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Department of Mechanical and Aerospace Engineering

Strategies for Harnessing Solar Thermal Energy for Industrial Decarbonization

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POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Cheap Energy Storage is Key for the Renewable Energy Transition

- As market penetration of renewables increases there is a growing need to integrate energy storage solutions, which increase cost.
- Li-ion battery energy storage is viable solution for short term energy storage.
- 4-hour energy storage duration at utility scale roughly doubles the price.
- Much of the cost tied to Li-ion battery cost itself.

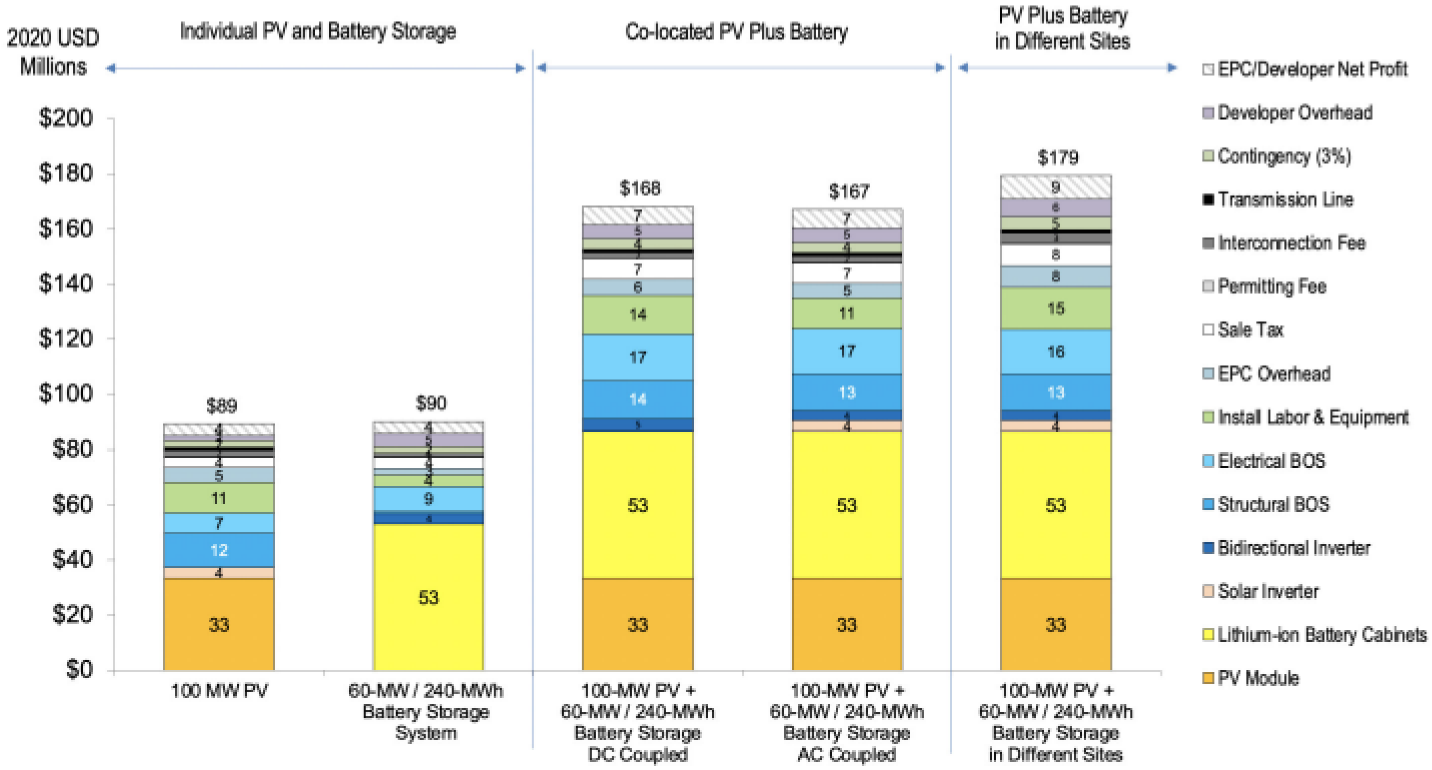
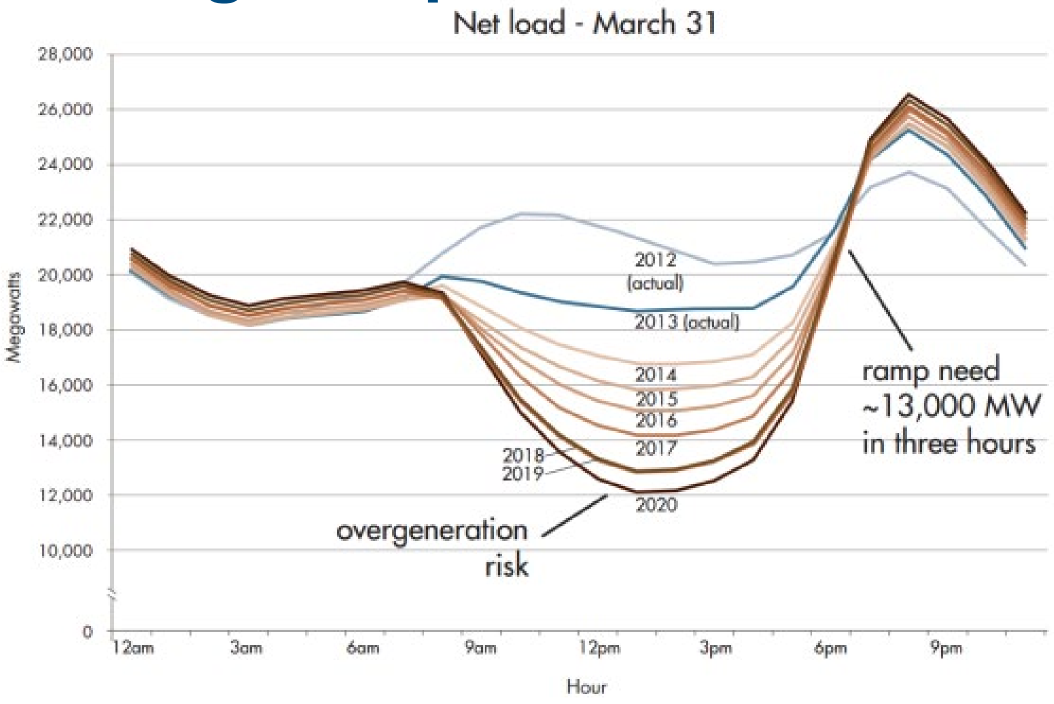


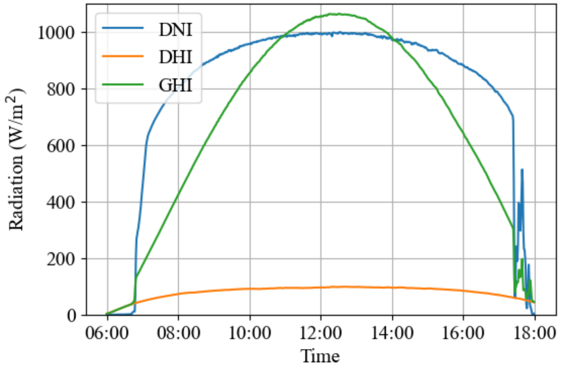
Figure 24. Cost benchmark for Utility PV-plus-storage systems (4-hour duration) in different sites and the same site (DC-coupled and AC-coupled cases), Q1 2021

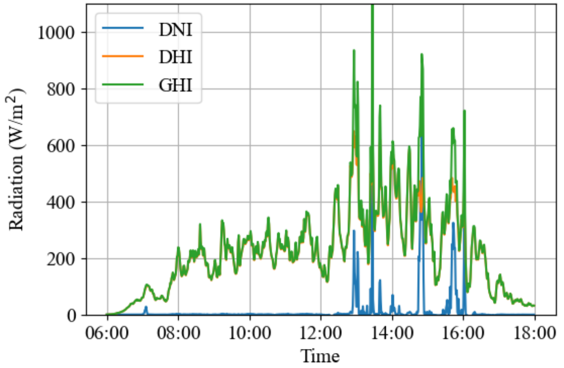
U.S. Solar Photovoltaic System Cost Benchmarks: Q1 2021 Vignesh Ramasamy, David Feldman, Jal Desai, and Robert Margolis National Renewable Energy Laboratory

Short-Term and Long-Term Energy Storage Requirements

- Classic duck curve (top right) shows effect of increased solar penetration in California from 2012 to 2020
- Belly a result of typical solar profile (bottom left).
- But solar generation also can be highly variable on a day-to-day basis (bottom right).
- Can be flattened and smoothed by short term energy storage (e.g., 4-hour Li-ion battery)





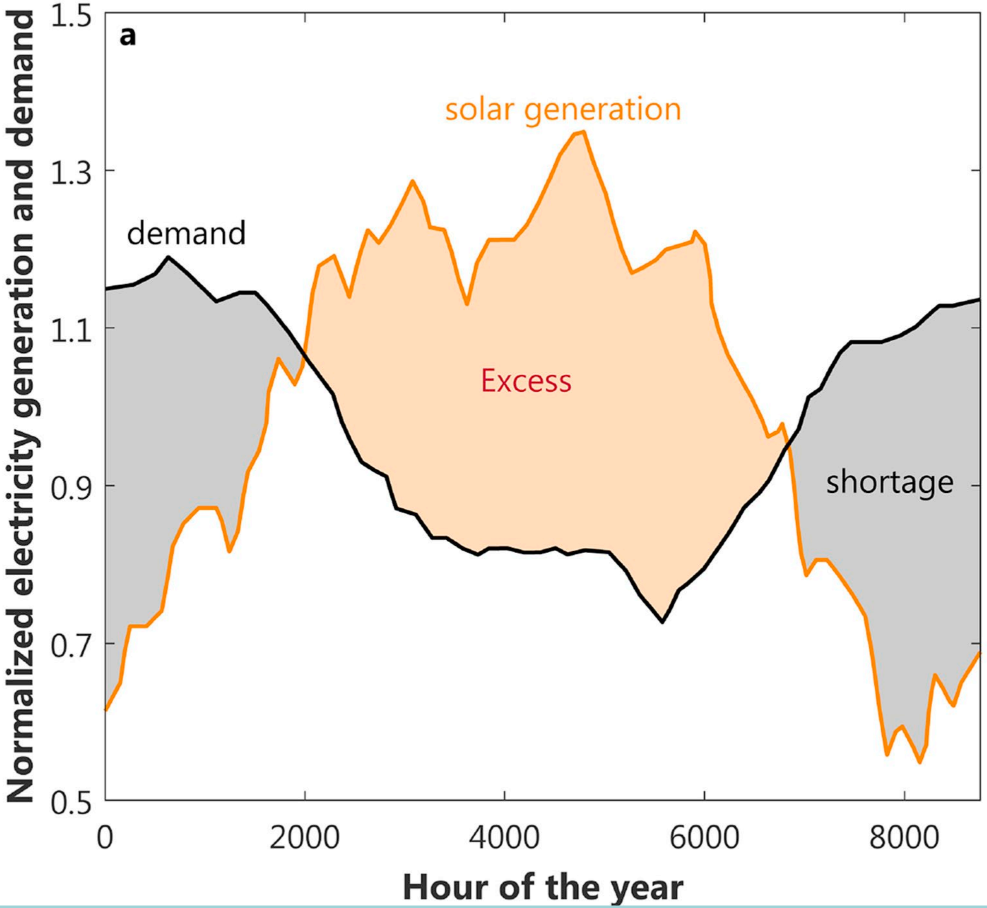


Duck curve source - Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart Paul Denholm, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson National Renewable Energy Laboratory

Solar Measurements – University of Florida Energy and Research Park - https://midcdmz.nrel.gov/

Short-Term and Long-Term Energy Storage Requirements

- Alternative storage solutions (e.g., mechanical, chemical, thermal) are needed for long duration energy storage, such as seasonal energy storage.
- There is excess solar generation in the summer months and a shortage in winter months (figure shown for Europe)
- Electrical demand will increase, and dynamics will change as electrification of transportation (e.g., battery electric vehicles) and households (e.g., heat pump heating)



Gabrielli, P., Poluzzi, A., Kramer, G.J., Spiers, C., Mazzotti, M. and Gazzani, M., 2020. Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. Renewable and Sustainable Energy Reviews, 121, p.109629.

Several Industries Are Not Easily Electrified

- Industry and transportation are largest energy consumers (end-use).
- Transportation sector currently represents 28% of the U.S. primary energy consumption (about 28 quadrillion BTU’s), of which 24.5% is due to commercial and freight transport, 8.7% aviation and 4.6% shipping.
  - Aviation, heavy transport and shipping rely on energy dense fuels in order to have space for transporting people or goods. Kerosene is ~50x more energy dense (volumetric) than Li-ion batteries.
- Energy use in industrial sector dominated by natural gas and petroleum, not electricity.
  - Industrial heating and drying applications
  - Raw feedstocks, e.g. plastics and chemicals
  - Some stand-out examples include
    - Cement manufacturing ~ 8% worldwide CO_2 emissions, requires thermal energy @ 1450 ˚ C.
    - Iron and steel ~ 8% worldwide CO_2 emissions, requires carbon feedstock and thermal energy @ 1500 to 1650 ˚ C
    - Ammonia Production – requires H_2, currently derived primarily from natural gas. ~ 2% of total worldwide energy consumption and 1.3% of CO_2 emissions.

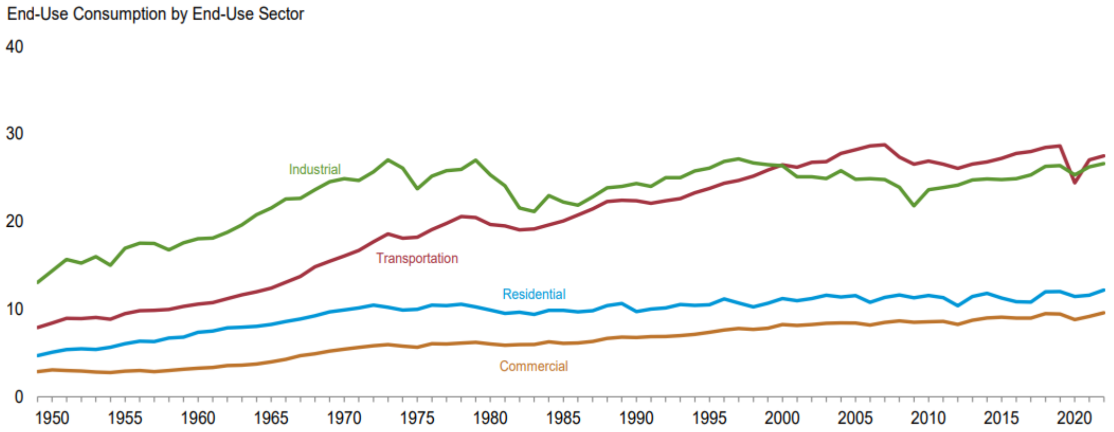
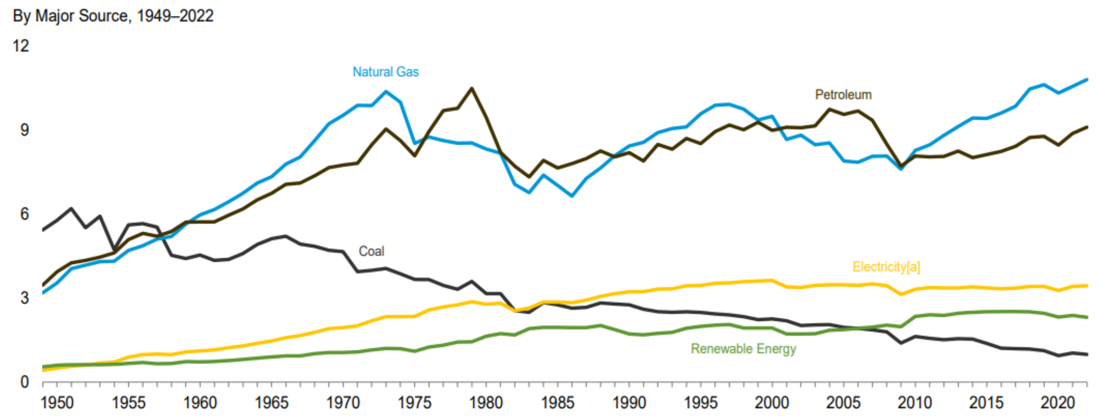
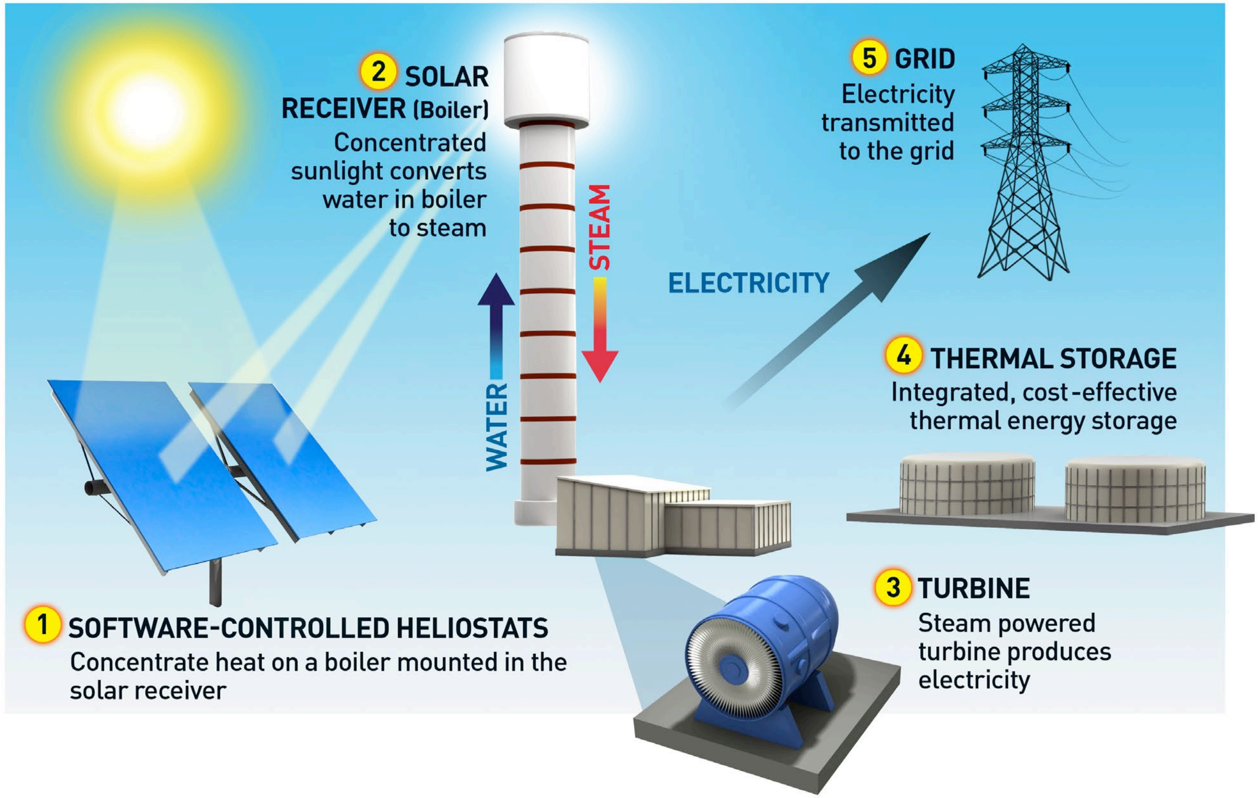


Figure 2.4 Industrial Sector Energy Consumption
(Quadrillion Btu)



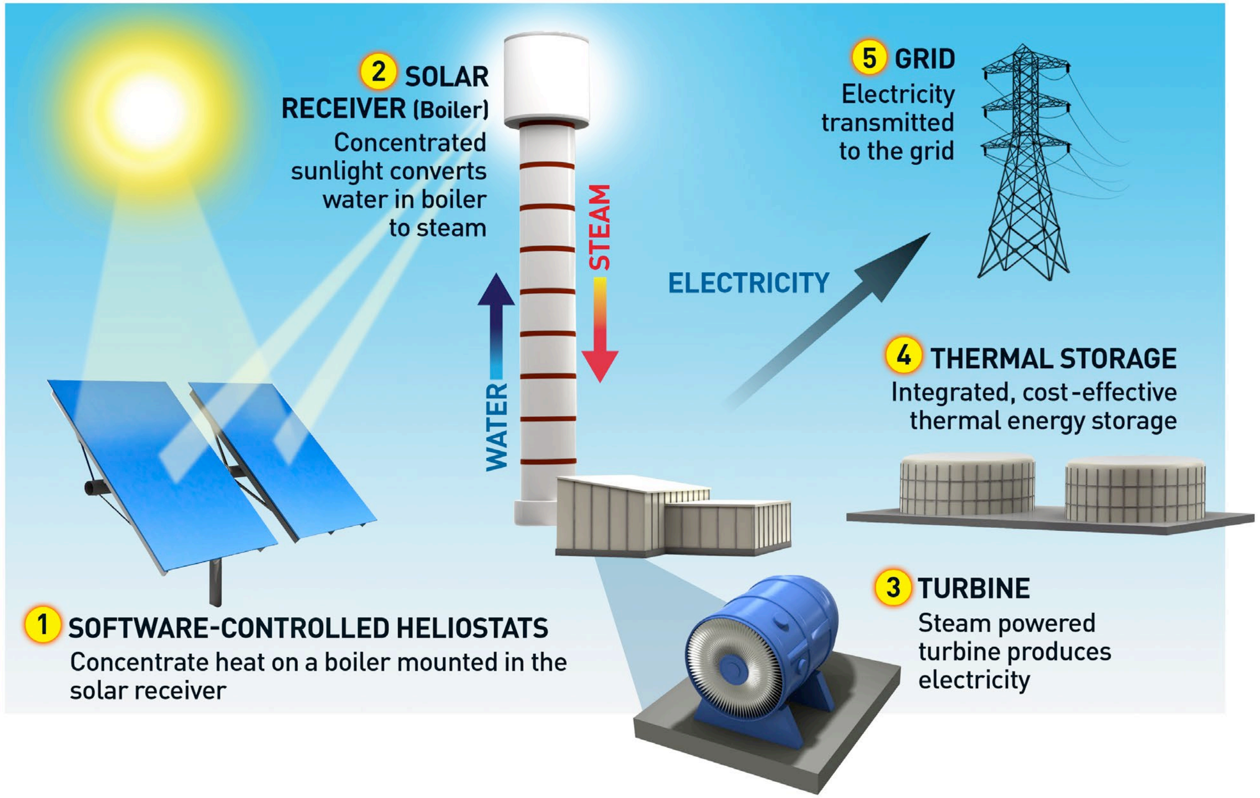
U.S. Energy Information Administration, Monthly Energy Review, July 2023, https://www.eia.gov/totalenergy/data/monthly/

Concentrating Solar Power (CSP) at a Promising Intersection



Images: http://www.brightsourceenergy.com/

Concentrating Solar Power (CSP) at a Promising Intersection



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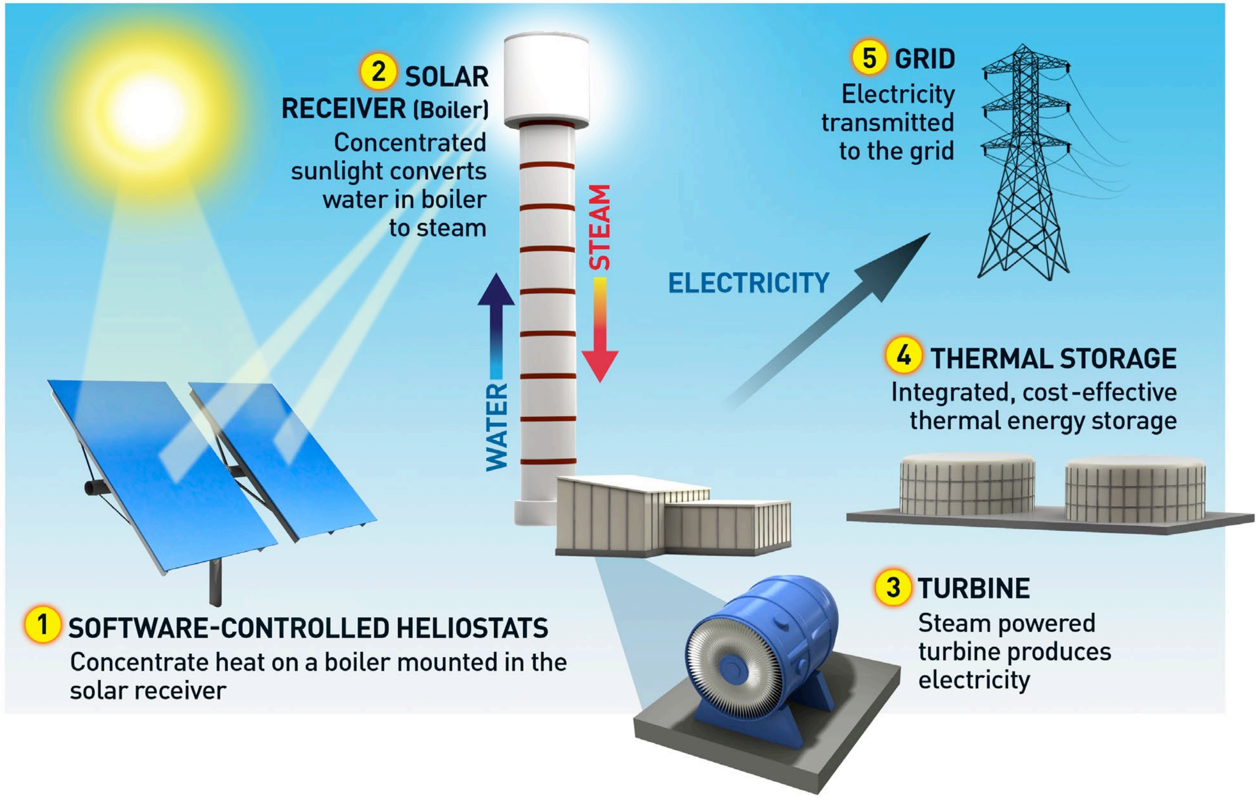
Concentrating Solar Power (CSP) at a Promising Intersection

- Cheap thermal energy storage for 24/7 utilization
- High temperature process heat - up to 1500 ˚C or higher.
  - Cement or steel manufacturing
- Production of energy dense fuels, such as sustainable aviation fuel and H_2
  - Seasonal energy storage and heavy transportation sector



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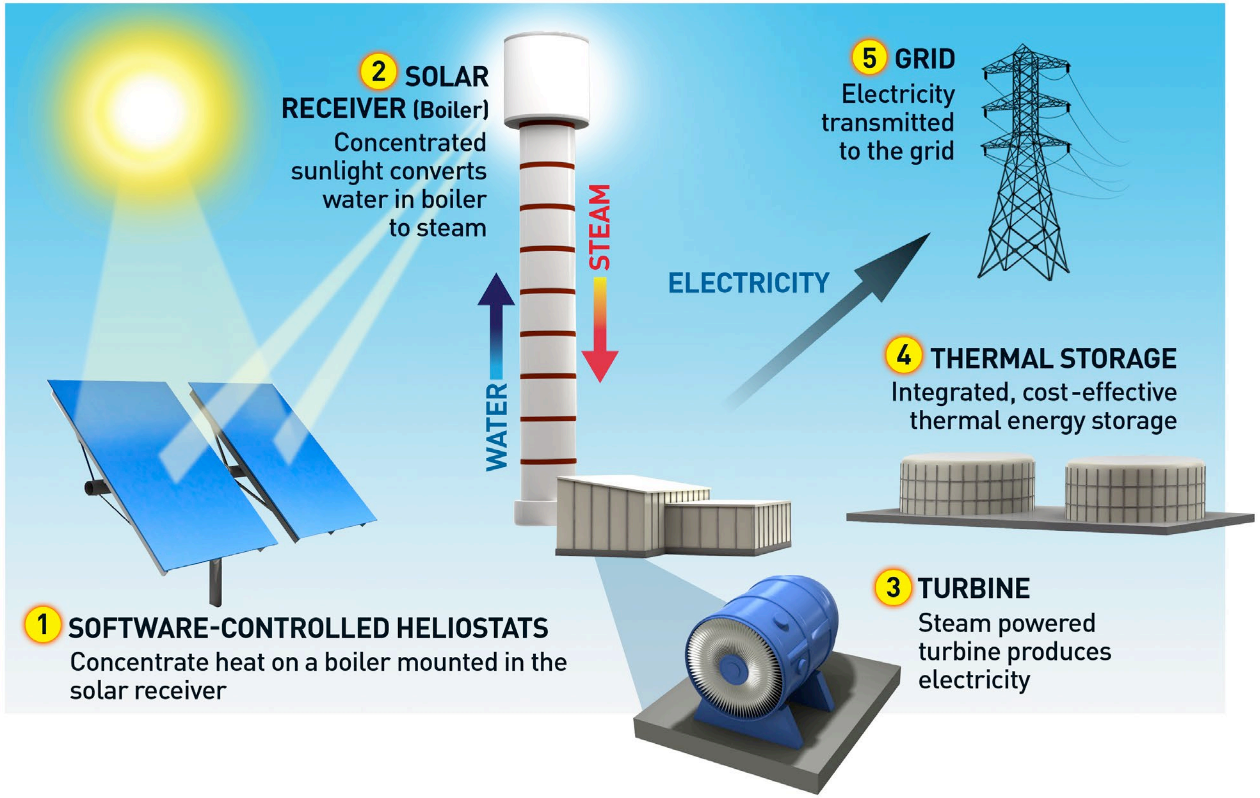
Concentrating Solar Power (CSP) at a Promising Intersection

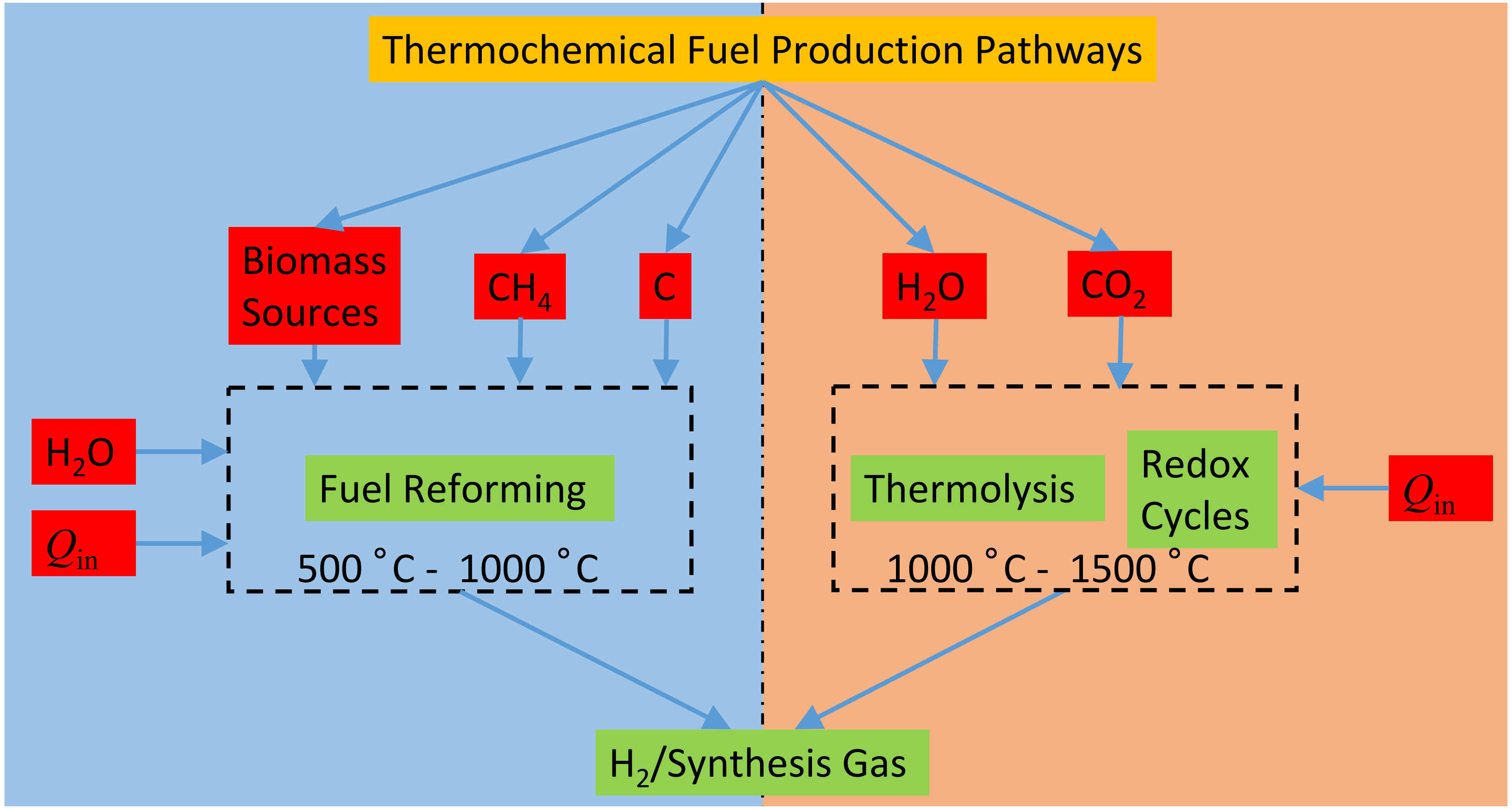
- Thermal Energy Storage (TES) Costs estimated to be $22/kWh$_{th}$ by NREL – compared to Li-Ion costs of $132/kWh
- Total cost of CSP with 6-hours TES is 0.11-0.15 $/kWh
- Economy of scale has yet to be realized like it has for PV modules
- Cost of manufacturing of heliostats is one of largest drivers of cost
- Commercial use typically limited to 600 °C for power production – **higher temperatures open new pathways**



Turchi, C.; Boyd, M.; Kesseli, D.; Kurup, P.; Mehos, M.; Neises, T.; Sharan, P.; Wagner, M.; Wendelin, T. (2019) CSP Systems Analysis - Final Project Report. NREL/TP-5500-72856. (PDF 4.9 MB)

Images: http://www.brightsourceenergy.com/

Thermal Routes to Solar Fuel Production

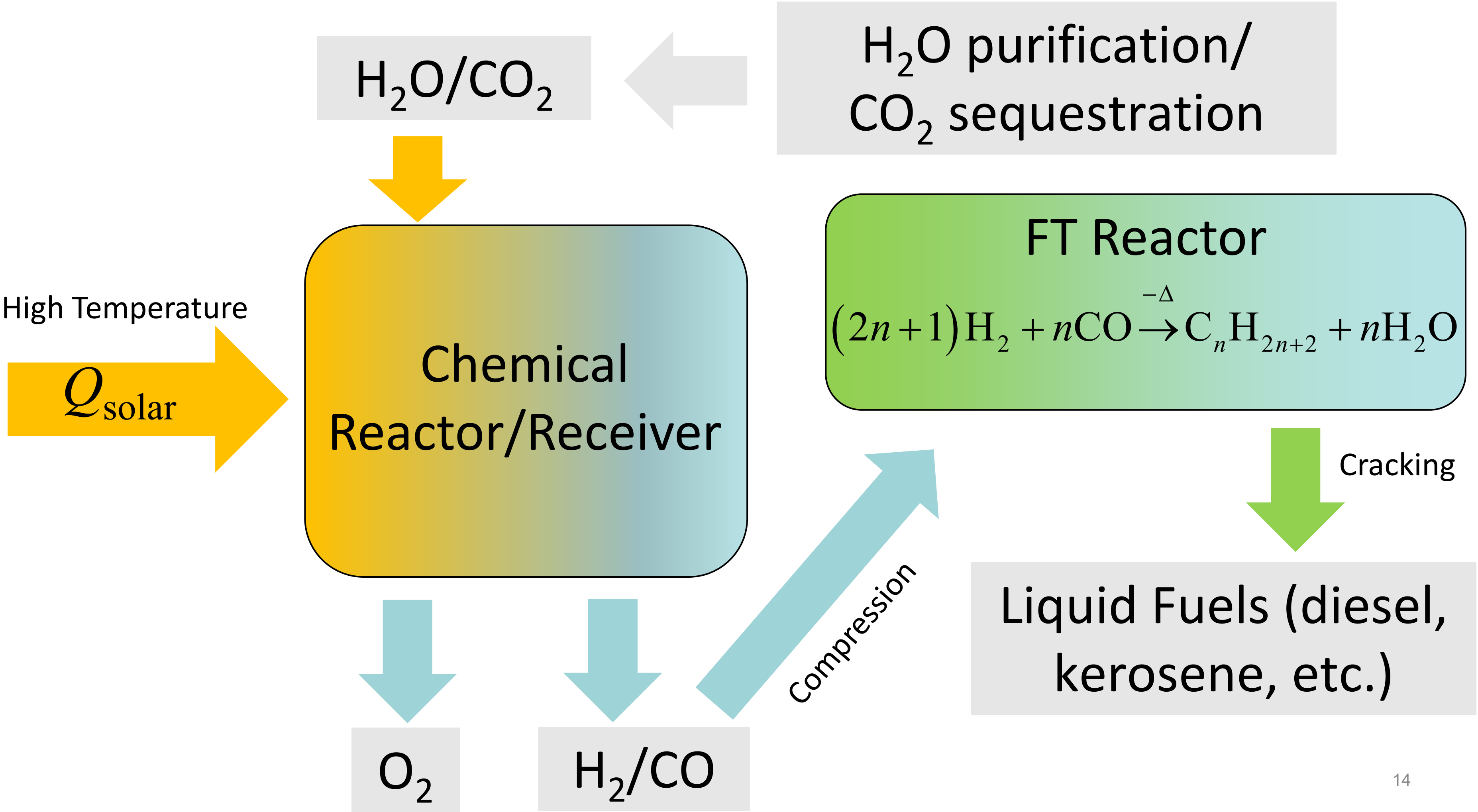


Scheffe, J., McCord, D. and Gordon, D., 2022. Hydrogen (or Syngas) Generation–Solar Thermal. Advances in Energy Storage: Latest Developments from R&D to the Market, pp.439-487.

Thermochemical Fuel Production

Solar Concentration

Image: http://www.brightsourceenergy.com/



Thermochemical Dissociation of H_2O

Q_{solar}

H_2O

Two-Step Redox Cycle

Direct Dissociation

1) $MO \rightarrow MO_{1-\delta} + \delta/2 O_2$

$H_2O \rightarrow H_2 + 0.5O_2$

Chemical Reactor

2) $MO_{1-\delta} + \delta H_2O \rightarrow MO + \delta H_2$

O_2

H_2

Direct Dissociation

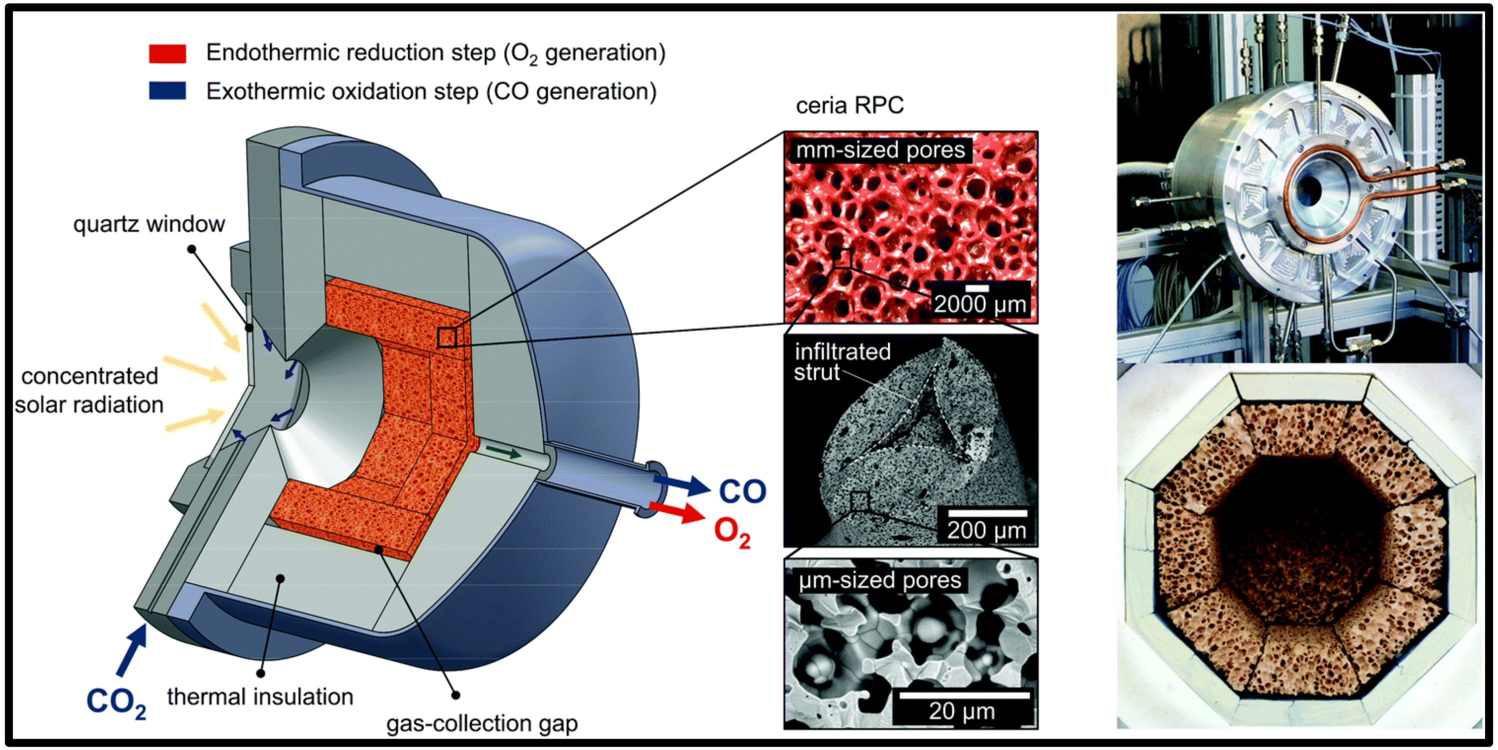
- High temperatures (> 2500 °C)
- Rapid quenching or separation of products

Two-Step Redox Cycle

- Lower temperatures (1673 °C)
- Inherent separation of product gases

SOA ETH Zurich Reactor

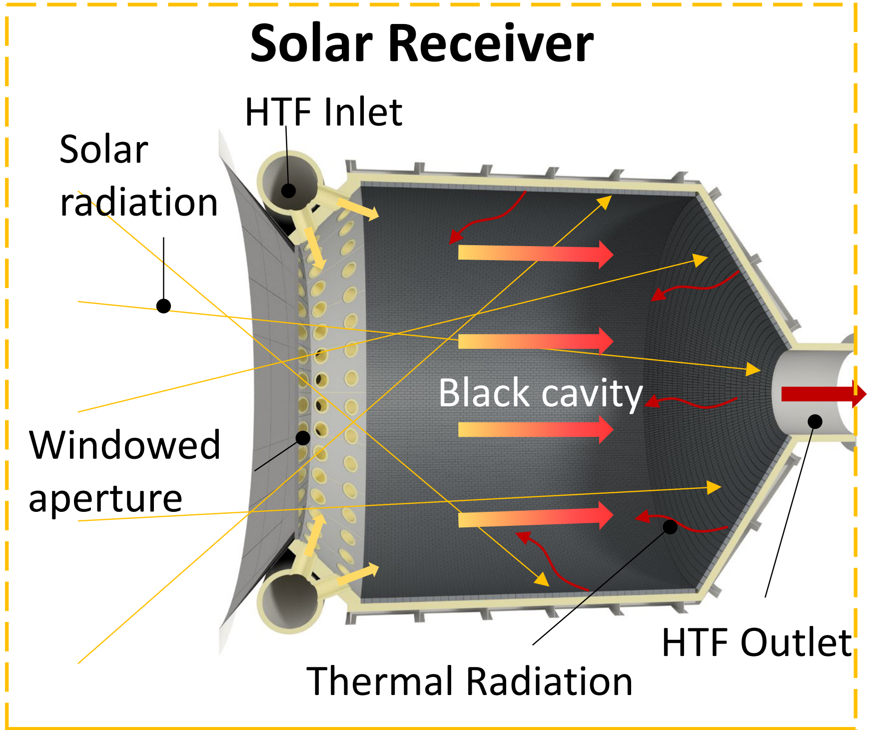
- First Step:
  - $CeO_{2-\delta i} \rightarrow CeO_{2-\delta f} + \Delta\delta O_2$
- Second Step:
  - $CeO_{2-\delta f} + H_2O \rightarrow CeO_{2-\delta i} + H_2$
  - $CeO_{2-\delta f} + CO_2 \rightarrow CeO_{2-\delta i} + CO$
- Directly irradiated concept
- Ceria SOA material – record 5% solar to fuel efficiency
- Relatively high temperature (1500 ˚C) and large temperature swing between first and second steps (~500 ˚C), leading to large irreversibility



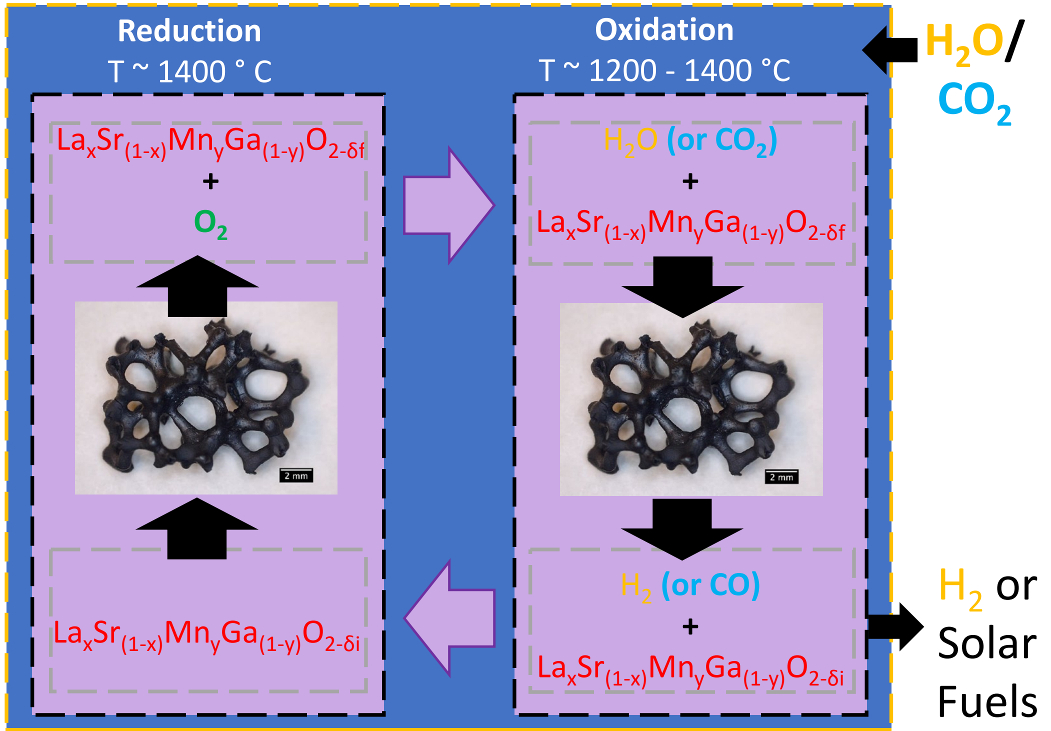
Marxer, Daniel, et al. "Solar thermochemical splitting of CO 2 into separate streams of CO and O 2 with high selectivity, stability, conversion, and efficiency." *Energy & Environmental Science* 10.5 (2017): 1142-1149.

Our New Concept Aimed at Scaleup of Solar Fuels

- Our prior work has aimed at discovery of redox active materials beyond ceria and has led to new perovskite compositions.
- Aim to operate at lower temperature (~1400 ° C) with smaller temperature swings.
- Indirectly heated reactor concept which will enable optimal design of reactor and receiver
- Collaboration between U. Florida and Synhelion SA.



Efficient Solar Radiation Absorption Integrated with TES for 24/7 Operation



Solar Thermochemical H_2O (or CO_2) Splitting with Candidate La-Sr-Mn-Ga Replica Foam

Solar-driven Chemical Looping Reforming of Methane

Solar Concentration

Image: http://www.brightsourceenergy.com/

CH_4

H_2O/CO_2

H_2O purification/
CO_2 sequestration

High Temperature

Q_{solar}

Chemical
Reactor/Receiver

H_2/CO

Compression

FT Reactor

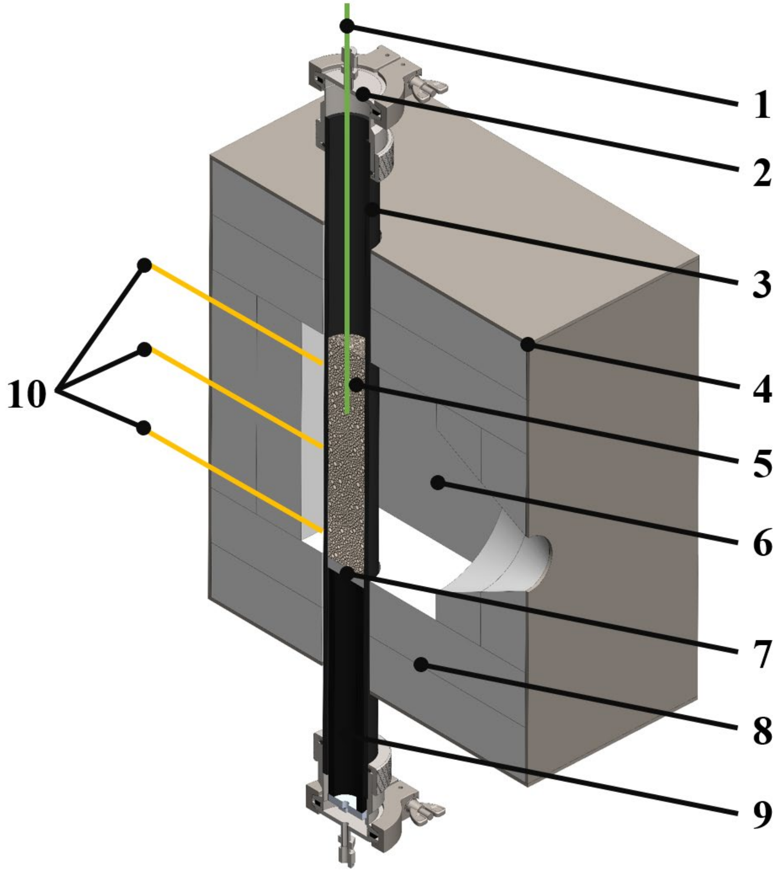
$$(2n+1)\mathrm{H}_2 + n\mathrm{CO} \xrightarrow{-\Delta} \mathrm{C}_n\mathrm{H}_{2n+2} + n\mathrm{H}_2\mathrm{O}$$

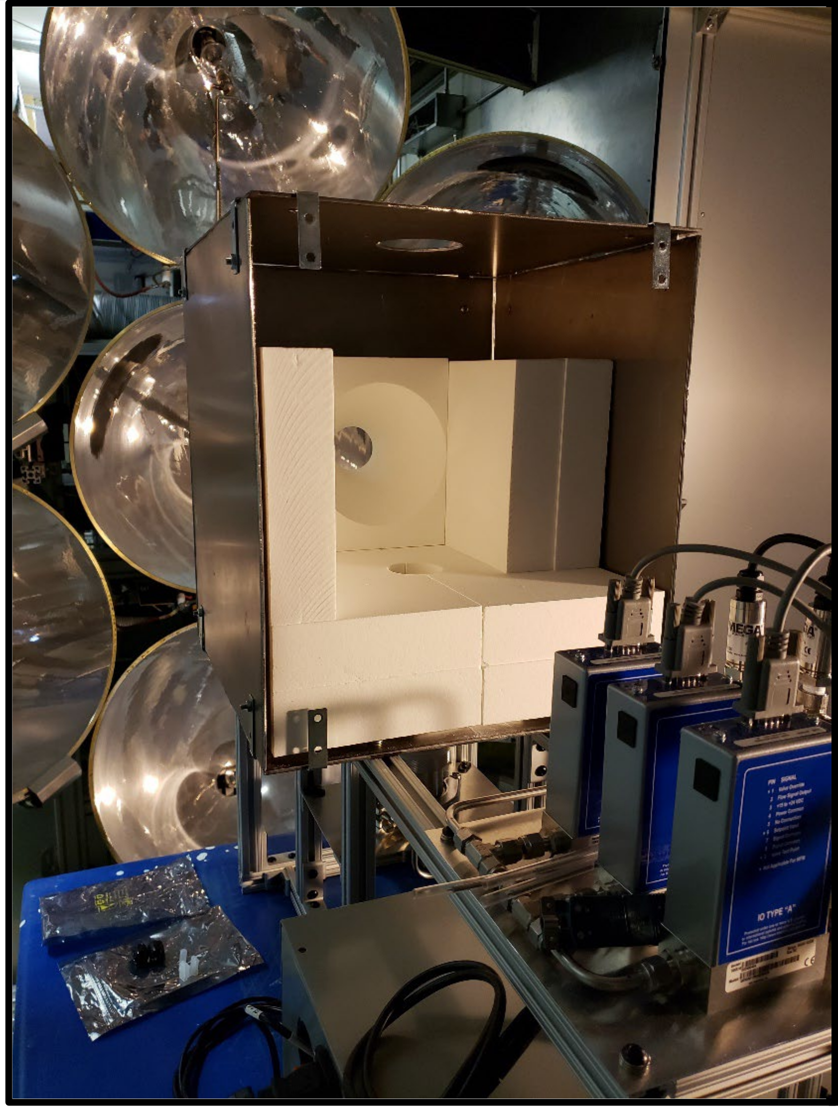
Cracking

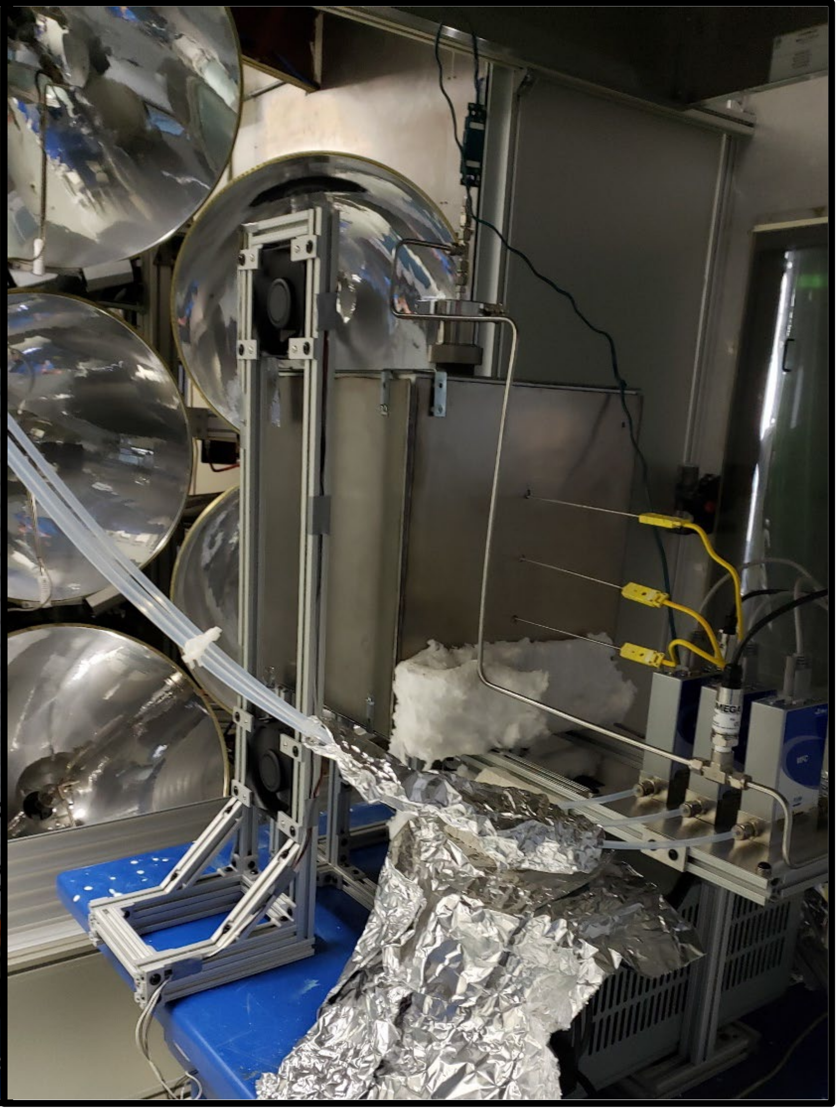
Liquid Fuels (diesel,
kerosene, etc.)

Solar Reactor Development

- (1) inner R-type thermocouple
- (2) KF-50 quick coupling, compression port adapter
- (3) outer silicon carbide tube
- (4) steel enclosure
- (5) packed bed of ceria
- (6) heated cavity
- (7) reticulated alumina foam
- (8) alumina/mullite fiber board insulation
- (9) inner porous silicon carbide tube
- (10) K-type thermocouples

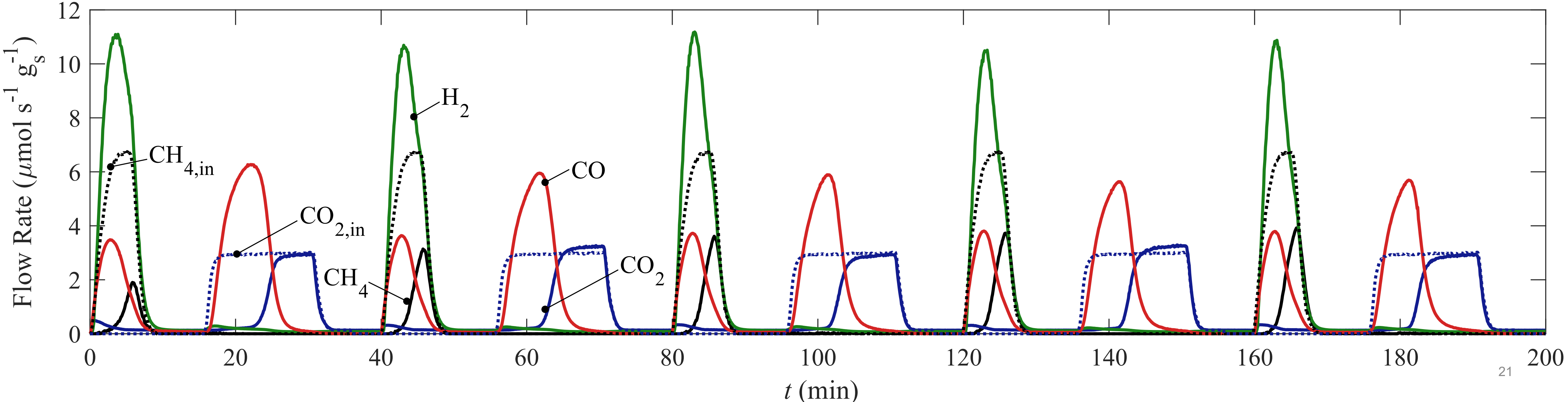






Chemical Looping Enables Ultra High Conversions and Selectivity

- Step 1: $CH_4 + (1/\Delta\delta)CeO_{2-\delta i} \rightarrow (1/\Delta\delta)\ CeO_{2-\delta f} + CO + 2H_2$
- Step 2: $CO_2 + (1/\Delta\delta)CeO_{2-\delta f} \rightarrow (1/\Delta\delta)\ CeO_{2-\delta i} + CO$
- Exemplary results shown below for 5% Ni-CeO_2 at 700 ˚C
- Experiments conducted in packed bed with no temperature swing
- Have demonstrated CH_4 conversion > than 98% and syngas selectivity > 95%



Conclusions

- Thermal energy storage solutions are a cost-effective energy storage strategy.
  - Can enable long duration storage technologies such as H_2.
  - Provides a pathway to produce sustainable aviation or transport fuels required by aviation and shipping sectors.
  - Can provide high temperature process heat for a variety of other industrial sectors that are not easily electrified, such as steel manufacturing, cement manufacturing, ammonia production and even plastics or waste recycling.
- Higher temperatures than CSP are required, which lead to technical challenges that can be overcome with manufacturing innovations.
  - Improved heliostat design and manufacturing – as temperature increase cost of heliostats will become even more important because of increases losses.
  - Improved reactive structures that enable efficient radiative heat transfer – additive manufacturing opportunities?

Acknowledgements

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U.S. DEPARTMENT OF ENERGY

HydroGEN Advanced Water Splitting Materials

synhelion solar fuels

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