COST OPTIMAL DESIGN OF ELECTROCHEMICAL HYDROGEN PRODUCTION SYSTEMS POWERED BY CSP/PV HYBRID POWER PLANTS

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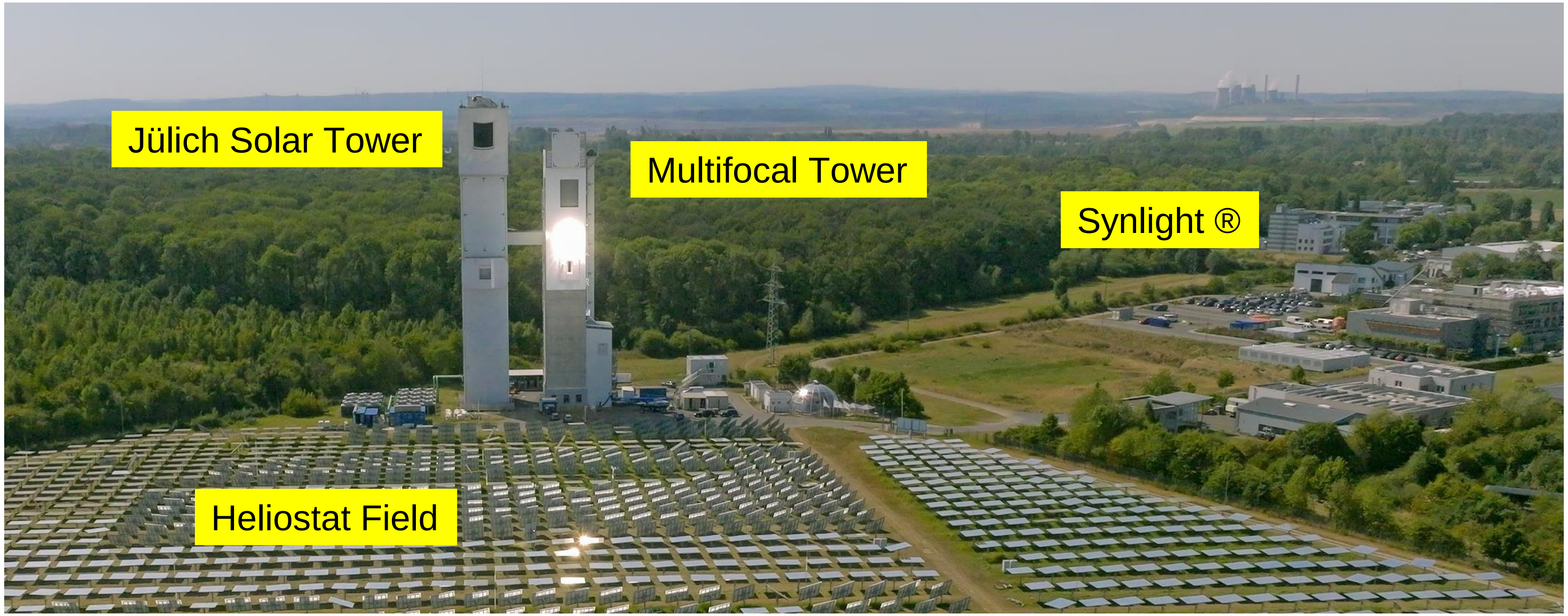
Credit: DLR (CC BY-NC-ND 3.0)

MOTIVATION

Motivation: DLR Institute of Future Fuels

- **Research for global CO_2 neutrality**: We develop solutions for cost-efficient hydrogen and fuels production on an industrial scale from the raw materials water, CO_2 and nitrogen using renewable energies.



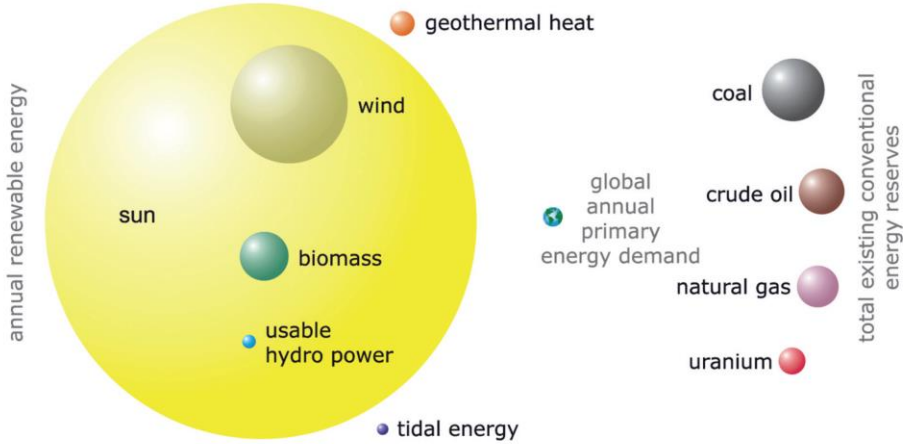
Synlight® Solar Simulator
(„Largest artificial sun“)

- Former part of DLR Institute of Solar Research
- Locations: Jülich and Cologne, increase to 120 employees
- Support for structural change in the Rhenish (coal) region

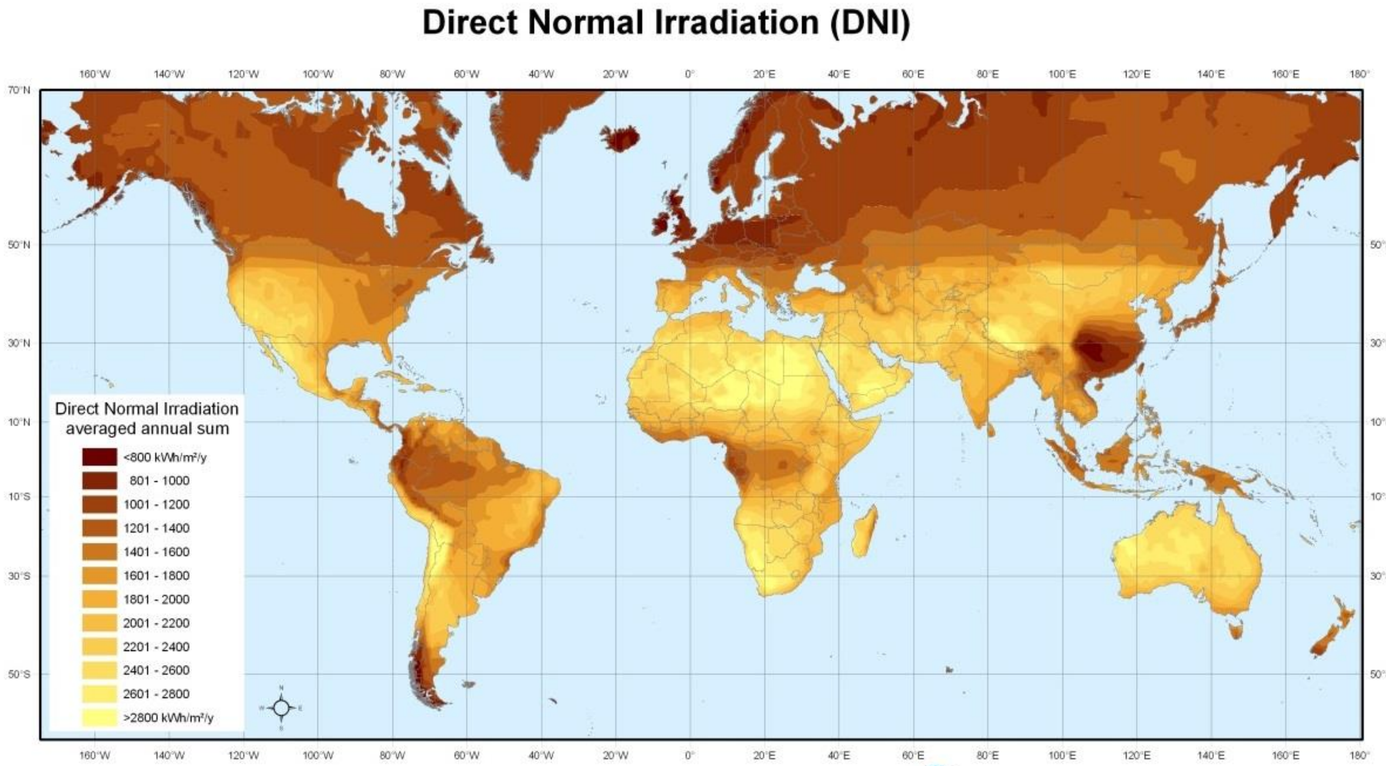
- Contributions to the decarbonization of energy, aviation and transport
- Infrastructure and large-scale facilities for process development

Motivation: Solar fuels potential

- Total solar irradiation potential ~ 6000 times world’s primary energy demand (1).
- Available land in the dry and sunny regions which is not used for agriculture.
- ➢ Sunbelt has great potential for the production and export of renewable synfuels.
- ➢ Focus of my work: Development of cost-optimized systems for the production of solar fuels with the lowest possible environmental impact
- ➢ Focus on stand-alone plants for synfuel production with (almost) no exchange with an electricity grid.



Quaschning 2019

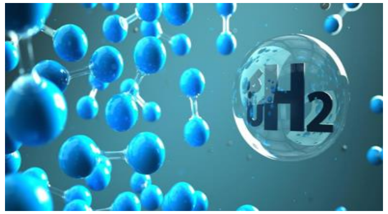


Data based on SSE 6.0 dataset for a 22-year period (July 1983 - June 2005)
(http://eosweb.larc.nasa.gov/sse/)

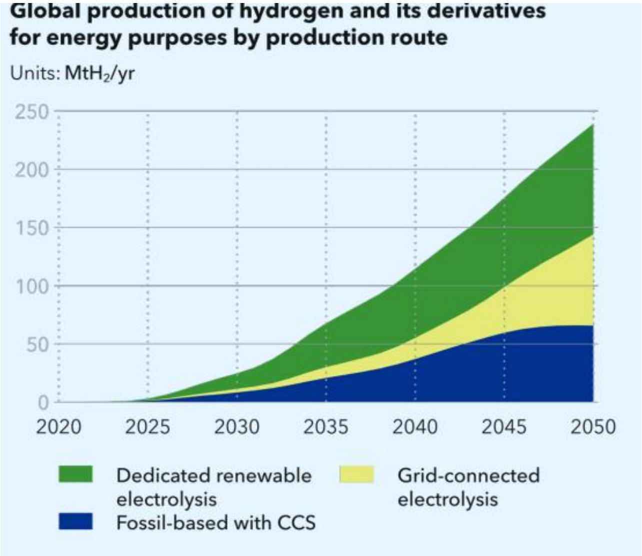
Map created and map layout by DLR 2008
(http://www.dlr.de)

Motivation: Hydrogen as an energy carrier

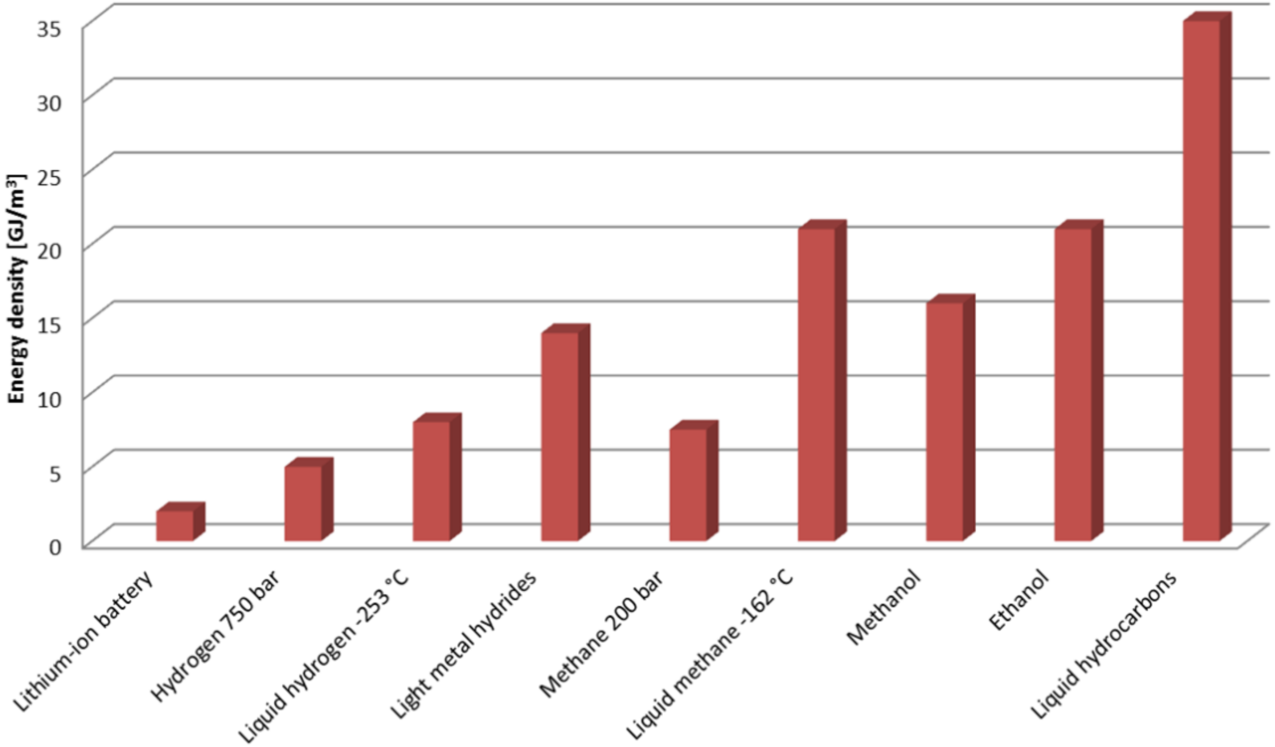
- How can we bring the solar energy from sweet spots to places with high energy demand?
- Solar energy to electricity, electrochemical water splitting
- ➢ Chemical storage of renewable energy with H_2 and H_2 derivatives (e.g. ammonia, methanol)
- Renewable energy sweet spots with lowest LCOH (levelized cost of hydrogen)
  - E.g. Chile, Saudi Arabia, Namibia, Australia



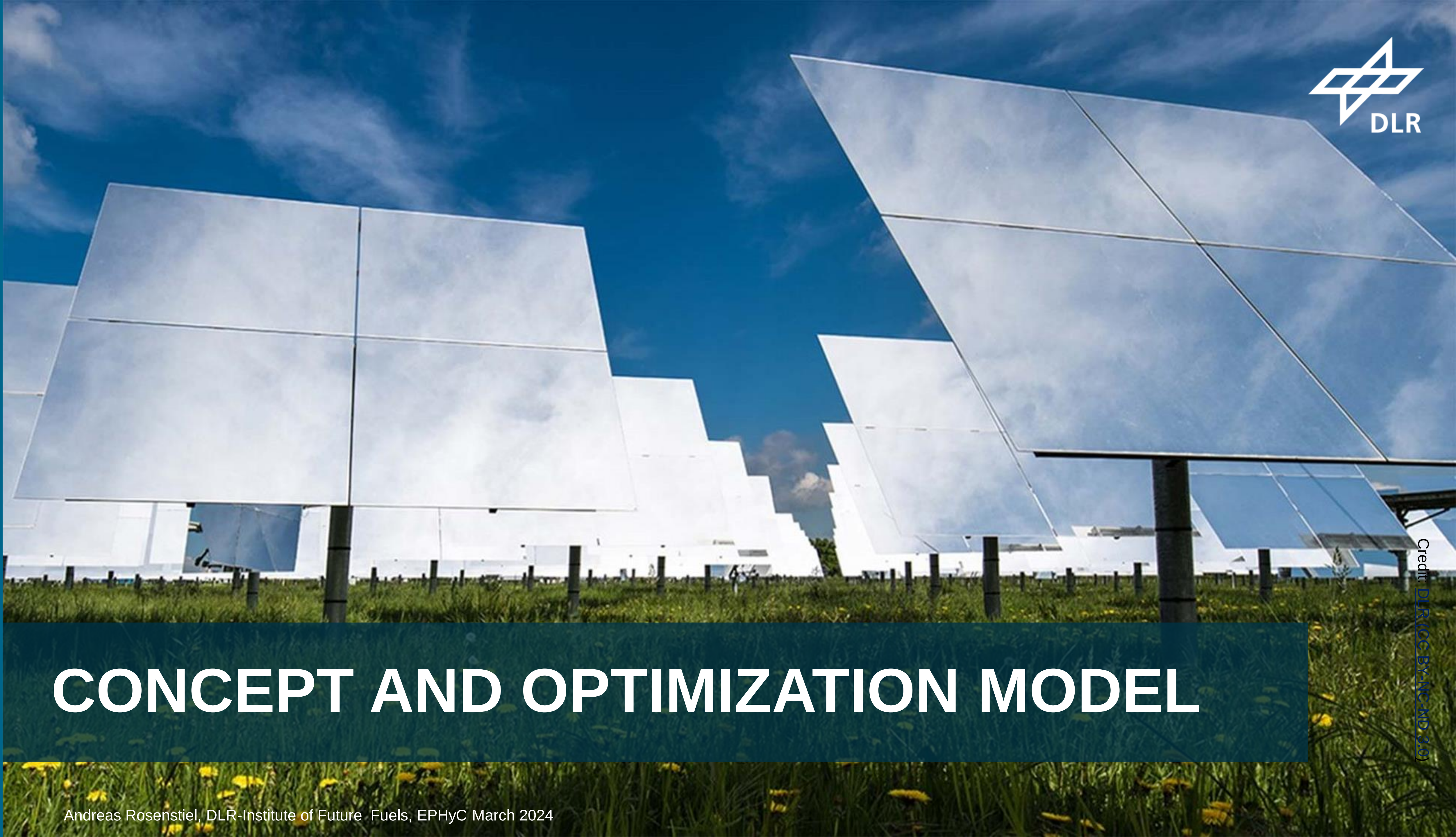
souce: picture alliance / Zoonar



DNV 2022: Hydrogen forecast to 2050.



Willner (2006)



CONCEPT AND OPTIMIZATION MODEL

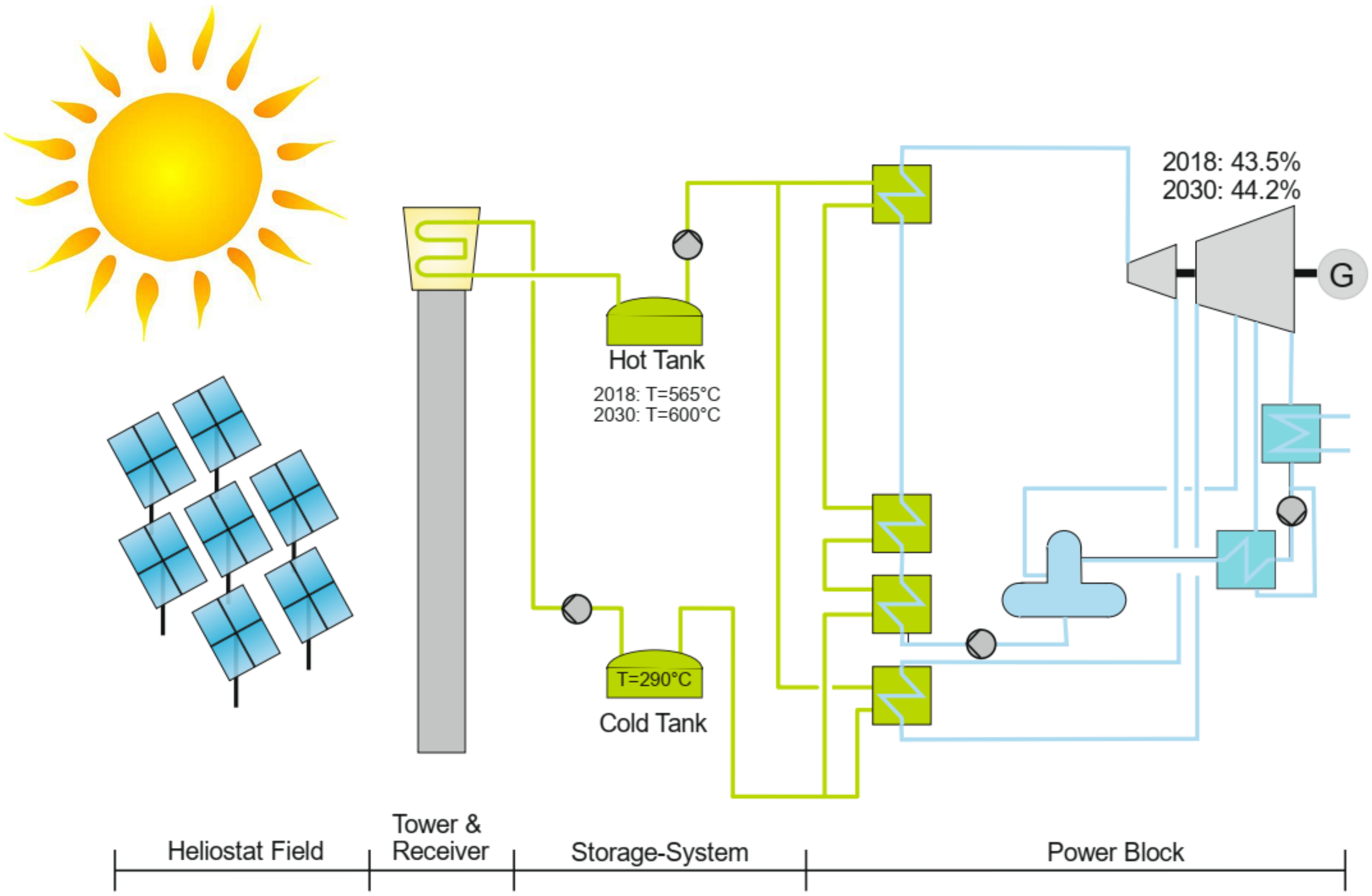
Credit: DLR (CC BY-NC-ND 3.0)

Concept CSP/PV hybrid power plant for hydrogen and hydrogen derivatives production

How does a Concentrated Solar Power (CSP) plant work?

- Heliostat field concentrates solar irradiation on focal point (receiver) on the tower
- Molten salt as working fluid
- Thermal storage system
- Steam cycle produces electricity when needed

➢ Solar electricity even at night!



Dersch at al 2020:

Concept CSP/PV hybrid power plant for hydrogen and H_2 derivatives production

- Which technologies are suitable for solar electrochemical hydrogen production?

Electricity provision:

Photovoltaics (PV)

- Low levelized cost of electricity
- Availability depends on solar irradiation

Concentrated Solar Power (CSP)

- Flexible electricity production (steam cycle)
- Thermal storage (low cost)

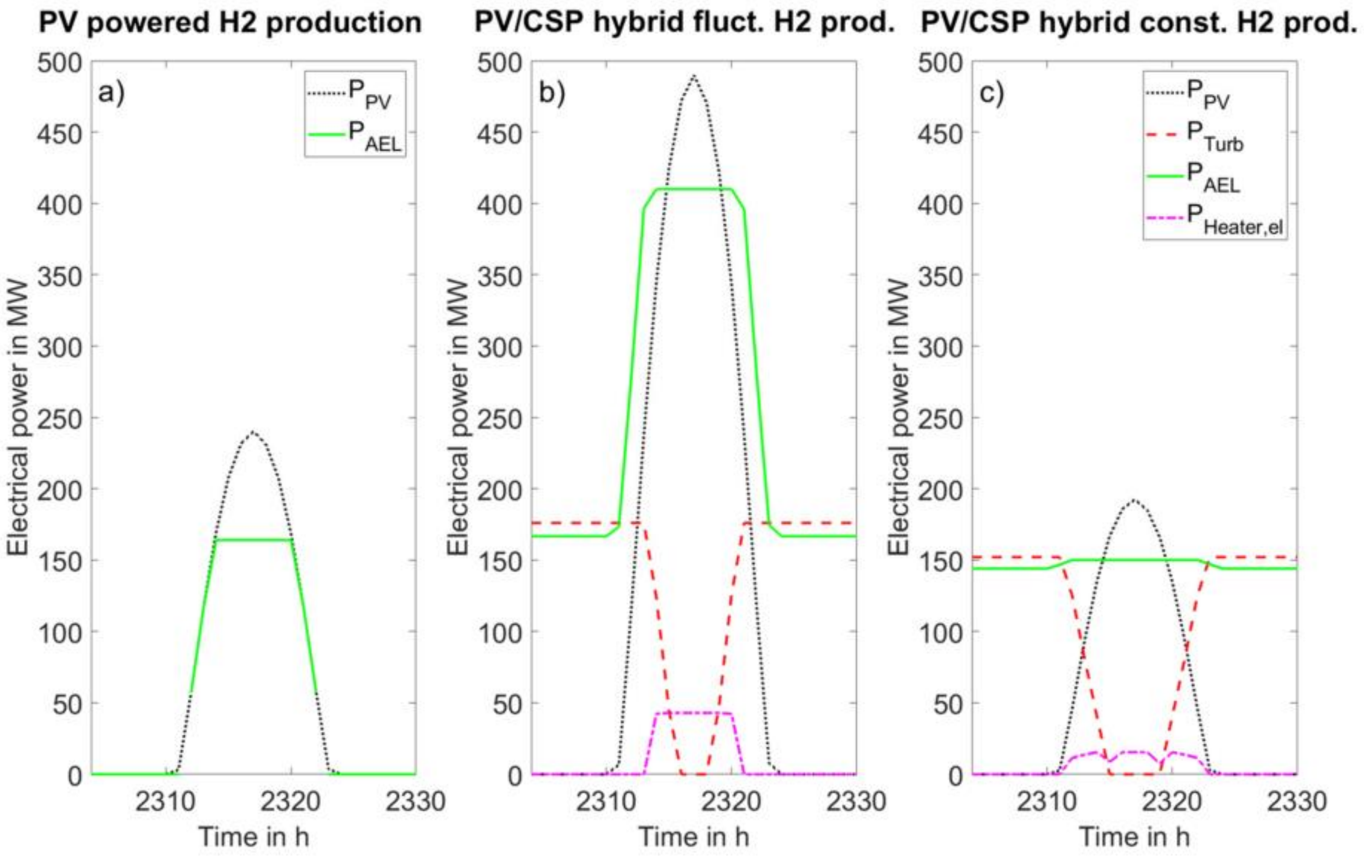
- Combination of PV and CSP can lead to high electrolyser full load hours with relatively low levelized cost of electricity.
- Synergies between in hybrid system: E.g. additional electric heater and usage of PV electricity for internal demand of CSP plant

CSP/PV hybrid concept cost-optimal operational strategy

a) Overscaled PV-only system: Fluctuating H_2 production

b) CSP/PV hybrid system: Fluctuating H_2 production with overscaled electrolysis and PV

c) CSP/PV hybrid system: Continuous H_2 production



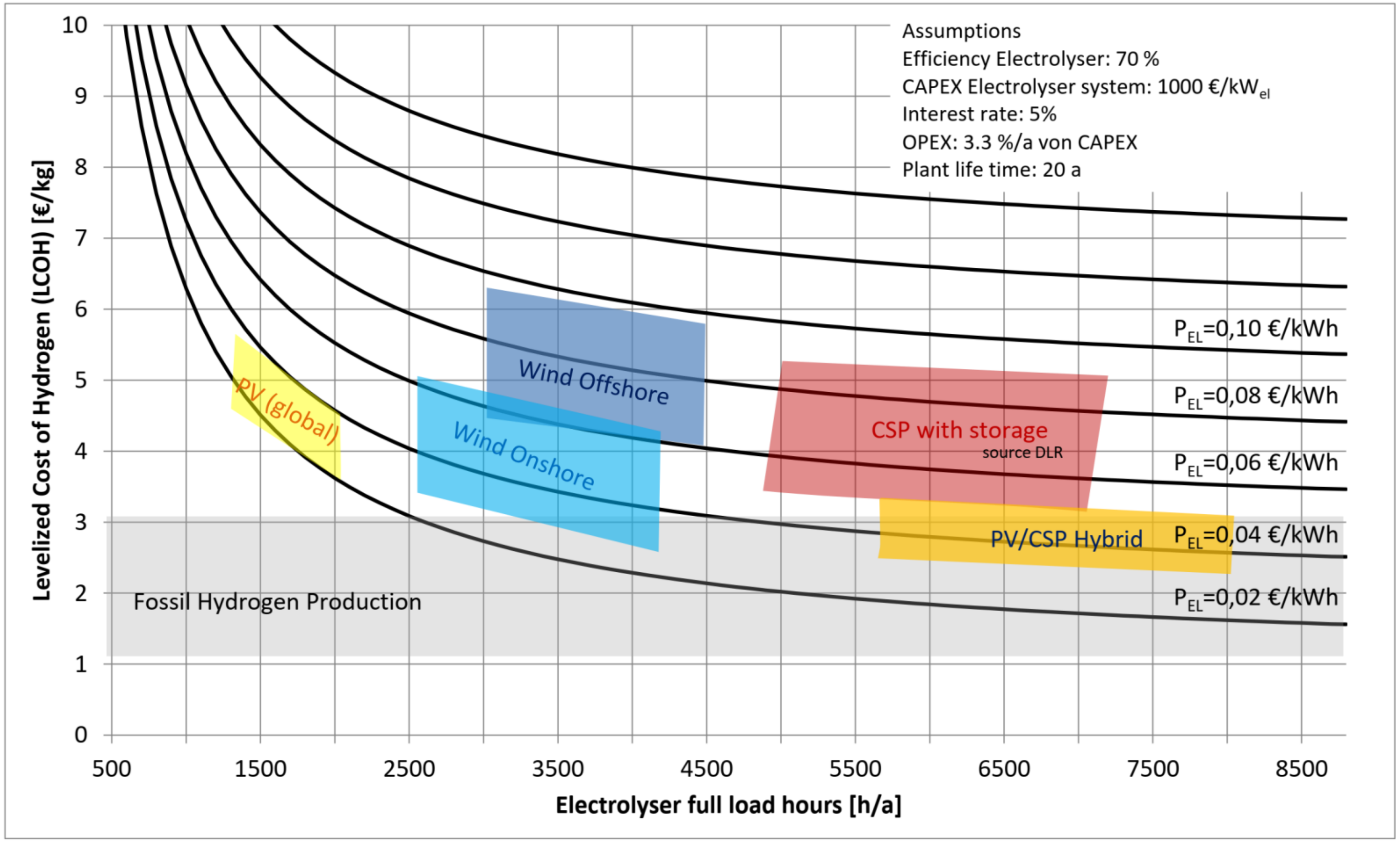
- ➢ Expectation: Coupling with Fuel synthesis processes (e.g. Methanol synthesis) favors continuous hydrogen production concepts

Rosenstiel et al (2021) https://doi.org/10.3390/en14123437

Concept CSP/PV hybrid power plant for hydrogen and hydrogen derivatives production

- Influence of electricity price and electrolyser full load hours on levelized cost of hydrogen (LCOH)

➢ Depending on electrolyser CAPEX, higher full load hours can lead to lower LCOH

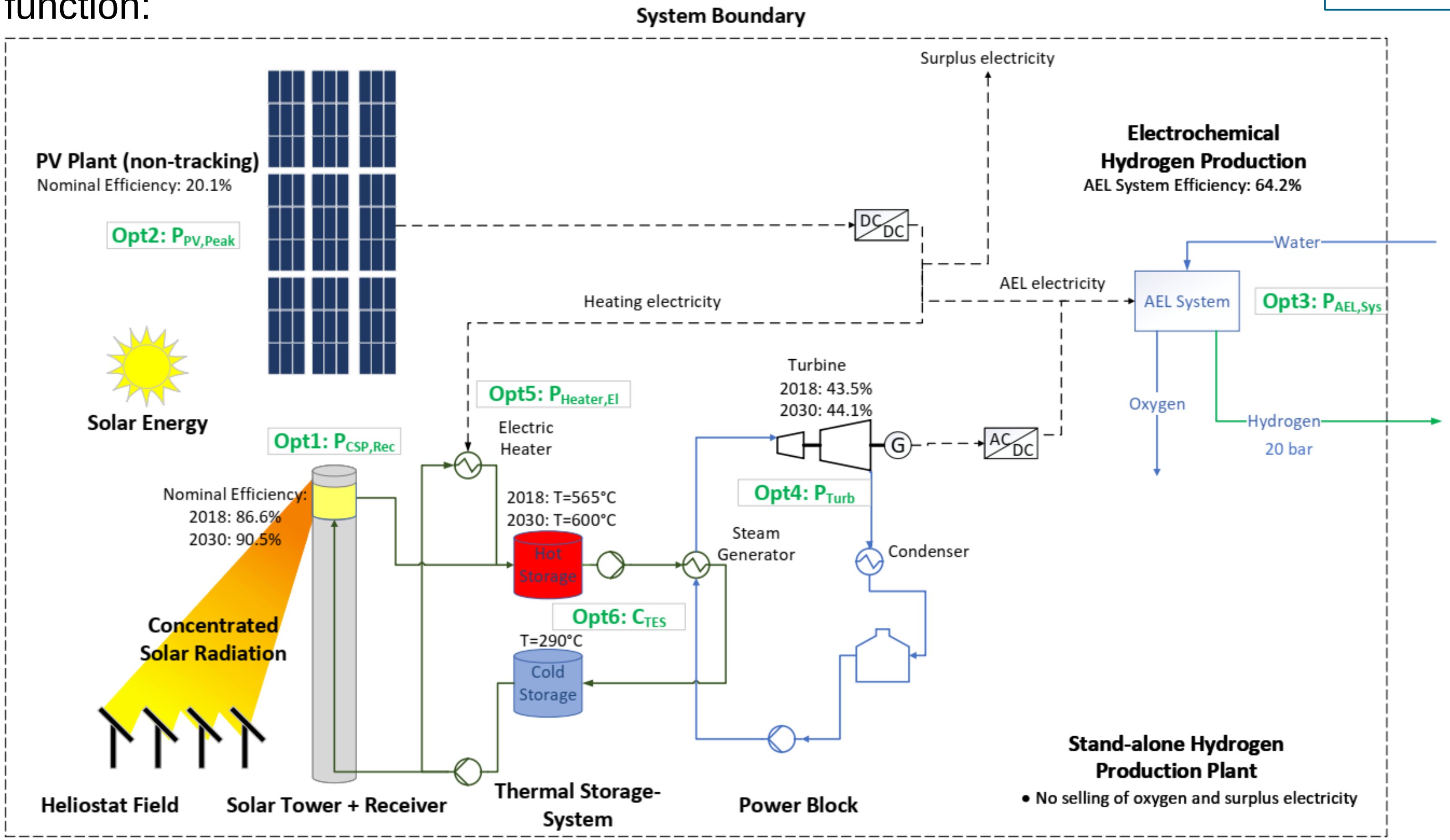


DLR 2020, Data from IRENA 2021, except cost data for CSP (source DLR)

CSP/PV hybrid concept and optimization variables

- Which CSP/PV hybrid system design leads to the lowest LCOH?
- Techno-economic energy system model with 6 optimization variable
- Cost-optimal sizing of systems components by minimization of product cost function:

$$\min(Levelized\ Cost\ of\ Hydrogen) = f\left(P_{CSP,Rec}, P_{PV,Peak}, P_{AEL}, P_{Turb}, \mathrm{P}_{Heater,el}, \mathrm{C}_{TES}\right)$$



- ➢ Stand-alone system
- ➢ System boundary: H_2 at 20 bar

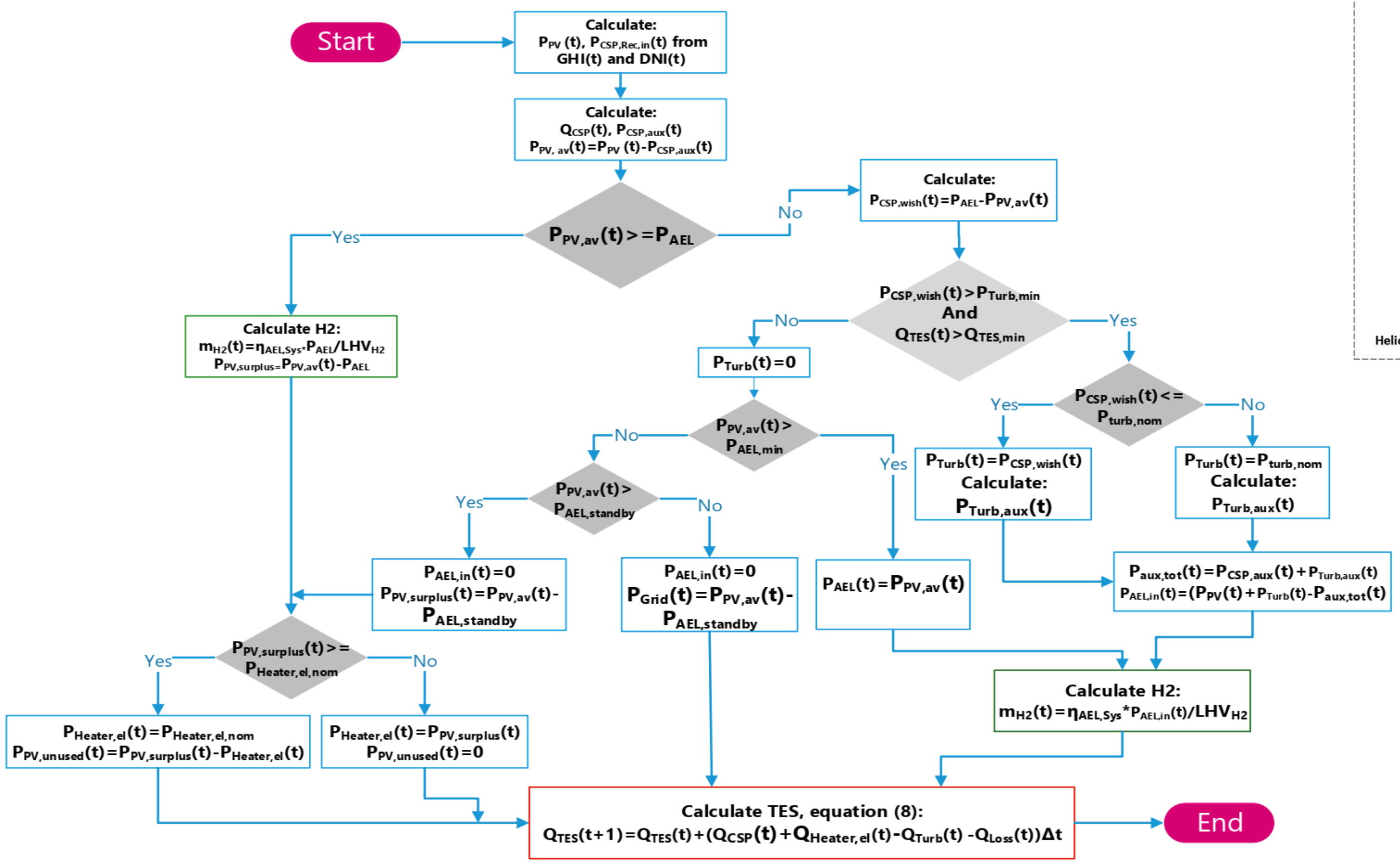
Further options in model:

- additional battery system
- Evaluation of only PV or CSP systems

Rosenstiel et al (2021) https://doi.org/10.3390/en14123437

CSP/PV hybrid concept operational strategy

- Techno-economic model including operational strategy to use fluctuating electricity in a cascade
- Timestep calculation algorithm
- Design specification: prioritization of fluctuating electricity source



Start

Calculate:
$P_{PV}(t)$, $P_{CSP,Rec,in}(t)$ from GHI(t) and DNI(t)

Calculate:
$Q_{CSP}(t)$, $P_{CSP,aux}(t)$
$P_{PV,av}(t)=P_{PV}(t)-P_{CSP,aux}(t)$

$P_{PV,av}(t)>=P_{AEL}$

Yes

Calculate H2:
$m_{H2}(t)=\eta_{AEL,Sys}\cdot P_{AEL}/LHV_{H2}$
$P_{PV,surplus}=P_{PV,av}(t)-P_{AEL}$

No

Calculate:
$P_{CSP,wish}(t)=P_{AEL}-P_{PV,av}(t)$

$P_{CSP,wish}(t)>P_{Turb,min}$ And $Q_{TES}(t)>Q_{TES,min}$

No

$P_{Turb}(t)=0$

$P_{PV,av}(t)>P_{AEL,min}$

No

$P_{PV,av}(t)>P_{AEL,standby}$

Yes

$P_{AEL,in}(t)=0$
$P_{PV,surplus}(t)=P_{PV,av}(t)-P_{AEL,standby}$

No

$P_{AEL,in}(t)=0$
$P_{Grid}(t)=P_{PV,av}(t)-P_{AEL,standby}$

Yes

$P_{AEL}(t)=P_{PV,av}(t)$

Yes

$P_{CSP,wish}(t)<=P_{turb,nom}$

Yes

$P_{Turb}(t)=P_{CSP,wish}(t)$
Calculate:
$P_{Turb,aux}(t)$

No

$P_{Turb}(t)=P_{turb,nom}$
Calculate:
$P_{Turb,aux}(t)$

$P_{aux,tot}(t)=P_{CSP,aux}(t)+P_{Turb,aux}(t)$
$P_{AEL,in}(t)=(P_{PV}(t)+P_{Turb}(t)-P_{aux,tot}(t)$

Calculate H2:
$m_{H2}(t)=\eta_{AEL,Sys}*P_{AEL,in}(t)/LHV_{H2}$

$P_{PV,surplus}(t)>=P_{Heater,el,nom}$

Yes

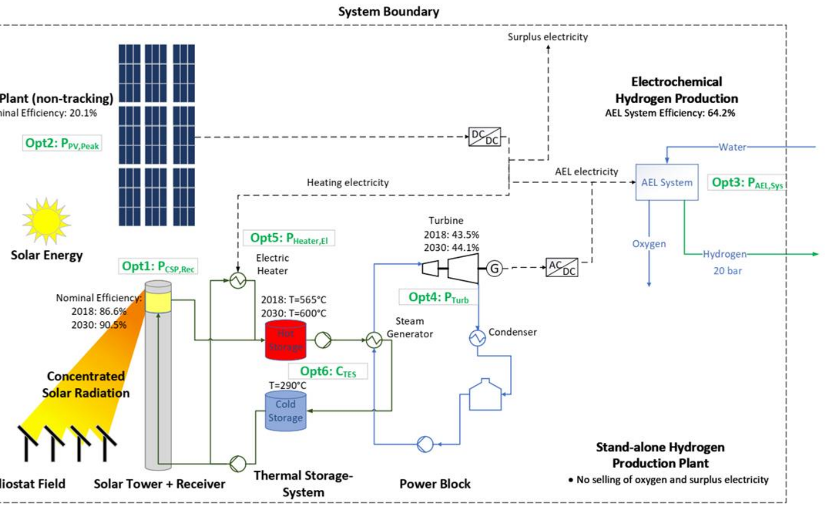
$P_{Heater,el}(t)=P_{Heater,el,nom}$
$P_{PV,unused}(t)=P_{PV,surplus}(t)-P_{Heater,el}(t)$

No

$P_{Heater,el}(t)=P_{PV,surplus}(t)$
$P_{PV,unused}(t)=0$

Calculate TES, equation (8):
$Q_{TES}(t+1)=Q_{TES}(t)+(Q_{CSP}(t)+Q_{Heater,el}(t)-Q_{Turb}(t)-Q_{Loss}(t))\Delta t$

End



Rosenstiel et al (2021) https://doi.org/10.3390/en14123437

RESULTS

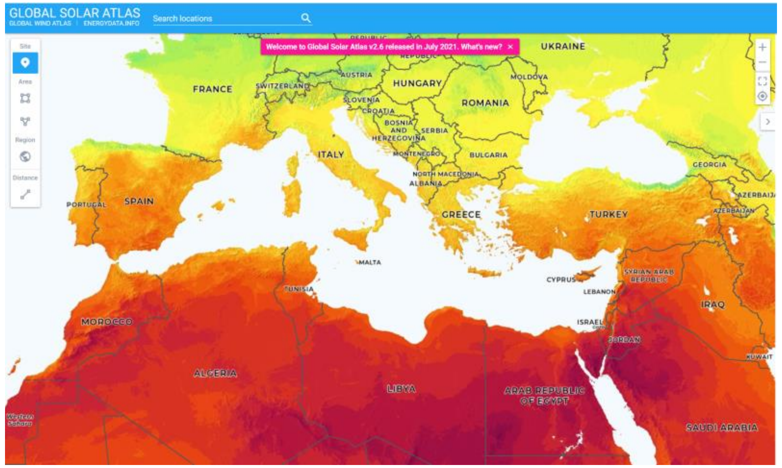
Credit: DLR (CC BY-NC-ND 3.0)

Techno-economic process evaluation: methodology

Weather data source: (Meteonorm 8.0) and Greenius (DLR tool)

- Freiburg, Germany: DNI: 971 kWh/(m^2a)
- Almeria, Spain, DNI: 1918 kWh/(m^2a)
- Ouarzazate, Morocco DNI: 2518 kWh/(m^2a)

- Process simulation(1h) steps

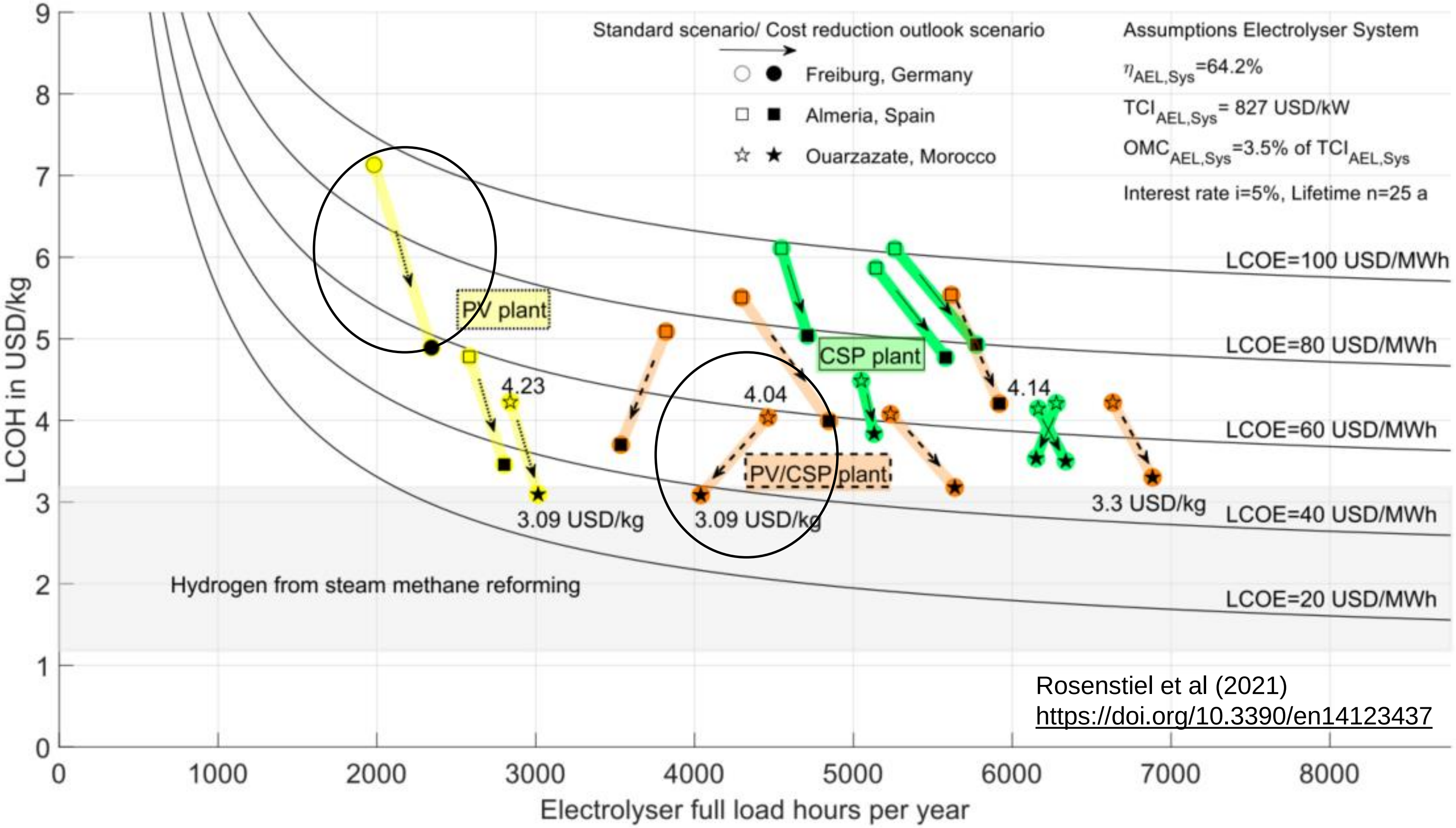


- Exemplary study with constant electrolyser Total investment cost (TCI): 827 USD/kW
- Standard PV, CSP scenario (today)
- Outlook scenario:
  - PV: -55% (760, 340 USD/kW)
  - CSP approx. – 25 %, higher efficiency

FLH and LCOE for Ouarzazate, Morocco

Scenario/Configuration	FLH AEL (h/a)	LCOE PV (USD/MWh)	LCOE CSP (USD/MWh)	LCOE to AEL (USD/MWh)	LCOE to AEL + Cost P_{add} (USD/MWh)
Standard cost scenario					
Only PV	2751	37.92	-	43.85	46.26
Only CSP	6163	-	62.87	62.87	63.90
PV/CSP hybrid fluctuating	4463	37.92	69.03	55.07	55.67
PV/CSP hybrid constant	6633	37.92	77.69	65.84	66.26
Outlook scenario					
Only PV	2973	19.83	-	24.87	27.09
Only CSP	6337	-	51.02	51.02	51.94
PV/CSP hybrid fluctuating	4039	19.83	58.69	34.48	35.07
PV/CSP hybrid constant	6884	19.83	65.02	48.75	49.10

Results CSP/PV hybrid power plant for hydrogen production



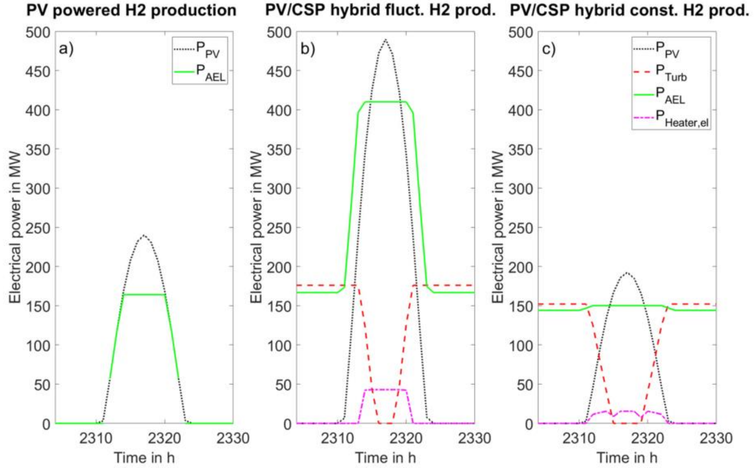
Rosenstiel et al (2021)
https://doi.org/10.3390/en14123437

Results depend on techno-economic assumptions!

- ➢ Next steps: cost sensitivity analysis for electrolyser system, PV and CSP.
- ➢ Identify cost ratios with determine the final design

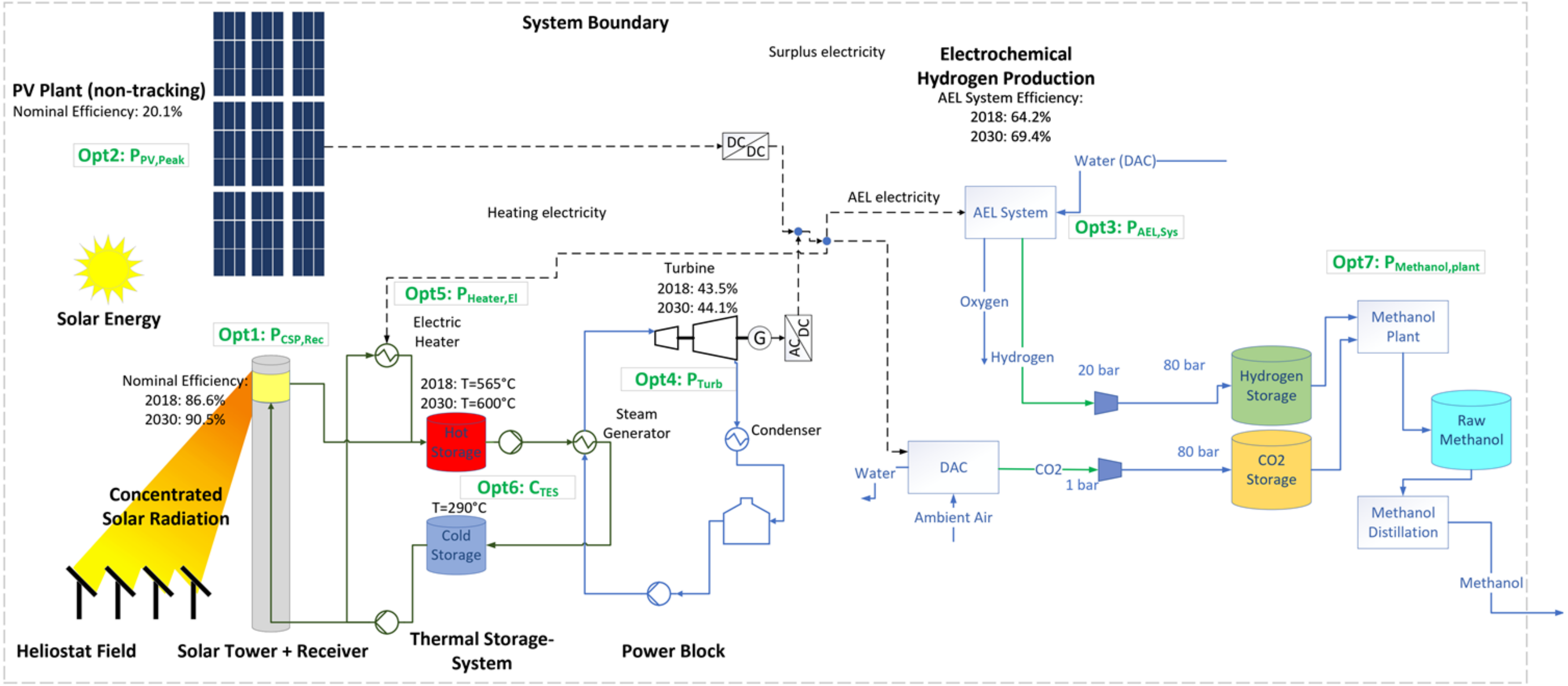
Main findings:

- Minimum LCOH (4.04 USD/kg) in standard scenario for PV/CSP system in Ouarzazate
- Decrease in PV costs leads to
  - Over scaling of PV system (more FLH) in PV only system.
  - More fluctuating operation in a PV/CSP plant (less FLH)



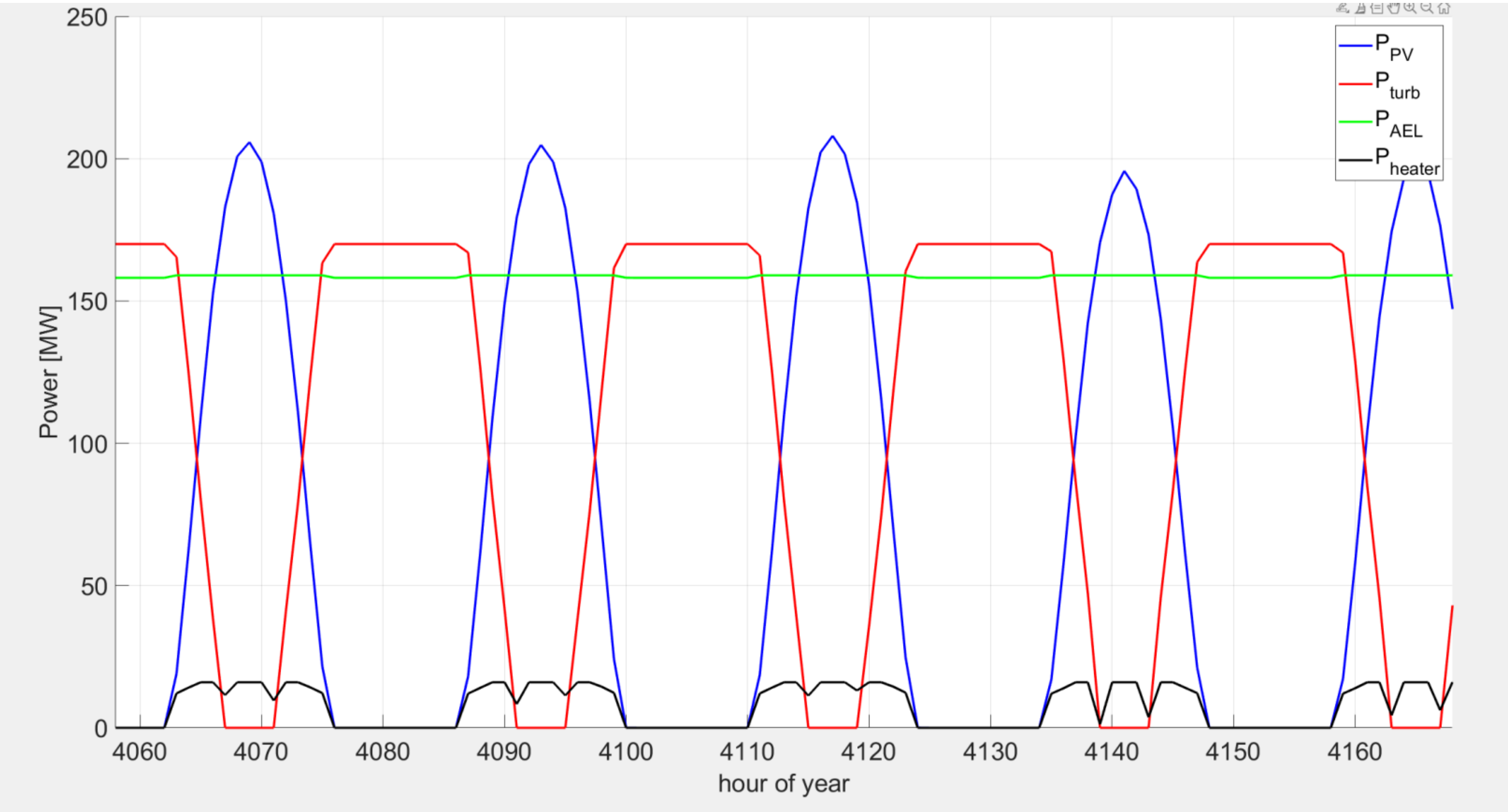
CSP/PV hybrid power plant for hydrogen derivatives production

- Reminder system boundary: hydrogen at 20 bar
- Cost-optimum for only hydrogen at lower FLH, slope LCOH as f(FLH) relatively small
- Expectation: Coupling of hydrogen production with subsequent processes will shift the optimum to higher FLH.
- Example: Methanol production

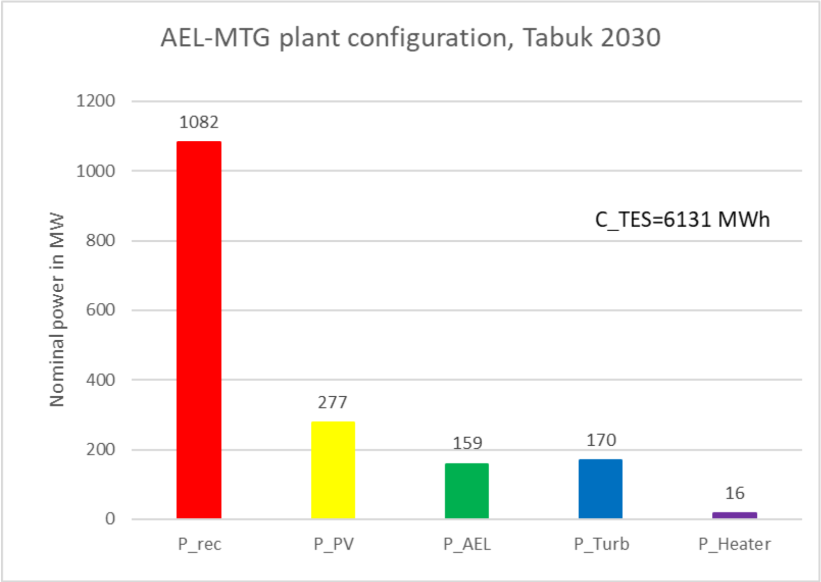


Cost-optimized plant design for solar E-Methanol production based on CSP/PV hybrid power plants

Plant operation at very good CSP site

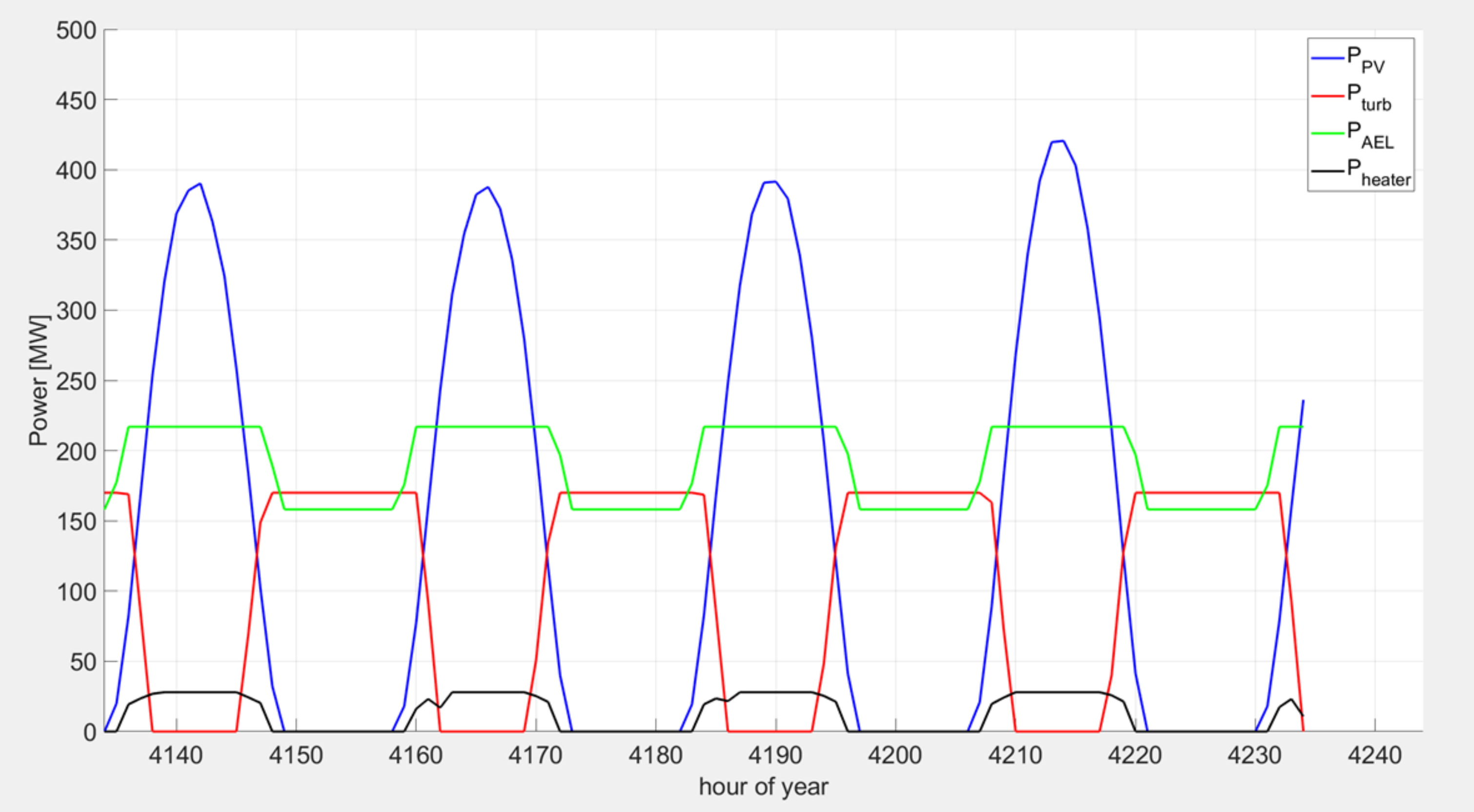


- Tabuk, Saudi Arabia (optimized for 2030)
- DNI 2882 kWh/m^{2}a
- >8000 Electrolyser full load hours
- LCOE (to Electrolyser): 40.5 €/MWh
- Equivalent LCOH: 2.72 €/kg

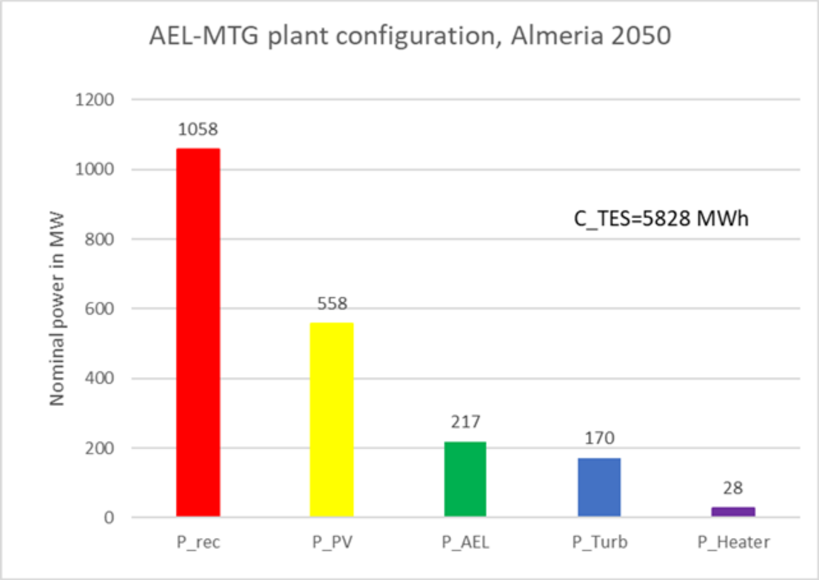


Cost-optimized plant design for solar E-Methanol production based on CSP/PV hybrid power plants

Plant operation at a regular CSP site



- Almeria, Spain
- DNI 1918 kWh/m^{2}a
- 5665 Electrolyser full load hours
- LCOE (to Electrolyser): 60.9 €/MWh
- Equivalent LCOH: 4.07 €/kg
- ➢ Over scaling of PV and Electrolyser



SUMMARY AND OUTLOOK

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Summary and Outlook

- Hydrogen production based on CSP/PV hybrid power plants with thermal energy storage can achieve very high full load hours at good solar locations
- Promising approach for the production of renewable fuels
- Lower PV system costs favor plant concepts with fluctuating hydrogen production (lower FLH).
- The combination of solar-powered electrochemical hydrogen production with downstream processes, such as e-methanol production, favors continuous process concepts (>8000 electrolyzer FLH possible).

Next steps:

Comparison with system including PV+ wind + battery system

- Sensitivity analysis:
    - Electrolyser system costs +/- 50 %
    - PV system costs +/- 50 %
    - Battery systems costs +/- 50%
    - CSP system costs +/- 50 %
    - Electric heater costs +/-50 %

➢ Determine costs ratios which finally define plant design

➢ Environmental system evaluation based on a LCA analysis

Impressum

Thank you very much!
Dank u wel! Merci!

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aufgrund eines Beschlusses
des Deutschen Bundestages

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