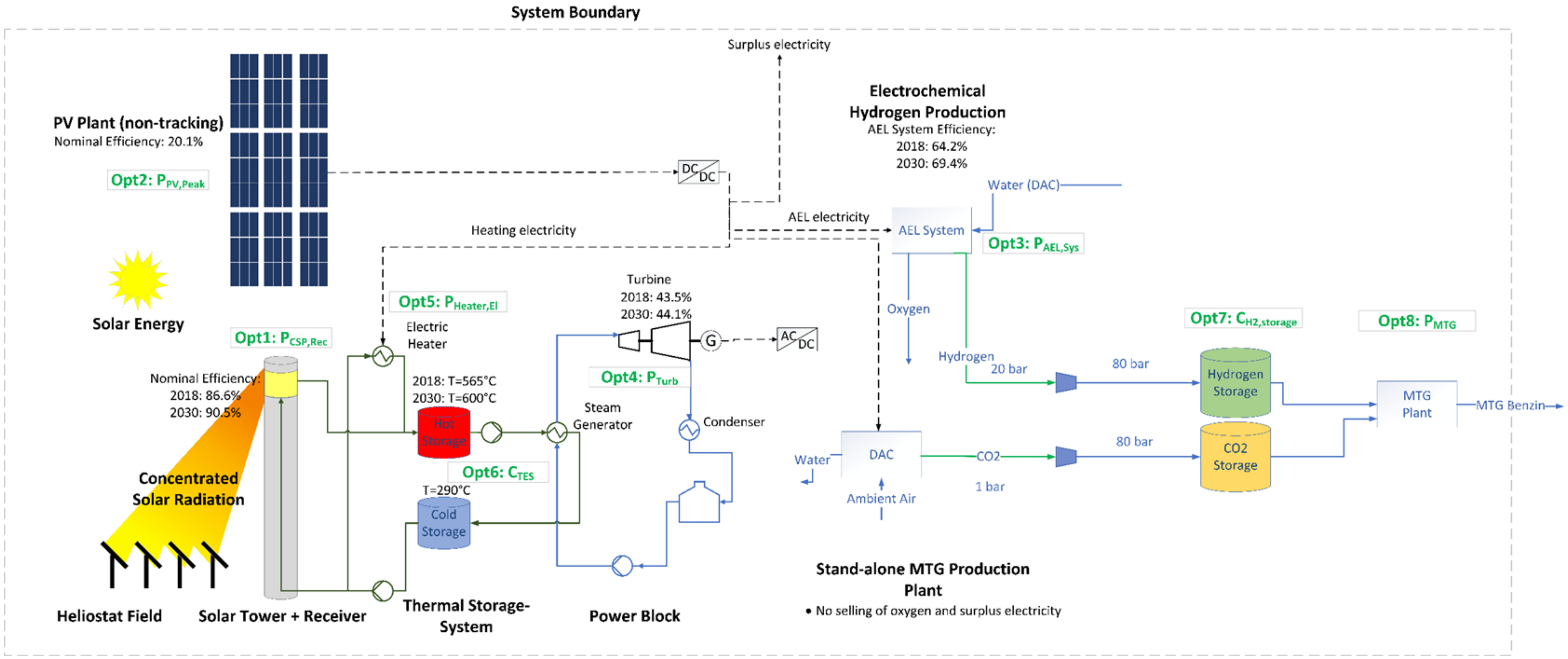
Simulations and results
Concept 1 - Flow diagram PV/CSP hybrid power plants



- PV plant: electricity production depending on the instantaneous solar irradiance
- CSP electricity production can be adapted to the demand
- Aim: combination of PV and CSP electricity production in the best way for cost-optimal operation of the alkaline electrolyser system

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results
Concept 1 - Flow diagram PV/CSP hybrid power plants



Coupling solar H2 production to MtG plant
Continuous gasoline production process

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

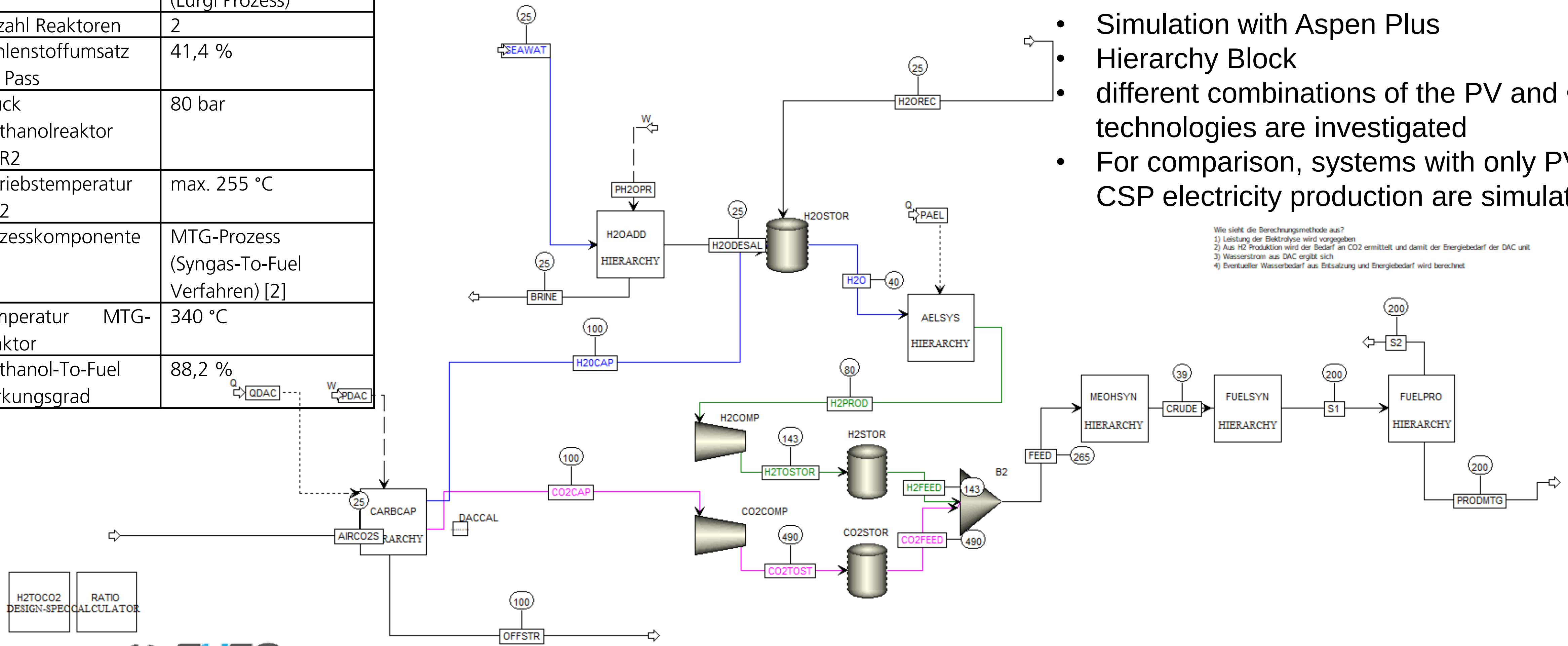
Simulations and results

Concept 1 - Process simulation: Hierarchy MTG process material

Prozesskomponente	Methanolsynthese (Lurgi Prozess)
Anzahl Reaktoren	2
Kohlenstoffumsatz per Pass	41,4 %
Druck Methanolreaktor R1/R2	80 bar
Betriebstemperatur R1/2	max. 255 °C
Prozesskomponente	MTG-Prozess (Syngas-To-Fuel Verfahren) [2]
Temperatur MTG-Reaktor	340 °C
Methanol-To-Fuel Wirkungsgrad	88,2 %

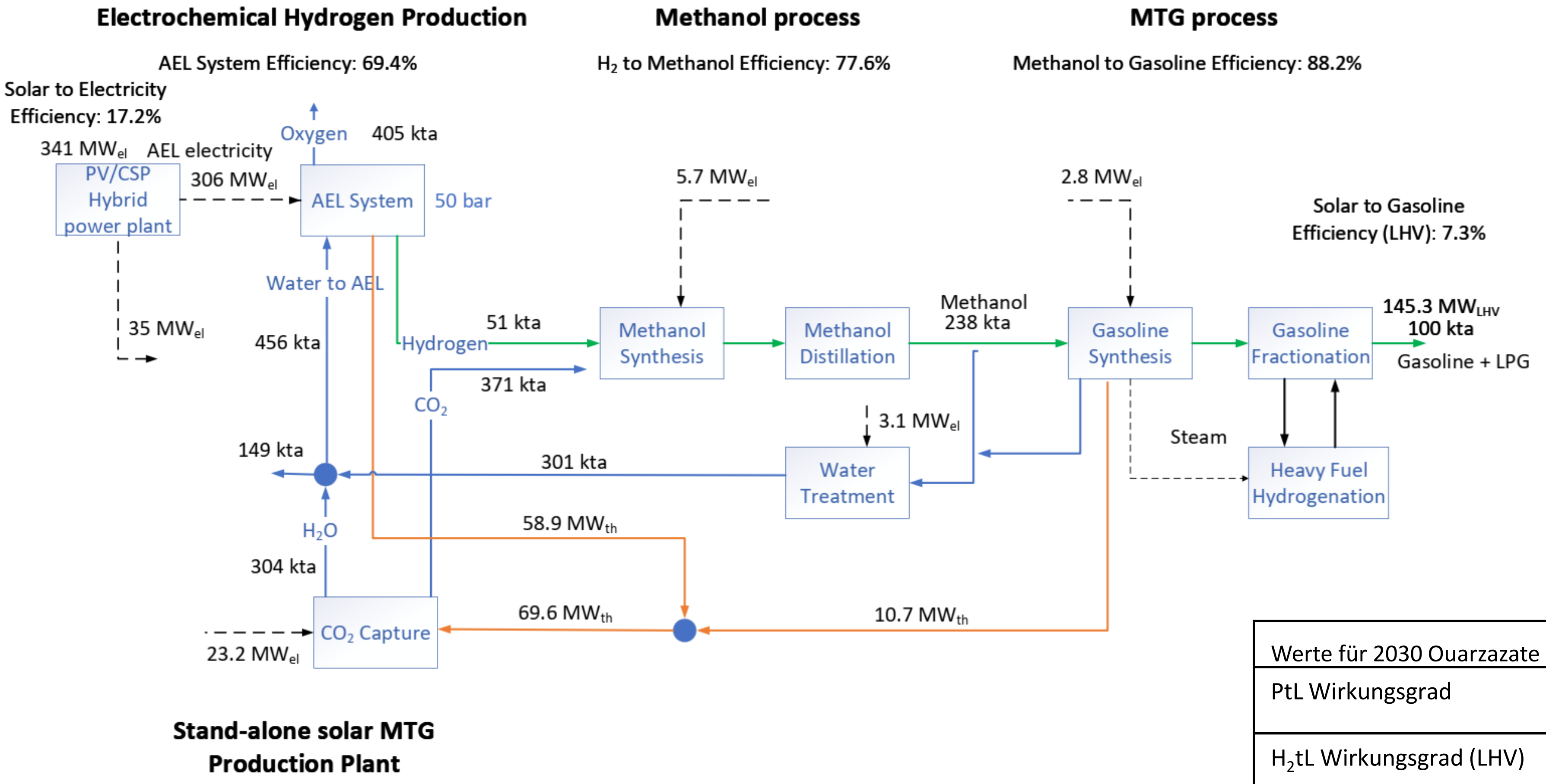
- Simulation with Aspen Plus
- Hierarchy Block
- different combinations of the PV and CSP technologies are investigated
- For comparison, systems with only PV or CSP electricity production are simulated

Wie sieht die Berechnungsmethode aus?
1) Leistung der Elektrolyse wird vorgegeben
2) Aus H2 Produktion wird der Bedarf an CO2 ermittelt und damit der Energiebedarf der DAC unit
3) Wasserstrom aus DAC ergibt sich
4) Eventueller Wasserbedarf aus Entsalzung und Energiebedarf wird berechnet



Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results
Concept 1 - Energy flow diagram of the overall process



Werte für 2030 Ouarzazate	
PtL Wirkungsgrad	47,5%
H_2tL Wirkungsgrad (LHV)	68,4%

Overall efficiency from solar to gasoline: 7,3%

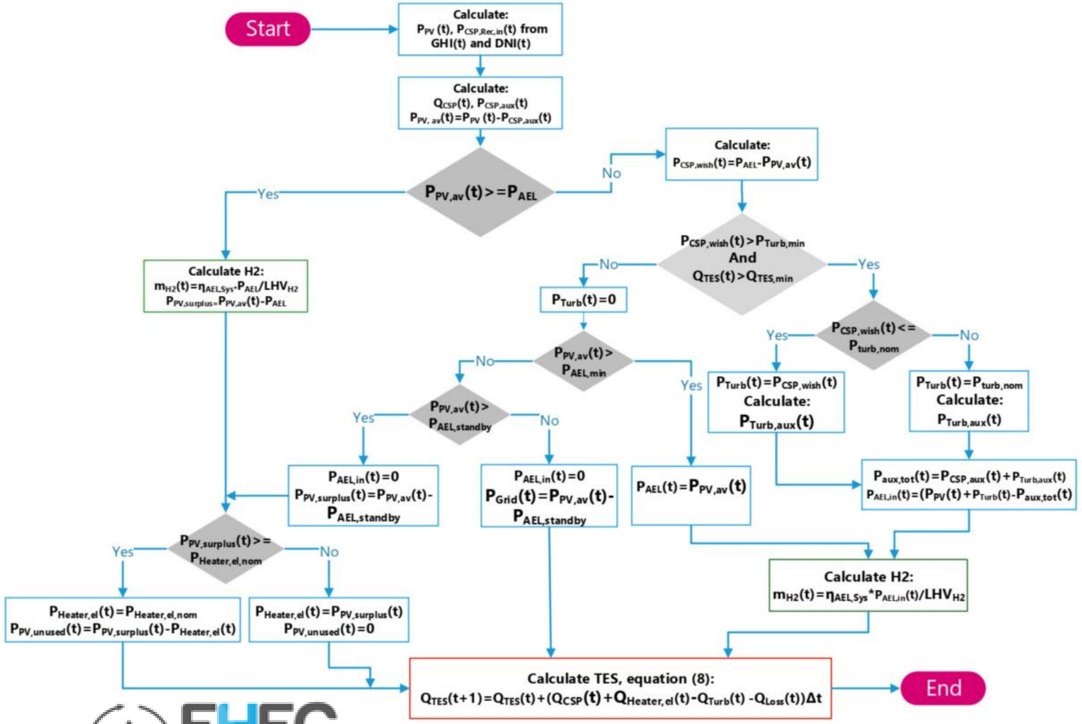
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

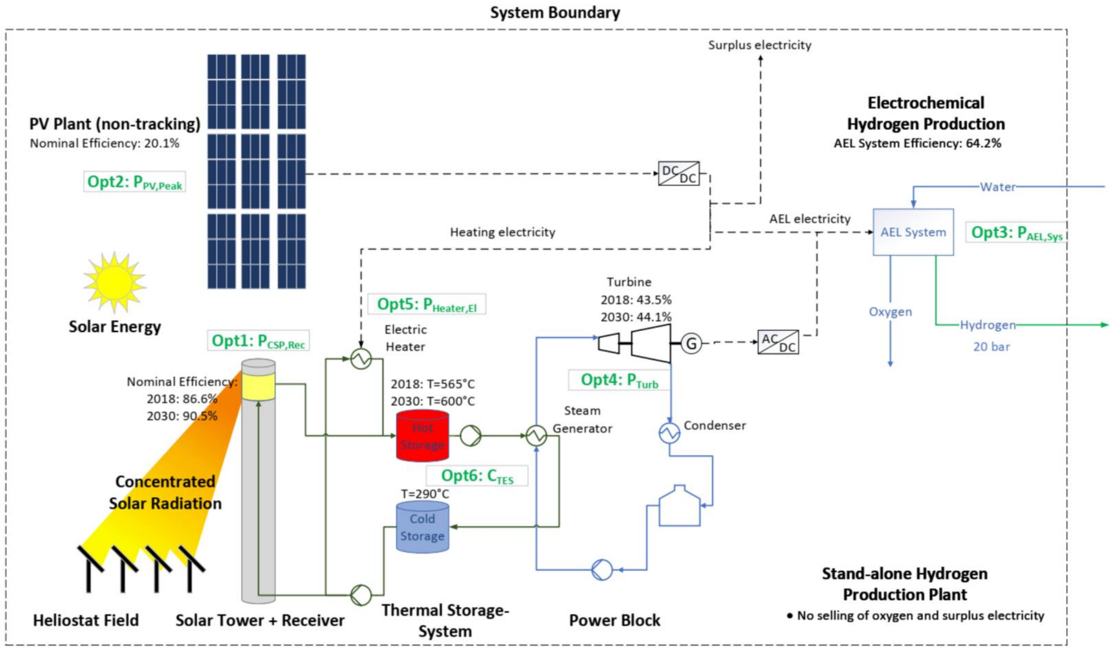
Simulations and results
Concept 1 - Techno-economic model

- dynamic annual simulations (temporal resolution of 1 h)

Overall plant design optimization approach:
Minimisation of product costs:

$$\min(LCOH) = f\,(P_{CSP,Rec}, P_{PV,Peak}, P_{AEL}, P_{Turb}, C_{TES}, P_{Heater,el})$$



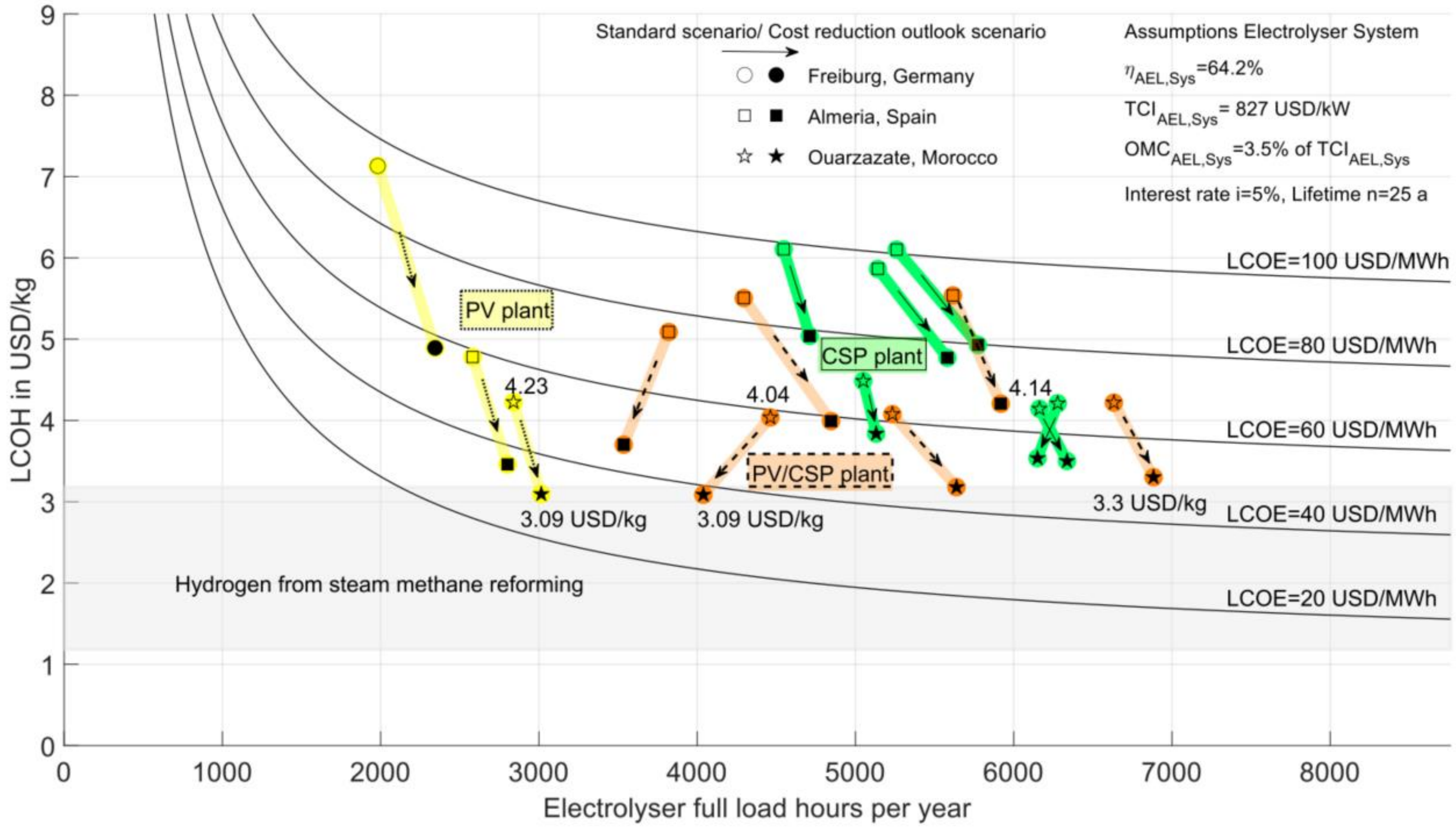


Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results
Concept 1 - Results Minimisation of hydrogen production costs



- influence of different solar resources
- Local price index for installation of solar equipment
- Freiburg: only PV
- CSP: for a DNI in the range of 2000 kWh/m2a and above
- 2 cost scenarios: today and scenario which considers the possible cost reductions until 2030
- -> today: lowest hydrogen costs :4.04 USD/kgH2 with AEL powered by a hybrid PV/CSP plant
- -> 2030: 3.09 USD/kg
- Selling of surplus electricity and of O2 as a by-product is not considered

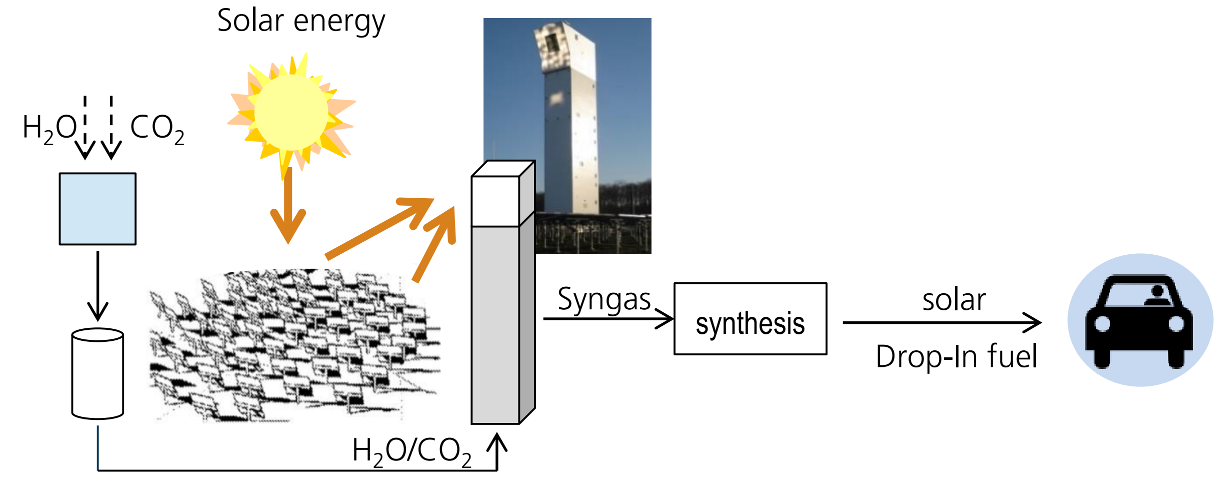
DLR

EHEC 2022 EUROPEAN HYDROGEN ENERGY CONFERENCE

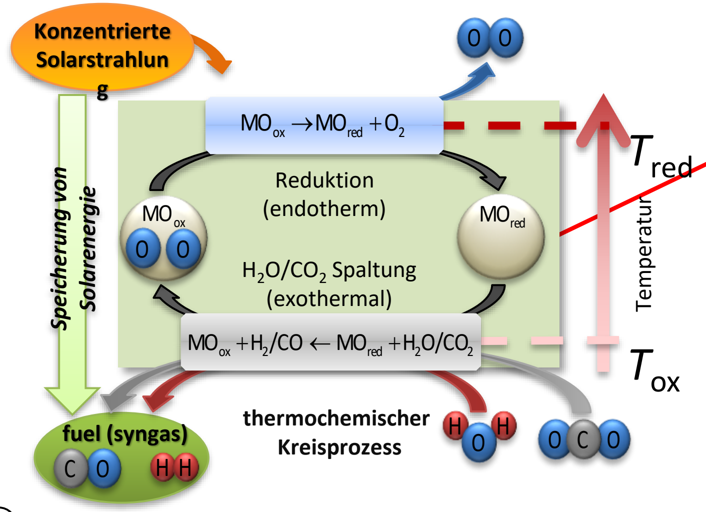
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results

Concept 2 - Solar thermochemical hydrogen and synthesis gas production



CO_2/H_2O storage | Thermochemical transformation | Fuel Design | Performance | Emission control



Source: sun-to-liquid.eu

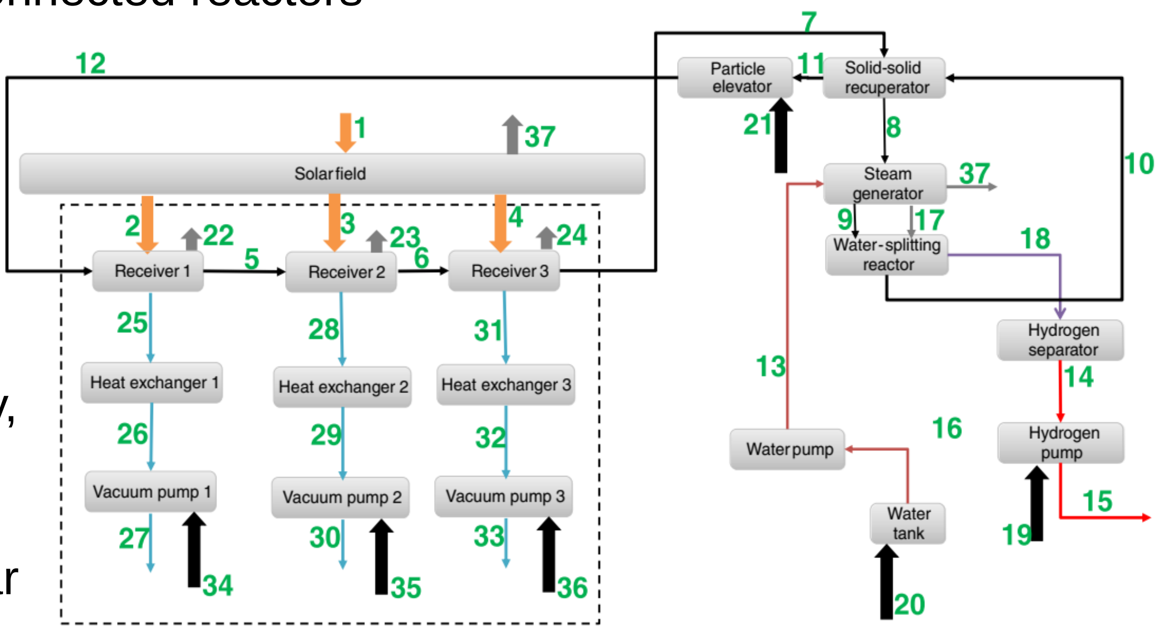
- Direct synthesis gas generation with solar high-temperature heat
- High potential in the mid-long term
- Synthesis gas then converted into a syncrude in a low-temperature Fischer-Tropsch process, from which the Fischer-Tropsch fuel is obtained through subsequent processing

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results

Concept 2 - Solar thermochemical hydrogen and synthesis gas production

- Based on an innovative thermochemical cycle and on a thermochemistry model with 3 receivers
- CeO_2 operating at 1773 K and 1300 K for reduction and oxidation step
- Faster kinetics and better stability and selectivity
- Particle form
- Carrying out of the reduction of cerium oxide in series-connected reactors
- Reduce the required vacuum pump work and to achieve thus higher efficiency in hydrogen or synthesis gas production
- Production of synthesis gas as continuously as possible
- 2 storage units provided in the process:
  - 1 for reduced particles to achieve a relatively continuous particle flow for the synthesis gas supply, which also enables continuous heat extraction
  - 1 for oxidised particles to adapt the particle flow to the reduction reactors to the currently available solar supply



Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results

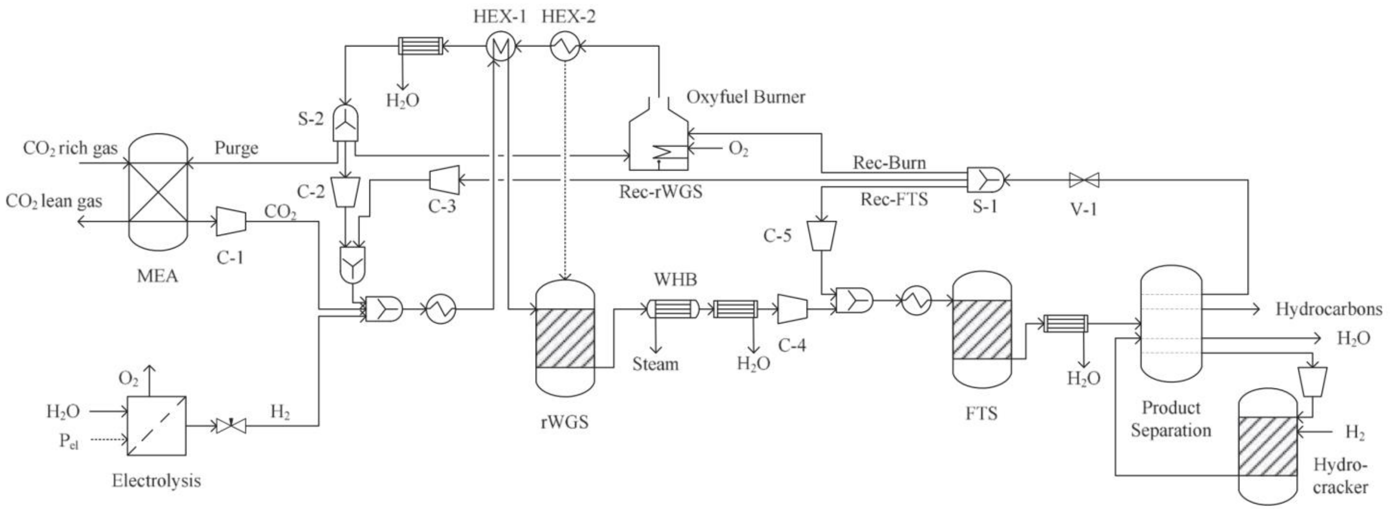
Concept 2 - Modelling Fischer-Tropsch process

- Modelling: approach Chain growth probability α as a function of reactor temperature and H_2/CO ratio

$$\alpha = \frac{1}{1 + 0.0567 \left(\frac{c_{H2}}{c_{CO}}\right)^{1.76} \exp\left(3620\ \mathrm{K}\left(\frac{1}{493.15\ \mathrm{K}}\right) - \left(\frac{1}{T}\right)\right)}$$

- Assumption: Only alkanes in the product

Prozesskomponente	Fischer-Tropsch Prozess (Cobalt-Festbett Reaktor)
Kettenwachstumsgeschwindigkeit α	83,9 %
CO-Umsatz [6]	40 %
Druck FT-Reaktor [6].	25 bar
Reaktortemperatur [6].	220 °C
Prozesskomponente	RWGS Reforming Reaktor
Temperatur RWGS-Reforming Reaktor	900 °C
Druck RWGS-Reforming Reaktor	1,5 bar
Prozesskomponente	Hydrocracker
Temperatur Hydrocracker [7]	370 °C
Druck Hydrocracker [7]	35 bar



(*) Vervoloet et al (2012), DOI: 10.1039/c2cy20060k
(**) Adelung et al (2020)´, https://doi.org/10.1016/j.seta.2020.100897

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results

Concept 2 – Coupling to solar thermochemical synthesis gas production with Fischer-Tropsch process

Reverse water-gas shift reaction

$H_2 + CO_2 \leftrightarrow CO + H_2O$

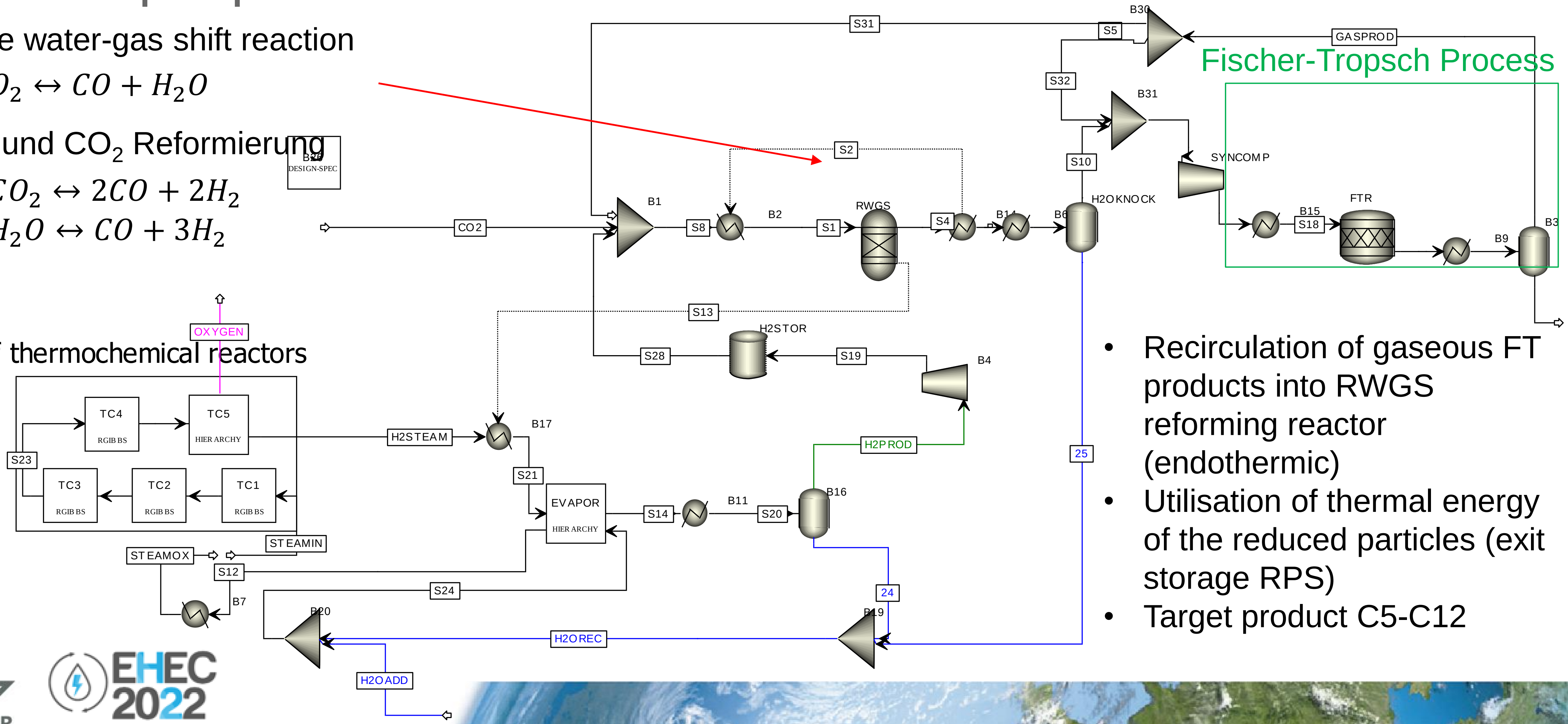
Dampf- und CO_2 Reformierung

$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$

$CH_4 + H_2O \leftrightarrow CO + 3H_2$

Array of thermochemical reactors

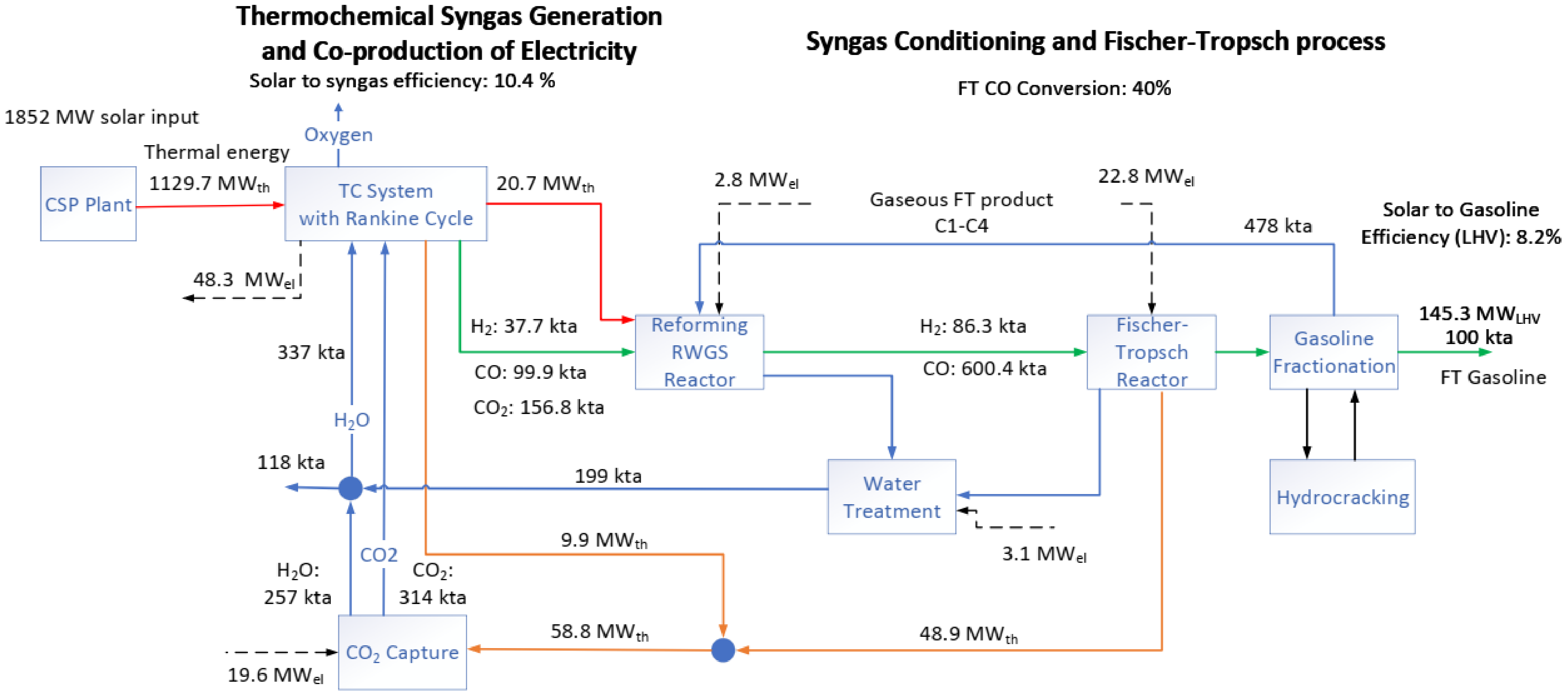
Fischer-Tropsch Process



- Recirculation of gaseous FT products into RWGS reforming reactor (endothermic)
- Utilisation of thermal energy of the reduced particles (exit storage RPS)
- Target product C5-C12

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Simulations and results
Concept 2 – Energy flow diagram solar thermochemical Fischer-Tropsch process



Stand-alone solar thermochemical Fischer-Tropsch gasoline plant

Location: Ouarzazate (Morroco)

Overall efficiency from solar to gasoline: 8,2%

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Summary and Outlook

- Two solar concepts have been investigated:
  - Concept 1: PV/CSP + alkaline electrolysis + Methanol-to-Gasoline: overall η:7.3%
  - Concept 2: solar thermochemical cycle + Fisher-Tropsch plant: overall η:8.2%

- Techno-economic model was developed:
  - H_2 Production cost (Concept 1): 3.09 USD/kg

- Final techno-economic / ecologic assessment
  - Consideration for three locations: Spain (Almeria), Morocco (Ouarzazate), United Arab Emirates.

- Optimised plant configuration for each site
  - Minimisation of the CO_2 footprint
  - Minimisation of product costs taking into account all positive boundary conditions in the economic efficiency

- Sensitivity analysis: influence of the use of carbon point source

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Thank you for your attention!

The authors of this paper gratefully acknowledge the funding of the project SolareKraftstoffe (Grant agreement Nr. 03EIV221) by the Federal Ministry for Economic Affairs and Energy, on the basis of a decision by the German Bundestag.

nathalie.monnerie@dlr.de