COST OPTIMAL DESIGN OF SOLAR E-METHANOL PRODUCTION POWERED BY CSP/PV HYBRID POWER PLANTS

Andreas Rosenstiel, Nathalie Monnerie, Martin Roeb, Christian Sattler

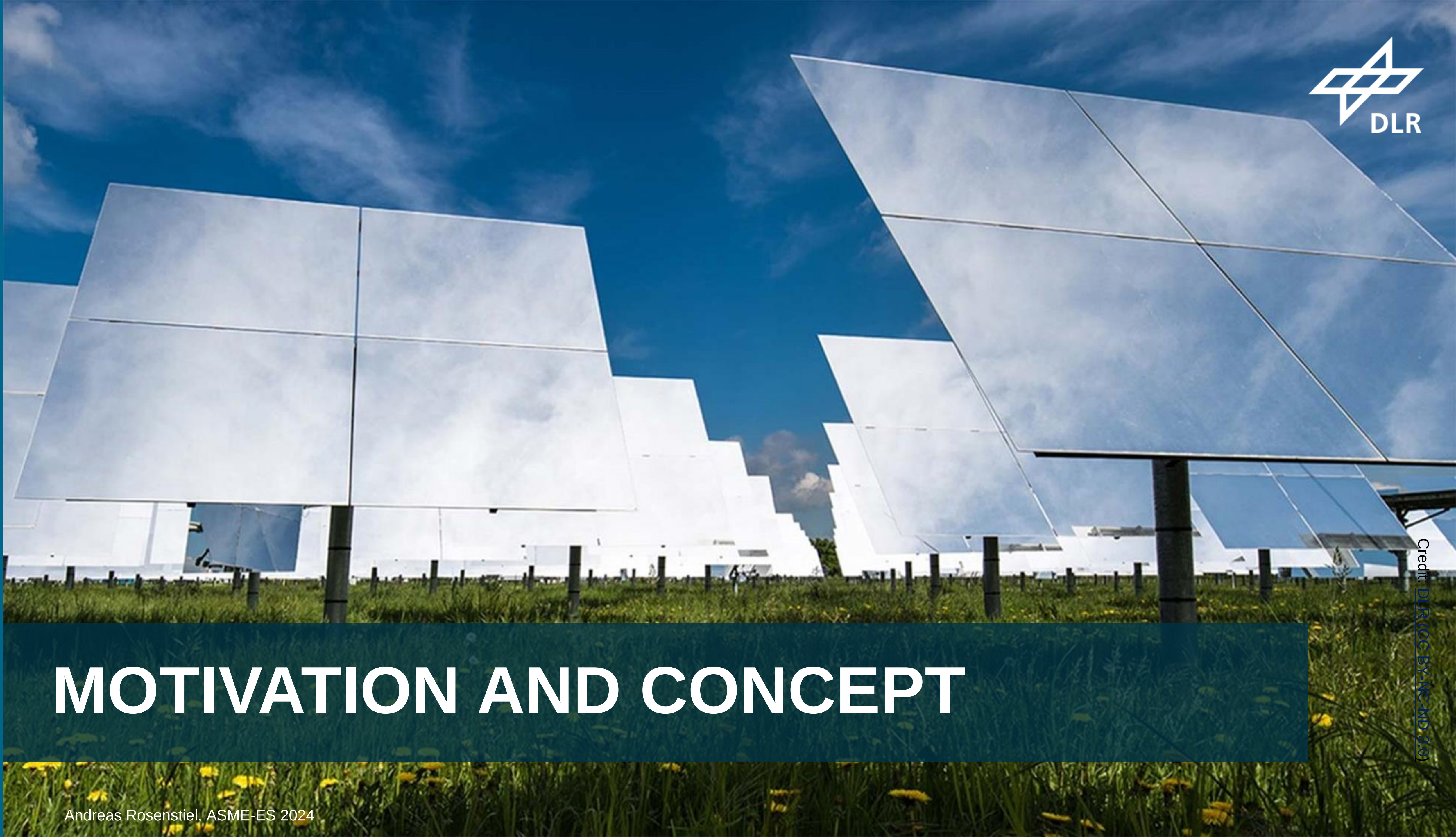
andreas.rosenstiel@dlr.de

18th ASME Energy Sustainability Conference (ES2024)

July 15-17, 2024.

Anaheim, CA, USA

DLR



MOTIVATION AND CONCEPT

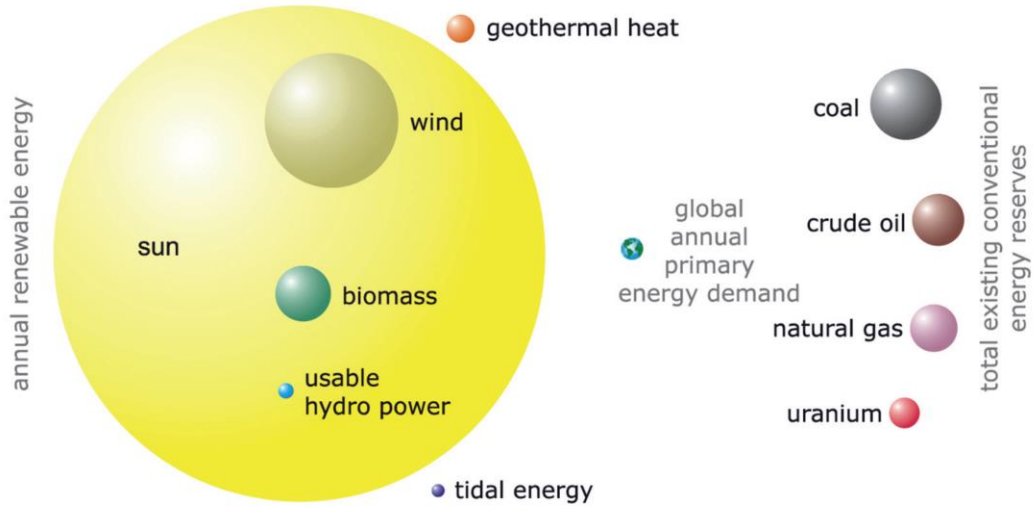
Motivation: Solar hydrogen potential

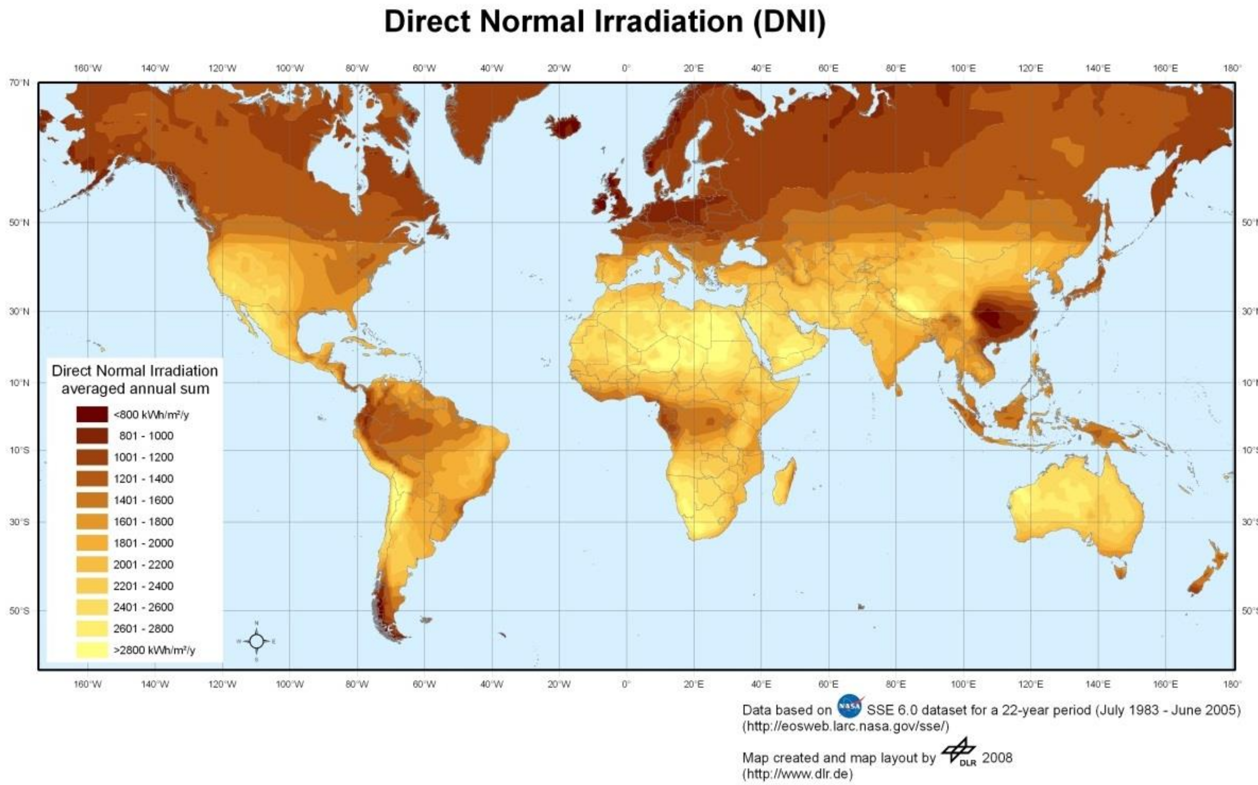
- Total solar irradiation potential ~ 6000 times world’s primary energy demand (1).

➢ Sunbelt has great potential for the production and export of renewable energy carriers (green H_2 and H_2 derivatives).

Focus of work:

- Development of cost-optimized systems for the production of solar fuels with the lowest possible environmental impact.

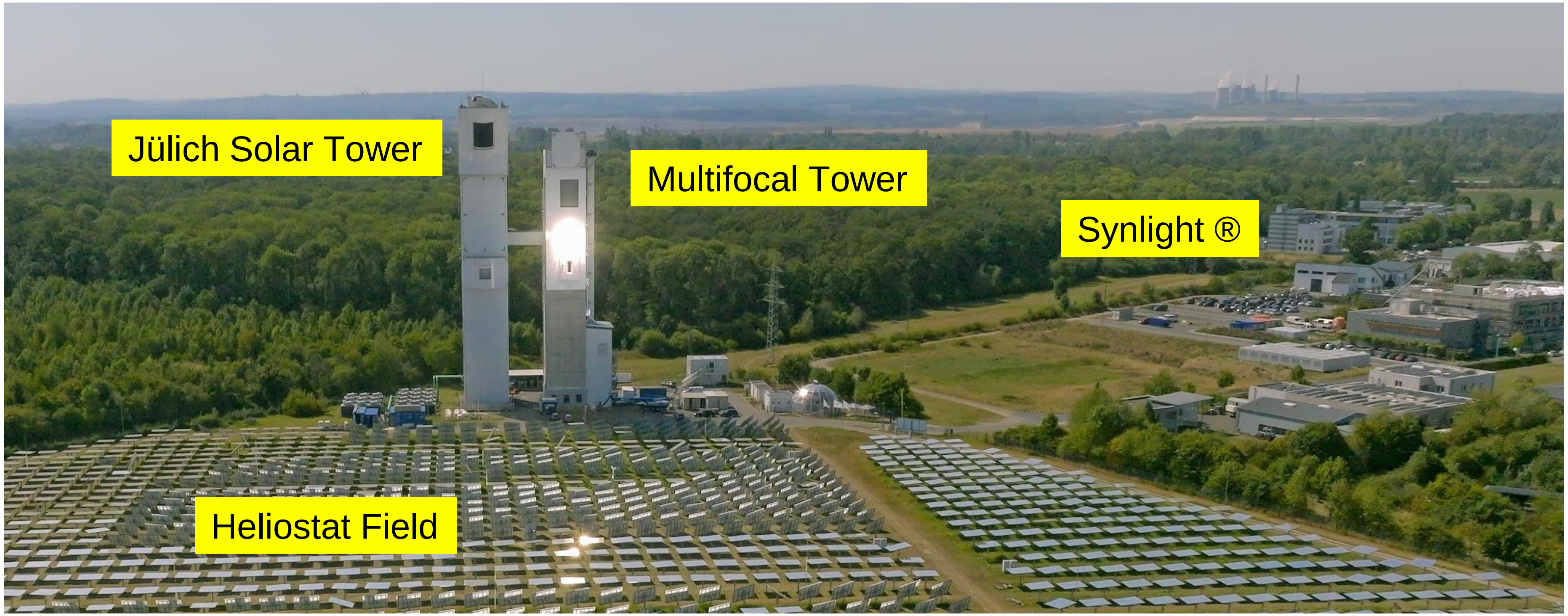




(1) Quaschning 2019

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“)

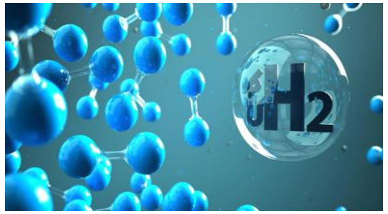
- Former part of DLR Institute of Solar Research
- Locations: Jülich and Cologne, increase to 120 employees
- Support for structural change in the Rhenish (coal) region

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

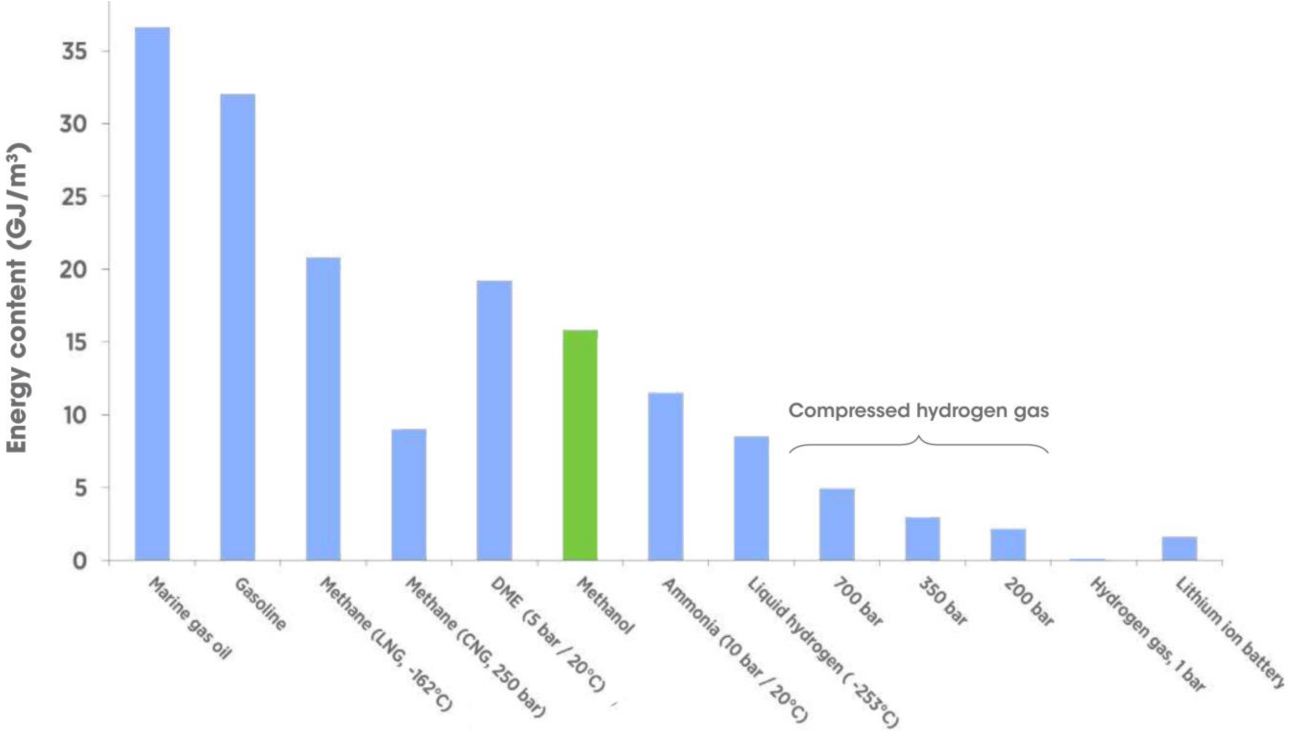
Motivation: Hydrogen derivatives as an energy carrier

- Renewable energy sweet spots with lowest LCOH (levelized cost of hydrogen)
  - E.g. Chile, Saudi Arabia, Namibia, Australia
- How can we bring the solar energy to places with high energy demand?

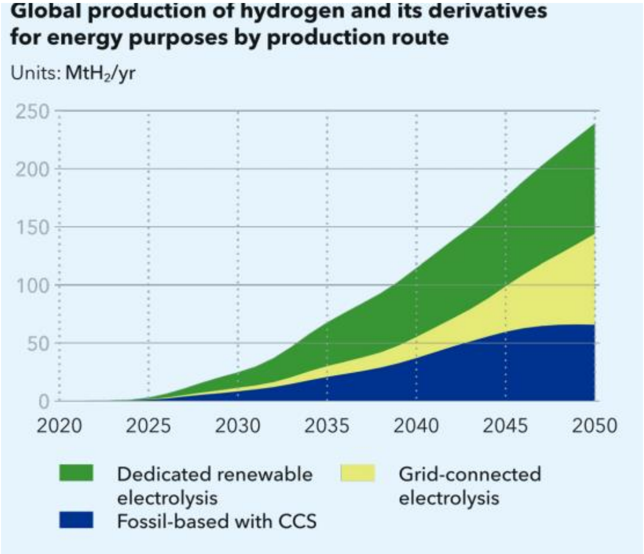
➢ Chemical storage of renewable energy with H_2 and H_2 derivatives (e.g. ammonia, methanol)



souce: picture alliance / Zoonar



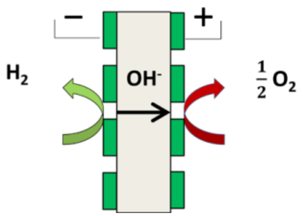
2) IRENA and METHANOL INSTITUTE 2021



3) DNV 2022: Hydrogen forecast to 2050

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

Electricity produced with solar energy → Electrochemical water splitting (AEL)



Photovoltaics (PV)

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

Concentrated Solar Power (CSP)

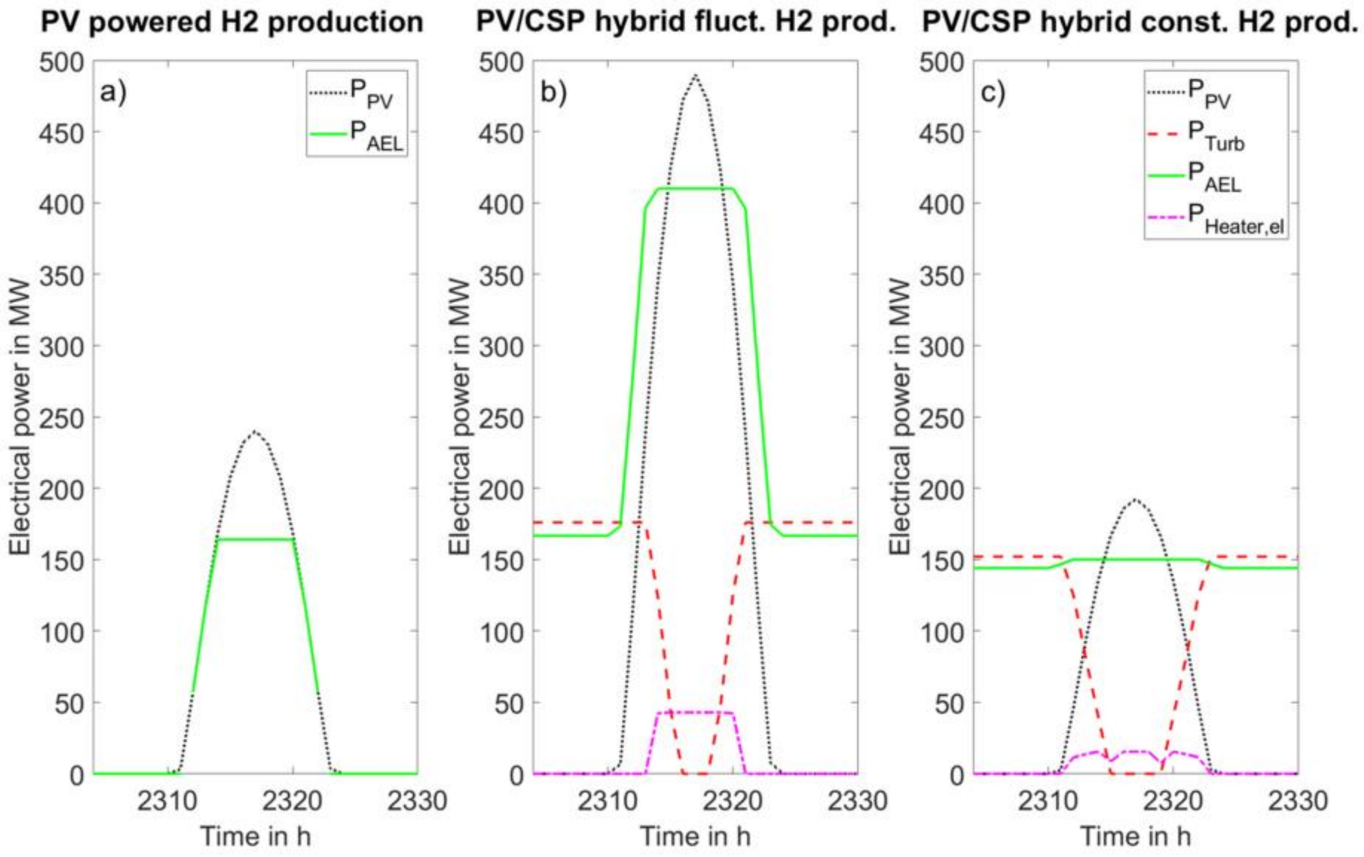
- Thermal storage (low cost)
- Flexible electricity production (steam cycle)

- ➢ Combination of PV and CSP can lead to high electrolyser full load hours with relatively low levelized cost of electricity.
- ➢ Synergies 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

- Different possibilities of CSP/PV system design and operation (CSP/PV ratio)
- Very low PV costs favors fluctuating concepts like b) or even a) for hydrogen production.

➢ Expectation: Coupling with hydrogen to X process favors more continuous process designs and increases CSP share.

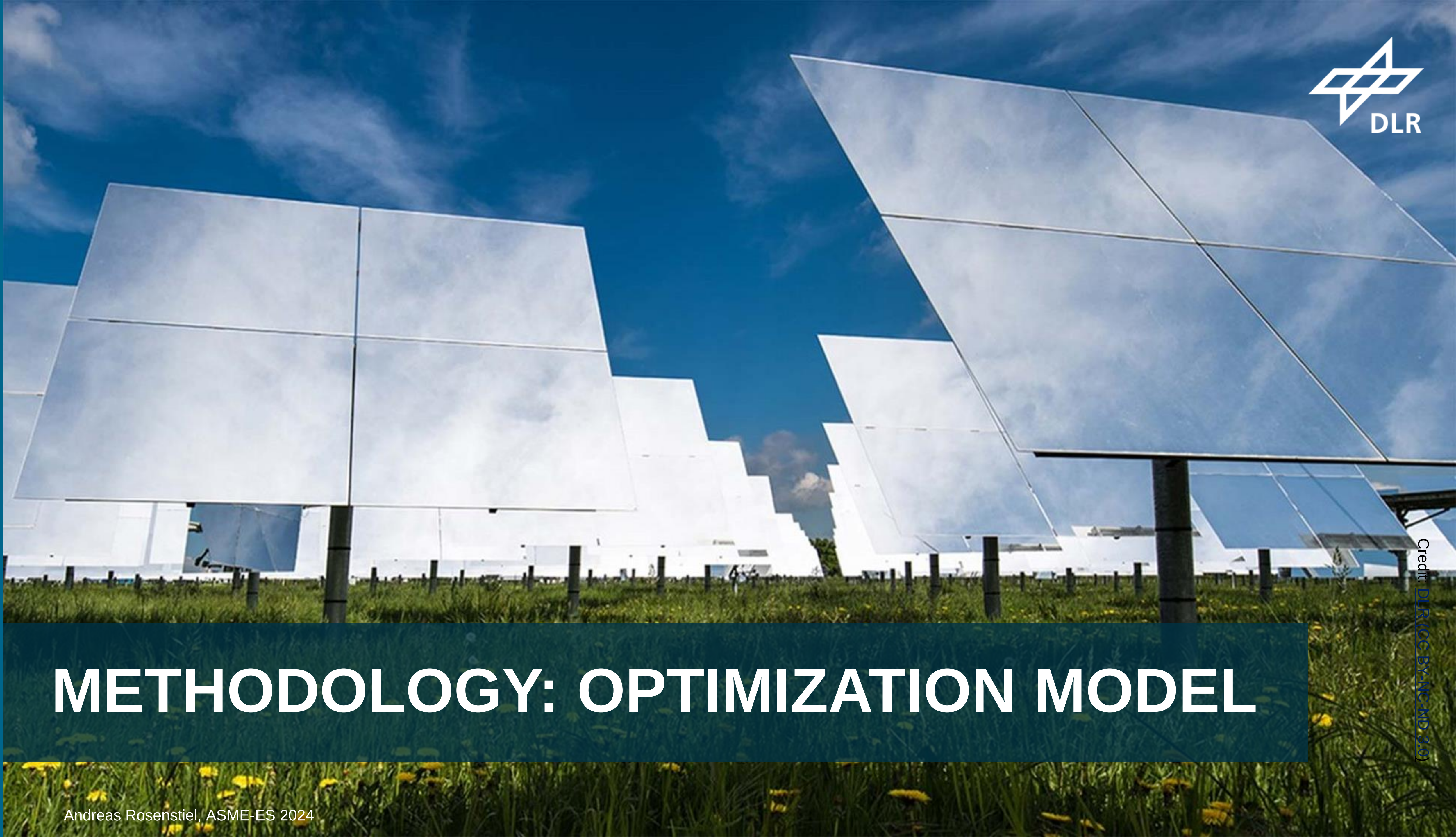


a) Overscaled PV-only system: fluctuating H_2 production

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

c) CSP/PV hybrid system: Continuous H_2 production

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

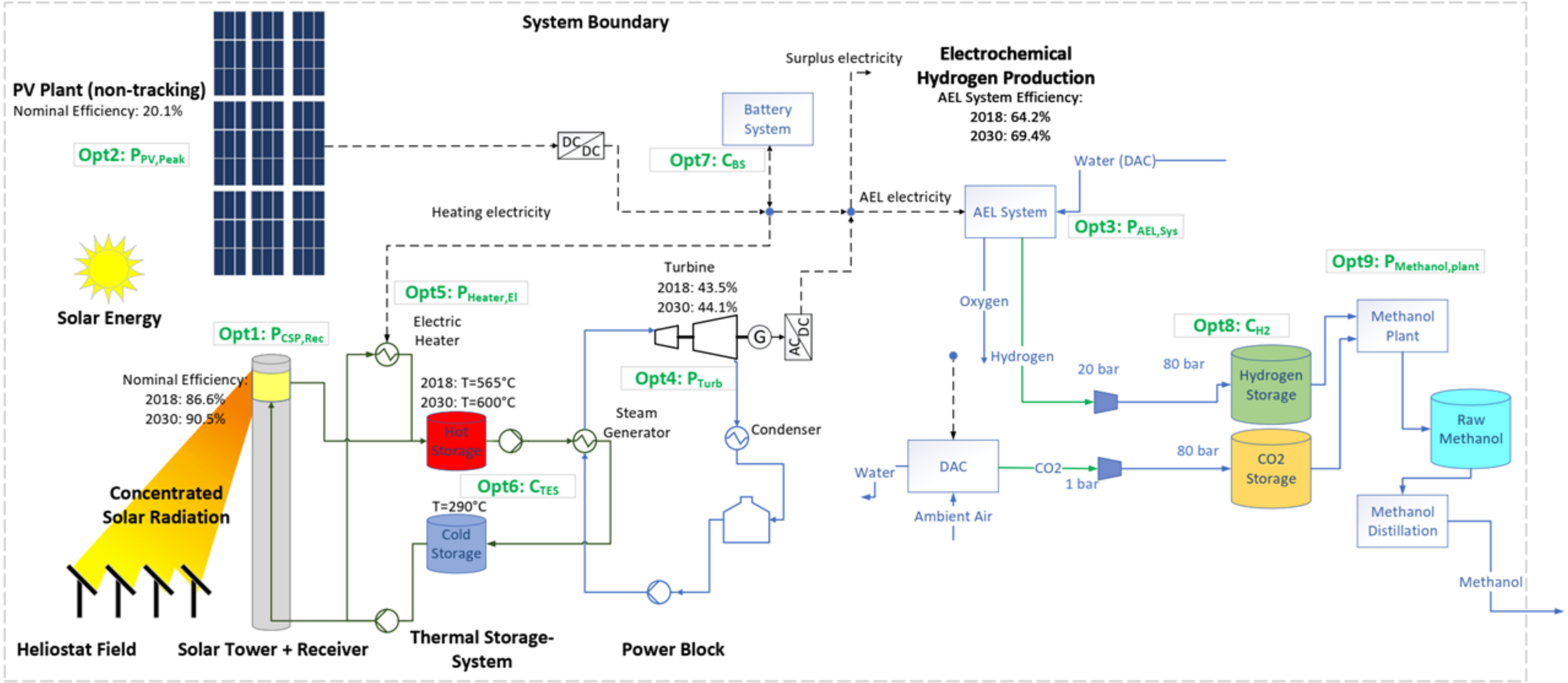


METHODOLOGY: OPTIMIZATION MODEL

CSP/PV hybrid concept and optimization variables

- Which CSP/PV hybrid system design leads to the lowest levelized cost of methanol?
- Techno-economic energy system model with 9 optimization variable
- Cost-optimal sizing of systems components by minimization of product cost function

$$\min(LC\ of\ MEOH) = f\left(P_{CSP,Rec}, P_{PV,Peak}, P_{AEL}, P_{Turb}, \mathrm{P}_{Heater,el}, \mathrm{C}_{TES}, C_{battery}, C_{H2,stor}, P_{MeOH}\right)$$

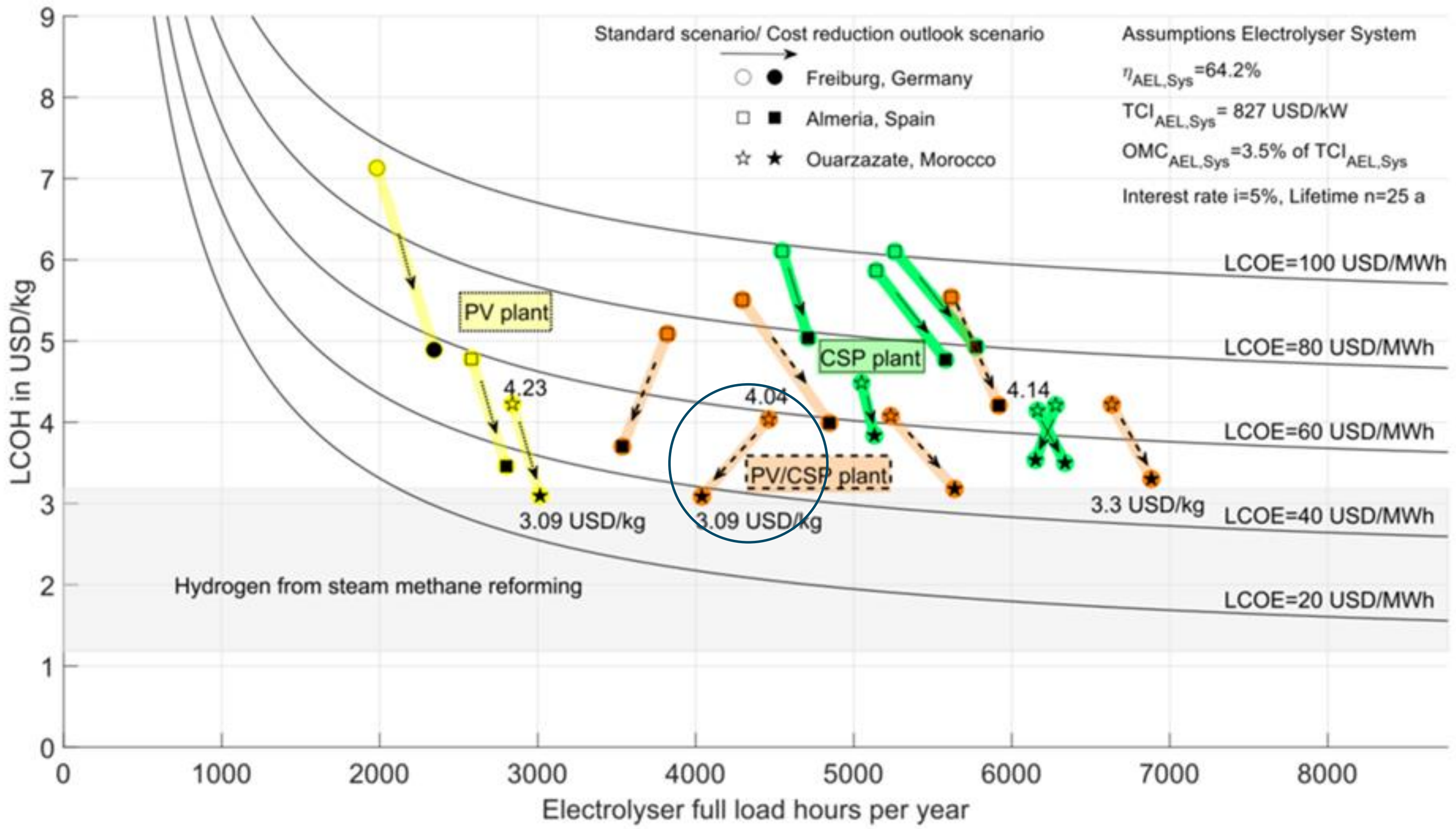


- Stand-alone system.
- CSP and PV yield calculation based on correlations and assumptions of DLR tool Greenius.
- The model includes an operating strategy for best possible utilization of fluctuating electricity.

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

CSP/PV hybrid power plant for hydrogen production

- Advantages of CSP/PV hybridization for hydrogen production shown in previous study (system boundary hydrogen at 20 bar) (4,5).
- Cost reduction outlook scenario: strongly decreasing PV costs and moderately decreasing CSP costs.
- Shifting of cost optimum of with lower PV costs to lower electrolyser full load hours (more fluctuating production).

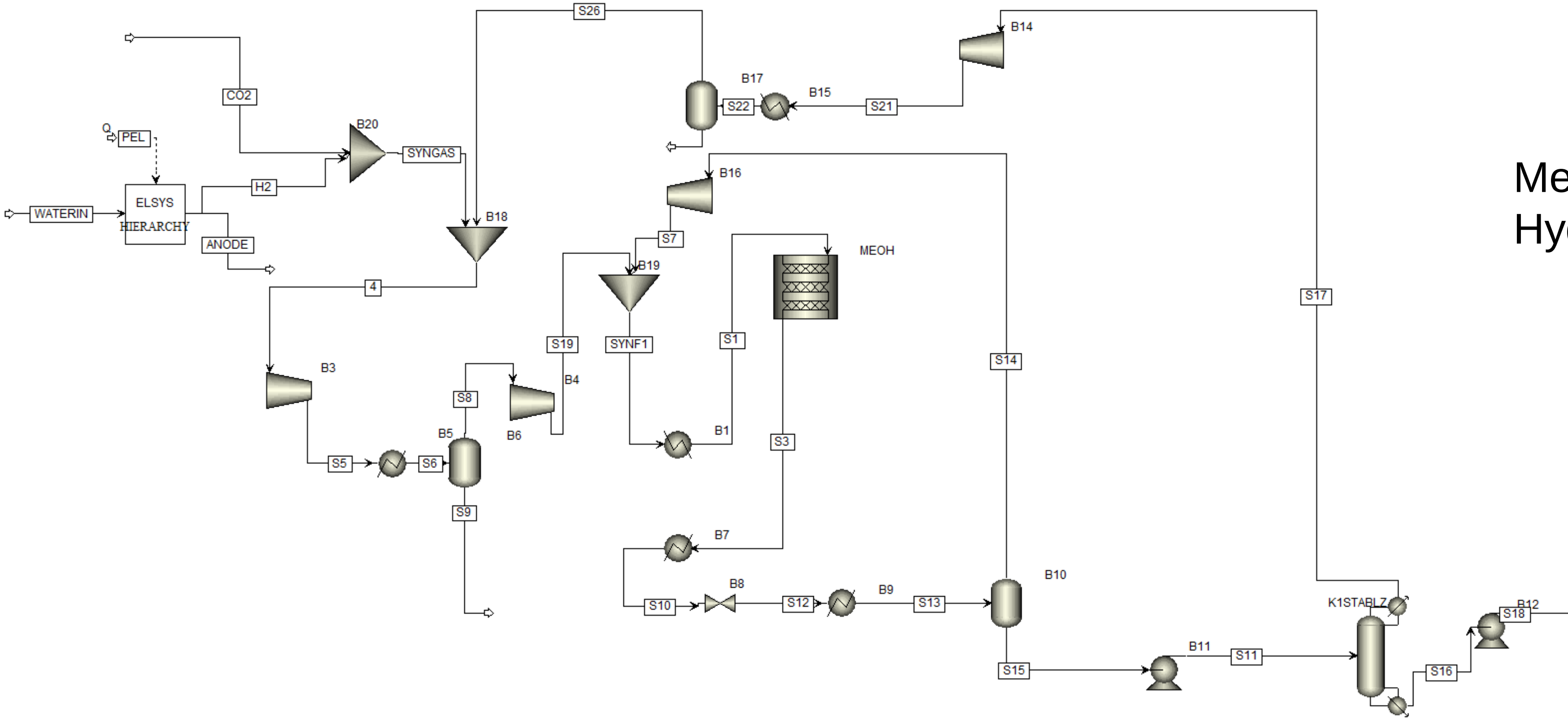


➢ Expectation: Coupling with methanol production process will favor more continuous process designs with higher electrolyser full load hours.

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

Methanol production concept

- CO_2 hydrogenation at 230 °C and 80 bar.



$$CO + 2H_2 \rightarrow CH_3OH$$
$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Methanol synthesis plant
Hydrogen to Methanol efficiency:

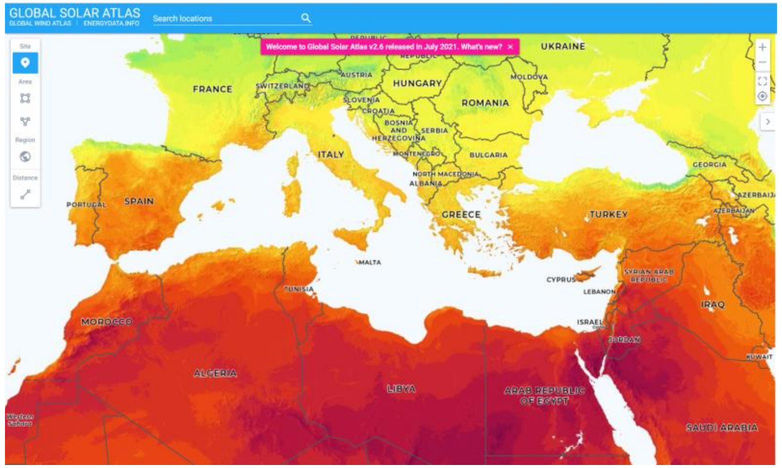
$$\eta_{H2-MeOH,LHV} = 81\%$$

Techno-economic process evaluation: methodology

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

Locations:

- Almeria, Spain, DNI: 1918 kWh/(m^2a)
- Tabuk, Saudi-Arabia DNI: 2882 kWh/(m^2a)
- Process simulation(1h) steps
- Optimization with MATLAB™ Patternsearch Global Optimization algorithm.



Source: https://globalsolaratlas.info/map

- Standard PV, CSP scenario (today)
- Outlook scenario:
    - PV: -55% (760, 340 USD/kW)
    - CSP approx. – 25 %, higher efficiency

CSP cost assumptions: Total Sub component cost (8)

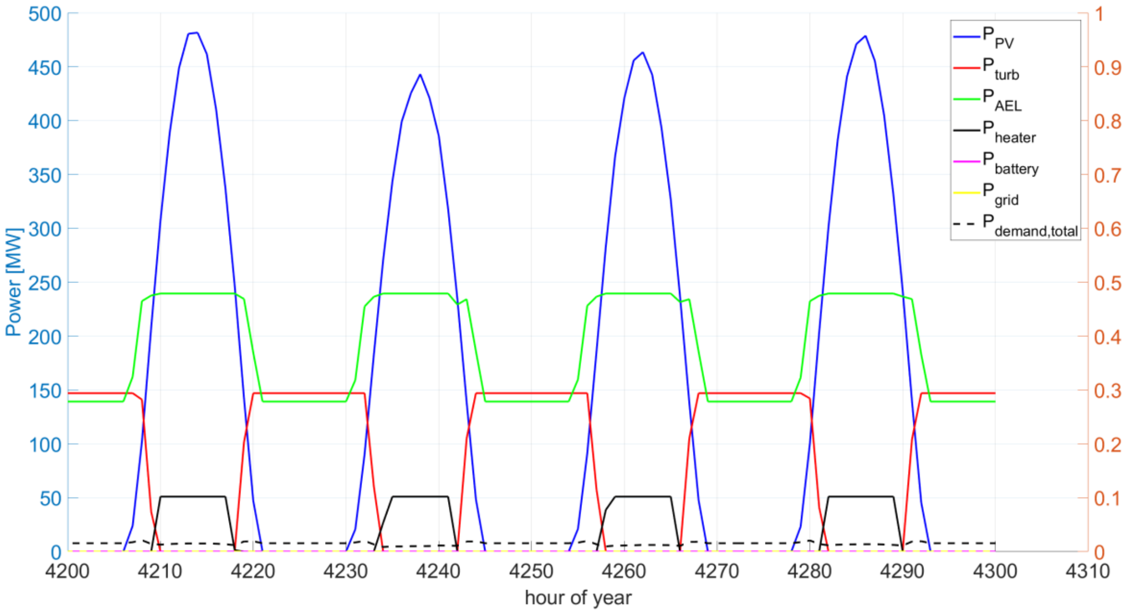
CSP equipment	**Location: Almeria, Spain Cost Index: 84**			**Location: Ouarzazate, Morocco Cost Index: 42**		
	Standard scenario	Outlook scenario	Cost reduction	Standard scenario	Outlook scenario	Cost reduction
Heliostat field (USD/m^2)	114.76	83.11	27.6%	87.88	65.27	25.7%
Tower (10^3USD/m	78.48	62.78	20.0%	48.24	38.59	20.0%
Receiver (USD/kW_{th})	146.57	102.60	30.0%	124.43	87.10	30.0%
Thermal storage (USD/kWh)	24.93	20.68	17.0%	21.09	17.75	15.8%
Power Block (USD/kW_{el})	785.12	708.45	9.8%	693.56	625.62	9.8%

(8) Dersch et al (2020) https://doi.org/10.1063/5.0028883

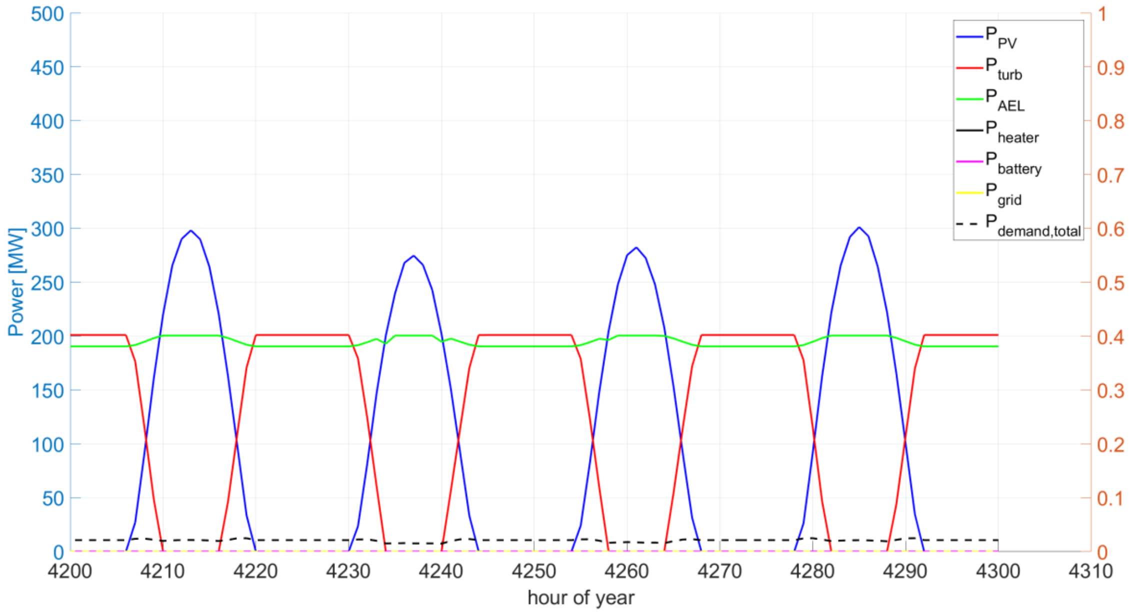
ECONOMIC PPROCESS EVALUATION

Cost-optimized MeOH plant design

Operational profile
Economic system optimization methanol production:
Regular CSP location: Almeria (Spain)



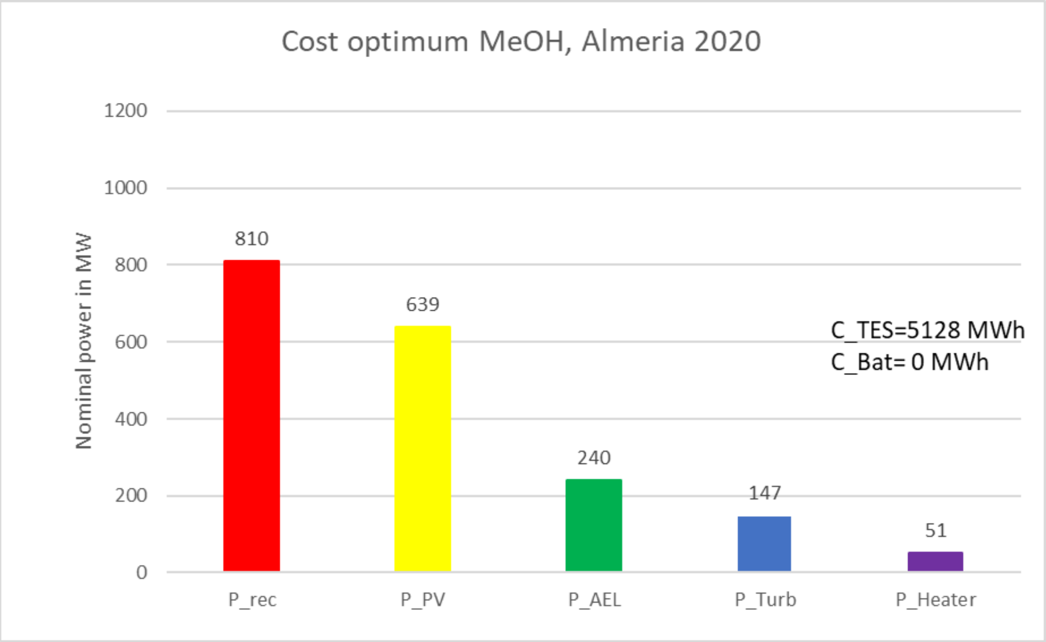
Operational profile
Economic system optimization methanol production,
Excellent CSP location: Tabuk (Saudi-Arabia)



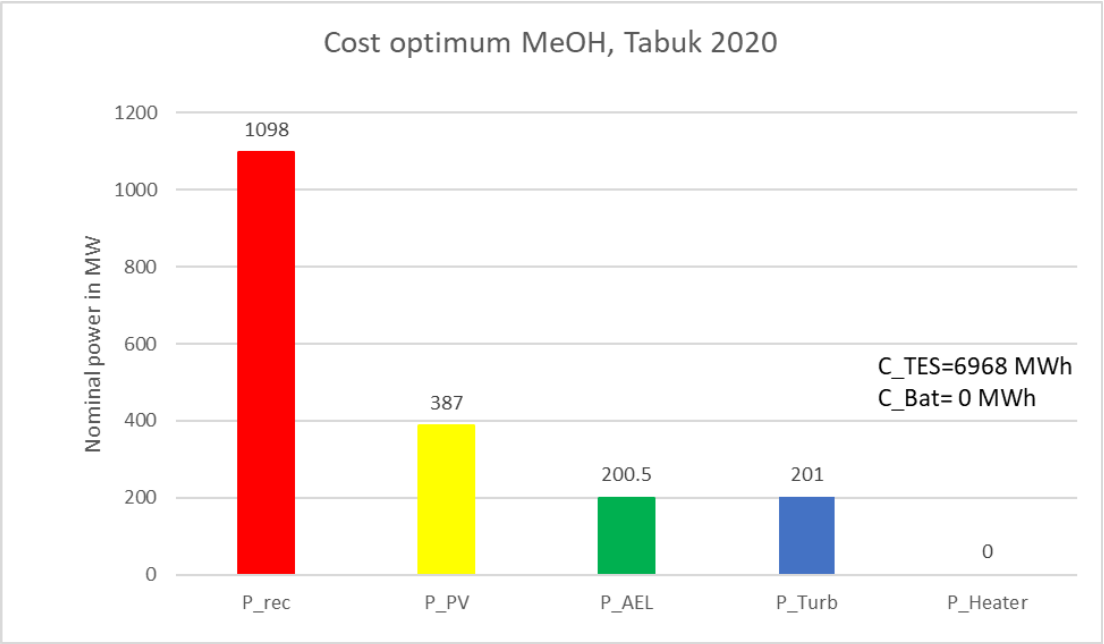
- At excellent solar location very continous electrolyser operation.

Cost-optimized MeOH plant design

Plant design
Economic system optimization methanol production:
Regular CSP location: Almeria (Spain)

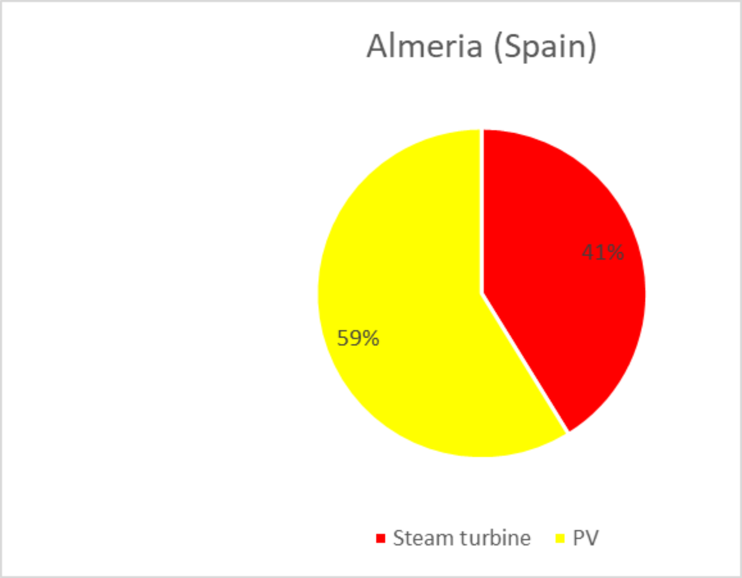


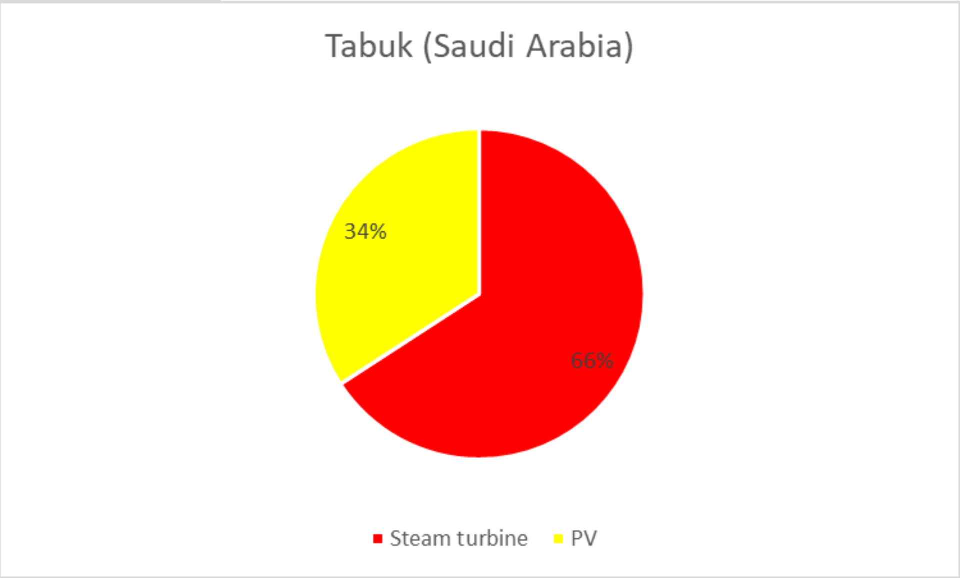
Plant design
Economic system optimization methanol production,
Excellent CSP location: Tabuk (Saudi-Arabia)



Share of electricity provision for E-Methanol production based on CSP/PV hybrid power plants

- Regular CSP site: PV supplies most of the electricity throughout the year.
- At very good CSP sites, 2/3 of the electricity is supplied by the steam turbine.

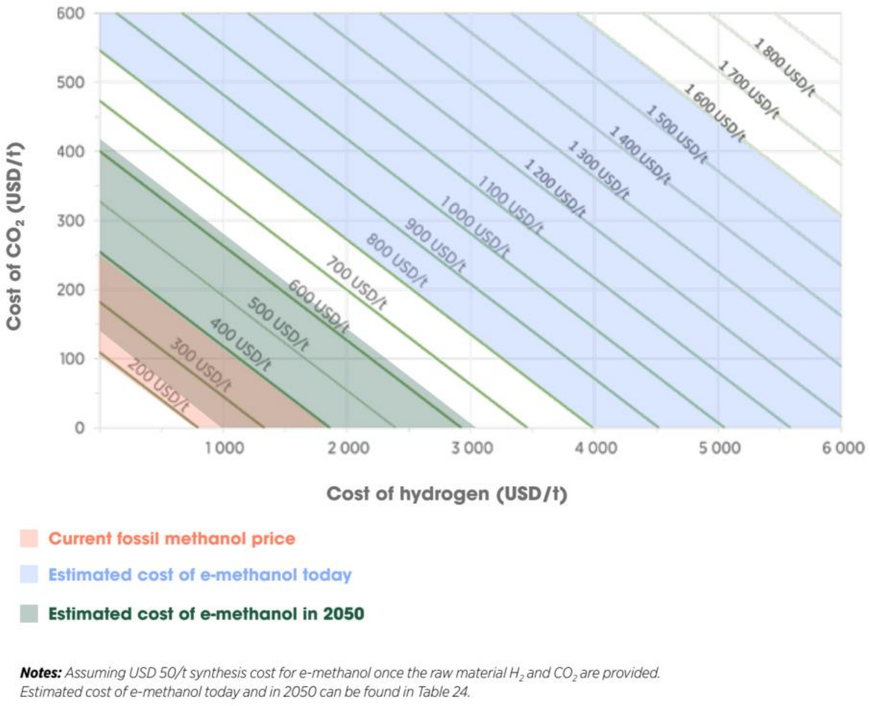




Methanol production price

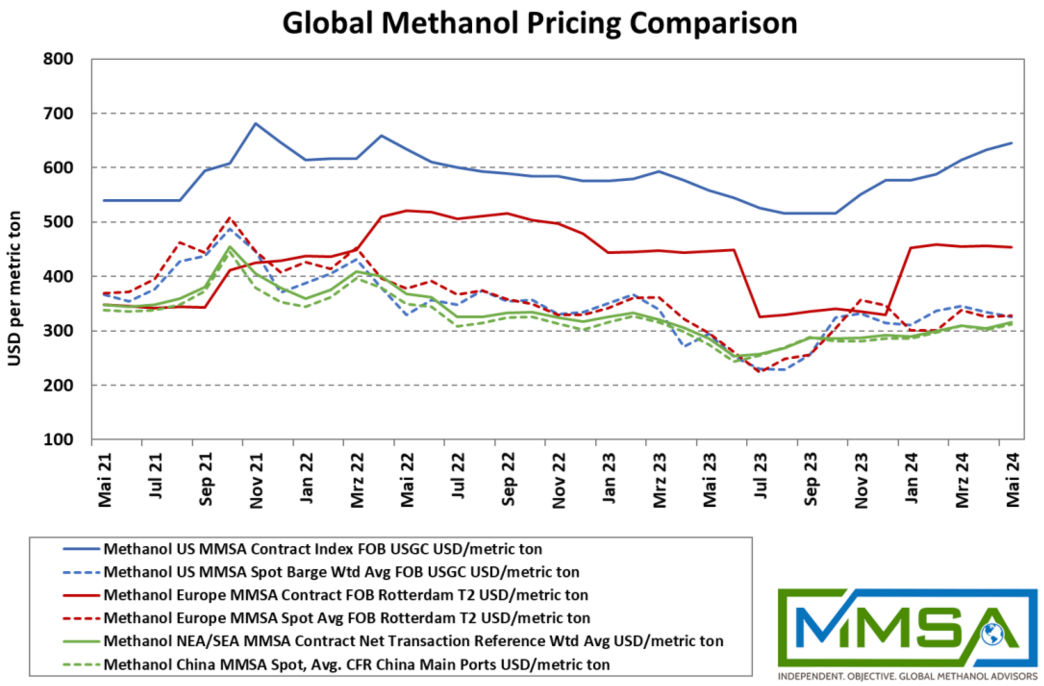
Methanol production price depends on:

- Hydrogen price which is a function of CAPEX, LCOE and electrolyser full load hours
- CO_2 price



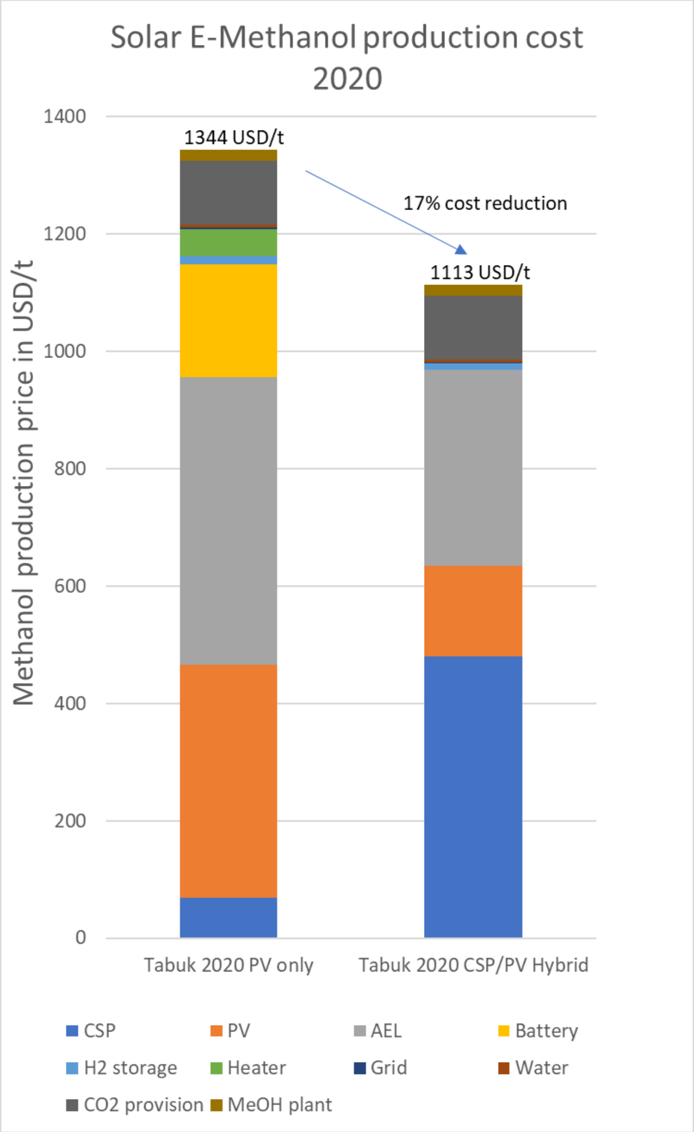
2) IRENA and METHANOL INSTITUTE 2021

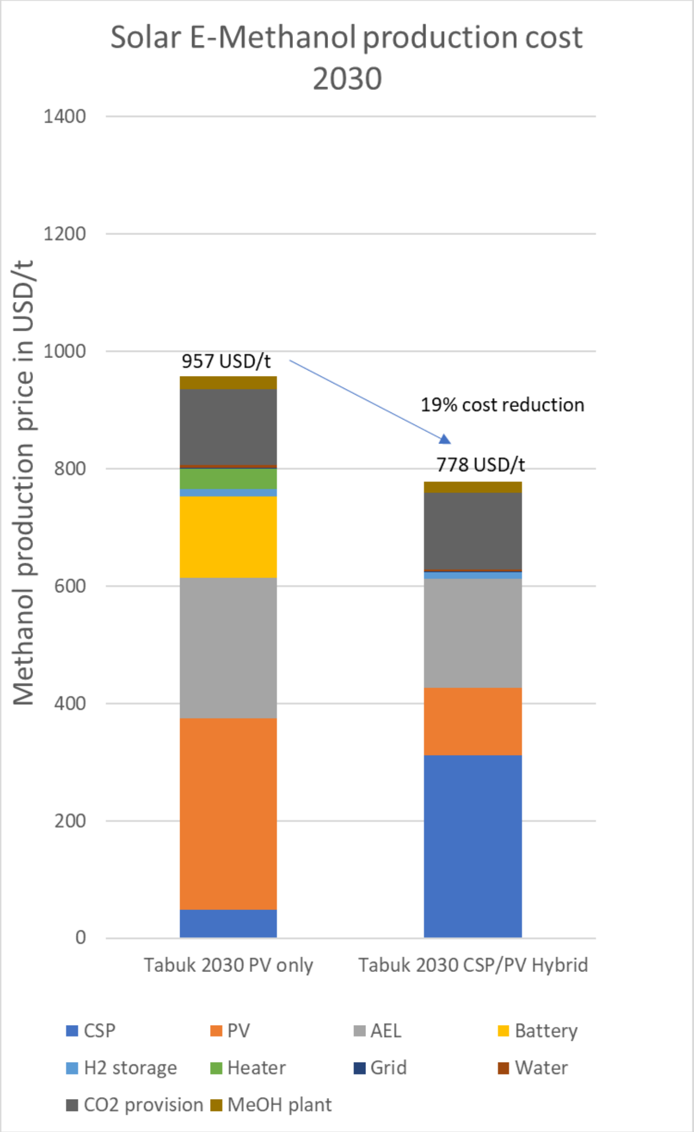
Fossil-based Methanol market price in the range of 300 to 600 USD/t.



METHANOL INSTITUTE July 2024

Methanol production price



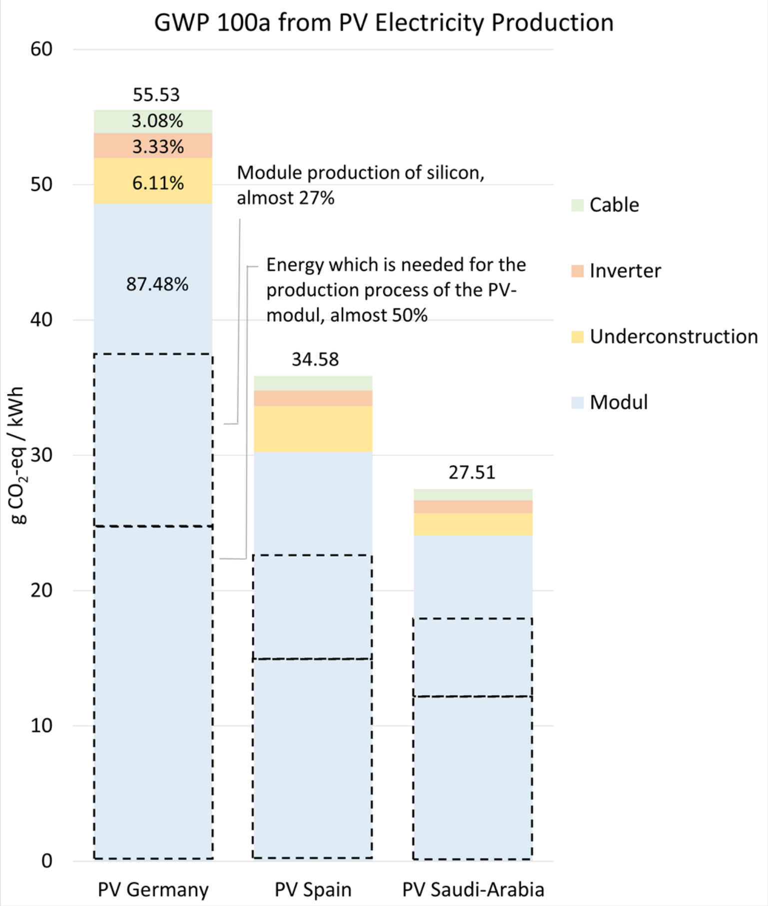


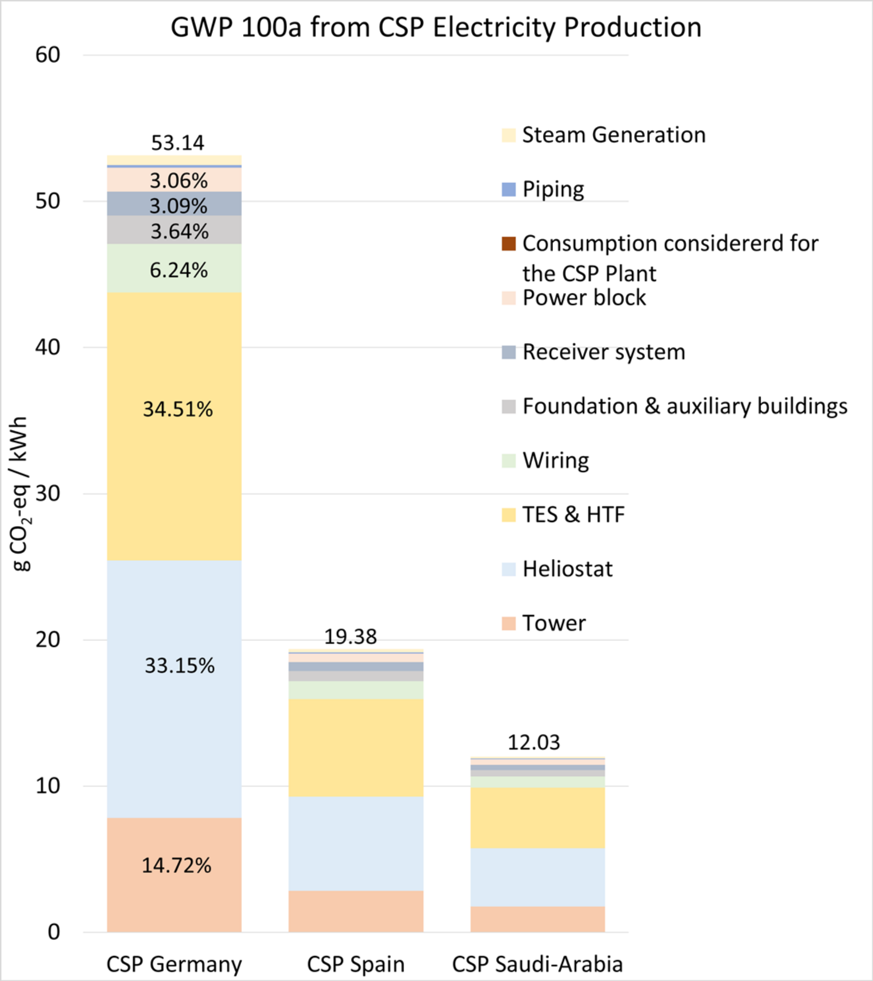
- The methanol production costs with the CSP/PV hybrid concept are significantly lower than with the pure PV concept (up to 19 %).
- The production costs for 2030 appear very promising compared to the current methanol market price.

Price assumption generic CO_2 source: 73 USD/t in 2020 (point source), 87 USD/t in 2030 (point source+DAC)

ENVIRONMENTAL ASPECTS

Environmental process evaluation:
Global warming potential (GWP100) of PV and CSP electricity provision



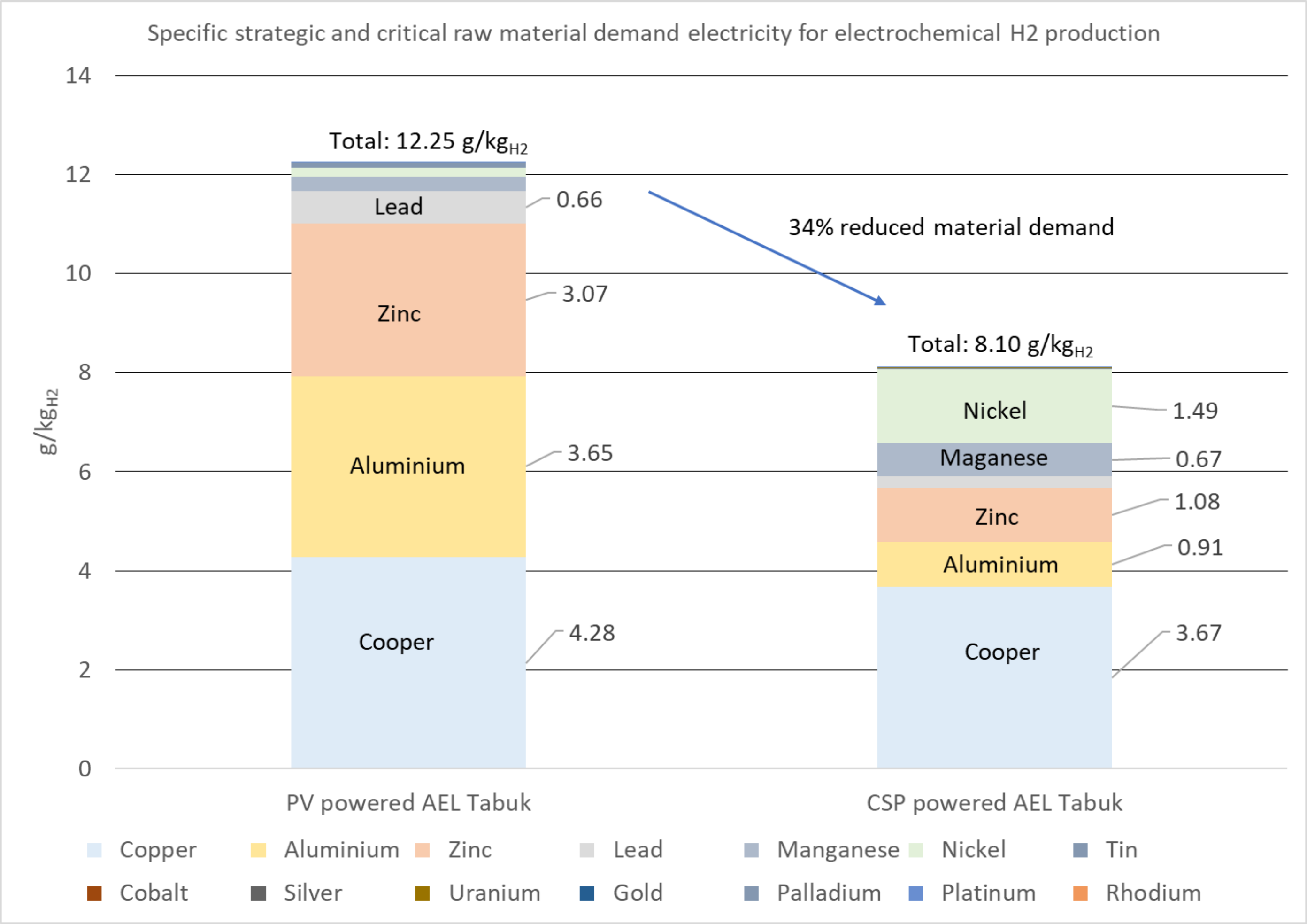


- Analysis for 3 locations
- Assumption lifetime 20 a
- ➢ CSP GWP potential up to 56% lower at good solar locations.

CSP evaluation based on publication of Gasa et al 2021 (9) and Gasa et al 2022 (10)

PV LCA evaluation based on Umweltbundesamt 2021 (11) and IEA 2020 (12)

Critical raw material demand for solar electrochemical hydrogen production (only electricity)



- Analysis for plant site with high solar irradiation potential (Tabuk, Saudi-Arabia)
- Production of PV electricity requires significantly more critical and strategic raw materials than CSP electricity provision.

OUTLOOK

Summary and Outlook

- CSP/PV hybrid power plants with thermal energy storage are a promising approach for the production of renewable fuels with solar energy.
- Lower PV system costs favor plant concepts with fluctuating hydrogen production (lower electrolyser FLH).
- In good solar locations, cost-optimized continuous operating concepts (>8000 electrolyser FLH possible) with a high proportion of CSP electricity production (2/3).
- Environmental aspects such as life cycle emissions and the need for critical raw materials show further advantages of incorporating CSP.

Next steps:

- Further sensitivity studies
  - Electrolyser, PV, CSP system costs +/- 50 %
- Include environmental system evaluation based on a LCA analysis
  - Plant design to minimize CO_2 abatement costs

References

(1) Quaschning 2019, Renewable Energy and Climate Change

(2) IRENA AND METHANOL INSTITUTE (2021), Innovation Outlook : Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.

(3) DNV: Hydrogen forecast to 2050.

(4) DLR 2020, Wasserstoff als ein Fundament der Energiewende, https://www.dlr.de/content/de/downloads/publikationen/broschueren/2020/wasserstoffstudie-teil-1.pdf?__blob=publicationFile&v=3

(5) Rosenstiel, A., et al., *Electrochemical Hydrogen Production Powered by PV/CSP Hybrid Power Plants: A Modelling Approach for Cost Optimal System Design.* Energies, 2021. **14**(12). https://doi.org/10.3390/en14123437

(6) Jung, C., et al., *Ottokraftstoffe aus erneuerbarem Methanol.* 2020. **92**(1-2): p. 100-115.DOI: 10.1002/cite.201900108

(7) Schemme, S., *Techno-ökonomische Bewertung von Verfahren zur Herstellung von Kraftstoffen aus H2 und CO2*, Doktorarbeit RWTH Aachen, 2020.

(8) Dersch, J., et al., *LCOE reduction potential of parabolic trough and solar tower technology in G20 countries until 2030*, AIP Conference Proceedings, 2020. https://doi.org/10.1063/5.0028883

(9) Gasa G. et al., *Life Cycle Assessment (LCA) of a Concentrating Solar Power (CSP) Plant in Tower Configuration with and without Thermal Energy Storage (TES),*2021. https://doi.org/10.3390/su13073672

(10) Gasa G. et al., Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with different storage capacity in molten salts, 2022. https://doi.org/10.1016/j.est.2022.105219

(11) Umweltbundesamt 2021. Abschlussbericht CLIMATE CHANGE 35/2021.

(12) IEA 2020. International Energy Agency (IEA) PVPS Task 12, Report T12-19:2020.

Impressum

Thank you for your attention!

DLR

Topic:	Cost Optimal Design of Solar E-Methanol Production Powered by CSP/PV Hybrid Power Plants
Date:	2024-07-17
Author:	Andreas Rosenstiel (andreas.rosenstiel@dlr.de)
Presenter:	Christian Sattler (christian.sattler@dlr.de)
Institute:	DLR-Institute of Future Fuels
Bildcredits:	All pictures are „DLR (CC BY-NC-ND 3.0)“, if no other source is provided

Acknowledgements: The authors of this work gratefully acknowledge the funding of the projects SolareKraftstoffe (Grant agreement Nr. 03EIV221), MENA-Fuels (Grant agreement Nr. 03EIV181A-C), TUNol (Grant agreement Nr. 03EE5123E) by the Federal Ministry for Economic Affairs and Energy, on the basis of a decision by the German Bundestag. Furthermore, financial support from DLR's basic funding for the project "NeoFuels" is gratefully acknowledged.

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages