PATHWAYS TO FUELS AND ELECTRICITY USING CONCENTRATED SUNLIGHT

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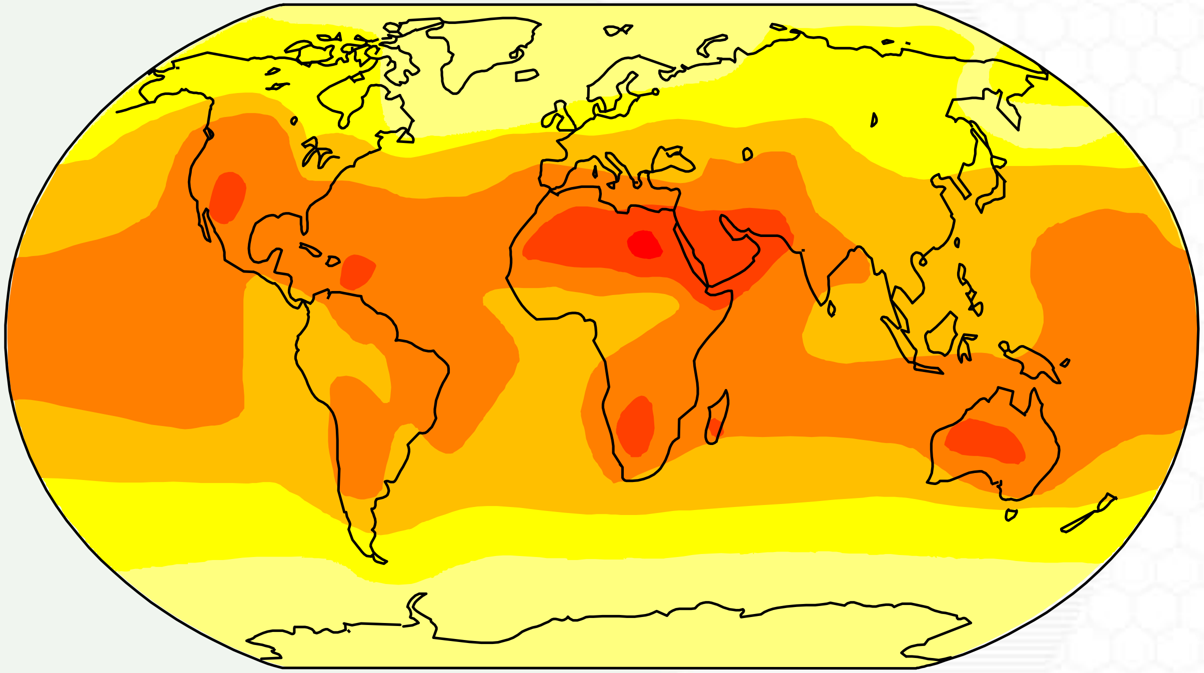
OUTLINE

- Background and motivation
- Solar thermochemical concept
- Syngas production via two-step solar thermochemical cycles
- Hybrid processes
- Solar thermochemical energy storage
- Summary and outlook

Annual solar irradiation



Limitations of Solar Energy

Dilute: Maximum direct-normal solar irradiance of 1 kW·m^{-2}

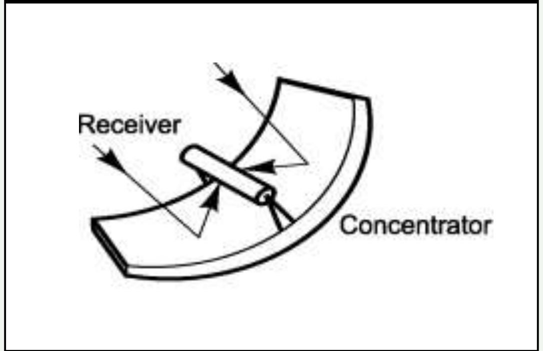
Intermittent: Solar energy can only be harvested when the sun is shining

Unequally distributed: Optimal areas for harvesting solar energy are near the equator away from population centers

CONCENTRATION SOLAR IRRADIATION

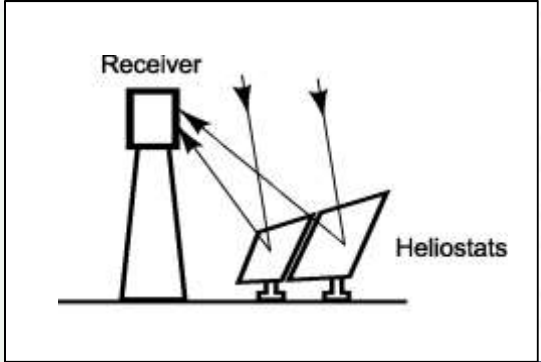
Trough

Solar concentrations of < 100 suns



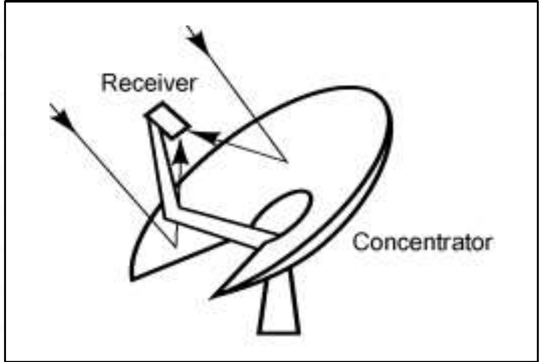
Tower

Solar concentrations of 500 – 2500 suns with secondary



Dish

Solar concentrations of 5000 – 10,000 suns



Steinfeld and Meier,
Encyclopedia of Energy
2004, 623-637

MAXIMUM WORK POTENTIAL EXTRACTION

$$\eta_{overall,ideal} = \eta_{absorption}\eta_{Exergy} = \underbrace{\left(1-\frac{\sigma T^4}{I_{DN}C}\right)}_{\frac{\dot{Q}_{solar}-\dot{Q}_{re-radiation}}{Q_{solar}}} \cdot \underbrace{\left(1-\frac{T_{ambient}}{T}\right)}_{\substack{\text{theoretical}\\ \text{work potential from heat}\\ \text{(exergy)}}}$$

$$\eta_{overall,ideal} = 0 \rightarrow T_{stagnation} = \left(\frac{I_{DN}C}{\sigma}\right)^{0.25}$$

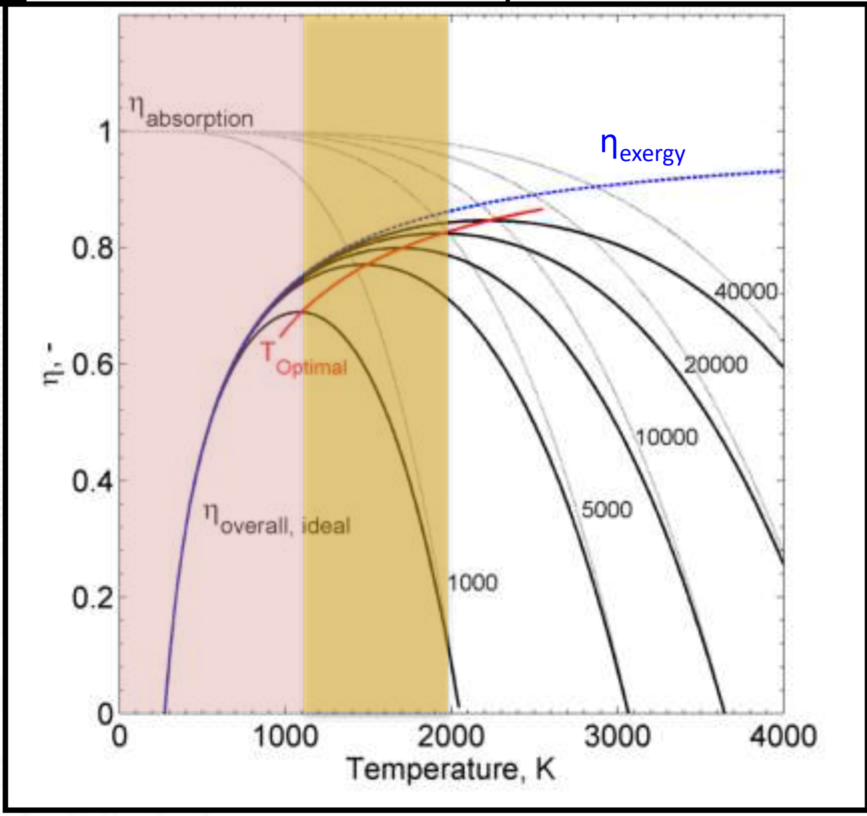
$$\frac{\partial \eta_{overall,ideal}}{\partial T_{optimal}} = 0$$

$$0 \rightarrow \left(T_{optimal}\right)^5 - 3/4T_{ambient}\left(T_{optimal}\right)^4 - \left(\frac{T_{ambient}I_{DN}C}{4\sigma}\right) = 0$$

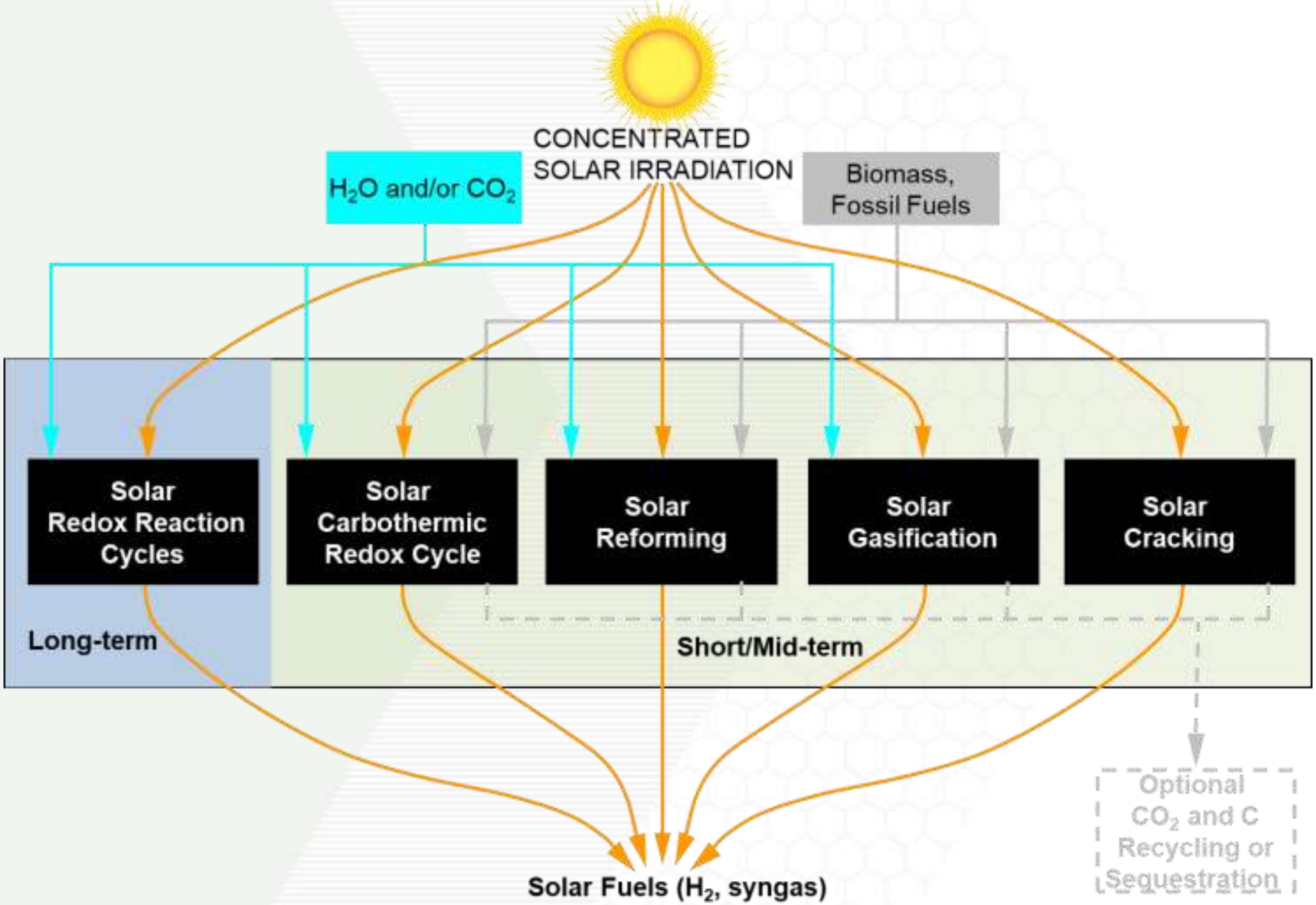
C	1000 suns	5000 suns	10000 suns
$T_{stagnation}$	2049 K	3064 K	3644 K
$T_{optimum}$	1106 K	1507 K	1724 K

nuclear range

ideal thermochemical cycles



OTHER SOLAR THERMOCHEMICAL PATHWAYS TO FUELS



Steinfeld, *Solar Energy* 78 (2005) 603-615

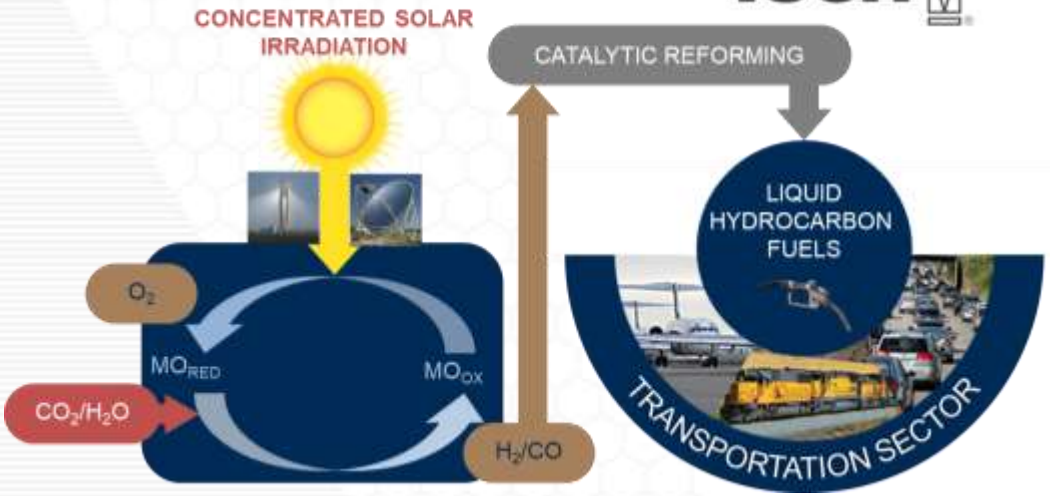
SOLAR THERMOCHEMICAL CONCEPT

Ivanpah Solar Electric Generating System
Ivanpah, California

- Contain 173,500 heliostat mirrors
- Gross capacity of 392 MW_{th}.
- Solar fuels development looks to place a solar thermochemical reactor in the focal point

SYNGAS PRODUCTION VIA TWO-STEP SOLAR THERMOCHEMICAL CYCLES BASED ON RED0X-ACTIVE MATERIALS

- Chemically reduce mixtures of H_2O and CO_2 to synthesis gas using concentrated solar irradiation for conversion to liquid fuels (reversing the combustion process with solar energy)
- Solar fuels decouple the intermittency and location and allow for storage and transportation
- Replaces fossil fuels without major changes in transportation/power generation infrastructure
- Creates carbon-neutral fuels with CO_2 captured from the air
- Alternative to CO_2 sequestration for direct capture from flue gases; CO_2 never introduced into atmosphere

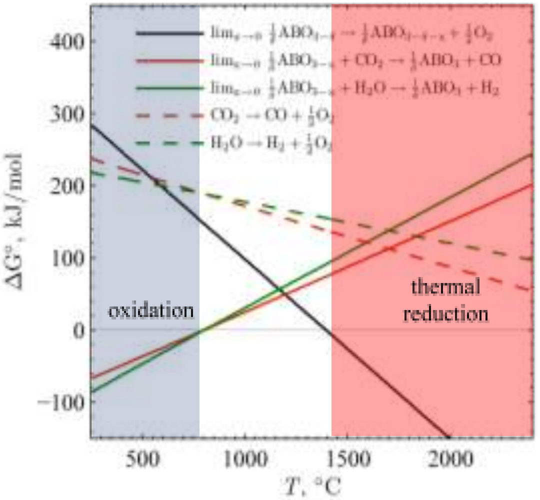


$MO_{OX} \rightarrow MO_{RED} + ½O_2$ endothermic, solar-driven reaction

$\underline{MO_{RED} + H_2O/CO_2 \rightarrow MO_{OX} + H_2/CO}$ exothermic reaction

$H_2O/CO_2 \rightarrow H_2/CO + ½O_2$ net reaction

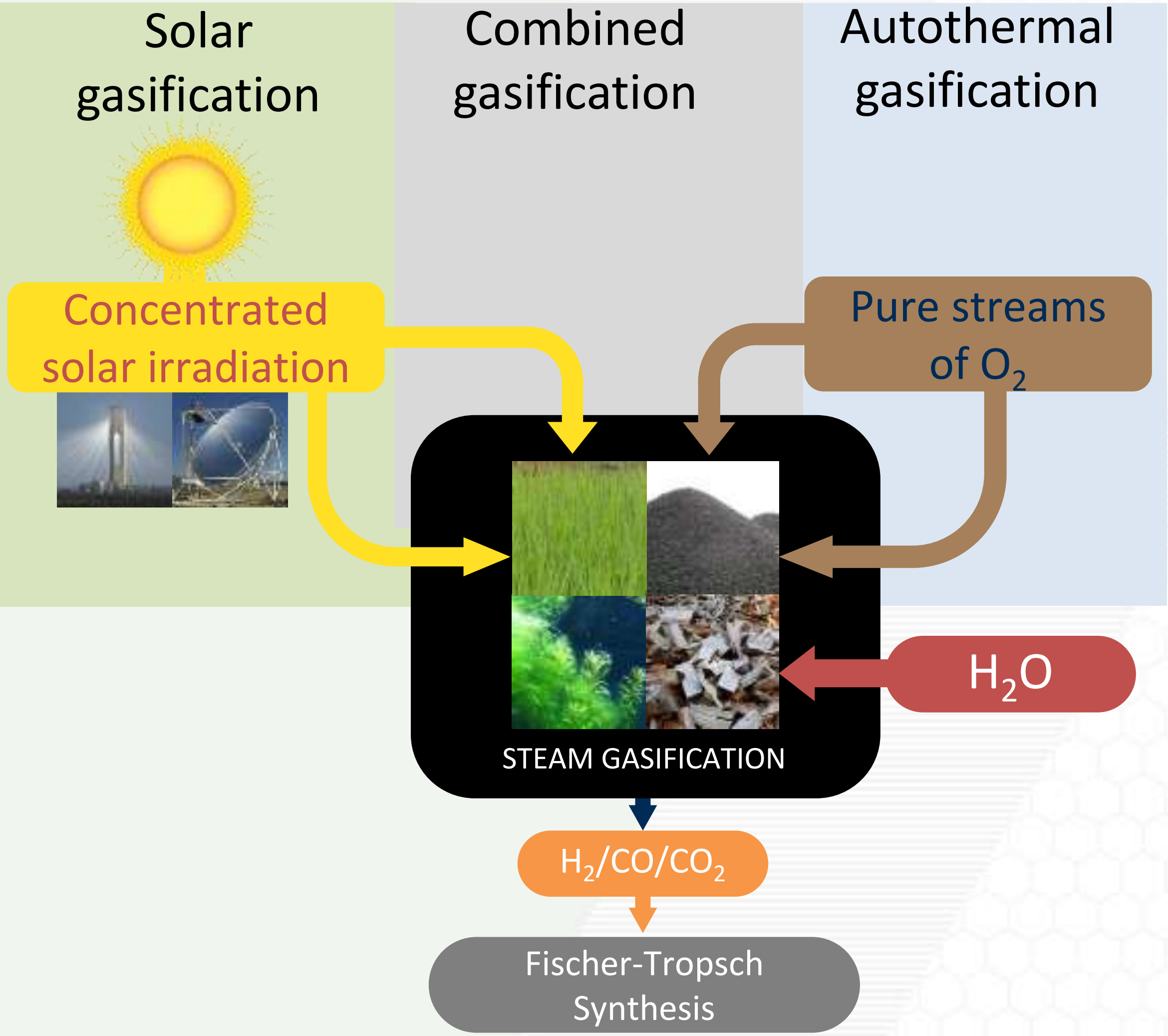
Redox-active pairs: ZnO/Zn, Fe_3O_4/FeO,
Redox-active MIECs: $ABO_{3-\delta}$ (tunable with cation substitution), $CeO_{2-\delta}$
Ideal performance curve for thermodynamics



SOLAR CHEMICAL HYBRID CYCLES

- Hybrid cycles combine different elements of solar processes/cycles to
    1. Lower the required solar reactor temperature
    2. Continuously produce syngas for further processing
- Discuss two-hybrid processes:
    1. Hybrid solar/autothermal gasification for continuous syngas production
    2. Solar thermoelectrolytics cycle for H_2 production

HYBRID SOLAR/AUTOTHERMAL GASIFICATION SCHEME



Solar gasification

Combined gasification

Autothermal gasification

Concentrated solar irradiation

Pure streams of O_2

H_2O

STEAM GASIFICATION

$H_2/CO/CO_2$

Fischer-Tropsch Synthesis

Solar gasification: Operation for periods of high direct-normal solar irradiation using only solar input to drive the syngas production process.

Combined gasification: Operation during periods of insufficient direct-normal solar irradiation where O_2 is injected to provide additional process heat to drive the reaction by combusting a portion of the coal feedstock.

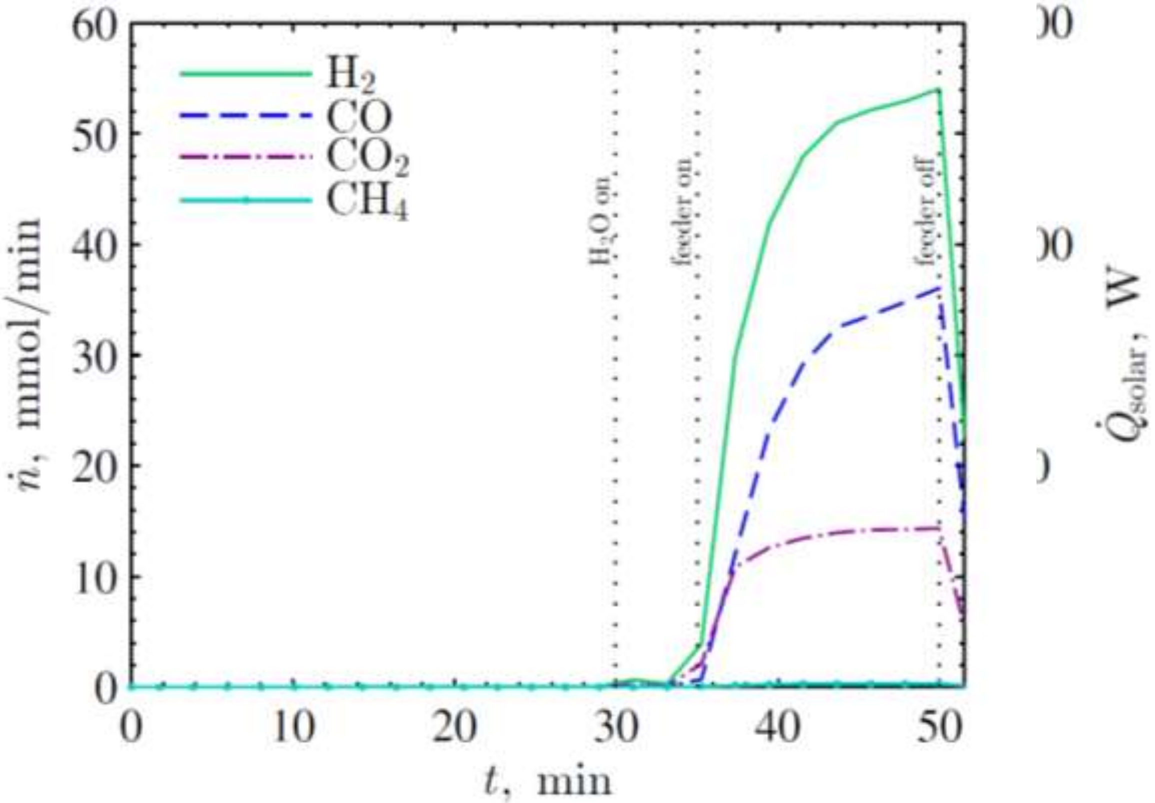
Autothermal gasification: Nighttime operation with insufficient where O_2 is injected to provide process heat to drive the reaction plus stored heat via thermal capacitance during the day.

Muroyama, et al. *Energy Fuels,* 2014, 28 (10), 6520–6530

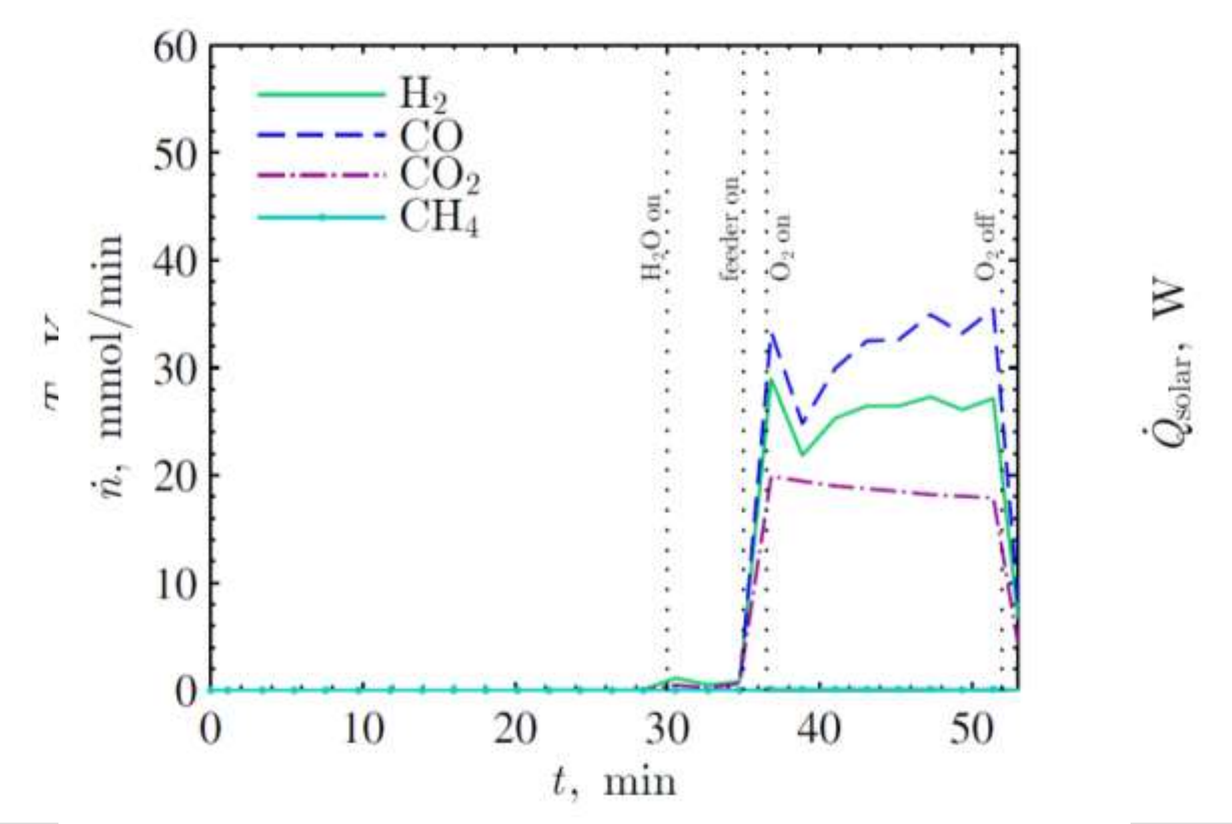
PROTOTYPE OF HYBRID GASIFIER

Muroyama, et al. *Fuel* 211 (2018) 331-340

RUN PROCEDURE [SOLAR ONLY]

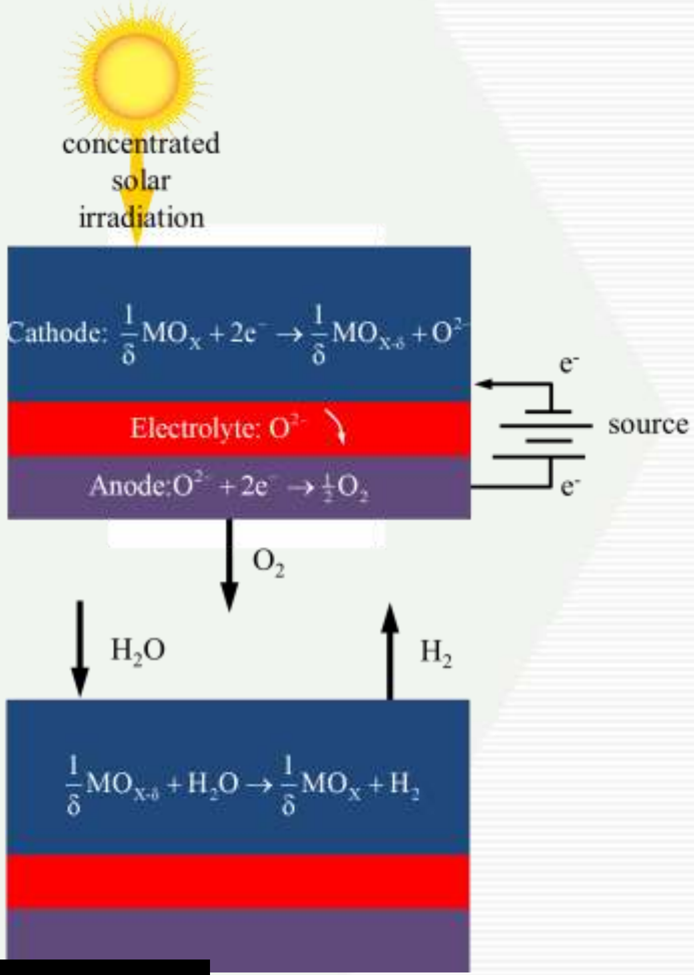


RUN PROCEDURE
[COMBINED SOLAR/AUTOTHERMAL]



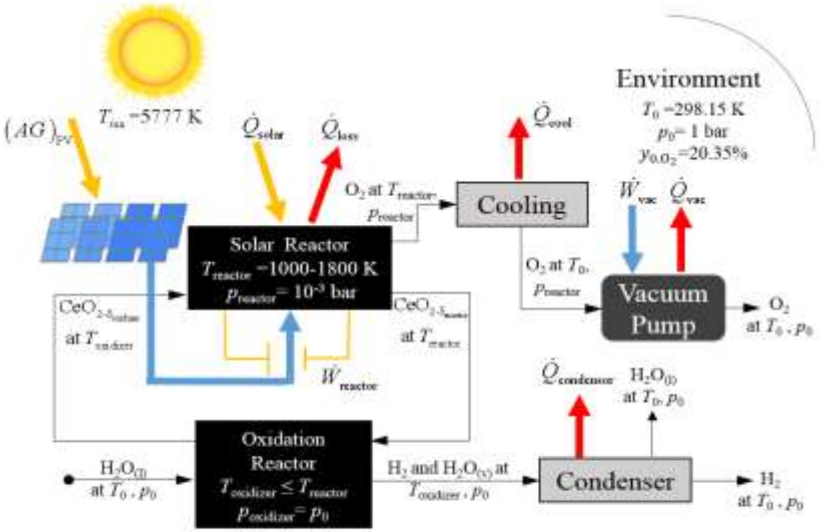
SOLAR THERMOELECTROLYTIC CYCLE

Schematic of the concept



G.L. Scheiber, et al., *Int. J. Hydrogen 42 (2017) 18785-18793*

Thermodynamic system



Optimal performance with $CeO_{2-\delta}$

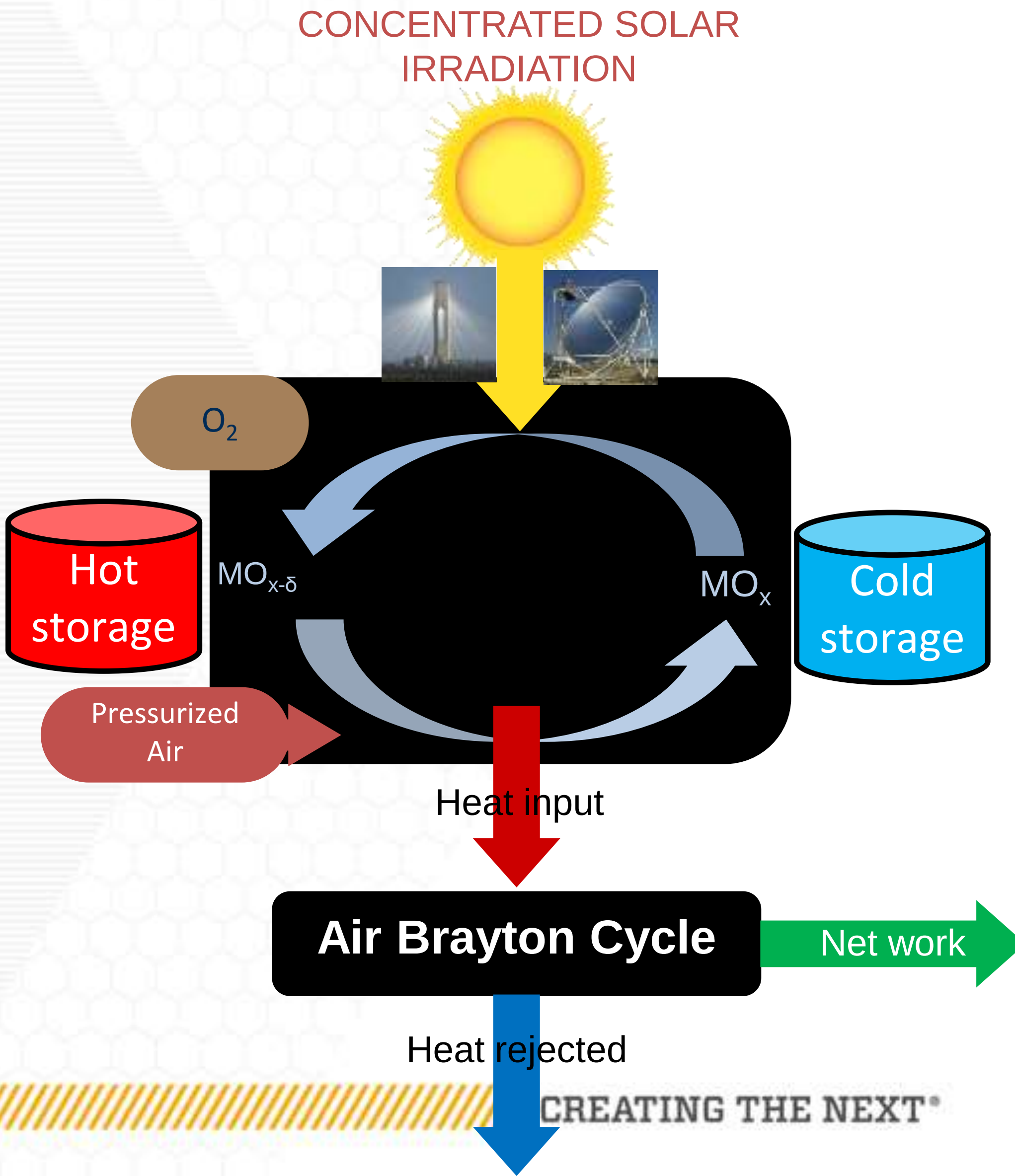
- 1000 suns
- Reactor temperature 1424 K
  - $\eta_{solar\text{-}to\text{-}fuel}$ = 31.1%
  - ε_{cycle} = 27.5%

SOLAR THERMOCHEMICAL ENERGY STORAGE

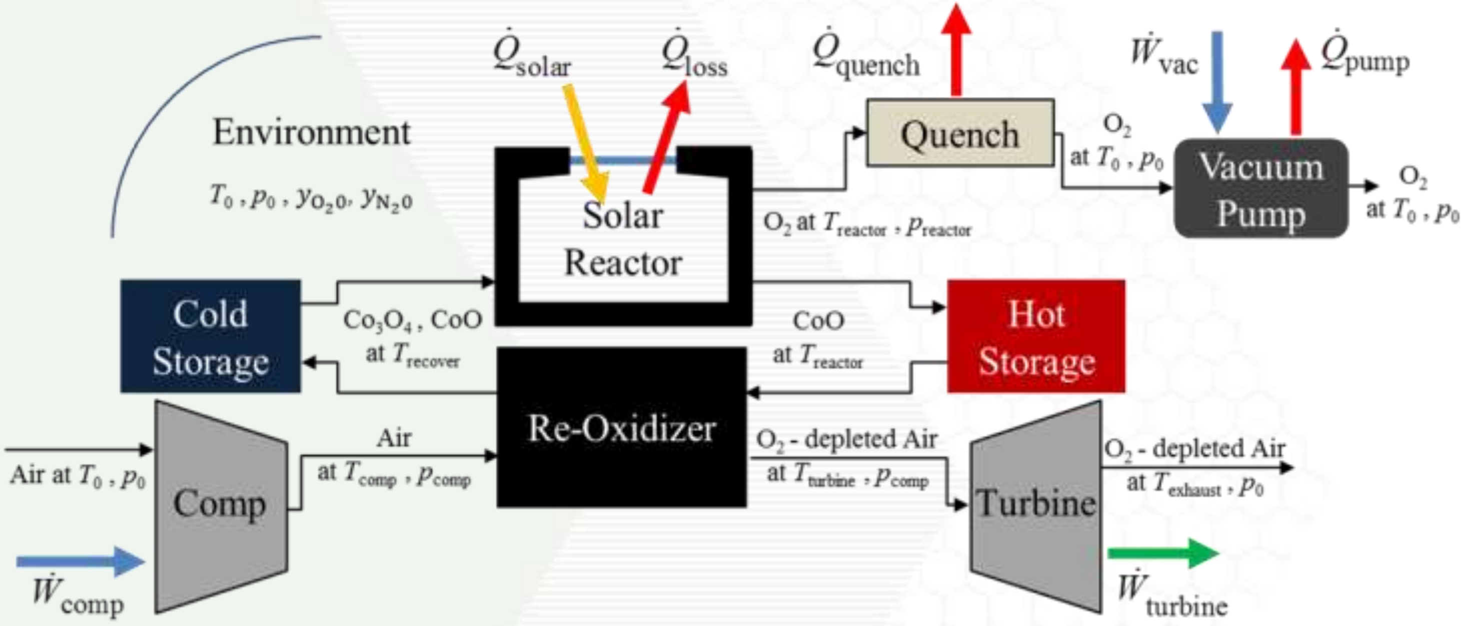
- Solar thermochemical energy storage via a two-step solar thermochemical cycle for integration in an Air Brayton cycle based off of redox-active materials:

$$MO_{x-\delta} + \frac{\delta}{2} O_2 \rightleftharpoons MO_x + \Delta h$$

- Enables heat storage in both a chemical and sensible form
- The added chemical storage increases the energy densities of the material to better account for intermittency of sunlight



THERMODYNAMIC INVESTIGATION OF CYCLE WITH Co_3O_4 / CoO



A flow diagram of the Air-Standard Brayton cycle with an integrated two-step solar thermochemical heat storage cycle based on Co_3O_4/CoO redox reactions is depicted with relevant heat and work flows into and out of the system

$\eta_{cycle,\ ideal} \rightarrow 0.44$

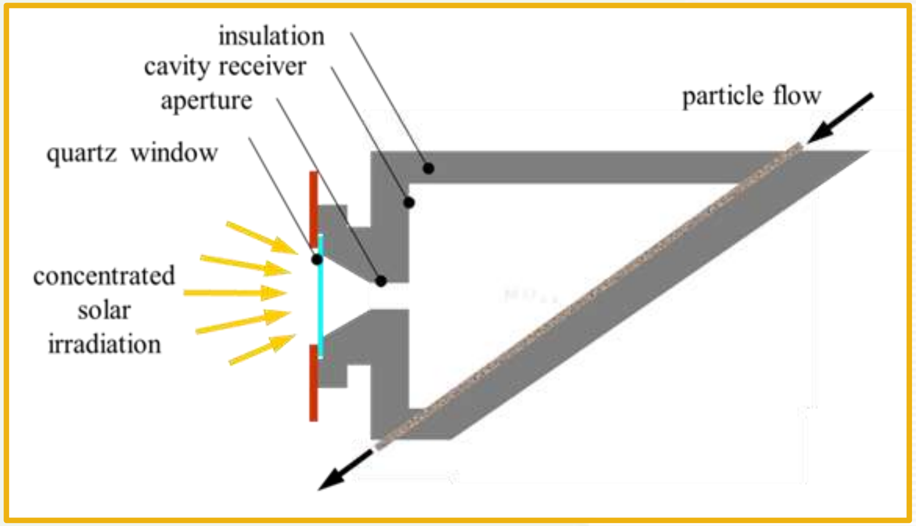
Cycle worth pursuing

Promote η_{cycle}, reduce solar reactor losses

Schrader et al., *Solar Energy* 118, 485-495.

SOLAR THERMOCHEMICAL REACTOR CONCEPT: SOLAR RECEIVER/REDUCER/REACTOR (SR3)

Solar Thermochemical INclined Granular flow Reactor (STINGR)



- Efficient thermal reduction within solar thermochemical reactor:
  - Direct solar irradiation
  - Continuous on-sun operation
  - Matched incident solar power to rate of sensible and chemical energy storage
- Reactor cavity designed to mitigate radiative losses through window and promote direct irradiation along inclined plane
- Reactor evacuated to promote low partial O_2, sealed with quartz window to introduce concentrated solar irradiation
- Combination of frictional and collisional effects of particles produce thin granular flow, increased particle residence times

5 KW$_{TH}$ STINGR FABRICATION

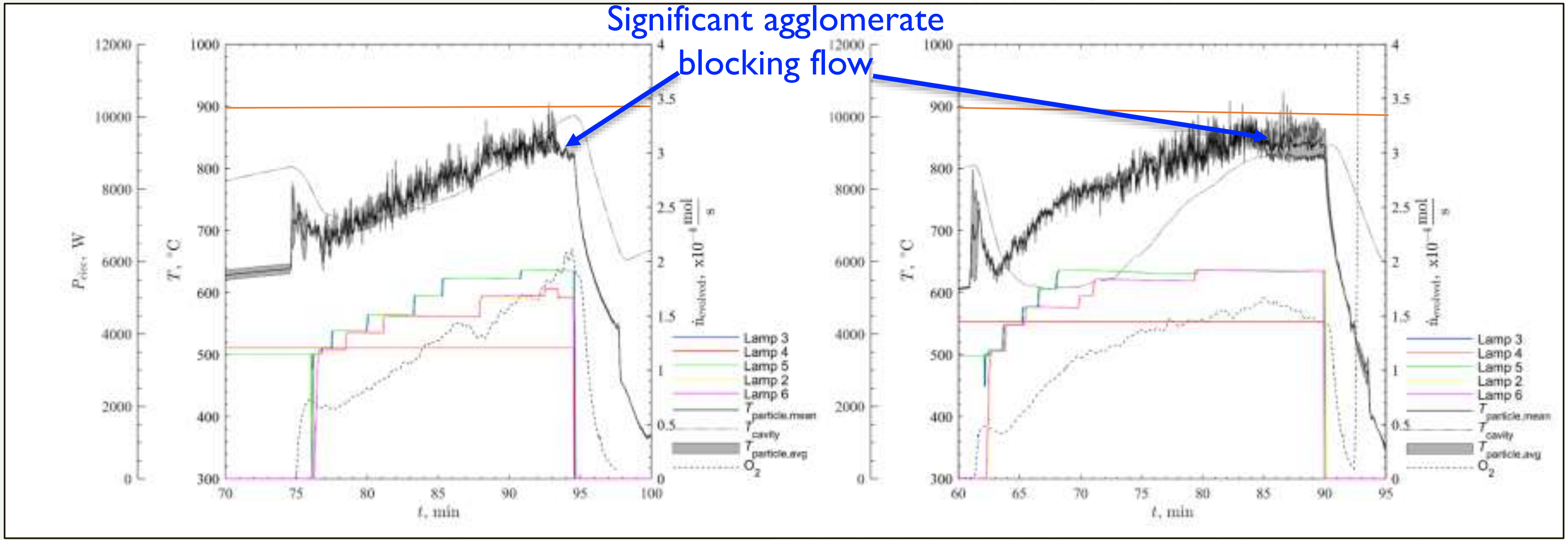
Fully fabricated SR3 cavity made of alumina

Water-cooled copper diaphragm with quartz window

SR3 mounted in front of the HFSS with hoppers

EXPERIMENTAL RESULTS

- For all parameter combinations investigated, severe particle agglomeration at T > 900 °C, phase impurities in particles limited reduction.
- Agglomerate formation observed in two experiments where $d_p < 100$ µm and 140 µm $< d_p <$ 350 µm



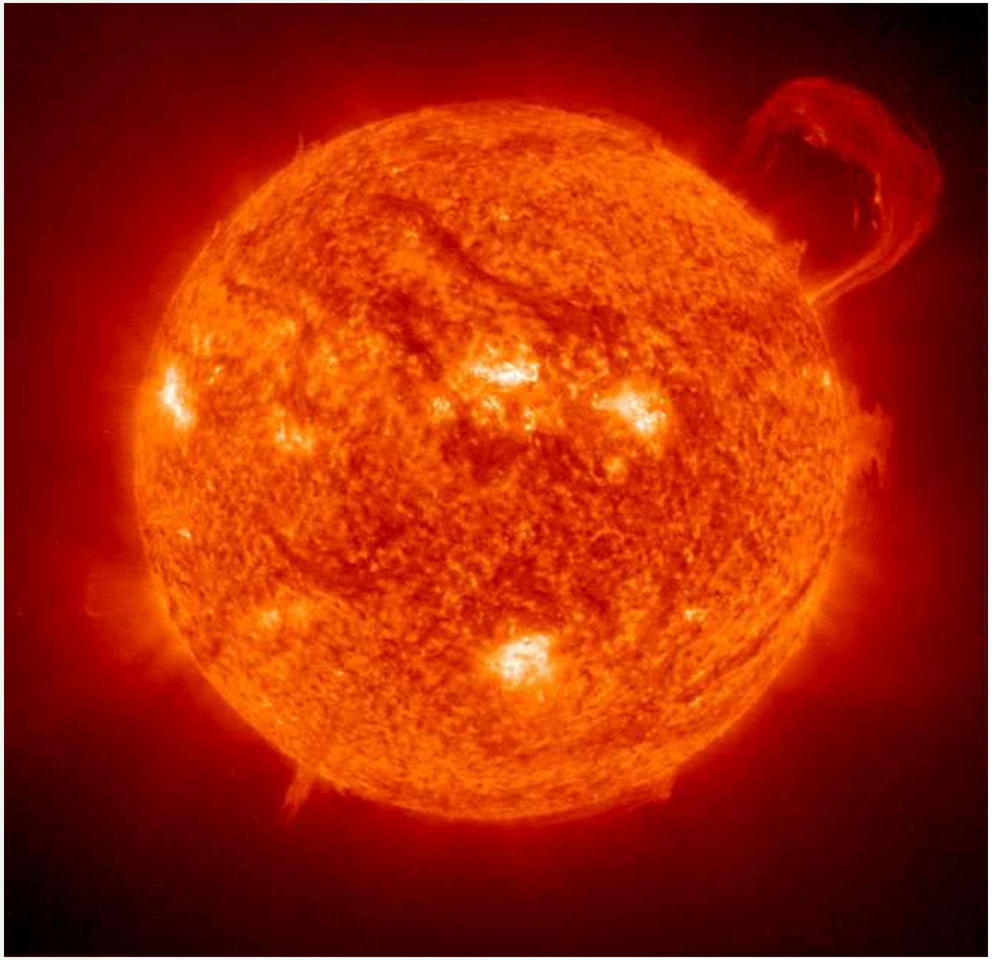
Significant agglomerate blocking flow

Measured temporal high flux solar simulator lamp powers, temperatures, and O2 evolution from 5 kW_{th} reactor experimentation using Coorstek particles with diameters less than 100 µm (left) and diameters between 140 and 350 µm (right)

SUMMARY AND CONCLUSIONS

- Solar thermochemistry is an innovative pathway that employs concentrated sunlight as process heat to drive chemical processes to produce fuels and electricity
- Long-term solar thermochemical cycles for producing syngas still face challenges, including relatively high temperatures and storage of H_2 and/or CO
- Hybrid processes and electricity production via solar thermochemical storage can be used in some measure to address these concerns to provide long-term storage
- Further efforts need to be made for long-term storage and reducing the solar thermochemical reactor temperatures to match large scale solar concentrating facilities
- A multidisciplinary approach is required to address ongoing challenges related materials and reactor designs

HOW DOES THE FUTURE LOOK?



ACKNOWLEDGEMENTS

- Funding: U.S. Department of Energy SunShot initiative under Award No. DE-FOA-0000805-1541 and the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1148903
- ETH Zurich: Professor Aldo Steinfeld
- Georgia Tech: Evan Bush, Robert Gill, Alex Muroyama, Garrett Schieber, Andrew Schrader, and Sheldon Jeter
- SNL: Andrea Ambrosini, Sean Babiniec, Cliff Ho, and James Miller
- ASU: Ellen Stechel and Nathan Johnson
- KSU: Haney Al-Ansary