LightWorks®

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Solar/ Thermochemical Processes

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Hydrogen Shot Summit

Arizona State University
Julie Ann Wrigley Global Futures Laboratory™

VALUING DIVERSITY

ASU CHARTER

Measured not by whom we exclude, but rather by whom **we include** and how they **succeed**

ASU LIGHTWORKS® VISION

Envisions a **resilient** and **equitable energy future** supported by innovations in **technology, policy, law, governance, and markets**

INTENTIONALITY & MAKING A POSITIVE DIFFERENCE

"Seal of Excelencia"
Hispanic enrollment is nearly **29,000** but ASU is not designated HSI (< 25%)

THE VALUE OF DIVERSITY & INCLUSION

Diverse teams are better positioned **to unlock innovation** and solve hard problems

VALUING DIVERSITY NOT ONLY FOR HUMAN CAPITAL

MULTIPLE VIABLE APPROACHES WOULD BE A GOOD THING

$\$1/_{kg} \approx \$30.6/_{MWh}$

Alternative to electrolysis is to use thermal energy **Heat** to do the work of **breaking bonds**

SUPPLY CHAIN RESILIENCY

Technologies based on materials with well-developed supply chains

Steel, Glass, Firebrick, Concrete

Made in America

Not all our eggs in the same basket or dependent on the same resources

COMPETENCIES

High temperature processes **not new** to industry

Capital assets can be **highly cost-effective**

EXAMPLES

Rotary cement kilns operate at **1450°C** for years

Massive scale: ~4.1B t/yr and < $0.1/kg

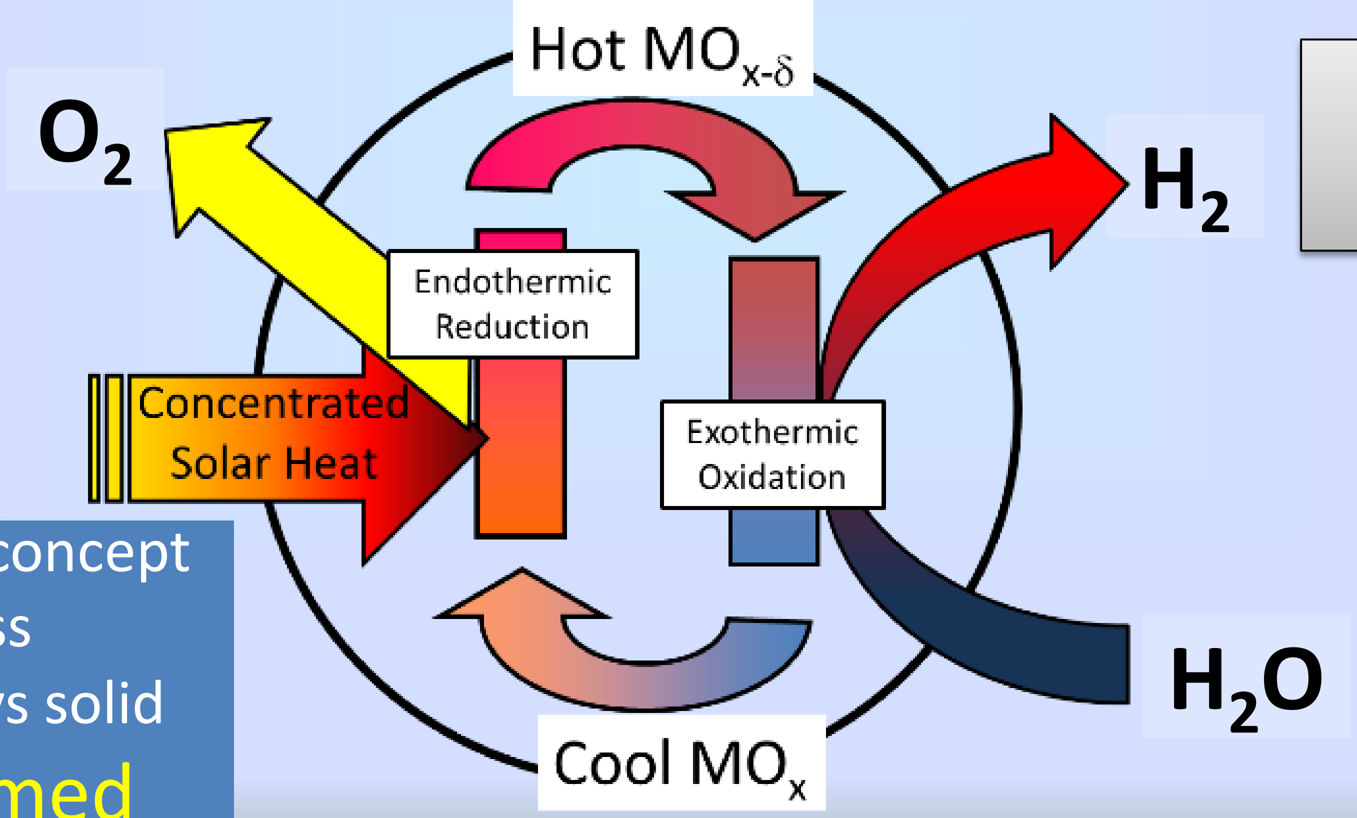
Fused glass 1700°C; Jet Engines 1600°C

SO HOW DOES THIS PATHWAY WORK?

A SPECIALLY DESIGNED "REDOX ACTIVE" MATERIAL "BREATHES" OXYGEN AND "CHARGES" SIMILAR TO A BATTERY

Energy In, Oxygen Out

Oxygen In, Energy Out



Relatively simple in concept
Cyclical process
Active material stays solid and not consumed

Two steps
Other cycles and with more steps possible

WHAT IS IT GOING TO TAKE?

KEY FEATURES

Robust high-temperature process

Heat input agnostic as long as carbon-free and low-cost

Potential for low cost capital like other thermal processing technologies

<$100/kW

SPECIFIC CHALLENGES

High temperature (~1500°C)

Low reduction partial pressure of O_2 (~10 Pa or ~100 ppm): separations challenge

Material redox chemistry

Materials by design challenge

TECHNOLOGICAL REQUIREMENTS

Scalability - TW

Reactor and material Durability

Design for efficient energy utilization

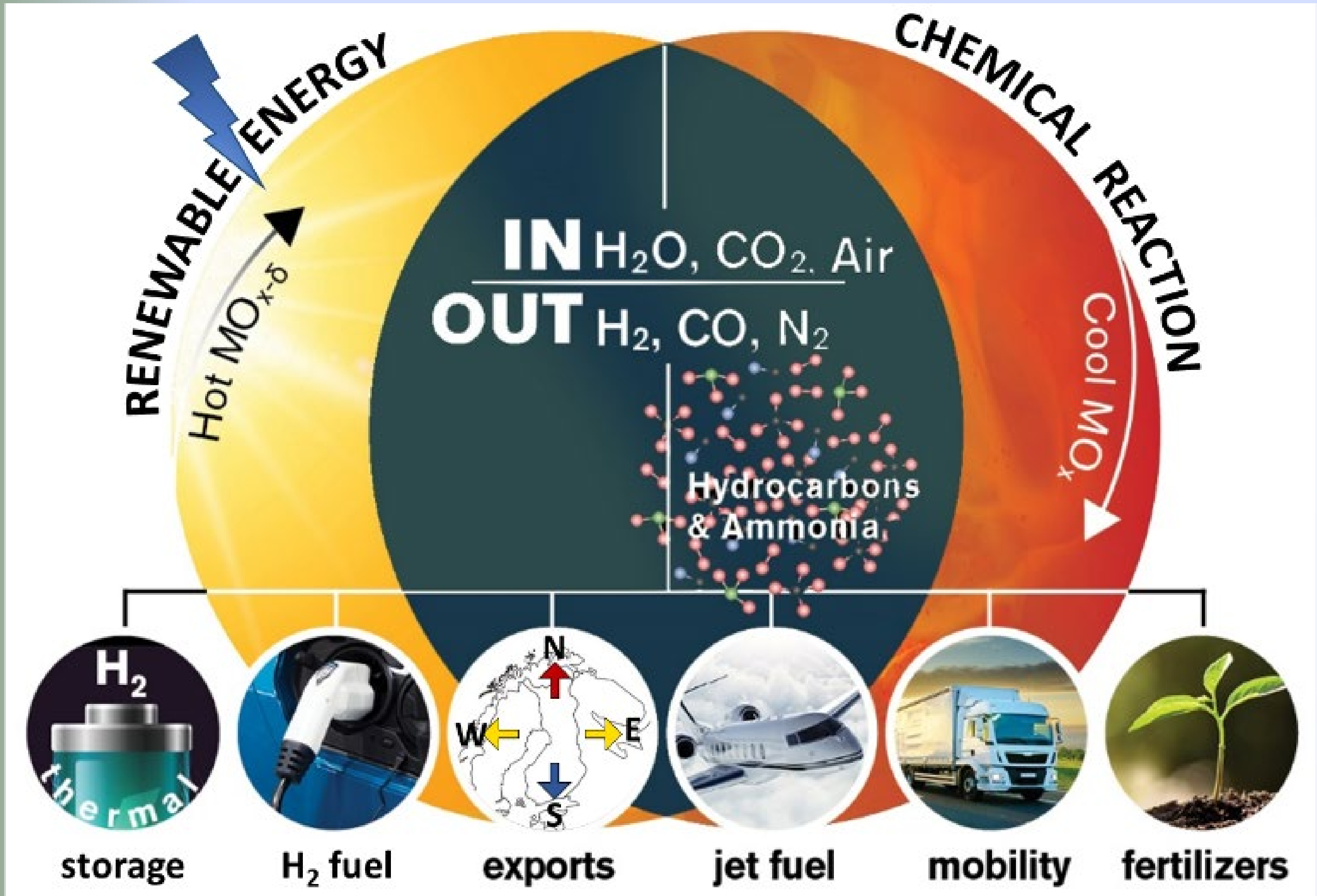
75 kWh/kg

OVERALL CHALLENGE

Develop efficient, scalable, modular thermochemical reactors, optimized materials, and optimized system configurations

Developing the workforce

VALUING INTEGRATION: NOT STANDALONE



Same or related functional materials and processes

Projections of potentially 2.5 TW of H_2 globally and multiple applications

If 100,000 kg/day or 136 MW H_2 energy >18,000 such plants (~# airports)
High quality jobs

H_2 hubs – production and use can be co-located – opportunity to reduce costs through integration, shared infrastructure, shared competencies

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THANK YOU FOR YOUR KIND ATTENTION

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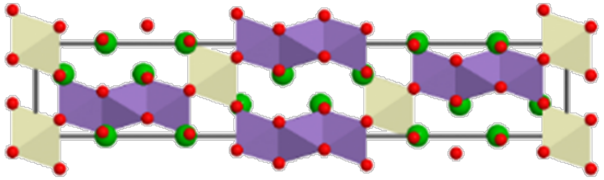
I skate to where the puck is going to be and not where it has been.

Wayne Gretzky

Solar/Thermochemical Processes



PRESENTED BY

Anthony McDaniel

Hydrogen Shot Summit, Sep. 1, 2021

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Carbon-Free High Temperature Heat Enables Deeply Endothermic Pathways to Large Scale H_2 Production

Both CSP and Nuclear currently designed to provide electricity

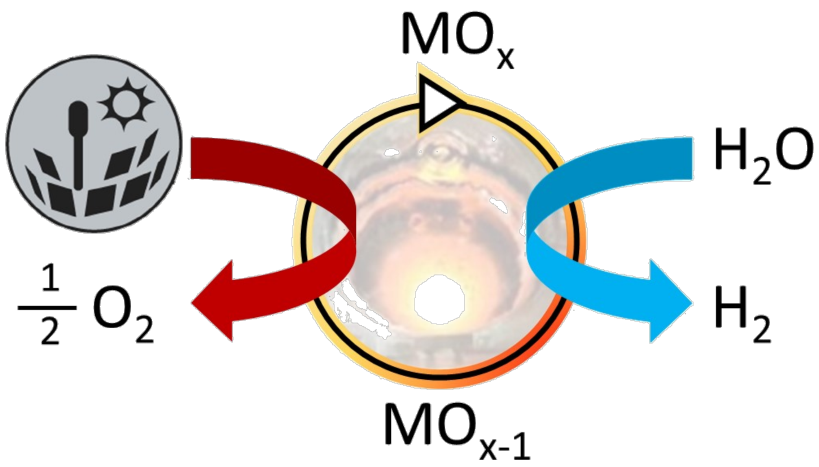
Concentrating solar-thermal power (CSP) can achieve process temperatures T > 1000 °C.

Conventional LWR nuclear reactors T ~ 330 °C.

Advanced HTGR nuclear reactors T ~ 850 °C.

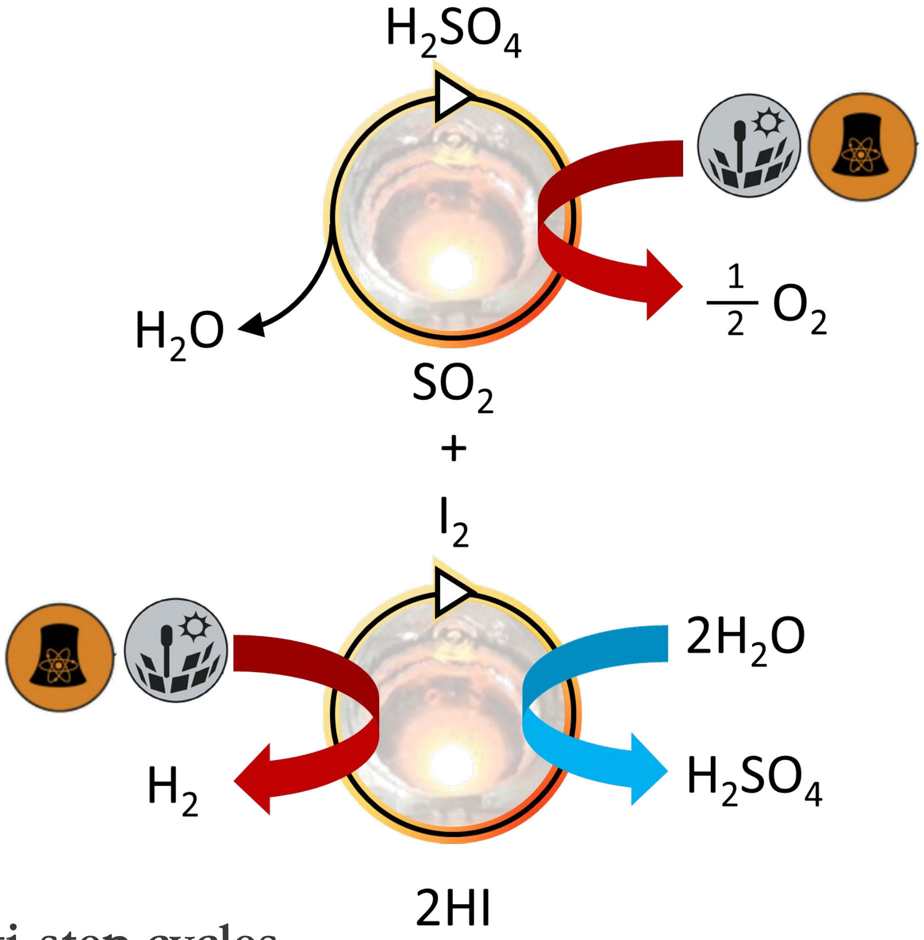
Thermochemical Water Splitting Cycles

M = Ce, Sn, 1st row transition metal, Zn group metal
MO_x = fluorite, perovskite, spinel, two-phase systems



Two-step metal oxide cycles.

- Change oxidation state of a single element
- Stoichiometric or non-stoichiometric
- May undergo phase changes (s, l, v, cryst)
- High process temperatures (T >1500 °C)

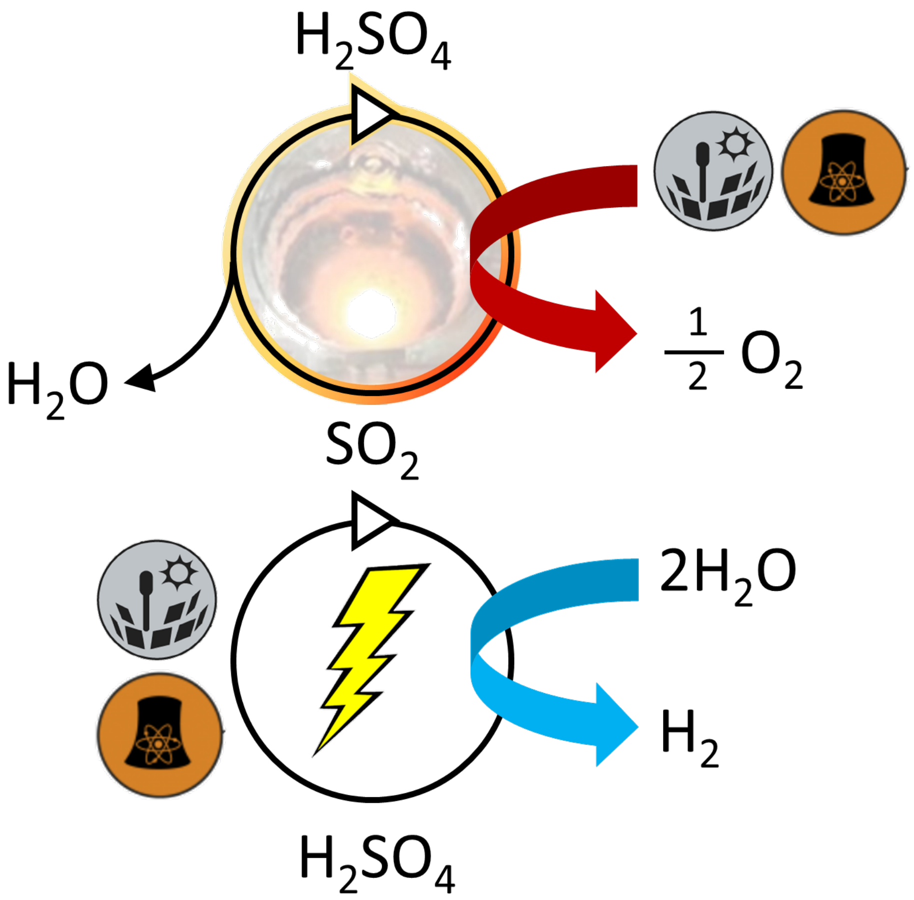


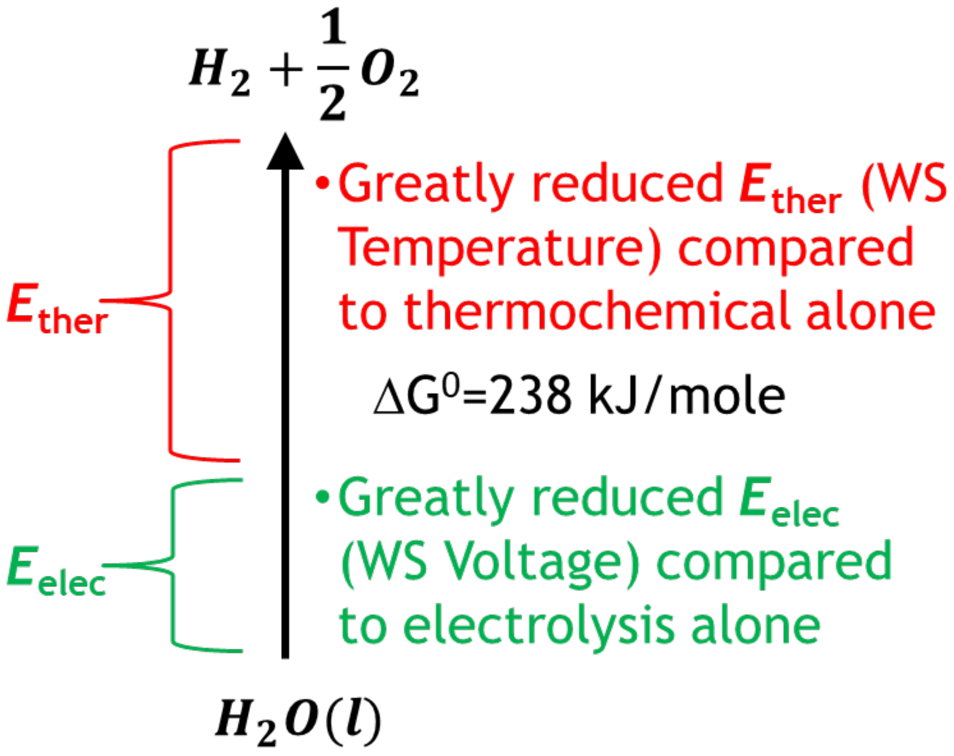
Multi-step cycles.

- Change oxidation state of two or more elements
- Multiple chemical species reacting in each step
- Moderate process temperatures (T <1000 °C)
- Several hundred cycles have been proposed

R. Perret, SAND Report (SAND2011-3622), Sandia National Laboratories, 2011.
G. J. Kolb, R. B. Diver, SAND Report (SAND2008-1900), Sandia National Laboratories, 2008.
S. Abanades, P. Charvin, G. Flamant, P. Neveu, *Energy*. **31**, 2805–2822, 2006.
F. Safari, I. Dincer, *Energy Conversion and Management*. **205**, 112182, 2020.

Hybrid Thermochemical-Electrochemical Water Splitting Cycles





Number of steps and number of reacting species dependent on cycle complexity.

Most known cycles designed for nuclear power industry.

- Tradeoff high process temperature for applied voltage to tailor cycle dynamics to available thermal resource

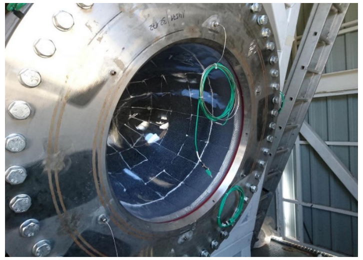
Electrochemical step is either oxidative or reductive, but NOT water electrolysis.

Global Pursuits to Collaboration and Scaling Up

Hydrosol Plant project is the largest solar thermochemical H_2 plant in the world.

- DLR (Germany), CIEMET (Spain), HYGEAR BV (Netherlands), and ELLINIKA PETRELAIA AE (Greece)
- Two-step metal oxide cycle @ 750 kW_{th}

REACTOR

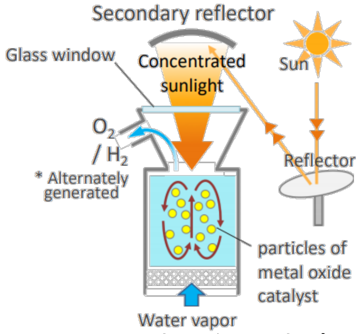


CONCENTRATOR

https://www.solarpaces.org/worlds-largest-solar-reactor-will-split-h2o-hydrogen/

Joint solar thermochemical hydrogen R&D.

- ARENA (Australia) and Niigata University (Japan)
- Two-step metal oxide cycle @ 500 kW_{th}



CSIRO's 500kW class solar concentrating system to be used in the project.

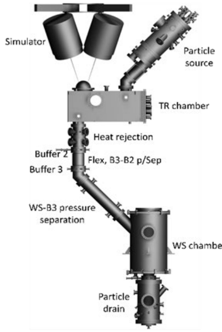
https://arena.gov.au/projects/solar-thermochemical-hydrogen-research-and-development/

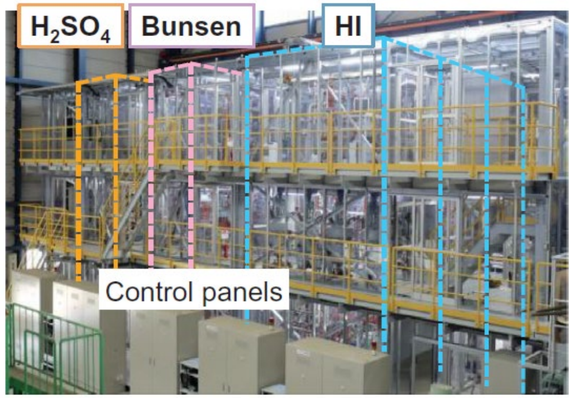
Iodine sulfur process for hydrogen production.

- Japan Atomic Energy Agency
- 100 NL/hr H_2 test facility using industrial structural materials

Advancing particle receiver design of solar thermochemical fuels.

- Sandia National Labs (USA) and DLR (Germany)
- Two-step metal oxide cycle @ 50 kW_{th}





Target large scale production plants that offer advantages in efficiency and cost.

- Can thermochemical H_2 challenge largest SMR facility in the world @ 345t H_2/day?

https://doi.org/10.1016/j.nucengdes.2019.110498

What is it Going to Take? Opportunities and Challenges…

Overall challenge is to develop efficient, scalable, thermochemical reactors, optimized materials, and optimized system configurations.

- Understanding behavior of materials in extreme environments
- Efficient heat integration (solar or nuclear)
- Novel methods for improving the efficiency of separations and heat exchange in harsh environments

Two-step MO_x all thermochemical.

- Engineering for extreme process temperatures
- Discovering "good" redox active materials

Multi-step all thermochemical.

- Engineering for high process complexity due to multi-species and multi-phase chemistries

Thermochemical – electrochemical hybrid.

- Similar issues as "multi-step all thermochemical"
- Efficient electrolytic integration

Thank You

QUESTIONS?