Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

High temperature reactor catalyst material development for low cost and efficient solar driven sulfur-based processes

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Greenway Energy

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Project ID: P169

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NREL | BERKELEY LAB | Sandia National Laboratories | INL Idaho National Laboratory | Lawrence Livermore National Laboratory | SRNL

Project Overview

Project Partners

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Monnier J (*co-PI*), Regalbuto J, Shimpalee S, Weidner J, Tengco J, Diao W (*USC*)

Ginosar D, Adhikari B (*INL*), Ma Z, Davenport P, Martinek J (*NREL*), Gorensek M, Caudle B (*SRNL*)

Award #	EE0008091
Start/End Date	9/01/2017 – TBD
Year 1 Funding*	$250,000

** this amount does not include cost share or support for HydroGEN resources leveraged by the project (which is provided separately by DOE)*

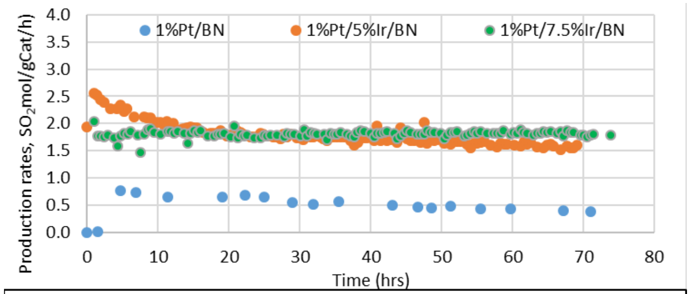
Project Vision

Development of:

- ***New catalyst material*** using our demonstrated surface free energy (SFE) and electro-less deposition technique,
- Novel integrated ***direct solar reactor-receiver***, based on a demonstrated cavity solar reactor,
- New effective ***solar-thermochemical plant process integration***

Objective:

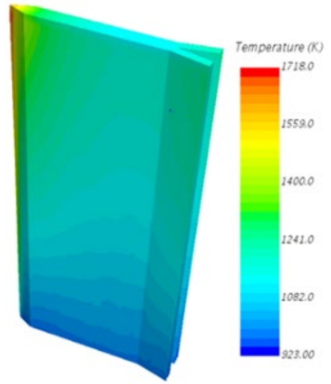
- ***efficient and low cost*** solar thermochemical process



Test conditions included temperature of 800 °C, pressure of 1 bar and H_2SO_4 concentration of 91 wt %. The catalyst used were 1%Pt/BN, 1%Pt/5%Ir/BN and 1%Pt/7.5%Ir/BN.

Project Impact

- Increase of the ***energetic efficiency*** (solar to H_2 energy efficiency > 20%),
- Projected reduction of the ***H_2 cost to < 2 $/kg***



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Approach- Summary

Results of Phase 1

- Baseline catalyst novel formulation identified with almost absence of degradation (≈ 100 h test) – *Provisional Patent Applied*
- Novel solar receiver-reactor concept for H_2SO_4 decomposition identified and numerically verified, allowing effective reaction and heat recovery – *ROI*
- Novel solar plant design and flowsheet identified allowing higher efficiency and cost reduction

Key Impact – Proposed targets

Metric - Milestones	*State of the Art*	*Proposed*	*Achieved (Phase 1)*
Catalyst Activity ($molSO_2/h/g_{Cat}$) Degradation (%/hour)	0.23 0.030	0.28 0.015	***1.8*** ***No degradation (75 hours)***
Sun to H_2 efficiency (%)	16 (LHV)	20% (LHV)	**21.2 (LHV)**
H_2 cost ($/kg)	3.6 – 7.6	2.0	**2.0**

Barriers	**Solutions**
Catalyst activity and lifetime	Bimetallic catalyst - ED technique
Materials of construction and BOP at high temperature	SiC material - Modeling and experimental stress tests
Efficient and cost effective solar- HyS plant integration	Unified intensified solar receiver-reactor
Efficient and cost effective solar HyS plant design	Augmented cross sectional heat recovery – Enhanced heat exchangers

Partnerships

GWE – Techno-economic analysis, design solutions and detailed transport phenomena model

USC – Catalyst development and CFD analysis

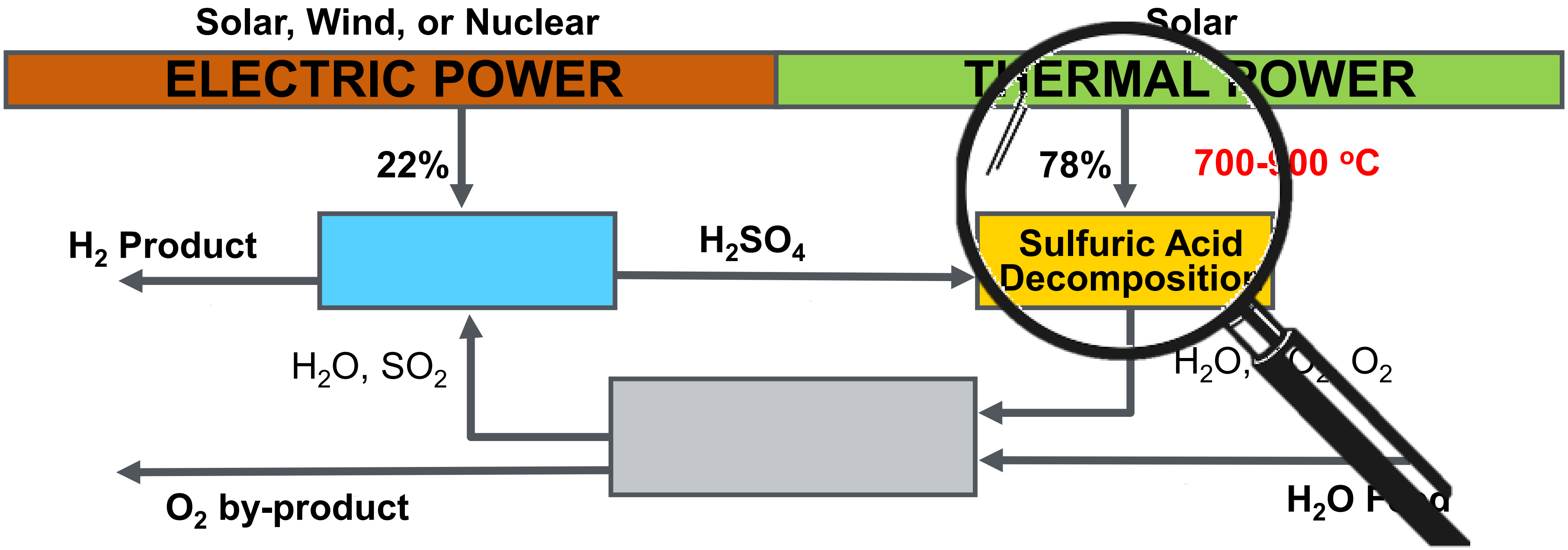
INL – Catalyst performance analysis under realistic conditions

SRNL – HyS process modeling and analysis

NREL – Solar plant design and cost assessment

ED = Electroless deposition
BOP = Balance of plant
LHV= Low heating value of H_2 (120 MJ/kg)
CFD= Computational fluid dynamics
HyS= Hybrid Sulfur
ROI = Record of invention

Approach- The HyS process



The high temperature decomposer is the key component for the solar driven process energy efficiency and cost reduction

HyS = Hybrid sulfur

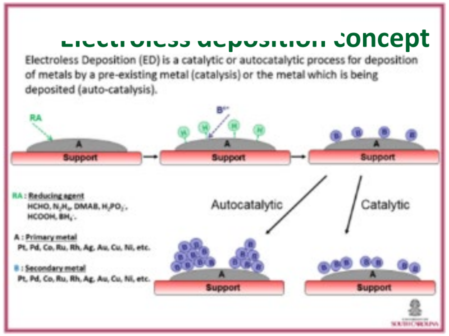
Approach- Innovation

LEVEL 1 – Catalysis fundamentals

H_2SO_4 reaction catalyst understanding and development

- Catalyst performance understanding
- Catalyst development and synthesis
- Catalyst performance experimental tests

Novel Electroless Deposition approach for bi-metallic catalyst formulations based on the Surface Free Energy of the metals

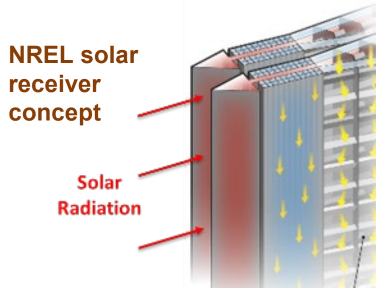


LEVEL 2 – Engineering design

H_2SO_4 reaction solar reactor design

- Novel reactor baseline configuration
- Numerical modeling of the reactor concept
- Reactor fabrication and experimental tests

Novel direct solar cavity receiver-reactor, based on NREL concept

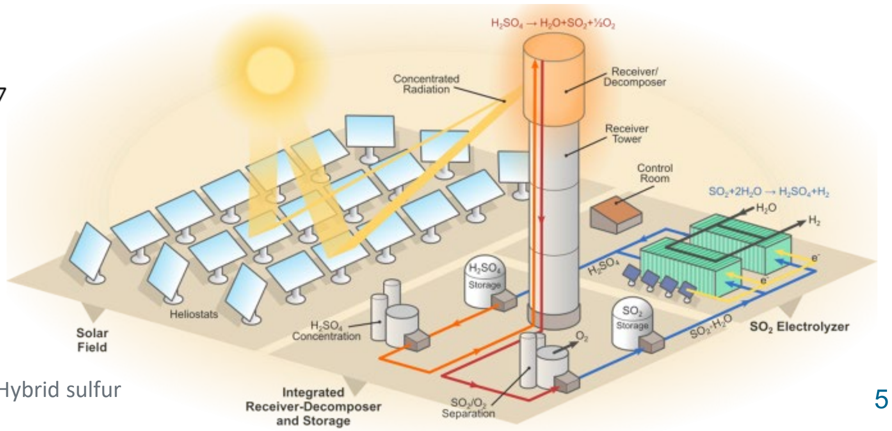


LEVEL 3 – System analysis

Techno-economic analysis of the solar plant

- Novel HyS process flowsheet
- Conceptual design of the overall solar plant
- Economic-financial analysis of the solar plant

Novel HyS flowsheet with chemical storage and direct solar receiver



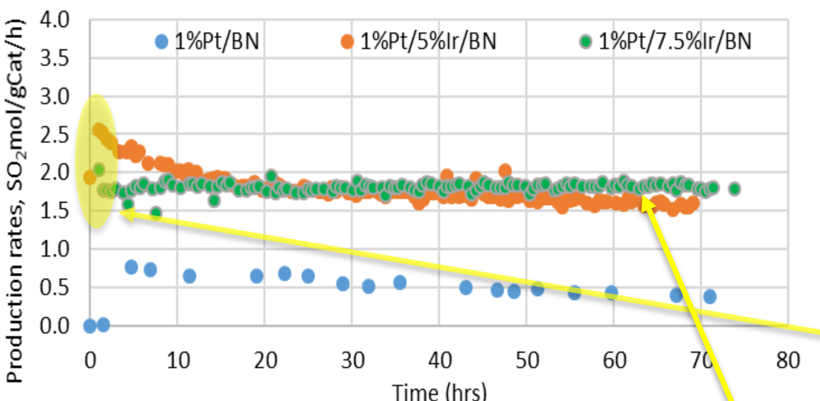
Final objective

H_2SO_4 decomposition system integrated in a solar HyS

- High energy and exergy efficiency (>20%, DOE target)
- Low hydrogen costs (<2 \$/kg, DOE target)

HyS = Hybrid sulfur

Relevance & Impact
Milestone accomplishment overview



Test conditions included temperature of 800 °C, pressure of 1 bar and H_2SO_4 concentration of 91 wt %. The catalyst used were 1%Pt/BN, 1%Pt/5%Ir/BN and 1%Pt/7.5%Ir/BN.

- Catalyst deactivation reduction required to reduce the lifetime costs of the plant and achieve 2 $/kg target
  - *HydroGEN node – Idaho Nat Lab*

    Unique capability to test catalytic decomposition of H_2SO_4 at the required operating conditions (T ~ 800 °C, concentrations ~ 90 wt%)

Catalyst activity

- ***Milestone 1.1***: *Preparation of the new catalyst, measurement of its nominal (fresh material) properties. The success of the milestone will be based on the following criteria: (1) catalyst activity at least 20% higher than the corresponding current baseline values obtained at Idaho National Laboratory (INL), i.e. SO$_2$ production rate of 0.28 mol$_{SO2}$/h/g$_{catalyst}$ (the current baseline value is about 0.23 mol$_{SO2}$/h/g$_{catalyst}$ obtained with concentrated sulfuric acid at 1123 K and atmospheric pressure*)*

All BN-based catalytic formulations achieved the catalyst activity (Milestone 1.1) targets

Catalyst degradation

- ***Milestone 1.2***: *Measurement of catalyst activation reduction after 100-hour tests. The success of the milestone will be based on the following criteria: (1) catalyst activity reduction 50% less than the corresponding current values obtained at INL, i.e. less than 1.5% reduction after the 100-hour tests, corresponding to a maximum 0.015% activity reduction per hour (the current baseline value is 0.03% activity reduction per hour obtained with concentrated sulfuric acid at 1123 K and atmospheric pressure*). The values will be measured after the catalyst reaches an initial stable condition with a possible statistical analysis of the data.*

The novel catalyst formulation, 1%Pt/7.5%Ir/BN (Provisional Patent Applied) achieved the catalyst degradation (Milestone 1.2) targets

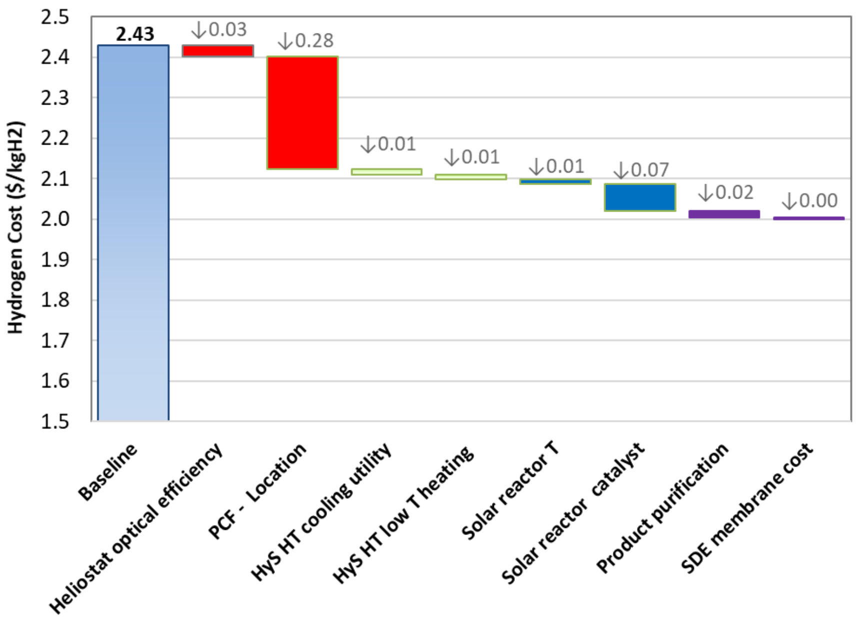
* Petkovic LM et al, Applied catalysis A, 338 (2008) 27-36

Relevance & Impact
Milestone accomplishment overview

- High-efficiency and low-cost plant configuration developed and demonstrated
  - *HydroGEN node – Savannah River Nat Lab*

    Unique capability to develop process models for H_2SO_4 based thermochemical processes
  - *HydroGEN node – National Ren Energy Lab*

    Unique capability to model and optimize the overall CSP and BOP components



System analysis

- *Milestone 1.3: Assessment of the techno-economic performance of the solar driven HyS process. The success of the milestone will be based on the following criteria: (1) mass and energy balances of the HyS process (available from the HyS flowsheet) will be provided; (2) efficiency of the thermochemical plant (HyS) higher than 35% (based on LHV of hydrogen), (the current value is 32%, see Ref. 2); (3) overall solar plant efficiency higher than 18%; (4) hydrogen production cost showing a viable path to \$2 /kg H_2.*

Novel reactor (being patented) and plant flowsheet HyS efficiency of >37% and S2H efficiency of 21%

- *Go/No-Go: The decision will be made based on the following criteria: (1) catalyst activity at least equal to a production rate of 0.28 molSO_2/h/gcatalyst (20% higher than the corresponding current baseline value of 0.23 molSO_2/h/gcatalyst obtained with concentrated sulfuric acid at 1123 K and atmospheric pressure); (2) catalyst activity reduction (100 hour test) lower than 1.5% after 100 h tests (50% lower than the corresponding current baseline value of 0.03% per hour obtained with concentrated sulfuric acid at 1123 K and atmospheric pressure); (3) the solar plant cost showing an overall plant efficiency > 18% (thermochemical plant efficiency >35%) and a viable path to reach a H_2 cost of 2 \$/kg_{H2}*

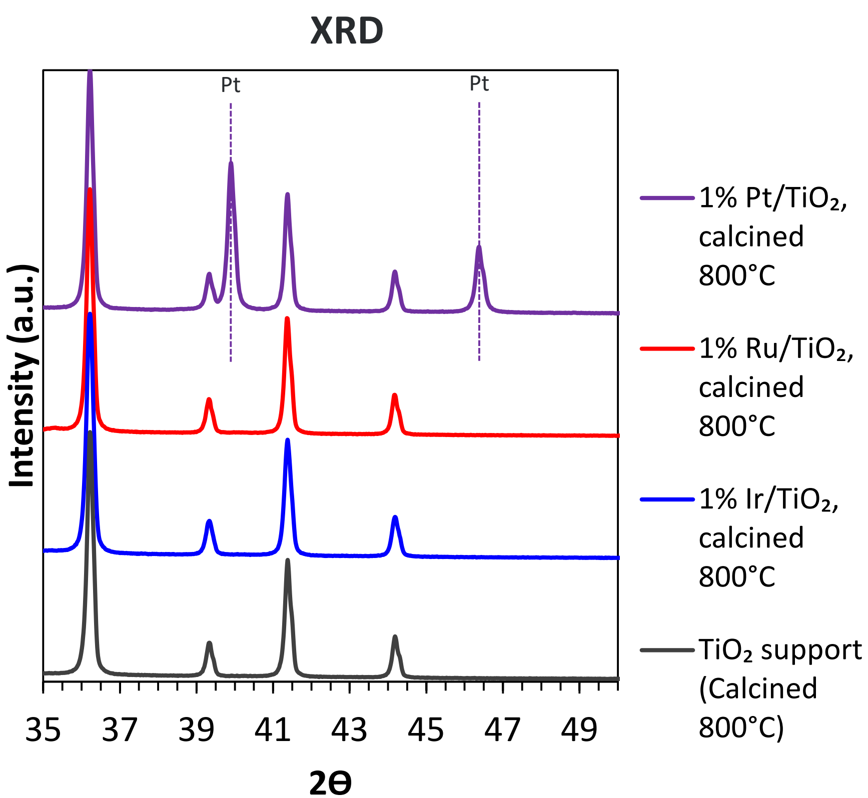
Current H_2 cost 2.43 \$/kg with a viable path to 2.0 \$/kg

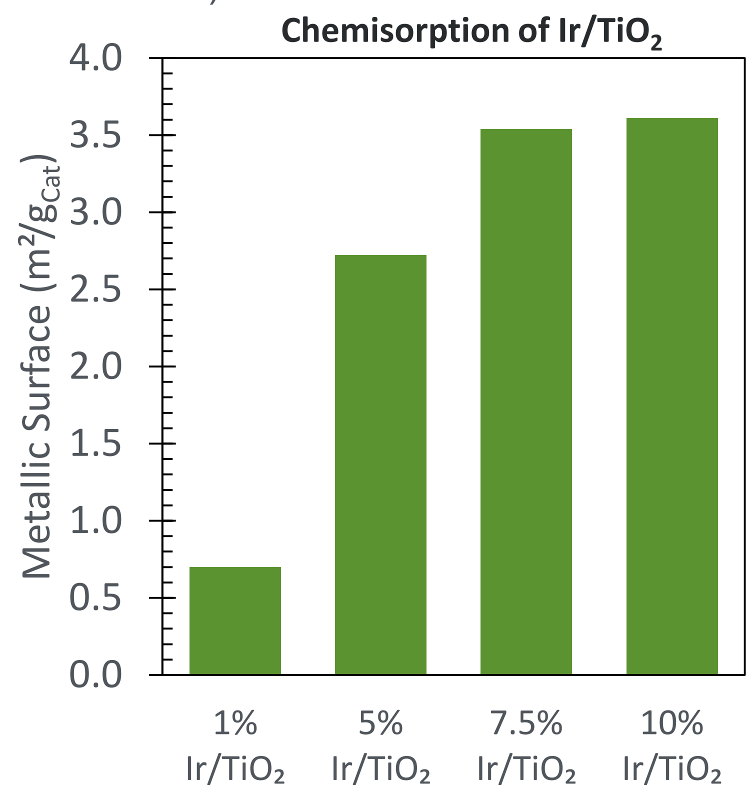
LHV = Low Heating Value (120 MJ/kg) CSP = Concentrating Solar Plant
S2H = Solar to hydrogen BOP = Balance of plant

Accomplishments - Sintering of monometallic catalysts on TiO_2

Level 1

- Monometallic catalysts prepared by dry impregnation method. After reduction at 300°C, metal particles were too small for detection by XRD (< 1.5 nm).
- Calcination then done in air at 800°C.
- Pt sintered to ~35 nm particles, while Ir and Ru are very stable on TiO_2 surface.
- Higher loading Ir and Ru provides more surface for Pt anchoring. Core catalysts of Ir and Ru made with 5% weight loading of metal on pretreated TiO_2 (calcined at 800ºC)

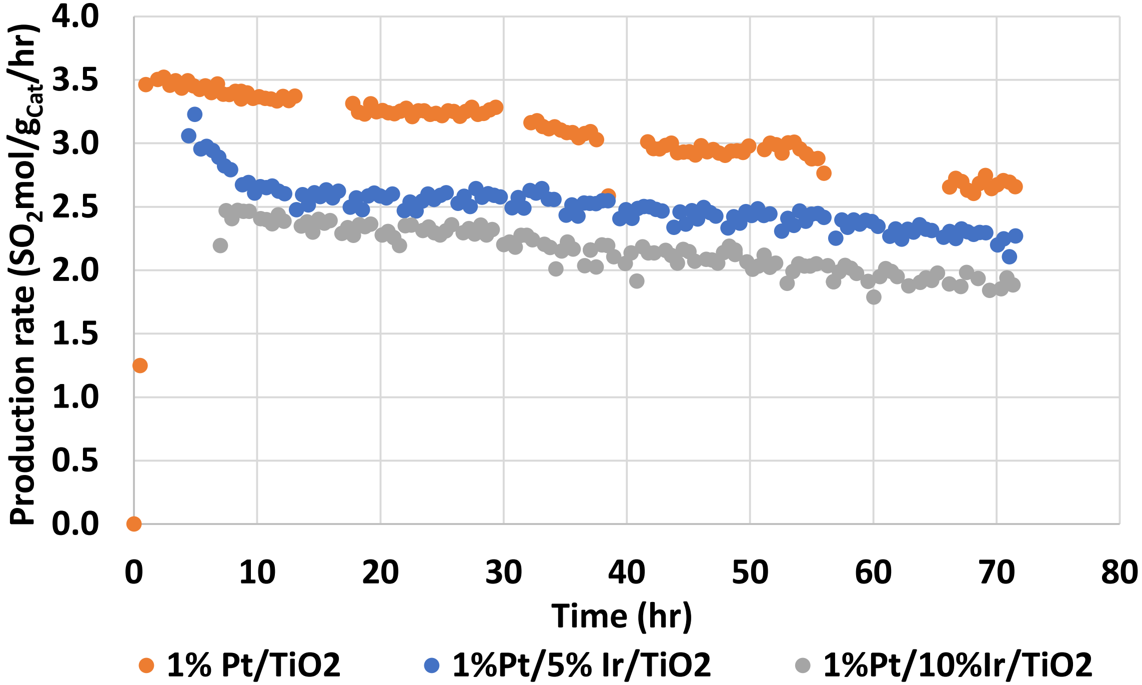




- Surface area scales with Ir wt loading

XRD = X ray diffraction

Accomplishments - Bimetallic TiO_2 catalysts
Level 1



Test conditions included:
temperature of 800 °C, pressure of 1 bar and H_2SO_4 concentration of 91 wt %.

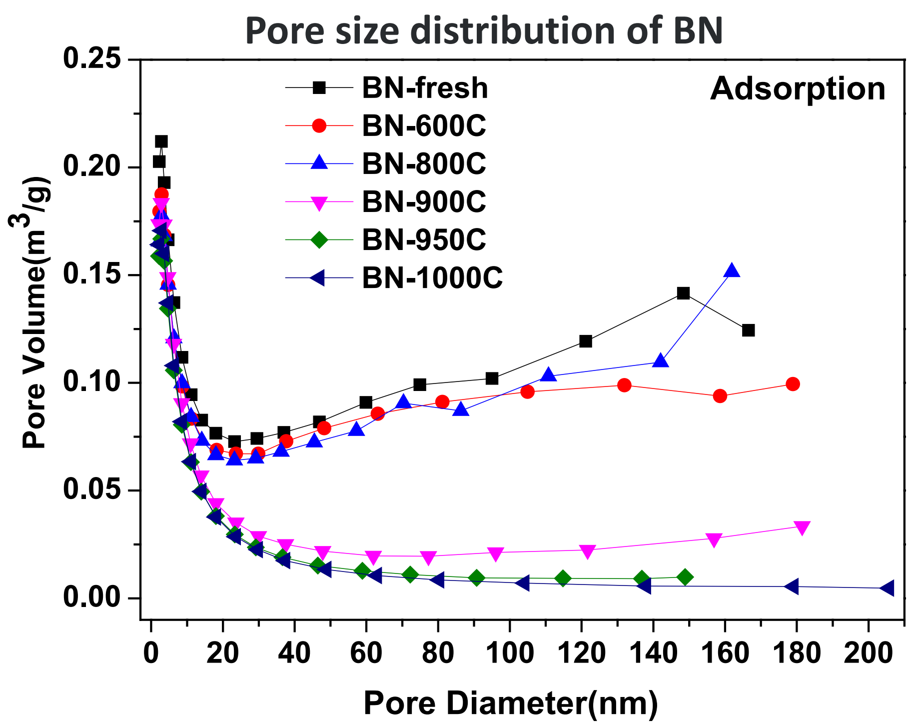
- Monometallic and bimetallic PGM/TiO_2 catalysts showed appreciable deactivation.
- Ir based catalysts had lower reaction rates than the monometallic catalyst.
- Increasing Ir content decreased reaction rates and did not reduce deactivation.

PGM = Platinum group material

Accomplishments - Boron Nitride (BN) support

Level 1

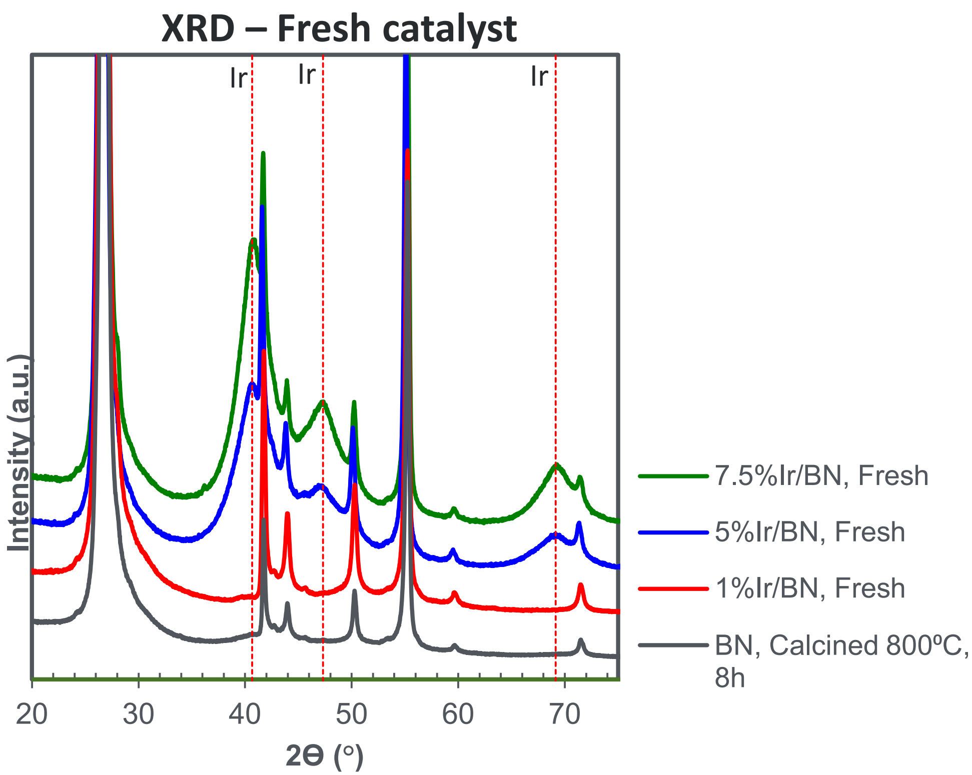
- BN is more stable support than TiO_2 with small loss of surface area at 800°C.
- At T ≥ 900°C, surface area increases dramatically due to large decrease in pore diameters.
- Pore diameters of ~ 3 – 5 nm likely not useful during reaction.

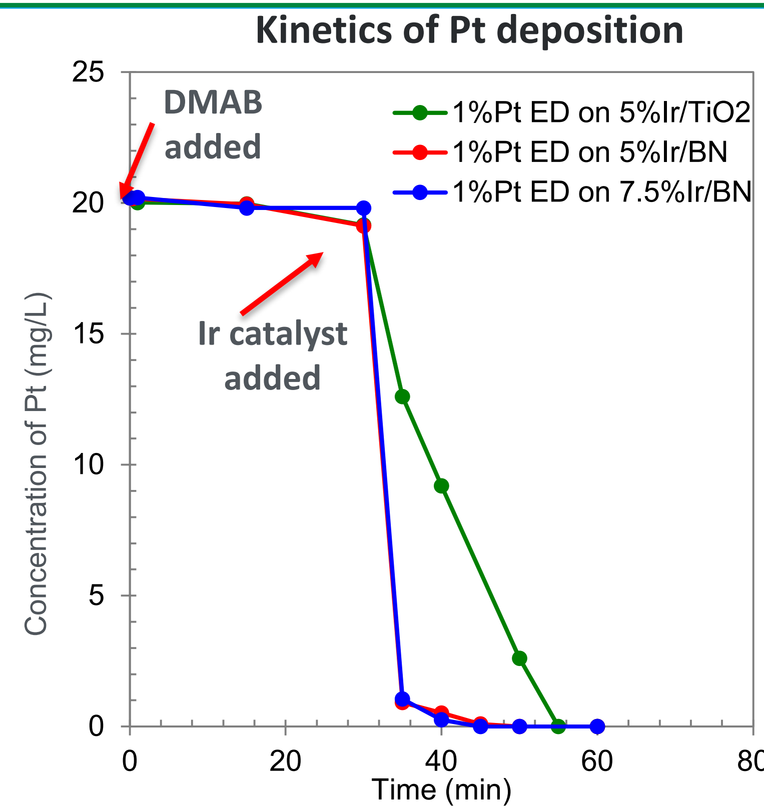


Sample	Surface area (SA, m^2/g)	V_{pore} (cm^3/g)	D_{ave} (nm)
BN-fresh	**61**	0.21	**13.7**
BN-600 °C	**54**	0.18	**13.8**
BN-800 °C	**53**	0.17	**13.1**
BN-900 °C	73	0.13	7.4
BN-950 °C	100	0.11	4.6
BN-1000 °C	135	0.11	3.5

Accomplishments - Bimetallic Pt-Ir catalysts supported on BN

Level 1





- BN was calcined at 800°C before Ir impregnation.
- Ir/BN reduced at 300°C in H_2/Ar gas mix.
- Pt deposited on Ir using ED.
- Deposition of Pt on Ir/BN faster than Ir/TiO_2 because of smaller Ir particles on BN.

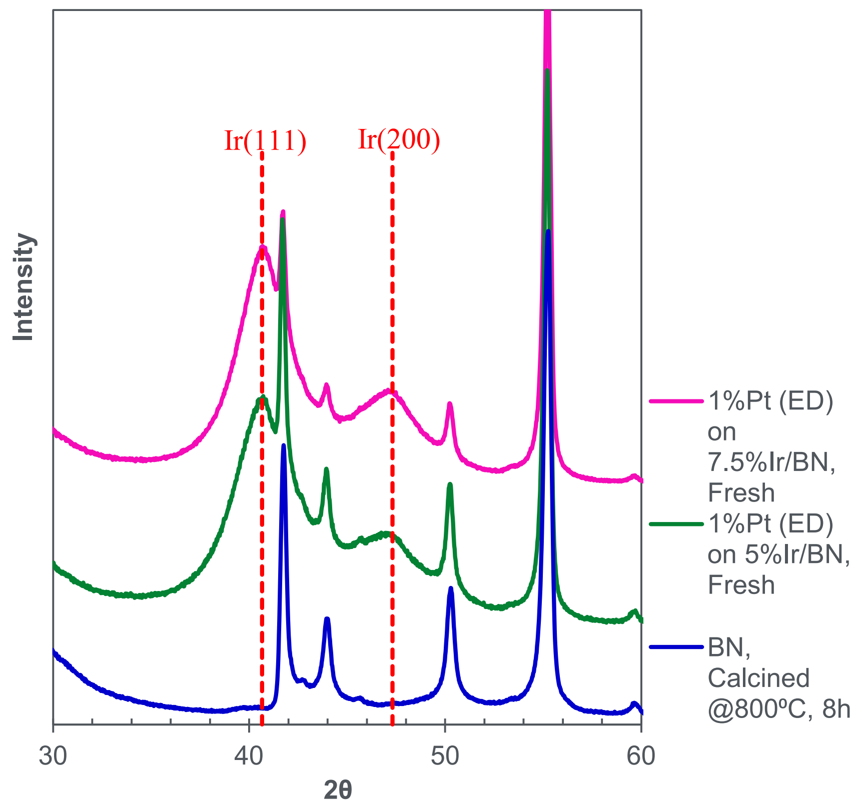
Temperature	50°C
[DMAB] : [EN] : [$PtCl_6^{2-}$]	5 : 4 : 1
Volume	500 mL
wt of base catalyst	1 g
Wt% Pt deposited	1%
pH	10

ED = Electroless deposition   XRD = X ray diffraction

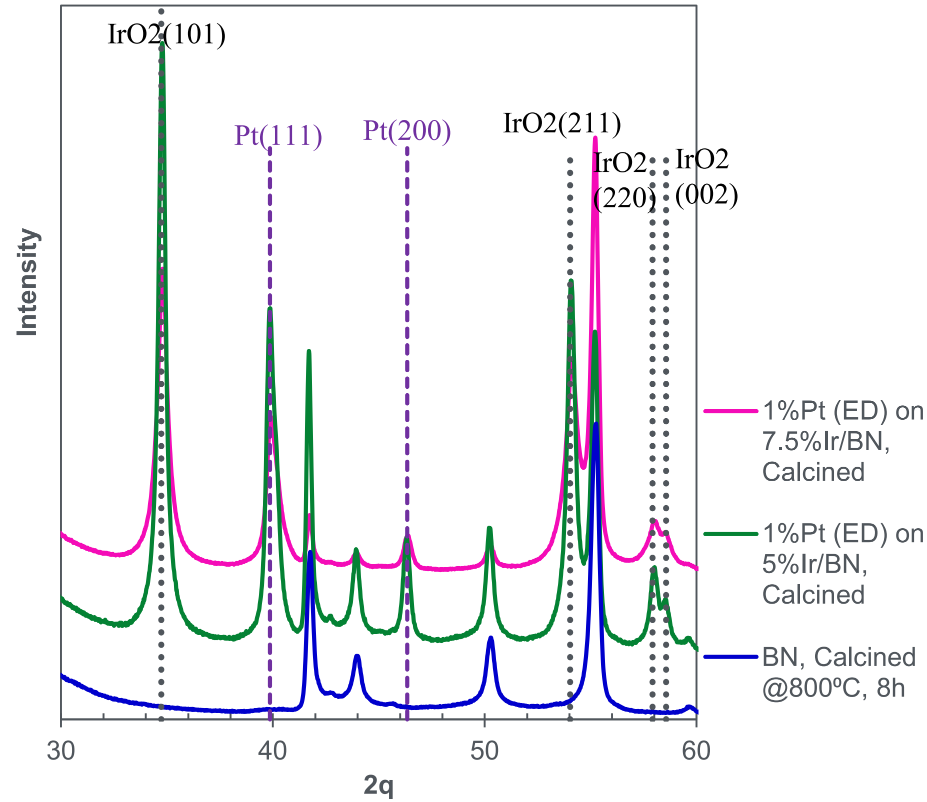
Accomplishments - Bimetallic Pt-Ir catalysts supported on BN

Level 1

XRD – Fresh catalyst



XRD – Calcined (800 °C) catalyst



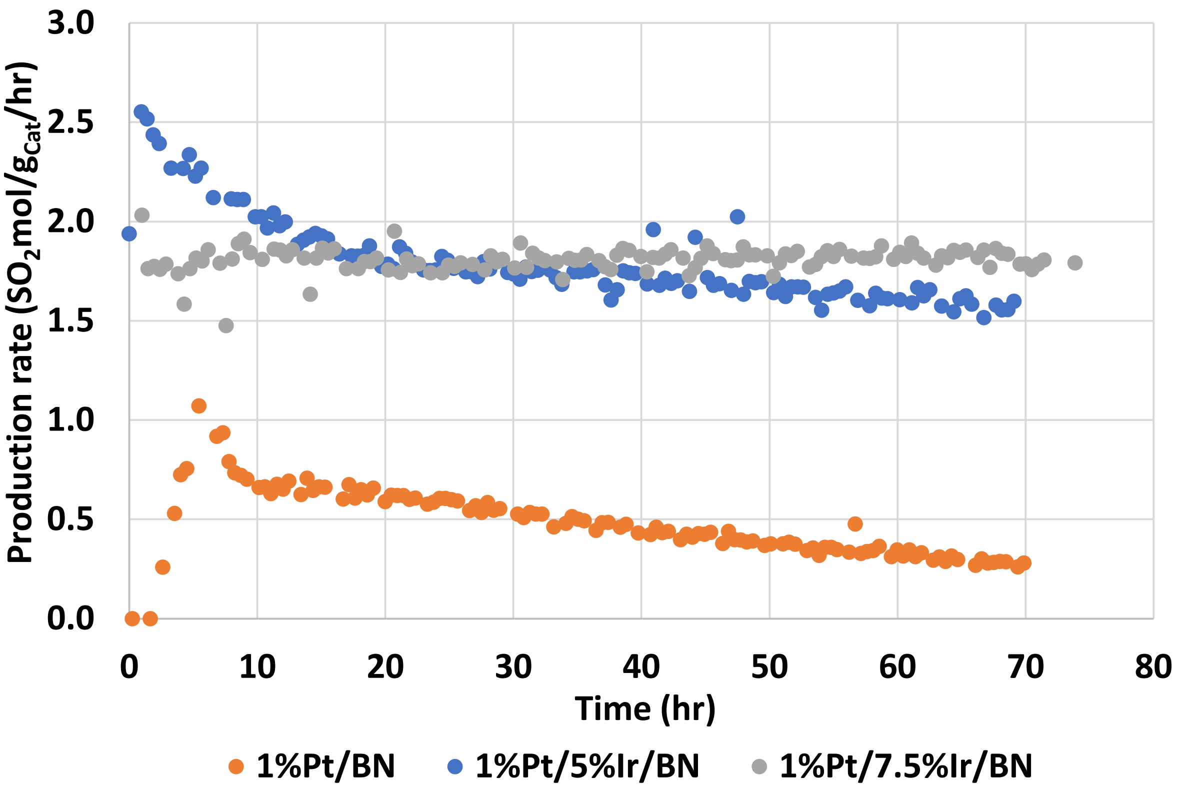
- BN was calcined at 800°C before Ir impregnation.
- Fresh catalyst shows the presence of broad Ir peaks and absence of Pt peaks → presence of Ir on the surface not well dispersed
- Calcined has only Ir oxides and broad and less intense Pt peaks → metal Ir well dispersed, Pt more stable on BN than TiO_2

	Calcined (Pt)	
	BN	TiO_2
1%Pt on 5%Ir	11.4	27
1%Pt on 7.5%Ir	16.4	22

ED = Electroless deposition XRD = X ray diffraction

Accomplishments - Bimetallic BN catalysts tests

Level 1

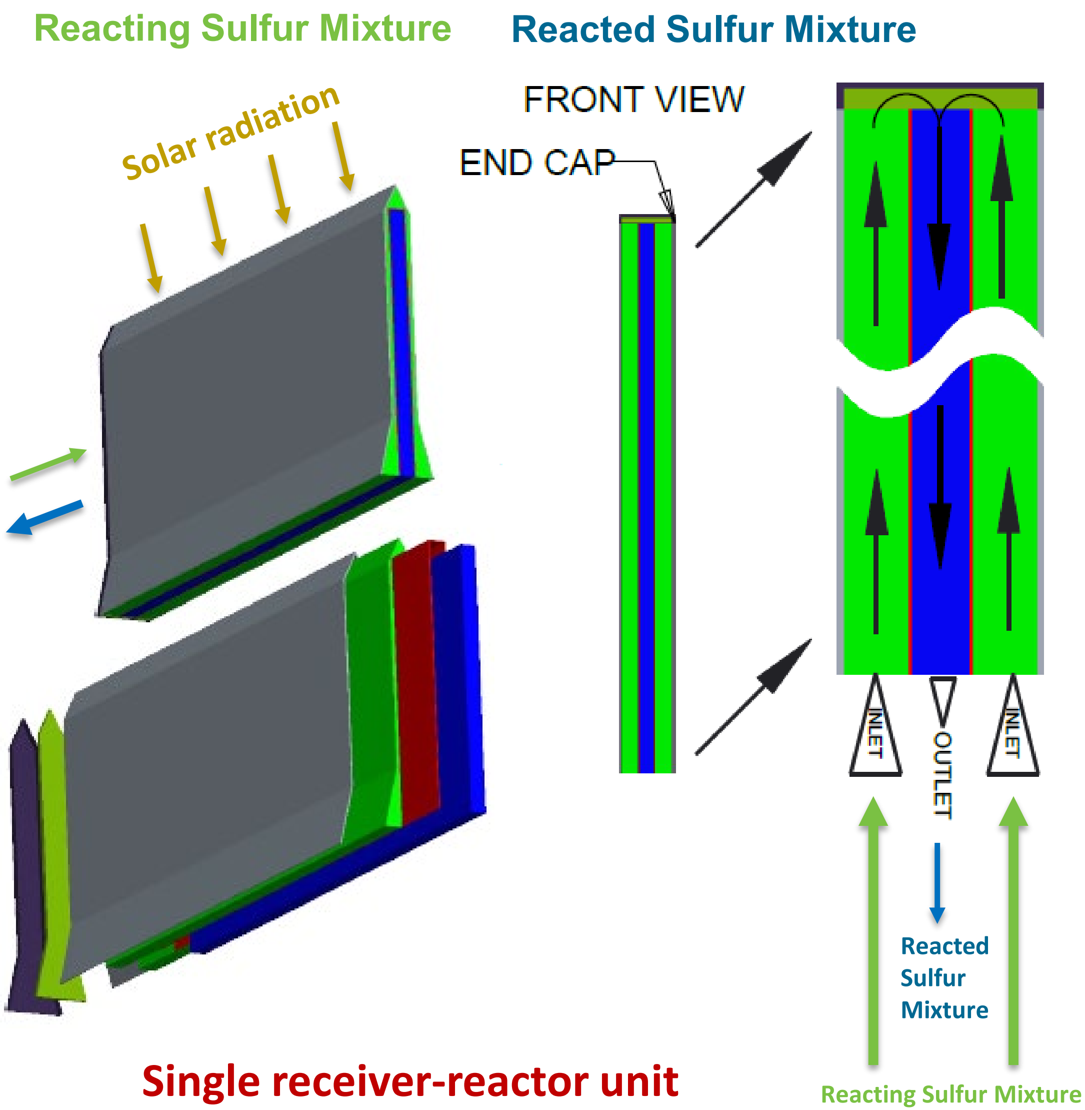


Test conditions included:
temperature of 800 °C, pressure of 1 bar and H_2SO_4 concentration of 91.28 wt %.

- Both bimetallic Ir/BN catalysts showed less deactivation then the momometallic catalyst.
- 1% Pt-7.5% Ir/BN catalyst showed nominal activity of 1.75 molSO2/h/gCat, **surpassing Milestone 1.1** .
- 1% Pt-7.5% Ir/BN catalyst showed no deactivation in 75 hours of testing **surpassing Milestone 1.2**, deactivation rate of 0.015%/hour.
- Increasing Ir content decreased reaction rates.

Accomplishments - Novel solar receiver/reactor concept

Level 2



Single receiver-reactor unit

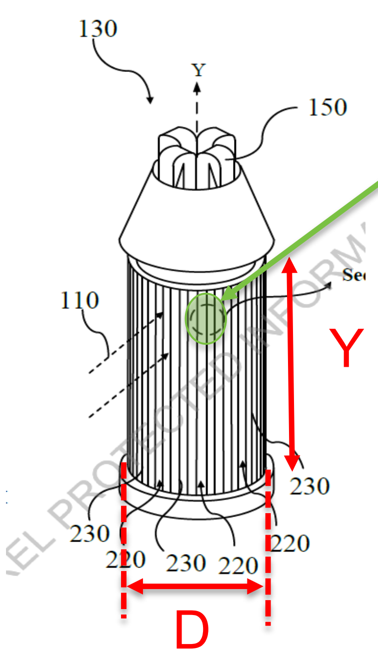
Novel GWE-NREL H_2SO_4 decomposition reactor configuration (ROI filled)

- Compact and intensified design
- External solar heating and internal heat recovery accomplished in a single SiC unit
- Technical feasibility demonstrated (AMR 2018) with CFD detailed transport modeling

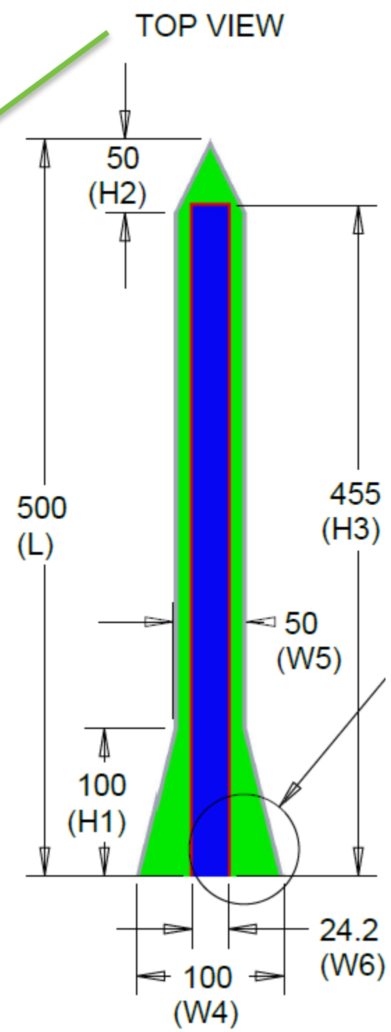
ROI = Record of Invention CFD = Computational Fluid Dynamics

Accomplishments - Solar reactor preliminary scale up

Level 2



Solar receiver-reactor assembled units on top of the solar tower



Single receiver-reactor

Sizing of the solar receiver-reactor for large scale production

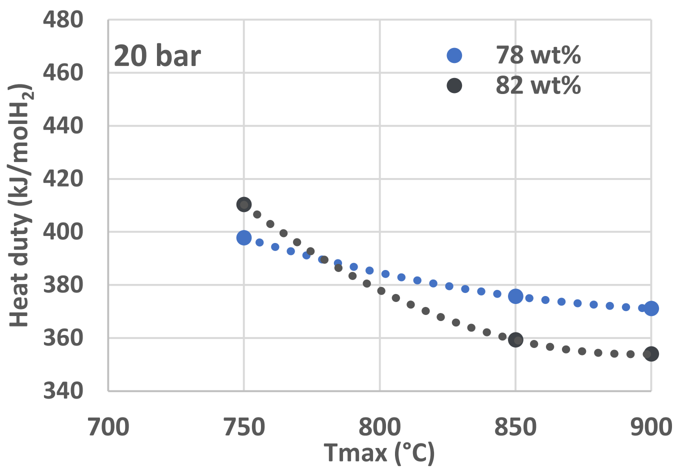
Initial configuration achieved

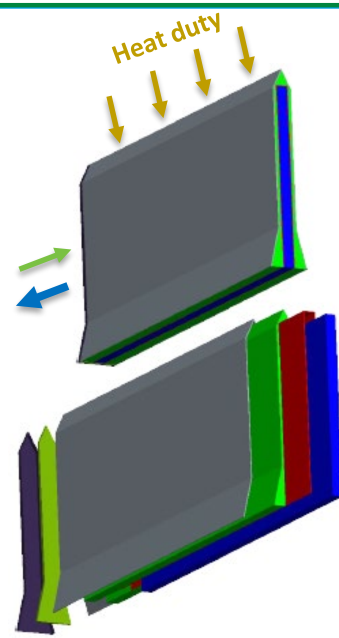
Matching between heat exchange power requirements and geometry constraints

Single unit receiver/reactor	
L (m)	0.5
W4 (m)	0.1
H_2SO_4 flow rate (kg/s)	0.285
Assembled units for 95.3TPD H_2 peak production	
D (m)	11.5 (single tower)
Y (m)	2-4 (projected total length) 1-1.5 (SO_3 catalytic decomposition section length)
Number of reactor units	364

Accomplishments - Solar reactor process analysis

Level 3



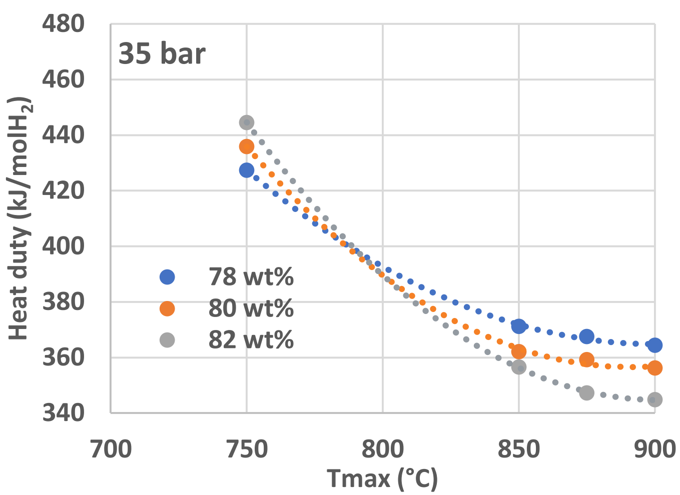


Sensitivity analysis conditions

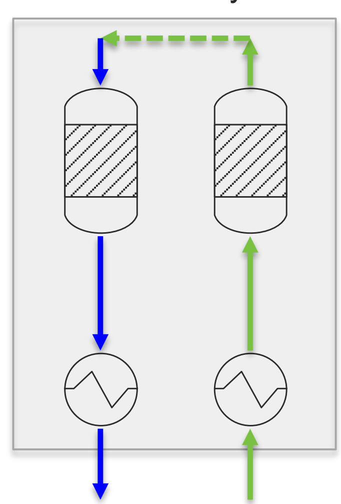
- Tmax = 750 – 900 ºC (assumed boundary T for BN support)
- P = 10 – 50 bar
- H_2SO_4 inlet concentration = 75 – 85 wt%

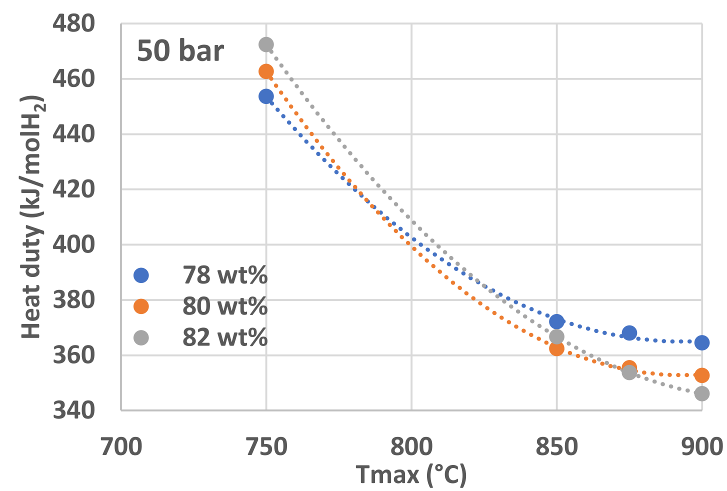
Results

- The heat duty (ΔH) is more sensitive to the operating conditions at high P
- At high T (i.e. current T range) high P is preferable
- Heat duties < 350 kJ/mol (i.e. HyS high efficiency projected value) achievable
- Baseline conditions: T = 875 ºC, P = 35 bar, H_2SO_4 conc = 82 wt% → ΔH = 347.3 kJ/mol



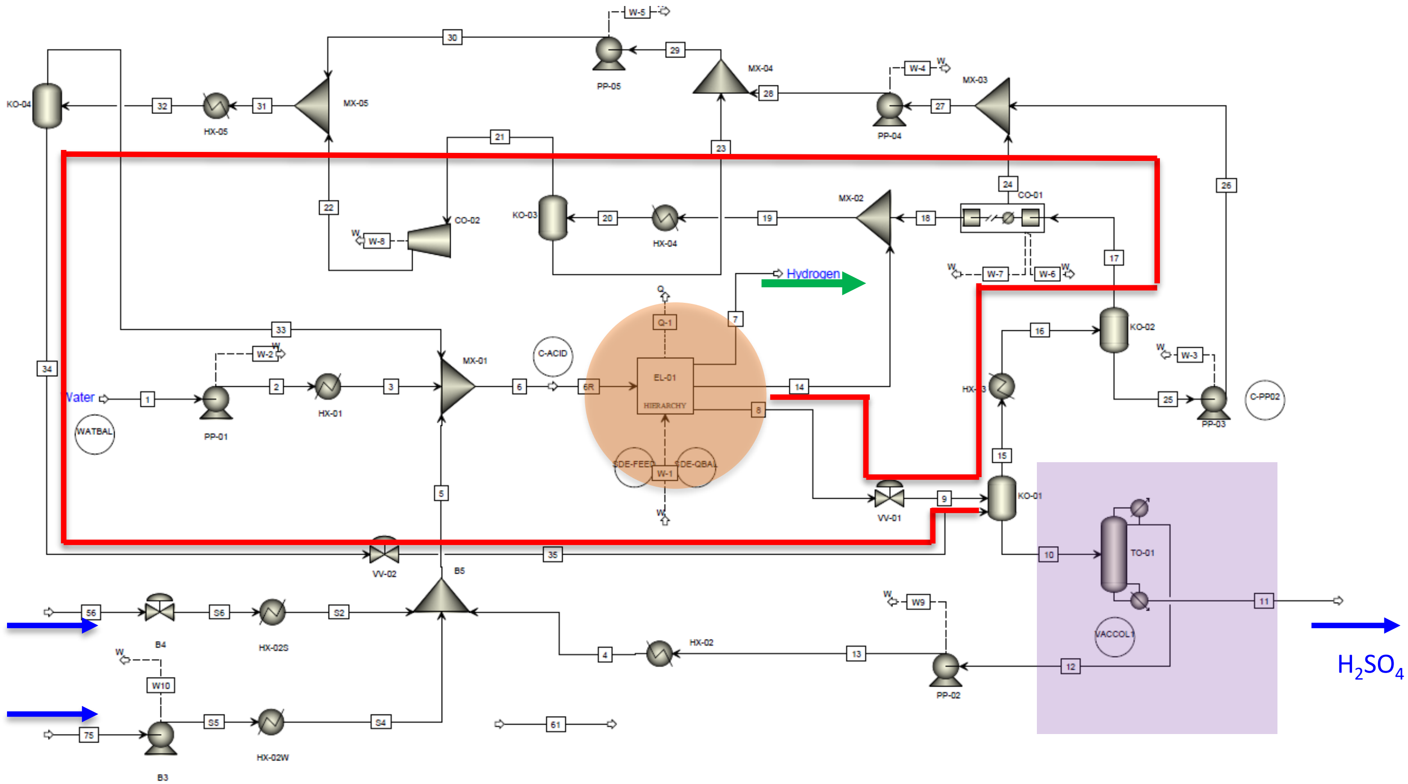
ASPEN Pinch analysis schematic





HyS = Hybrid sulfur

Accomplishments - Low T process flowsheet
Level 3



H$_2$SO$_4$ at 80 wt%

Low Temp flowsheet

SO_2 electrolyzer

To or from the high T section

SO_2 recirculation

Hydrogen product

H_2SO_4 conc

Novel HyS cycle flowsheet based on the vapor fed SDE section – 24/7 operation

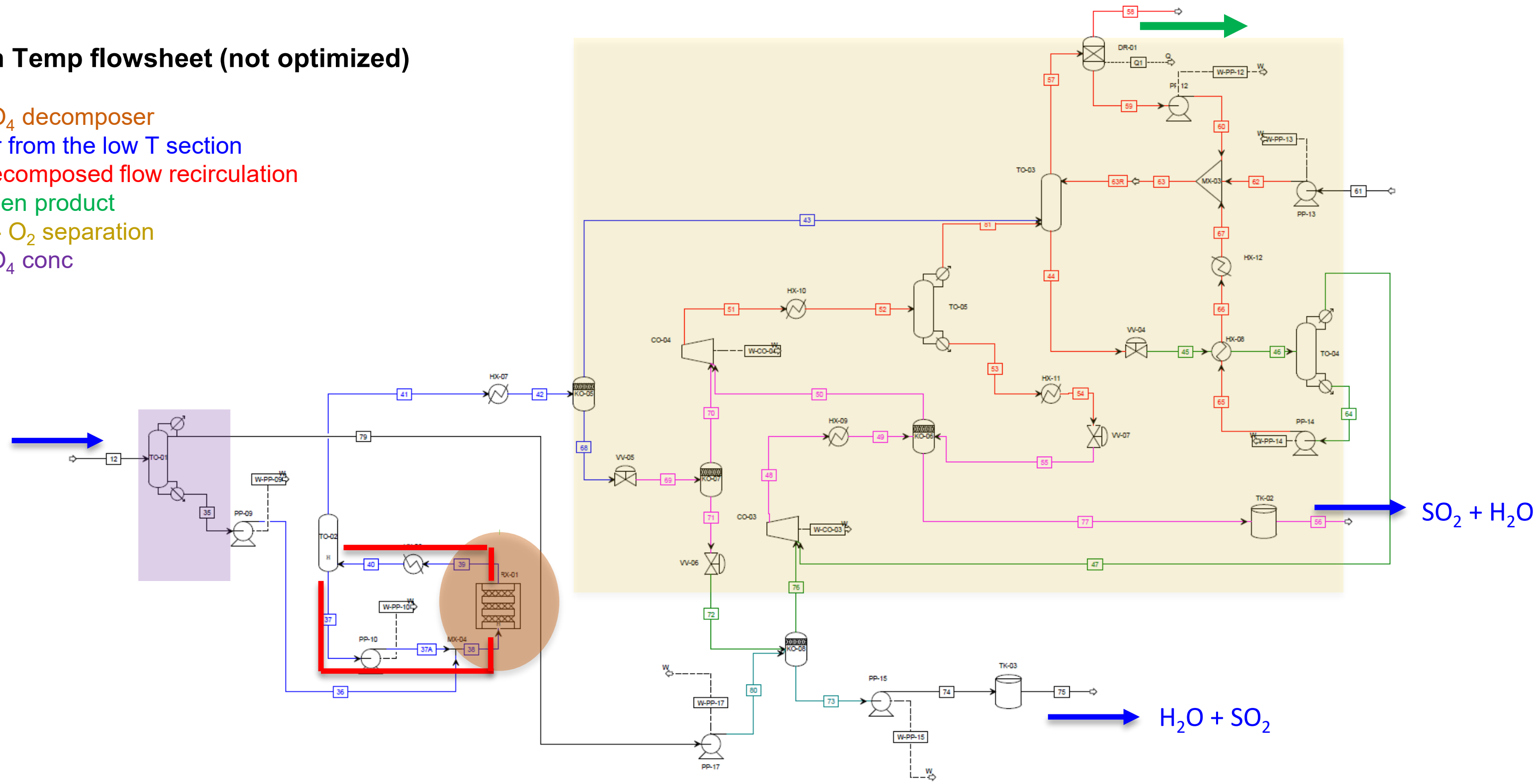
- SDE section (leveraged from externally financed USC work)
  - Increase of SDE efficiency at about 140 C
    - V= 575 mV, I= 500 mA/cm^2
    - W_{el} = 110.2 kJ/molH$_2$
  - Production of high concentration sulfuric acid
  - Higher temperature SDE waste heat (140 °C) internally recoverable to concentrate H_2SO_4 up to 80wt%

SDE = SO_2 Depolarized Electrolyzer

Accomplishments - High T process flowsheet
Level 3

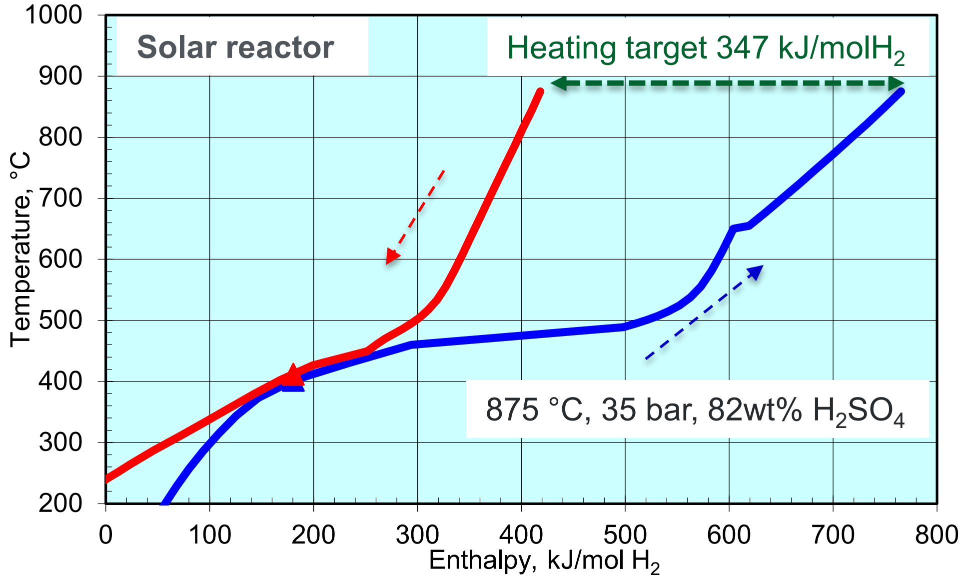
High Temp flowsheet (not optimized)

H_2SO_4 decomposer
To or from the low T section
Undecomposed flow recirculation
Oxygen product
SO_2 - O_2 separation
H_2SO_4 conc



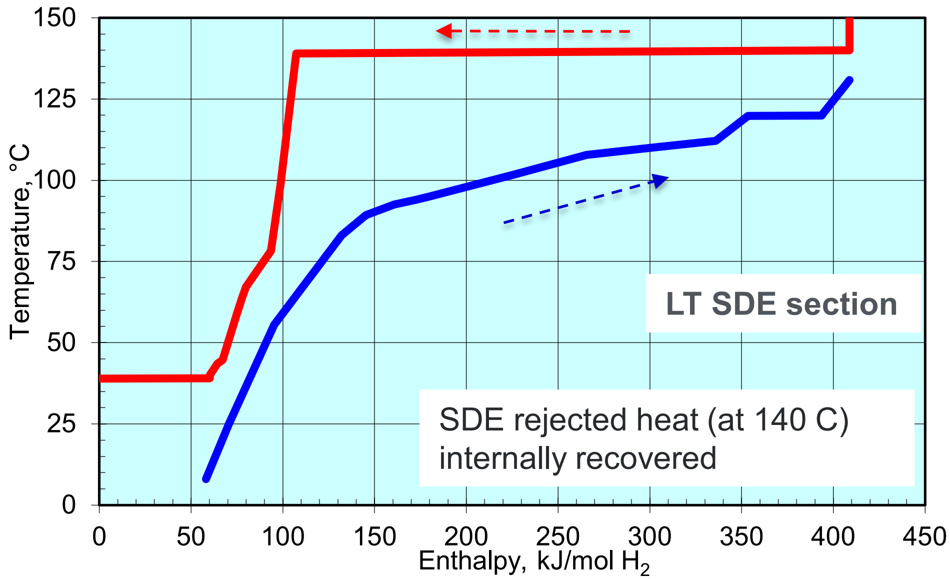
- High T section (not optimized version)
  - Decrease of the decomposer heat duty
  - Total internal heat recovery of undecomposed flow (> 200 °C) to concentrate H_2SO_4 up to 90wt%
  - Increase of the overall efficiency – need for small low T heat provided by solar vacuum tubes

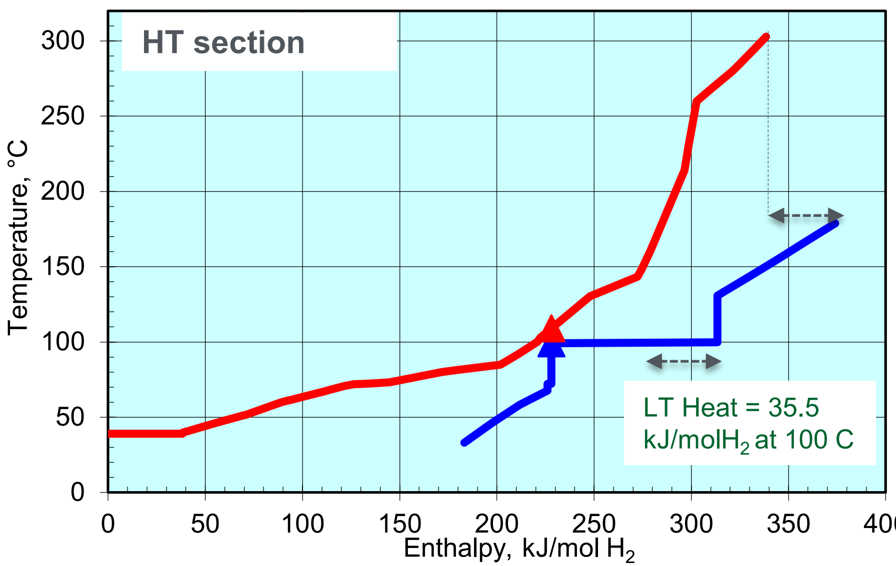
Accomplishments - Process pinch analysis
Level 3



	Total	HyS HT	HyS LT
HyS thermal input (kJ/mol)	347.3	347.3	-
HyS electric input (kJ/mol)	123.1	10.6	112.5
HyS efficiency (%)	**37.6** 35.7 (with LT heat)		
Solar plant efficiency	56.4		
S2H efficiency (%)	**21.2** 20.1 (with LT heat)		

Thermochemical (37.6%) and Solar to Hydrogen (S2H) (21.2%) efficiencies meet the **Milestone 1.3 target**

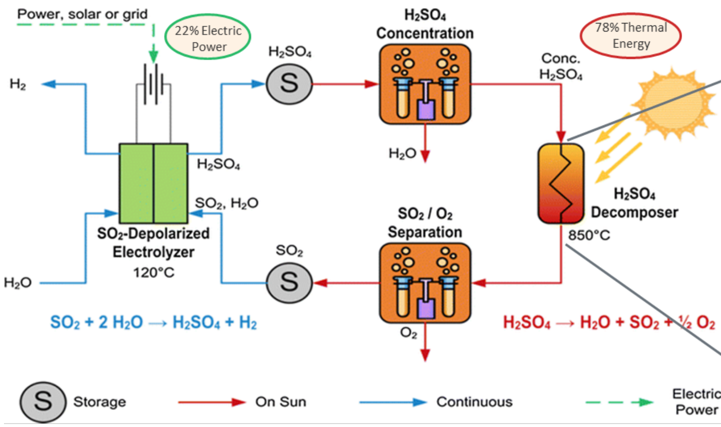


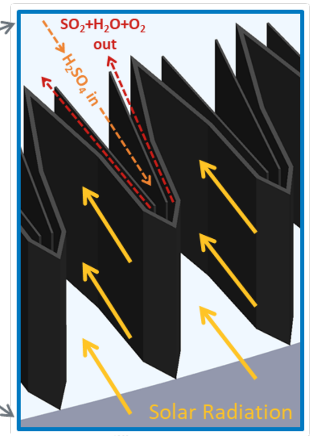


S2H = Solar to hydrogen
LT = Low temperature
HT = High temperature
SDE = SO_2 depolarized electrolyzer

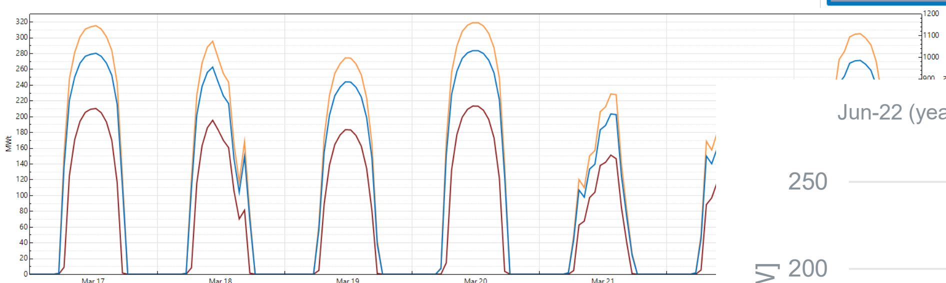
Accomplishments - Design nominal point

Level 3



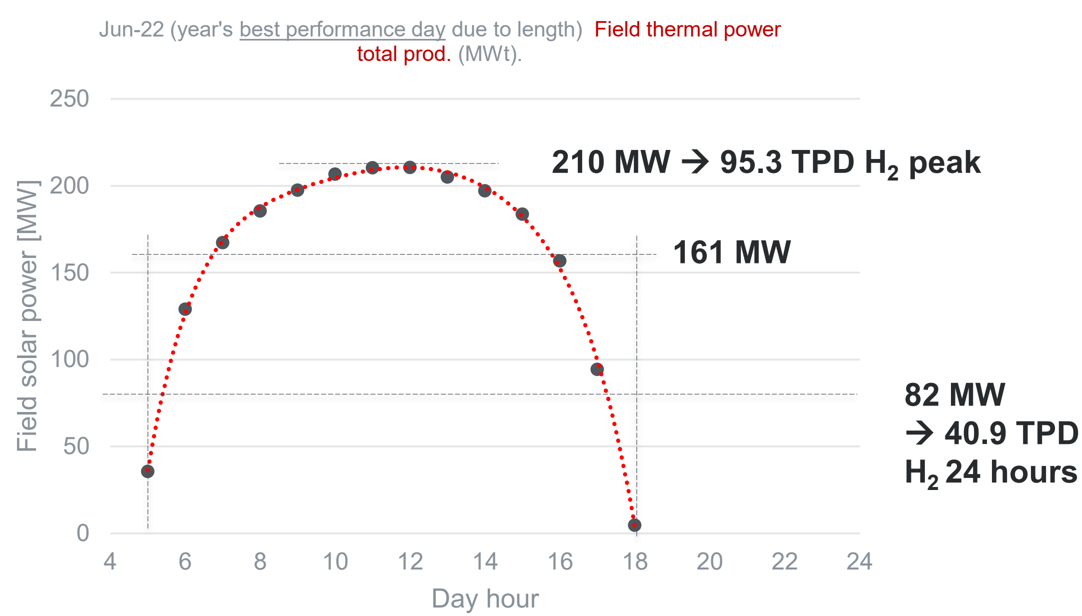


- High T section designed for on-sun operation (summer solstice solar peak)
- Low T section designed for 24/7 operation (summer solstice average 24/7)
- Optimum solar power plant power = 200 MWth (assessed last year AMR)
- Chemical storage required



Chemical storage of H_2SO_4 (from the low T section) and SO_2 and water (from the HT section) for 963 MWhth (12.2 hours)

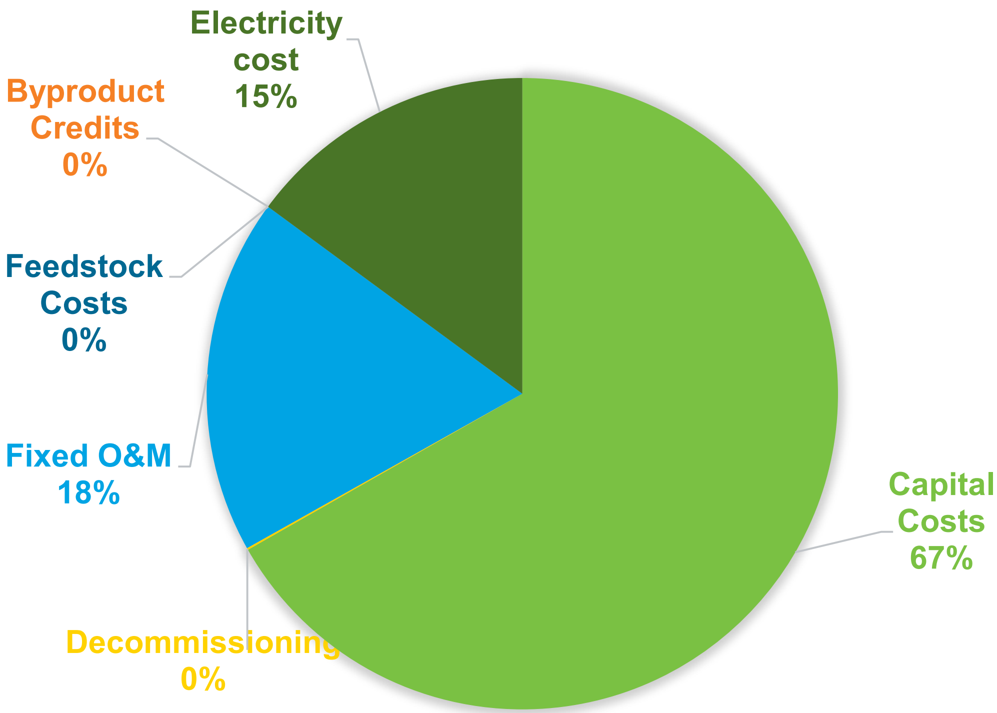
PCF of 63% for California location and 12.2 hour storage



PCF = Plant capacity factor

Accomplishments - Solar HyS plant cost evaluation

Level 3



Baseline hydrogen cost = 2.43 $/kg

Main baseline economic-financial assumptions

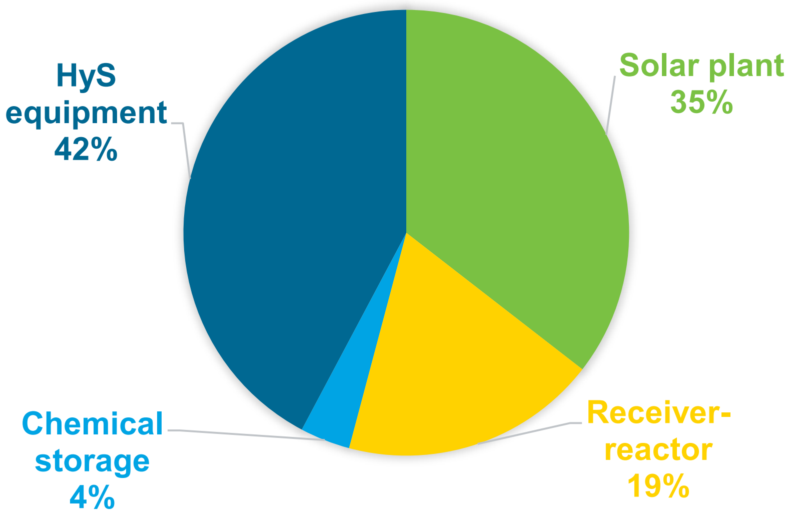
- Heliostat field cost = 75 $/m^2 (Sunshot value)
- Electricity cost = 2 c$/kWh
- Plant lifetime = 30 years
- Financial assumptions = H2A default

Results

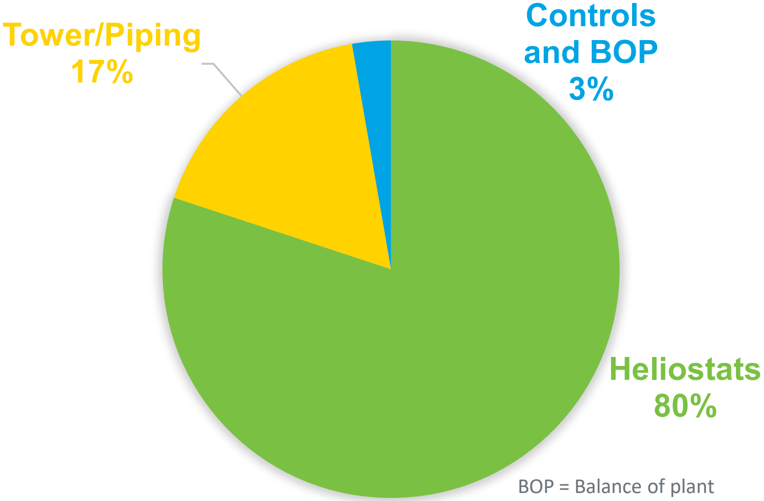
- H_2 baseline cost = 2.43 $/kg
- Utility cost (electricity) depending on efficiency and specific electricity cost
- Capital cost is the main cost item

Accomplishments - Solar HyS plant capital cost
Level 3

Total installed costs = 1.63 $/kg

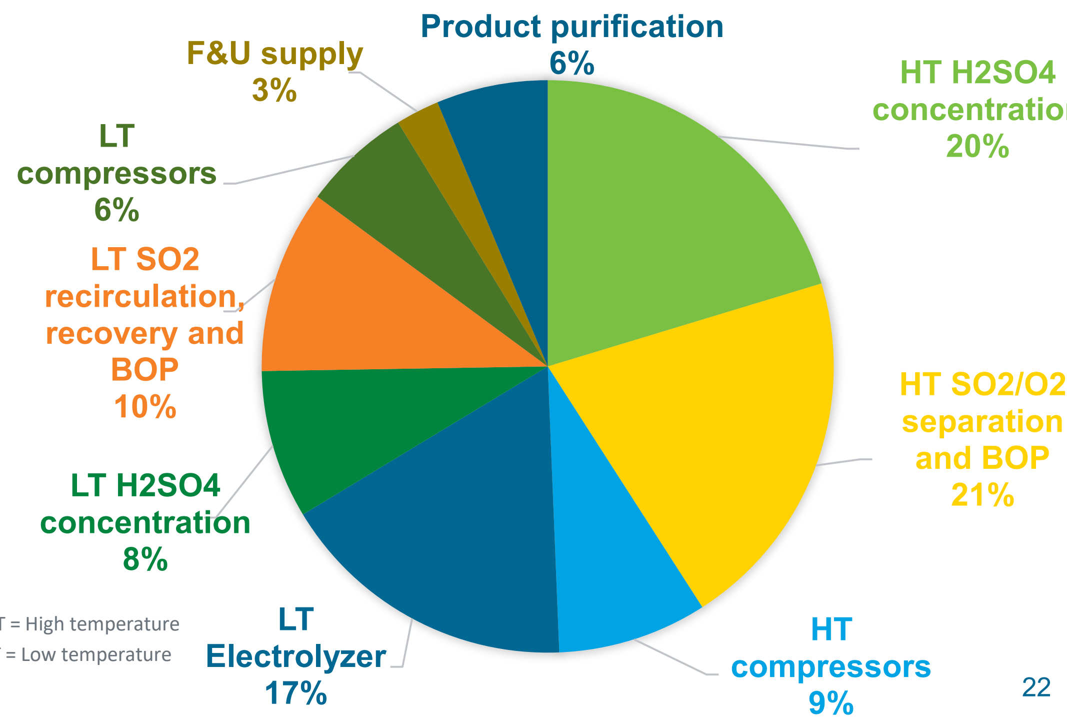


Solar plant cost = 0.57 $/kg



- Solar plant and HyS plant (the HT section is designed for on-sun operations) similar cost influence
- Heliostat field is the main cost factor → the efficiency is primary importance
- Flowsheeting and performance enhancement is of primary importance (mainly H_2SO_4 concentration)

HyS plant cost = 0.68 $/kg

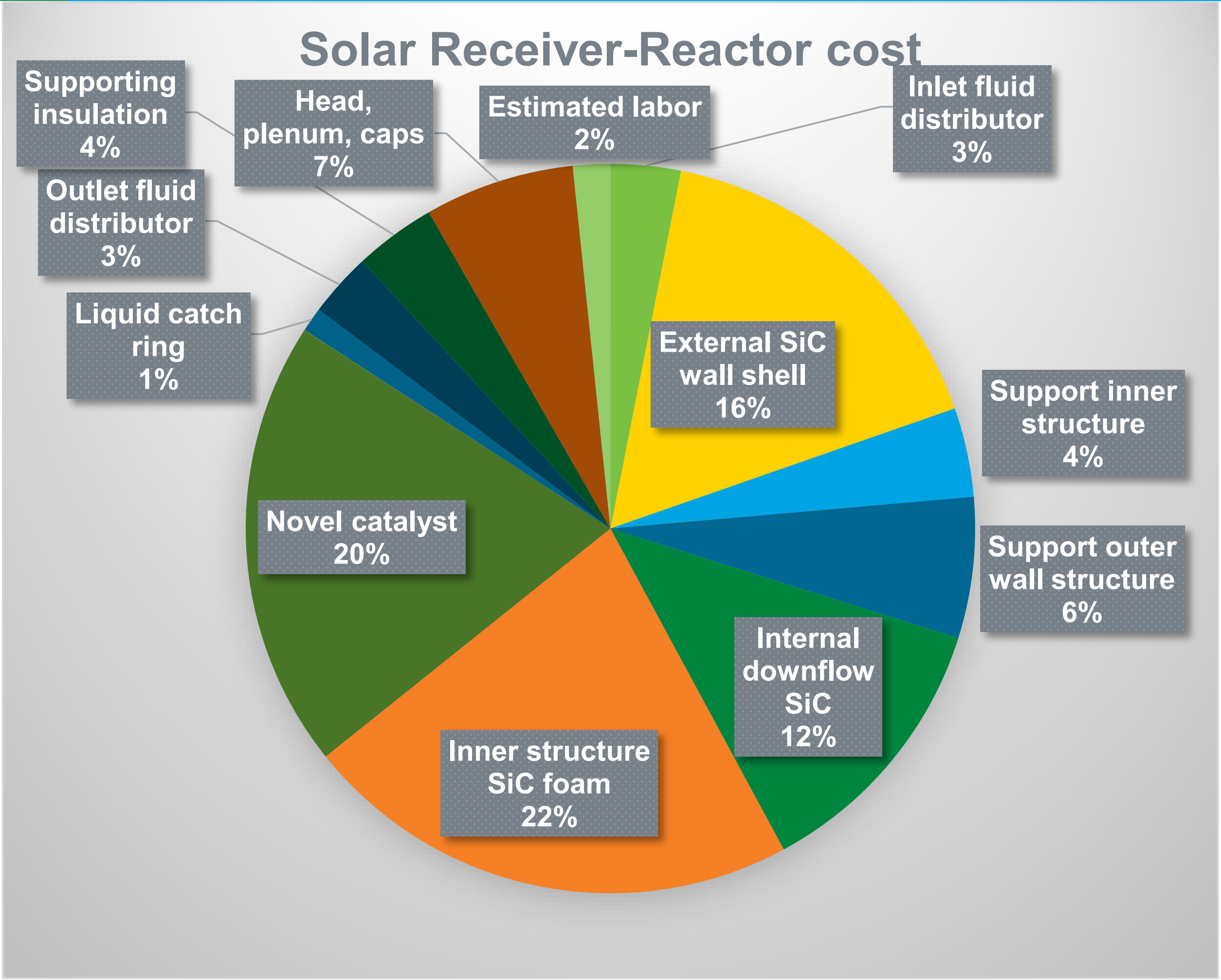


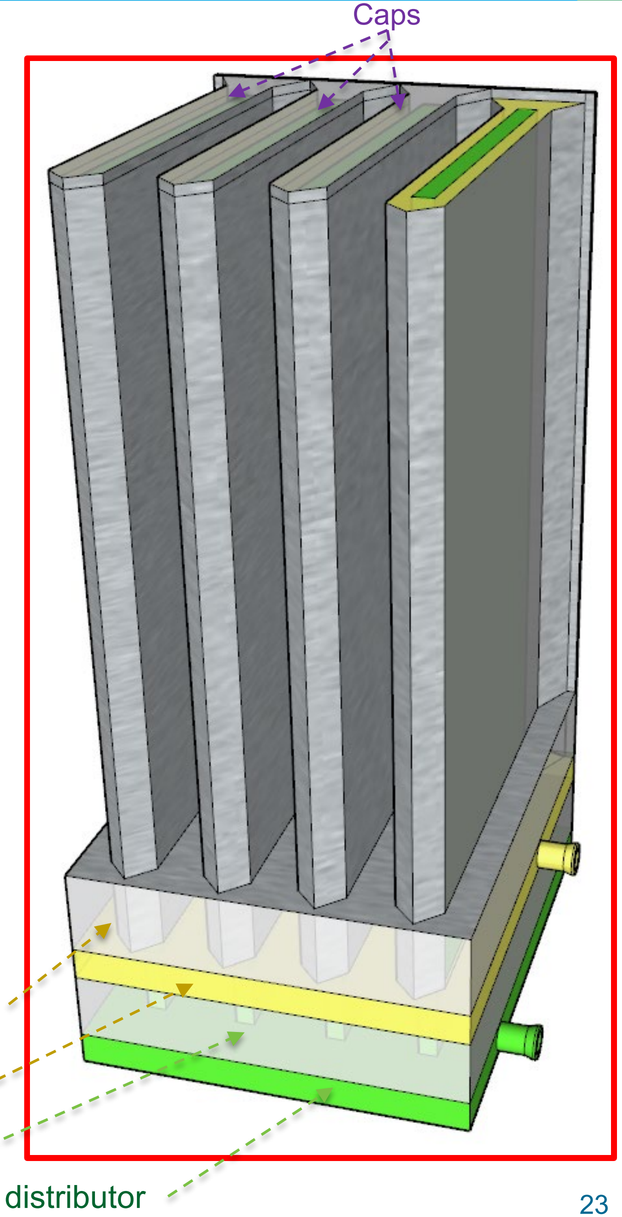
BOP = Balance of plant
HyS = Hybrid Sulfur

HT = High temperature
LT = Low temperature

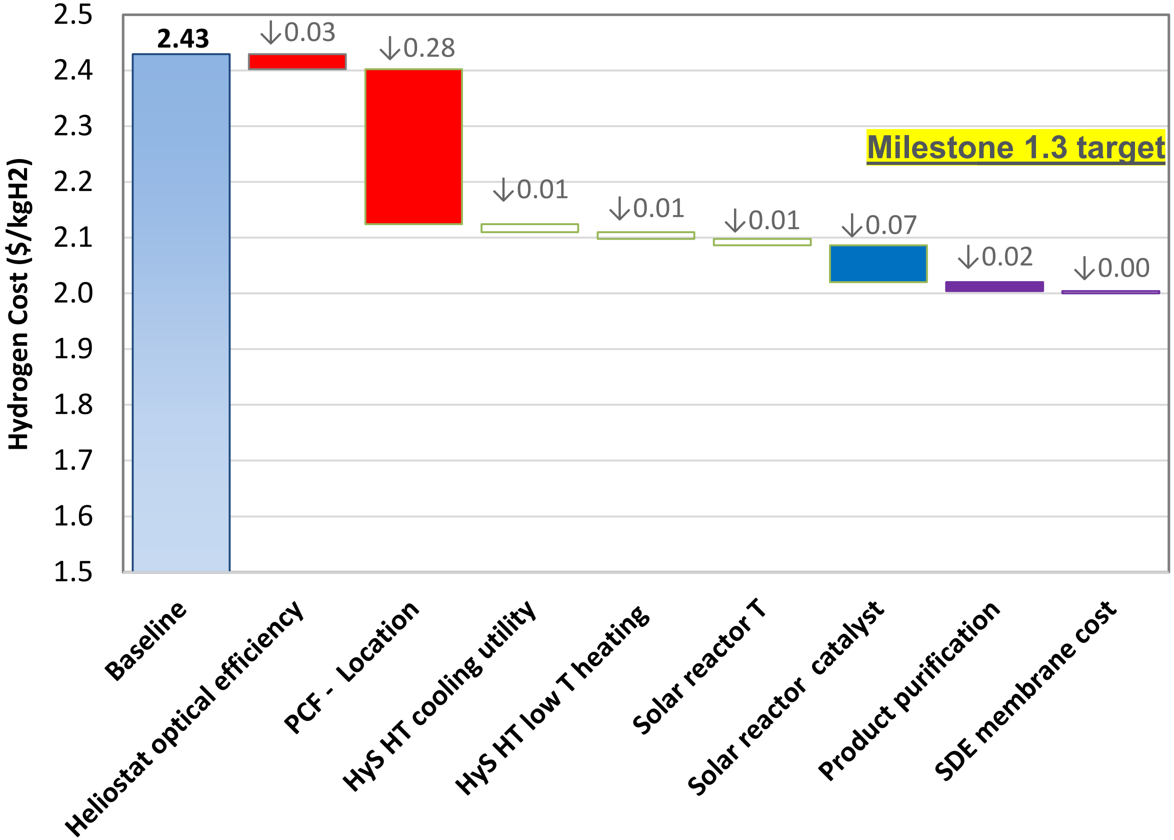
Accomplishments - Receiver-reactor cost

Level 3





Accomplishments - Viable path toward 2 $/kg
Level 3



Not included
- Oxygen byproduct cost
- Heliostat cost reduction
- Sulfuric acid concentration and SO_2/O_2 separation membranes
- Wind tower

*Wei M, et al. LBNL report on High T Fuel cell membranes, https://www.energy.gov/sites/prod/files/2017/06/f34/fcto_tco_model_hich_temp_pem_fc.pdf

Analysis based on ***KNOWN, VIABLE and ACHIEVABLE*** conditions

- *Heliostat efficiency:*

63.9 → 67.5 % (Edisun company discussions)

- *Plant Capacity Factor (PCF)*

63 → 73 % (different location, previous analyses)

- *HyS HT cooling utility and low T heating*

Novel optimized flowsheet being developed with reduced low T heating (35 → 8 kJ/mol) and cooling (power reduction of about 60%)

- *Solar reactor T*

Increase up to 900-920 C, reduction of heat duty 347 → 343 kJ/mol

- *Enhanced catalyst*

Being proposed a bimetal formulation with Co substituting Ir

- *Product purification*

Initial analysis with less expensive adsorbents and optimized flowsheet (projected -35% cost)

- *SDE membrane cost*

Enhanced second generation PBI* with about 100-200 systems/year (still initial market) (PBI cost reduction 23%)

PCF = Plant capacity Factor
HyS = Hybrid Sulfur
HT = High temperature section
PBI = Polibenzminide membranes
SDE = SO_2 depolarized electrolyzer

Collaboration: Effectiveness

Level 1 Action	Institution	Need for the AWSM
Novel BN catalyst development and synthesis (Patent)	USC	- ***INL*** → unique capability to run of H_2SO_4 decomposition tests at the required T, P and concentration – *Milestone 1.1 and 1.2*

Level 2 Action	Institution	Need for the AWSM
Detailed model of the new reactor	GWE – USC	- ***NREL*** → critical to identify, optimize the novel direct solar reactor, leveraging lab expertise and previous results for electricity production (ROI filled) – *Milestone 1.3*

Level 3 Action	Institution	Need for the AWSM
Novel HyS Flowsheet	GWE – *SRNL*	- ***NREL*** → design and characterization of solar tower plant and BOP - *Milestone 1.3* - ***SRNL*** → development of HyS process flowsheet – *Milestone 1.3*
Solar plant design with chemical storage	GWE – *NREL*	
Solar plant techno-economic analysis	GWE – *SRNL - NREL*	

ROI = Record Of Invention

Collaboration: Interactions

- Meetings and data sharing
  - By-weekly meetings between recipients (GWE and USC) and capable labs (INL, NREL, SRNL) → presentations uploaded in the NREL Sharepoint
  - Face to Face meetings
    - Meetings in GWE (August-December 2018) with GWE, USC, SRNL → identification of the baseline flowsheet concept for the high T section and variations of the configurations
    - NREL visit in GWE and USC (December 2018) → identification of the next steps especially about modeling and lab scale demonstration of the reactor concept
  - Teleconferences INL, USC and GWE (October-December 2018) for different catalyst testing
  - Interactions with the 'Benchmarking 2B' project
    - Defined the protocol for hybrid cycles (connections with both the electrolysis group and the STCH group) – Involvement of possible international partners
  - Reports uploaded in the NREL Sharepoint
- DataHub data
  - Flowsheeting data
    - Equilibrium data for sulfuric mixtures (based on the new ASPEN model by SRNL for high T and low T sections)
  - Solar plant design data (solar flux data, efficiencies, optimization and design data for solar tower and mirrors by NREL)
  - Novel BN catalysis test data

CFD = Computational Fluid Dynamics   SDE = SO_2 Depolarized Electrolyzer

Collaborations

- **Additional collaborations and potential partners**
  - *CoorsTek* – Design of the novel receiver-reactor with SiC structures, initial discussion for lab scale reactor and feasibility for large scale operations
  - *Edisun Microgrids* – Enhanced solar heliostat (higher efficiency and potential lower cost) available, NDA between GWE and Edisun being signed, high interest on on-sun demonstration for 10-100 kW plant with Edisun heliostat and HydroGEN HyS
  - *Proton Onsite, namely George Roberts* - Conceptual design, analysis and testing of compact heat exchanger loop to recover the SO_2 electrolyzer heat

Proposed Future Work

- **Catalyst development and testing**
  - Optimization of the new proposed BN catalyst
    - Co ED of Pt and Ir to achieve higher stability
    - Structural stability determination
    - Different bimetallic concentrations and depositions
  - Different first layer metal material, replacing Ir (e.g. Co)
  - Development of non PGM catalyst (e.g. Fe based materials)
  - Development of stable engineered catalytic geometries and structures
  - Long term duration tests (i.e. > 400 hours)
  - Kinetic rates determination for modeling and scale up
  - Higher pressure (i.e. 30-50 bar) tests – equipment to be built
  - Parallel reactor tests – reactors to be built
- **Reactor and system modeling**
  - Rector development and CFD analysis, including the two phase (liquid/vapor) flow
    - New reaction kinetics
    - Possibly different flow regimes
    - New geometries and configurations
  - Feasibility of novel reactor system scale up
  - Solar plant characterization and design
    - Analysis of different solar plant configurations (e.g. location, enhanced efficiency heliostat, wind towers, etc)
  - Storage
    - Analysis of alternative chem storage using membranes to separate O_2 at the exit of the high T reactor
    - Use of nanomaterials to store energy, embedded in the catalyst bed
  - HyS process
    - Optimization of the process flowsheet (P, T, concentrations)
    - Assessment of alternative solutions for H_2SO_4 concentration and SO_2/O_2 separation
    - Detailed component design and cost assessment based on optimized flowsheet (especially for non-conventional components)

ED = Electroless deposition CFD = Computational fluid dynamics
PGM = Platinum group materials

Project Summary

- Catalyst development and tests (USC – INL)
  - Novel BN-based bimetallic formulation identified
  - The catalyst performance meets the nominal activity target
  - The catalyst showed essentially no degradation for 75-hour tests
- Receiver reactor design (GWE – USC – NREL)
  - Initial scale up of the direct receiver-reactor carried out
  - Initial contacts with industrial partners for lab scale demo
- HyS process flowsheet (GWE – SRNL)
  - Novel vapor fed electrolyzer flowsheet developed
  - Baseline high T flowsheet identified
  - Thermochemical efficiency of 37.6% achieved
- Solar plant system design and analysis (GWE – NREL)
  - Chemical storage configuration downselected as the baseline storage approach
  - Conceptual design of solar thermochemical plant assessed, achieving solar to hydrogen efficiency of 21%
  - Economic assessment of the solar plant carried out
  - Identified viable path toward the target of 2 $/kg

Publications & Presentations

- Patents
  - Record Of Invention on the solar reactor receiver for sulfuric acid decomposition: Ma, Z., et al., NREL Record of Invention ROI-18-62, 2018.
  - Patent being filled on the BN catalyst – Invention disclosure: Monnier, J., et al., USC ID no. 1372, 2018
- Presentations/publications
  - Corgnale, C. et al. "Solar Driven Thermo-Electrochemical Hybrid Sulfur Process for Hydrogen Production" ECS AiMES Meeting 2018, Cancun (Mexico), October 2018. https://ecs.confex.com/ecs/aimes2018/meetingapp.cgi/Paper/112622
  - Corgnale, C. et al. "Numerical Modeling of a Novel Solar Driven Sulfuric Acid Decomposition Reactor" ECS AiMES Meeting 2018, Cancun (Mexico), October 2018. https://ecs.confex.com/ecs/aimes2018/meetingapp.cgi/Paper/112623
  - Adhikari, B. et al. "High temperature catalyst development and testing for low cost and efficient solar driven sulfur-based hydrogen production" AIChE Annual Meeting (514g), Pittsburg (PA), November 2018
  - Ma, Z. et al. "Integrating thermochemical and electrochemical processes with a concentrating solar thermal system for hydrogen production" ASME Power & Energy Conference and Exhibition, Lake Buena Vista (FL), June 2018
  - Gorensek, M. et al. Electrochem. Soc. Interface Spring 2018 volume 27, issue 1, 53-56

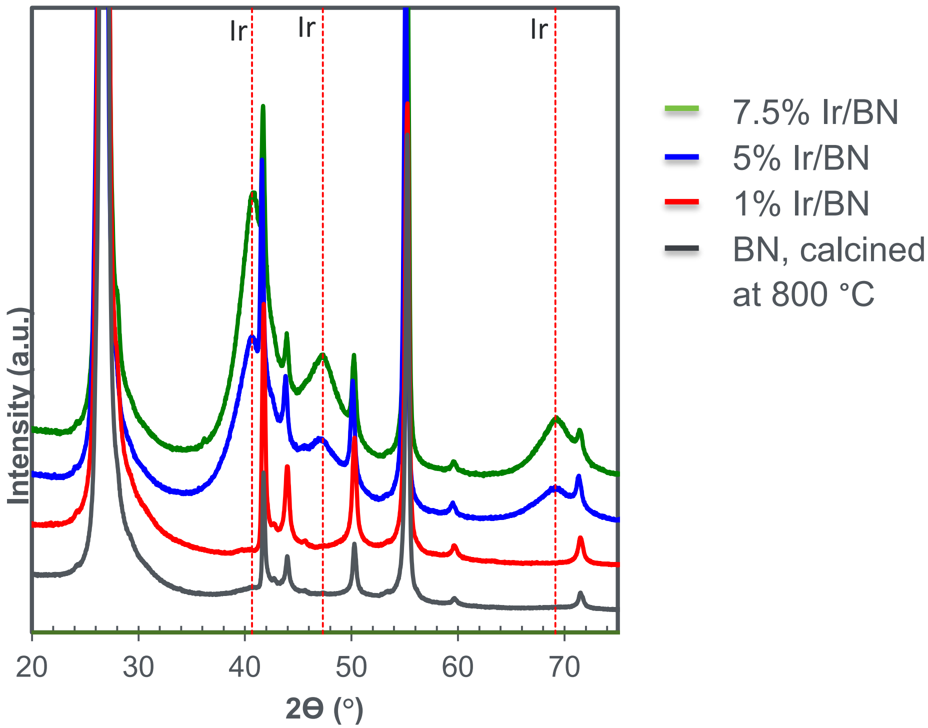
Technical Back-Up Slides

(Note: please include this “divider” slide if you are including back-up technical slides [maximum of five]. These back-up technical slides will be included in the USB drive and Web PDF files released to the public.)

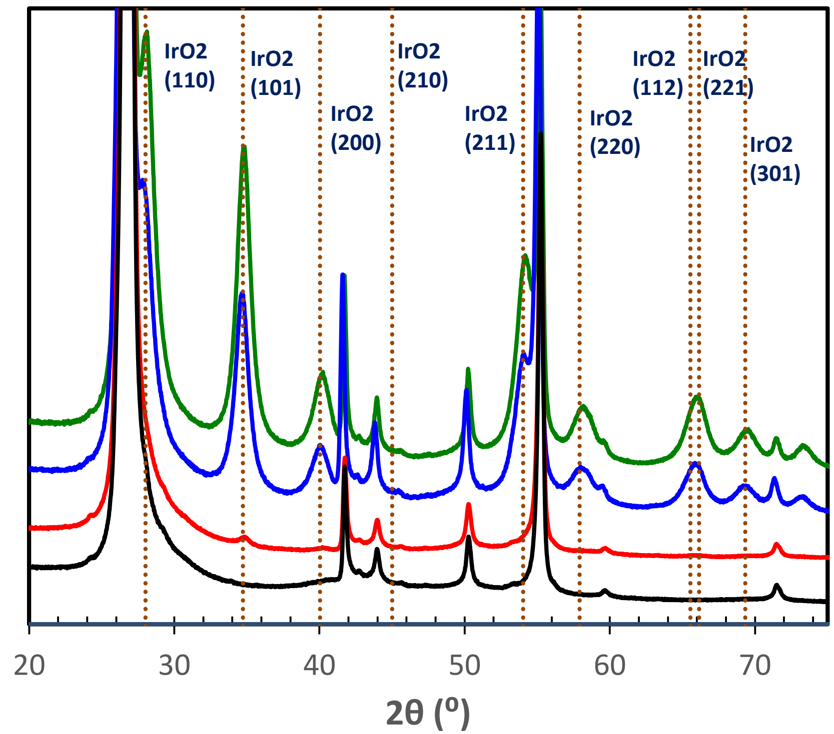
Bimetallic Pt-Ir catalysts supported on BN

Level 1

XRD – Fresh catalyst



XRD – Calcined (800 °C) catalyst



- BN was calcined at 800°C before Ir impregnation.
- Fresh Ir on BN catalyst shows the presence of broad Ir peaks → presence of Ir on the surface not well dispersed
- Calcined Ir on BN catalyst has only Ir oxides on the surface but not Ir metal → metal Ir well dispersed

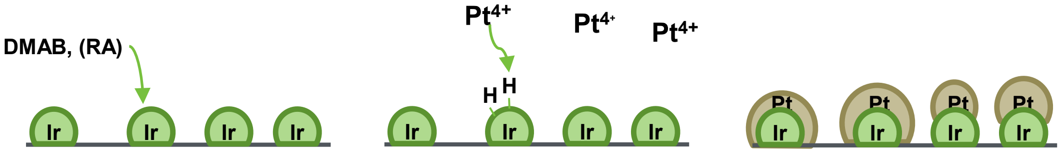
ED = Electroless deposition

Bimetallic Core-Shell Structures:

Stabilization using differential Surface Free Energy (SFE)

Level 1

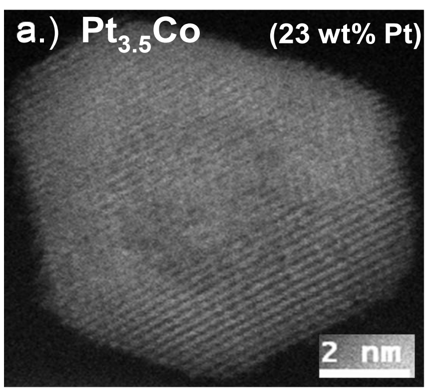
- *Enhanced stability of active metal surface by anchoring lower SFE metal (Pt) as shell on higher SFE cores (Ir or Ru).
- Pt can be selectively deposited on Ir or Ru surfaces using Electroless Deposition (ED) method.

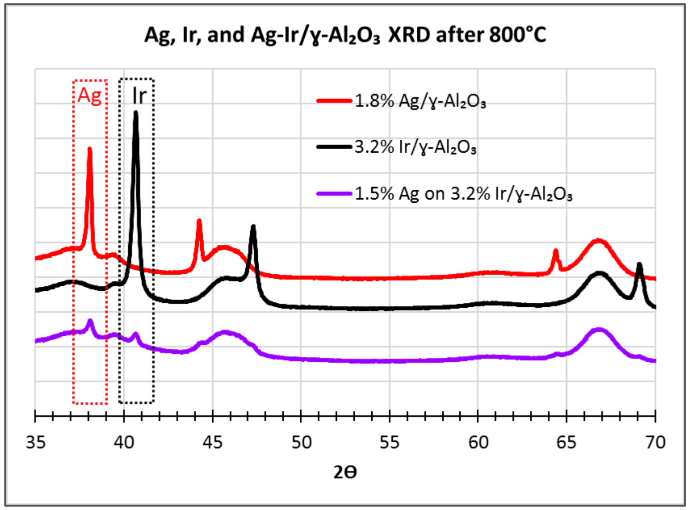


RA = Reducing Agent

Pt deposits Catalytically (on Ir) or Autocatalytically (on Pt)

- Stabilization using SFE difference in core-shell morphology has been demonstrated for other systems.



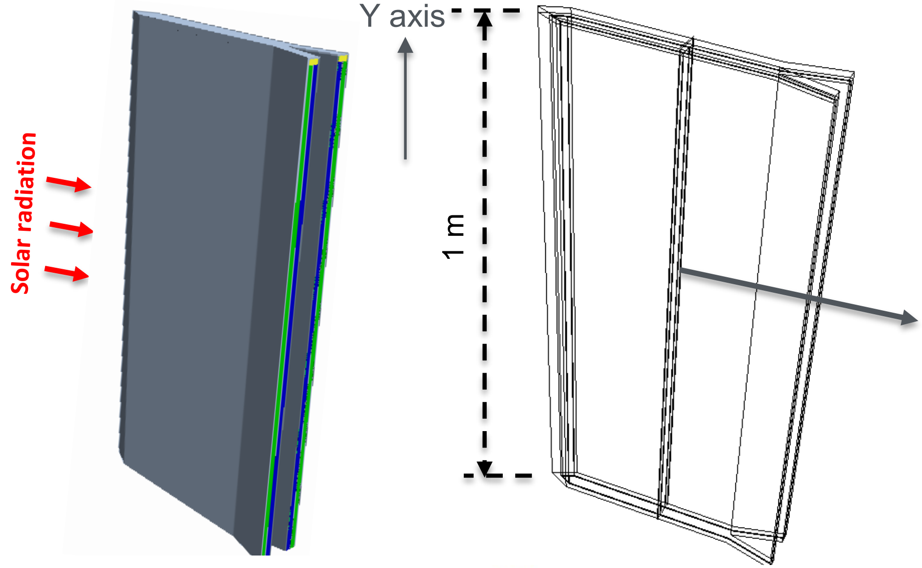


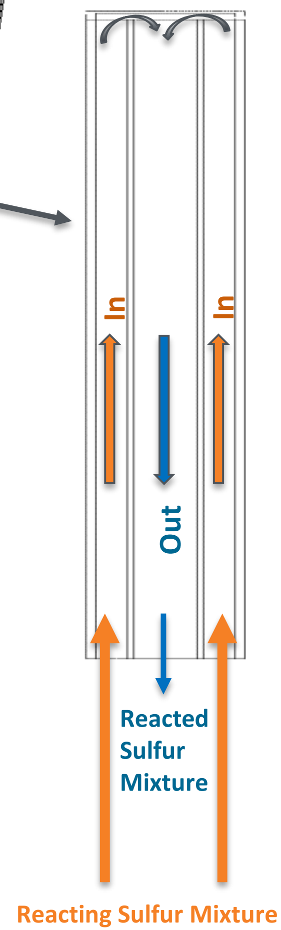
Component	Melting point, (°C)	Surface free energy (ergs/cm² surface)
Carbon	3550	506
SiO_2	1600	605
TiO_2	1843	670
Al_2O_3	2072	805
Ag	962	1302
Au	1064	1626
Cu	1083	1934
Pd	1554	2043
Ni	1453	2364
Pt	**1772**	**2691**
Co	1495	2709
Rh	1966	2828
Mo	2617	2877
Fe	1535	2939
Nb	2468	2983
Re	3180	3109
Ir	**2410**	**3231**
Ru	**2310**	**3409**
W	3410	3468

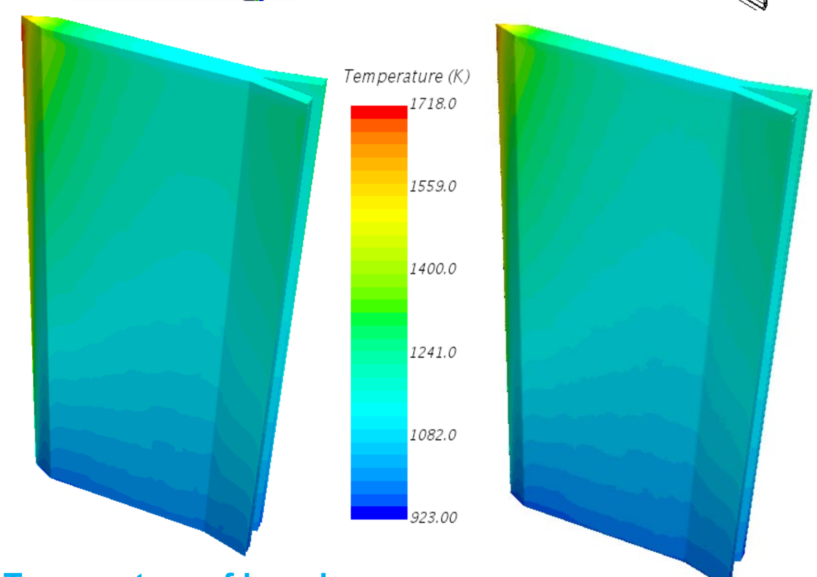
**US 10,016,751 “Supported, bimetallic nanoparticles for selective catalysis,” July 10, 2018*

SFE = Surface Free Energy   ED = Electroless deposition   XRD = X ray diffraction

Reactor simulation results
Level 2

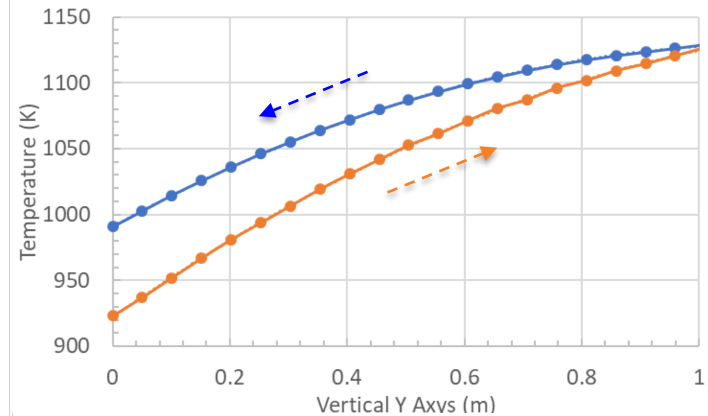


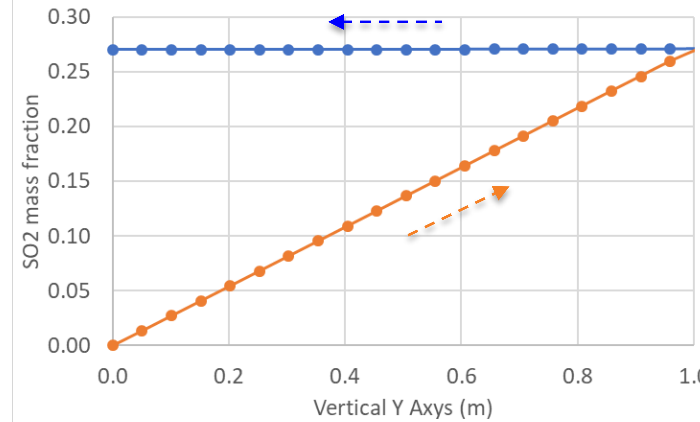




Temperature of housing

Temperature of gases



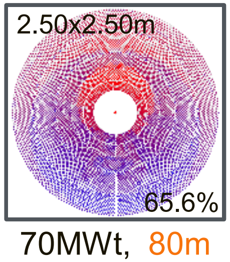


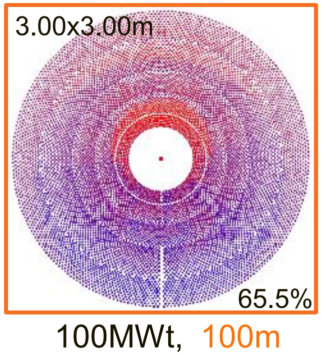
Excellent internal heat recovery without temperature decrease of the reactive mixture (as for the traditional bayonet system)

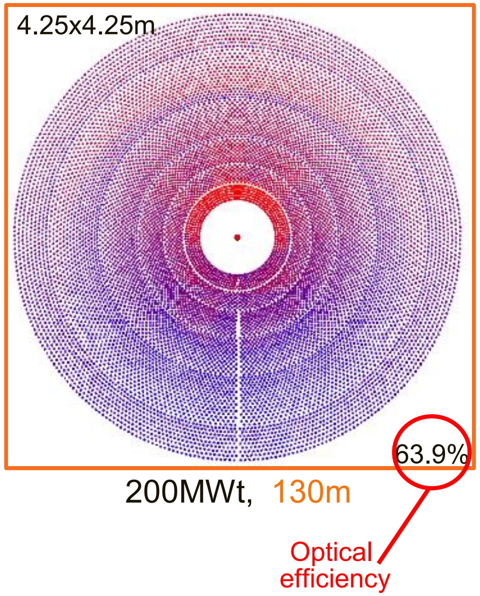
Effective SO_3 decomposition achieving almost the equilibrium SO_2 concentration

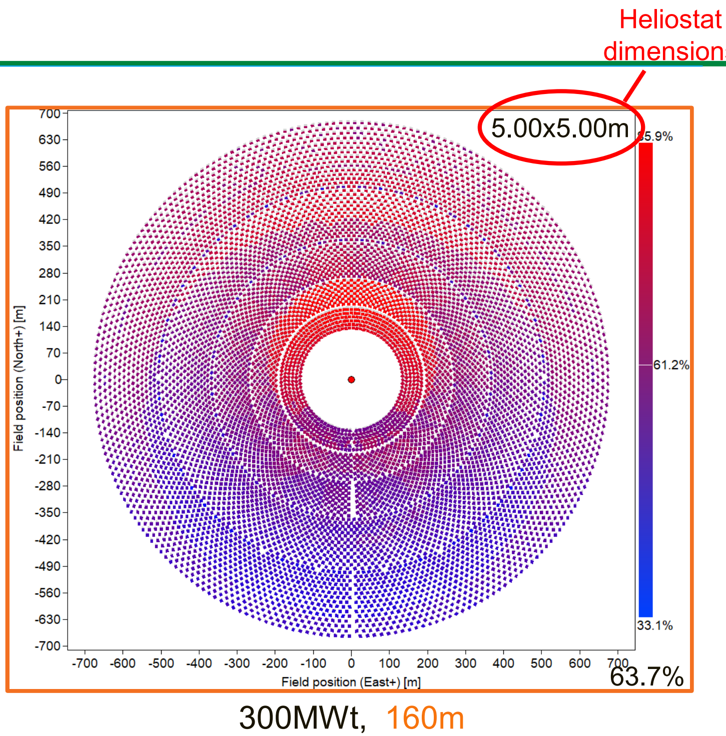
Reduced pressure drops (< 2 bar)

Solar plant design
Level 3









Design options

- Centralized H_2 production
- Distributed H_2 production (solar vs wind towers)

Relevant Assumptions:

- Dagget CA, Solar noon, Equinox
- Heliostat geometry
- Heliostat cost [$/m²]
- Land cost [$/acre]

Constants:

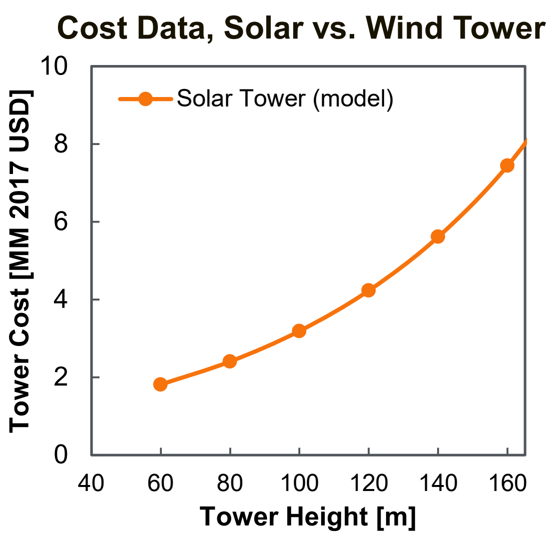
- Field roundness
- Desired power

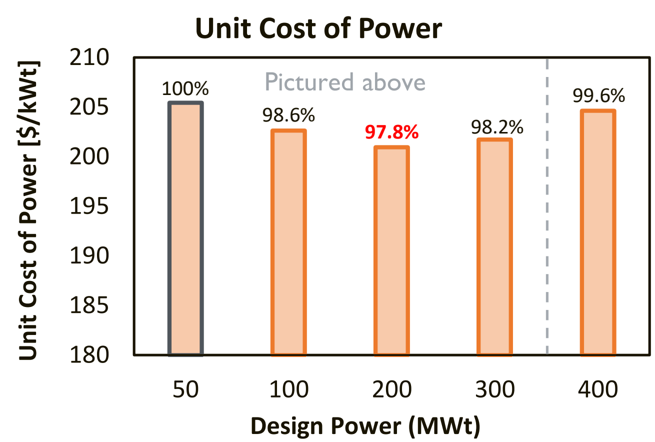
Degrees of freedom:

- Tower height [m] & Cost of tower [$/m]

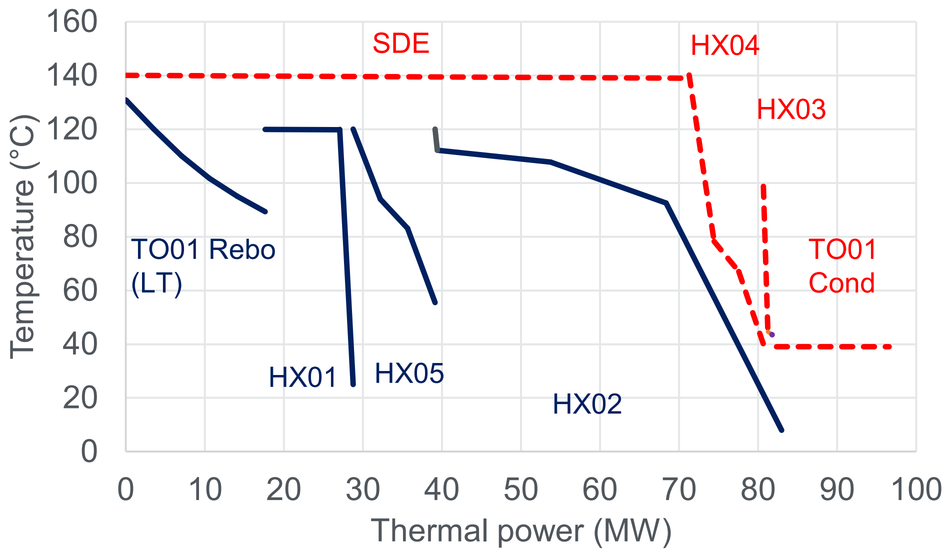
Optimized:

- Unit cost of power [$/MW]



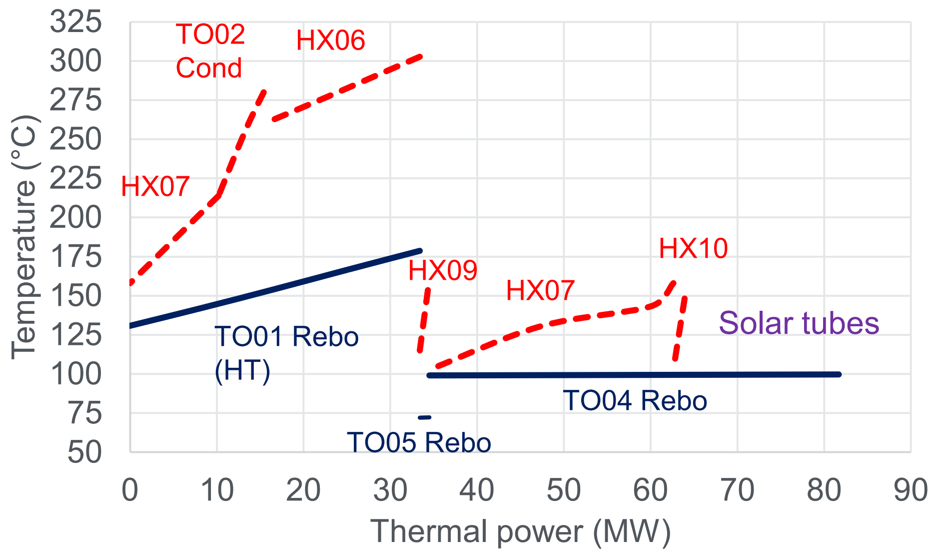


HyS heat recovery exchanger network design



LT section (40.9 TPD design)

- SDE waste heat recovered using 4 finned compact shell and plate heat exchangers (pressurized water)
- TO01 condenser waste heat rejected using water at 20 C
- All the heat exchangers and components are massive equipment with SS316, Carpenter 20 or Hastelloy B20 as materials



HT section (95.3 TPD design)

- Low T heat (SO_2 stripper reboiler, TO04) provided using intermediate heat exchanger (pressurized water) interfaced with evacuated solar tubes (almost 20 MW)
- Heat rejected using water at 20 C
- Components have been (initially) designed using Acid Brick Liners and cladding solutions, achieving important cost reductions

Questions?

Contact us by email:

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