Advances in Energy Storage Technologies

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- About Hydrogen and Fuel-Cell Center
- Current Important Research Activities
- Energy Storage Technologies in the US (US Department of Energy)
- Summary

Catalysis, Electrochemical and Characterization Facilities

Electrochemical Cells design and testing

Energy storage materials and systems

Catalyst Development for Energy Production

System integration

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- About Hydrogen and Fuel-Cell Center
- Energy Storage Technologies in the US (US Department of Energy)
- Selected Research Activities at USC

Energy Storage Technologies

technology	typical power (MW)	discharge time	storage capacity cost ($/kWh)	life time (cycle/years)	efficiency (%)	drawbacks
supercapacitors	0.25	<1 min	500–3000	500000/20	>90	explosion hazard, low energy density, cost
regenerative fuel cells with hydrogen storage	10[a]	>5 h		13	40–50	low-density storage, high cost, safety
lead-acid batteries	0.5–20	3–5 h	65–120	1000–1200/3–4	70–80	low energy density, short lifetime, temperature sensitive
Li-ion batteries		1–5 h	400–600	750–3000/6–8	80–90	cost, safety, short lifetime, self-discharge, temperature sensitive
NAS battery	0.25–1	6–8 h	360–500	2500–4500/6–12	87	cost, high-temperature operation, safety
flow battery (VRB)	0.5–12	10 h	150–2500	500–2000/10	70	low energy density

[a]Projected.

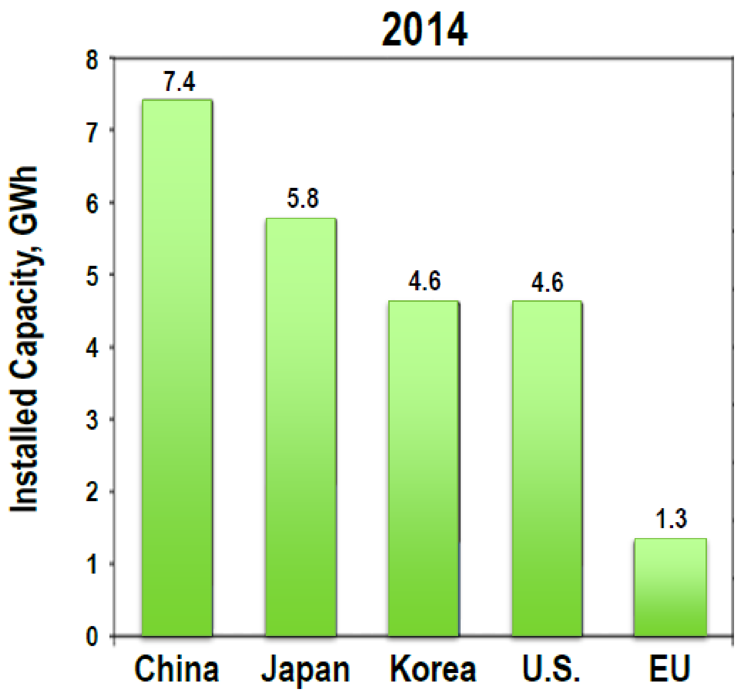
Energy Storage Technologies

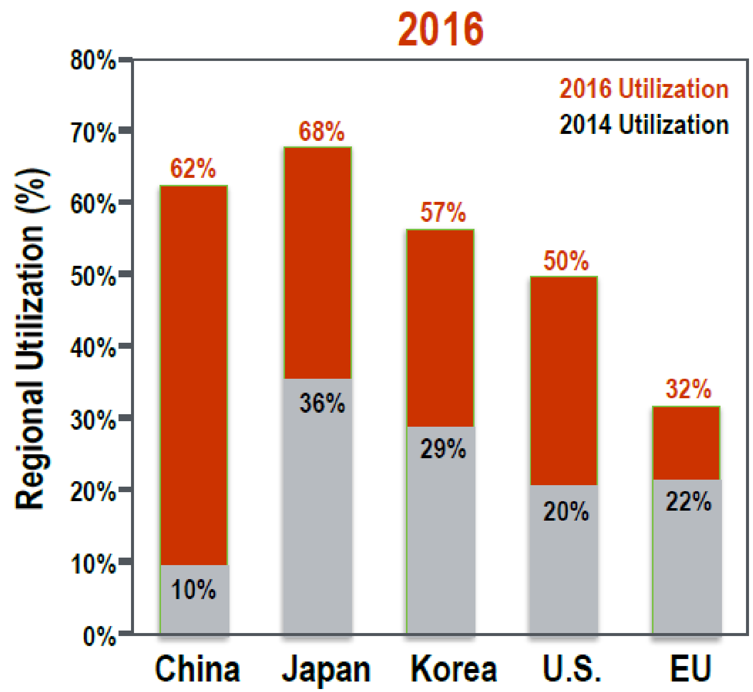
- Electrochemical Energy Storage
  - Battery
  - Flow Battery
- Solar Thermal Energy Storage

Electric Vehicle Market

Forecasted Demand

Regional Automotive LIB Cell Capacity and Utilization





- Automotive lithium-ion battery demand growing but short of global manufacturing capacity.
- Utilization of U.S. plants increased from 20% in 2014 to ~50% in 2016.
- Forecasted compound annual growth rates in lithium-ion demand: 22%–41% (through 2020).

VTO Battery R&D

Mission, Goals & Budget

Mission

Enable a large market penetration of electric drive vehicles through innovative battery research and development.

Goal

Research new battery chemistry and cell technologies that can reduce the cost of electric vehicle batteries to less than $100/kWh, increase range to 300 miles and decrease charge time to 15 minutes or less. Ultimate goal is $80/kWh.

Budget

Funding in millions	**FY 2016** Enacted	**FY 2017** Enacted
Battery Technology R&D	$103.0	$101.2

VTO Battery R&D

Future Battery Technology & Science

Current Technology
Lithium-ion
Graphite/NMC

Battery Pack Cost

- Current: $235/kWh
- Potential: $100-160/kWh

Large format EV cells	**20-60 Ah**
Current Cycle life	1000-5000
Calendar life	10-15 yrs
Mature manufacturing	
Fast Charge	

R&D Needs

- High Voltage Cathode/Electrolyte
- Lower Cost Electrode Processing Technology
- Extreme Fast Charging

VTO Battery R&D

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Next Generation Lithium-ion
Silicon Composite/High Voltage NMC

Battery Pack Cost
- Current: $256/kWh
- Potential: $90-125/kWh

Large format EV cells	20-60 Ah
Current Cycle life	500-700
Calendar life	Low
Mature manufacturing	
Fast Charge	

R&D Needs
- High Voltage Cathode/Electrolyte
- Lower Cost Electrode Processing
- Durable Silicon Anode with increase silicon content

VTO Battery R&D

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R&D Needs

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- Lower Cost Electrode Processing
- Durable Silicon Anode with increase silicon content

Longer Term Battery Technology
Lithium Metal

Battery Pack Cost

- Current: ~$320/KWh
- Potential: $70-120/kWh

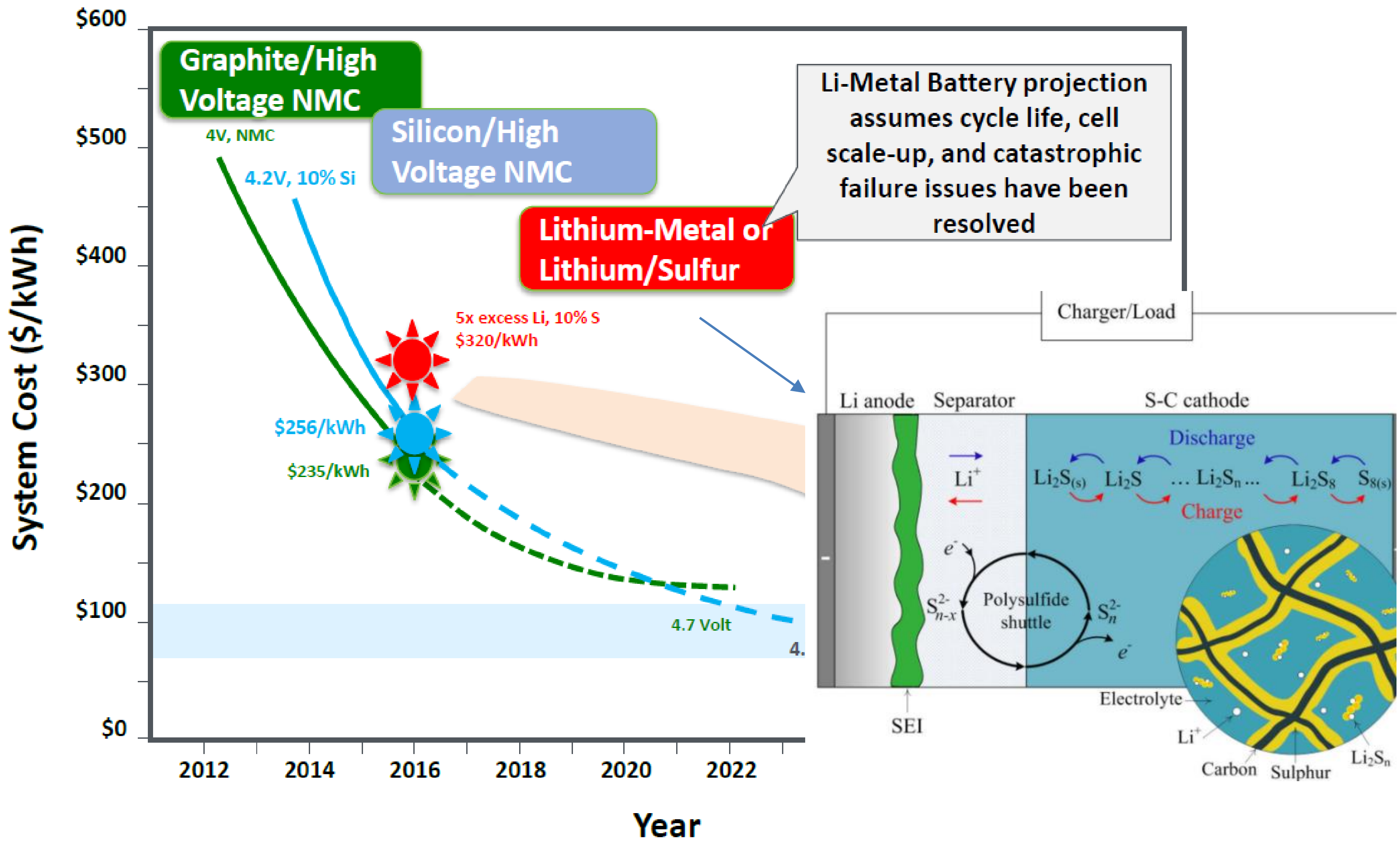
Large format EV cells	
Current Cycle life	50-100
Calendar life	TBD
Mature manufacturing	
Fast Charge	

R&D Needs

- High Voltage Cathode
- Lithium Protection
- High Conductive Solid Electrolyte

Battery Cost

Cost Trends for Lithium-based EV Batteries



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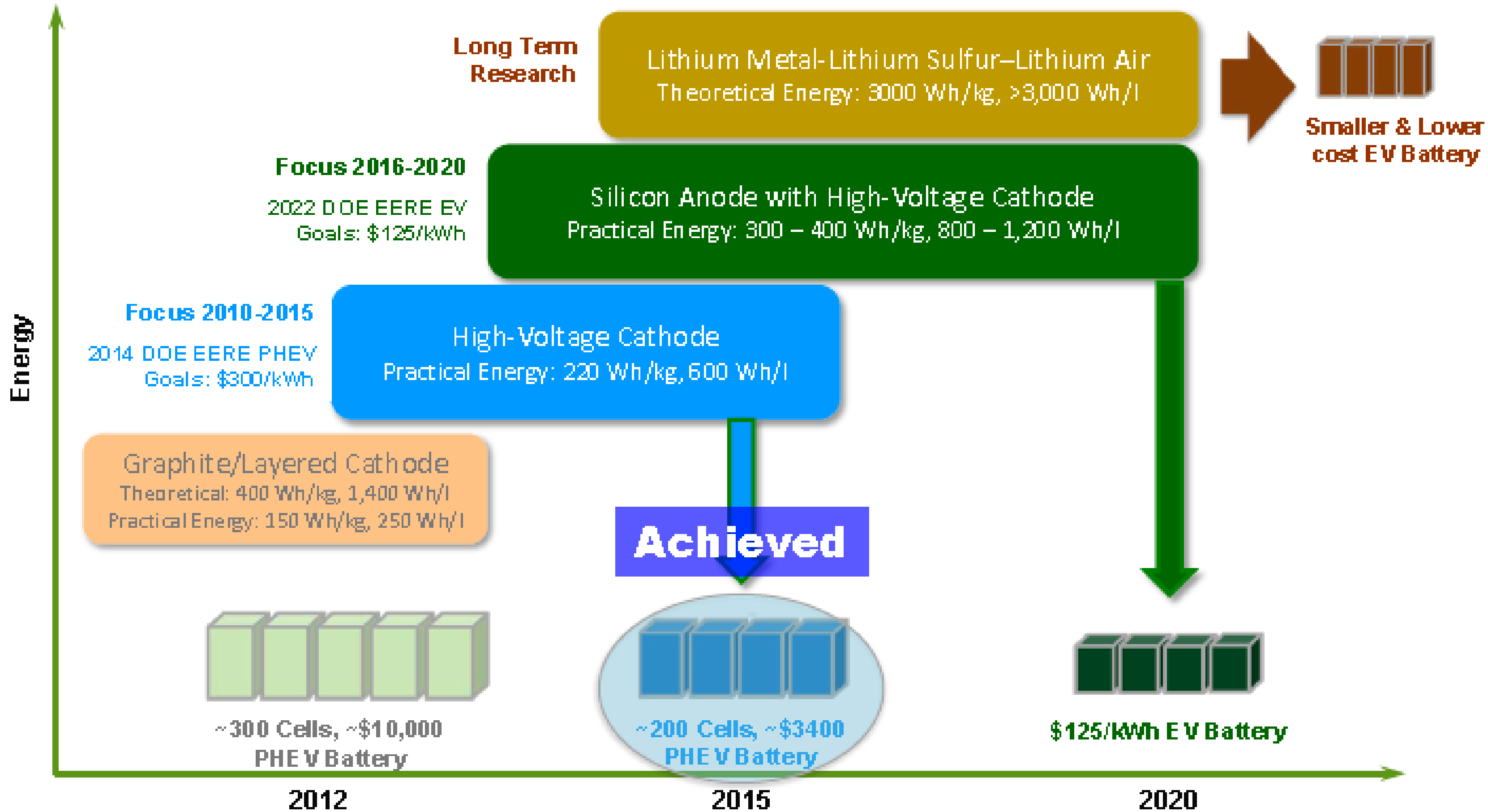
Research Roadmap for 2015 & Beyond

Current emphasis: The development of high voltage cathodes and electrolytes coupled with high capacity metal alloy anodes. Research to enable lithium metal-Li sulfur systems.



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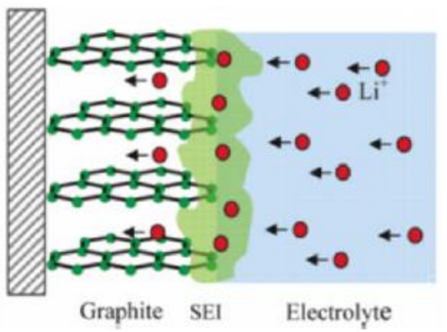
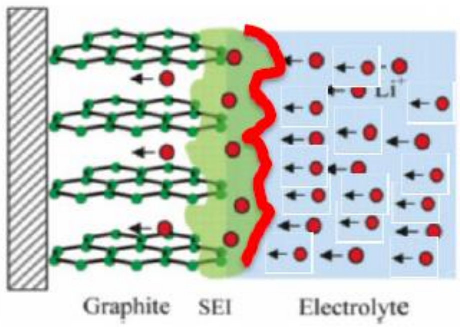
New Focused Research Activity

Extremely Fast Charging (XFC): 350-400 kW

- Combination of fast charge batteries and a network of high capacity chargers can minimize range anxiety and promote the market penetration of BEVs and increase total electric miles driven.
- **FY 2017 Study**
  - Assess the knowledge base of the fast charging capability of automotive batteries
  - Identify technical gaps for fast charging
  - Identify R&D opportunities
- **Issues Identified regarding Fast Charging**
  - Higher cost cells: (2X) compared to today's lithium-ion cells.
  - Cycle Life & Durability of Cells
    - Lithium plating/deposition occurs on the anode above a threshold current density.
    - Cell temperature rise during charge



Plated lithium due to fast-charging



Energy Storage Technologies

- Electrochemical Energy Storage
  - Battery
  - Flow Battery
- Solar Thermal Energy Storage

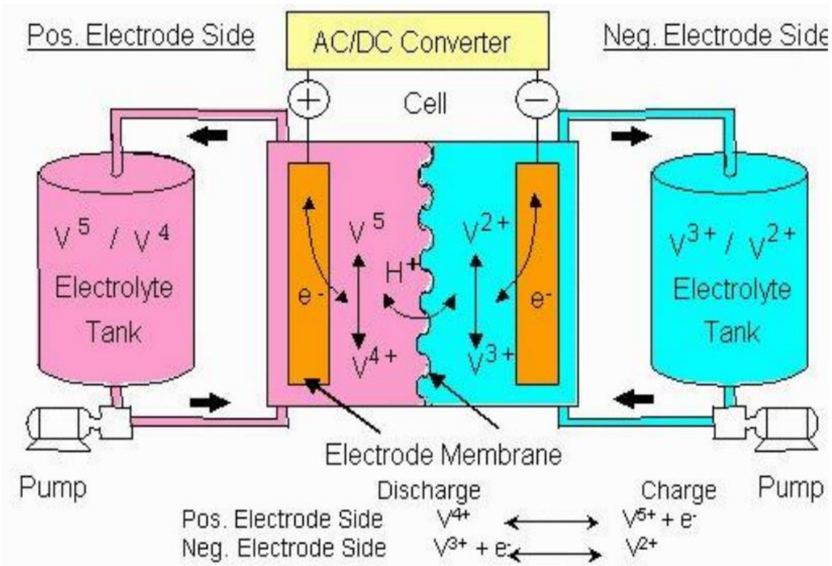
Flow Batteries

California's Central Valley

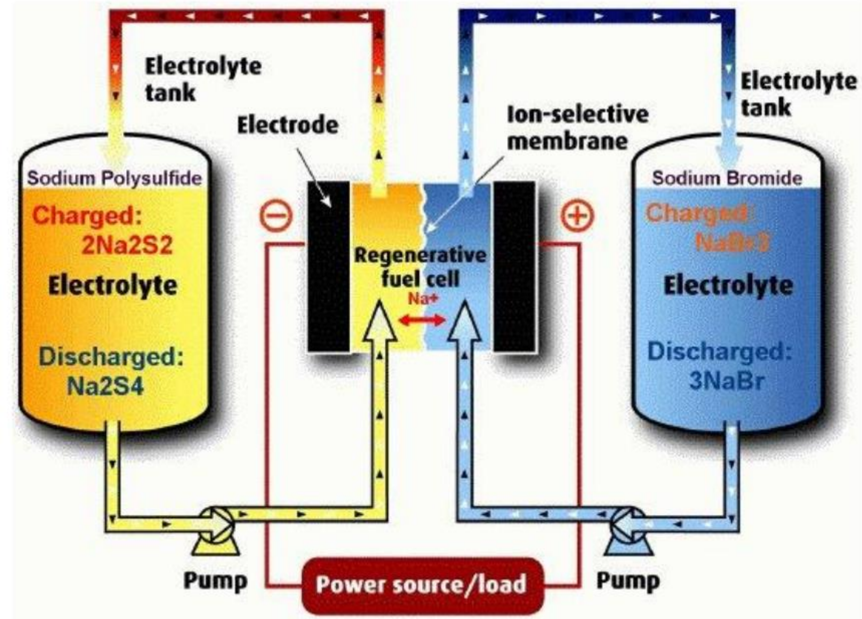
60MWh Flow battery on the island of Hokkaido

800-megawatt-hour storage station being built in Dalian, China

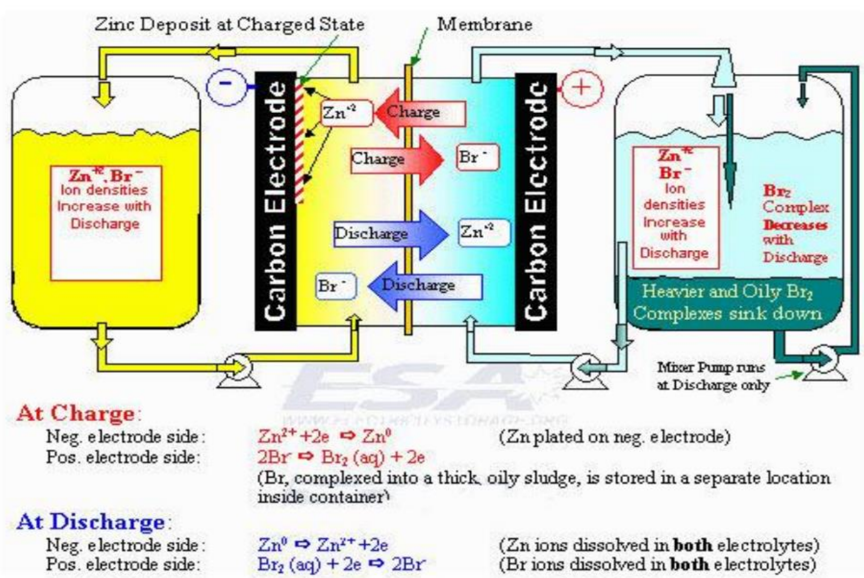
Vanadium Redox

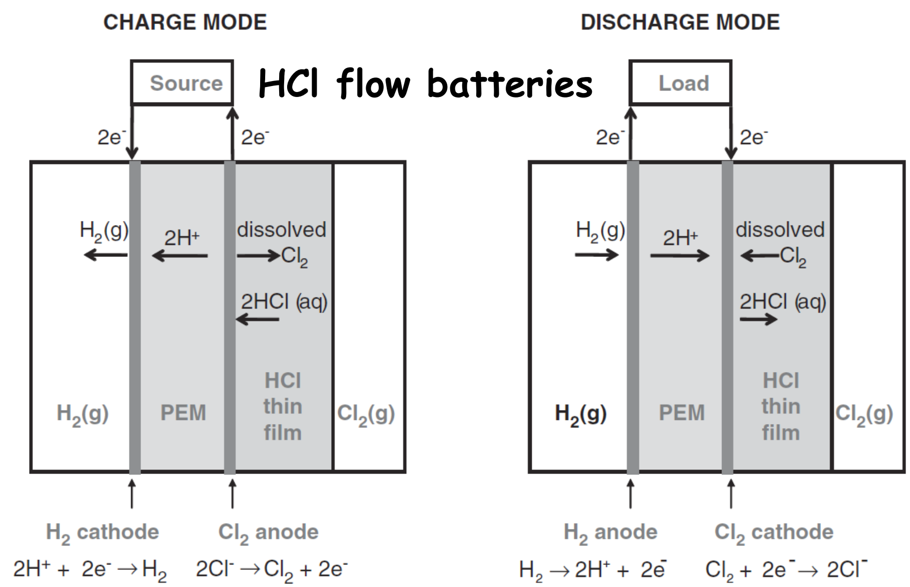


Polysulfide Bromide



Charging and discharging of Zinc Bromine batteries.





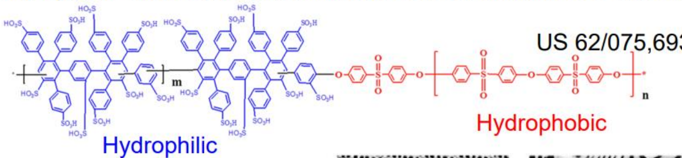
Membrane Development

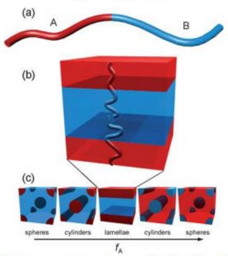
VRFB membranes

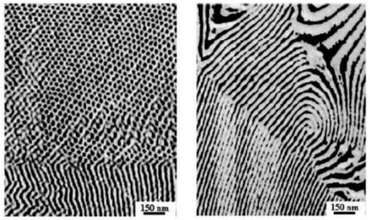
Sandia National Laboratories

Versatile chemistry allow block co-polymer synthesis
Block co-polymers allow for powerful control of water channel size and shape

US 62/075,693





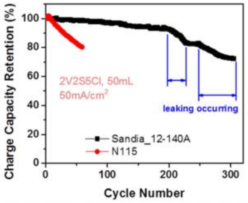


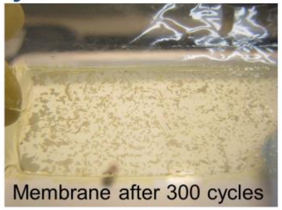
In VRFB, require high transport selective membranes
High H^+ flux and vanadium barrier

VRFB Membranes - Durability

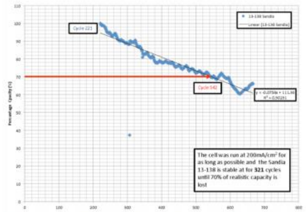
Sandia National Laboratories

Gen 4





Gen 5



Gen5 has higher chemical stability than Gen4
With PNNL data, improved segment lengths and sent to VRFB company for testing

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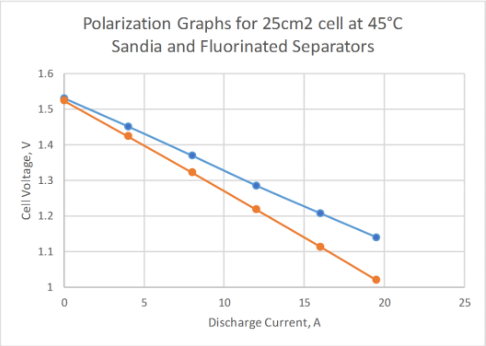
VRFB Membrane - Performance

Sandia National Laboratories

Membrane	Efficiency, Round Trip	Efficiency, Coulombic	Efficiency, Voltaic
Sandia	82.2%	96.2%	85.4%
Fluorinated	72.3%	92.5%	78.2%

	Pmax, mW/cm²	Specific Resistance, Ωcm²
Sandia	1159	0.505
Fluorinated	946	0.610



Cycling Performance Comparison in 25-cm² cell at 45°C
Sandia and Fluorinated Membranes
WattJoule Electrolyte (2M Vanadium)

Data from WattJoule shows Gen5 has higher energy efficiency (+10%). High coulombic ef

Energy Storage Technologies

- Electrochemical Energy Storage
  - Battery
  - Hydrogen Fuel Cells
  - Flow Battery
- Solar Energy Storage
    - Concentrating Solar Power (CSP) - Large scale

Concentrating solar power (CSP) plants

CSP plants use mirrors to focus sunlight and produce high-temperature thermal energy that can be stored inexpensively. This feature allows CSP to be a dispatchable electricity resource available whenever there is customer demand, including at times when the sun is not shining. CSP with thermal energy storage (or CSP-TES) thus provides considerable flexibility, increasing its own value to the grid and even enabling greater grid penetration of variable-generation technologies such as PV and wind.

SunShot Initiative goal of 6 cents/kWh by 2020

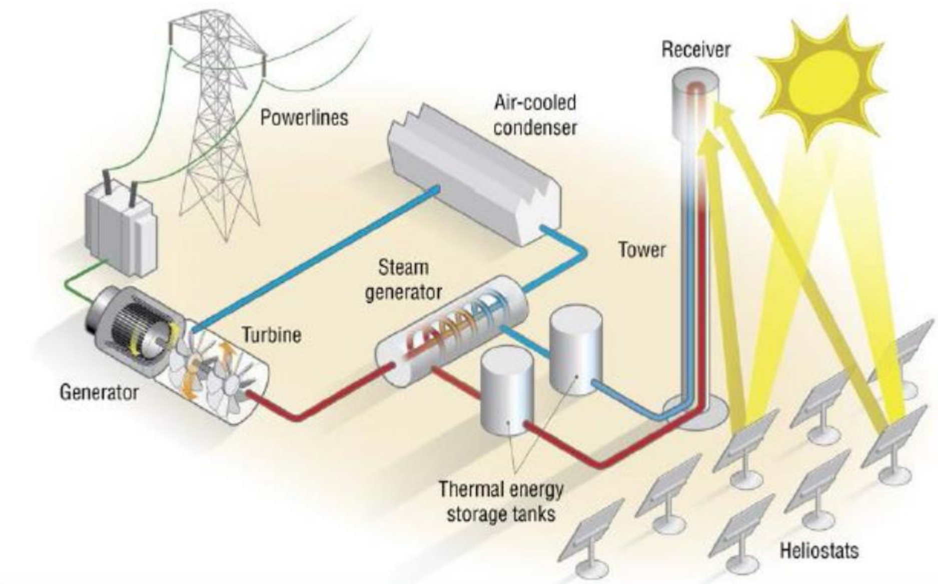
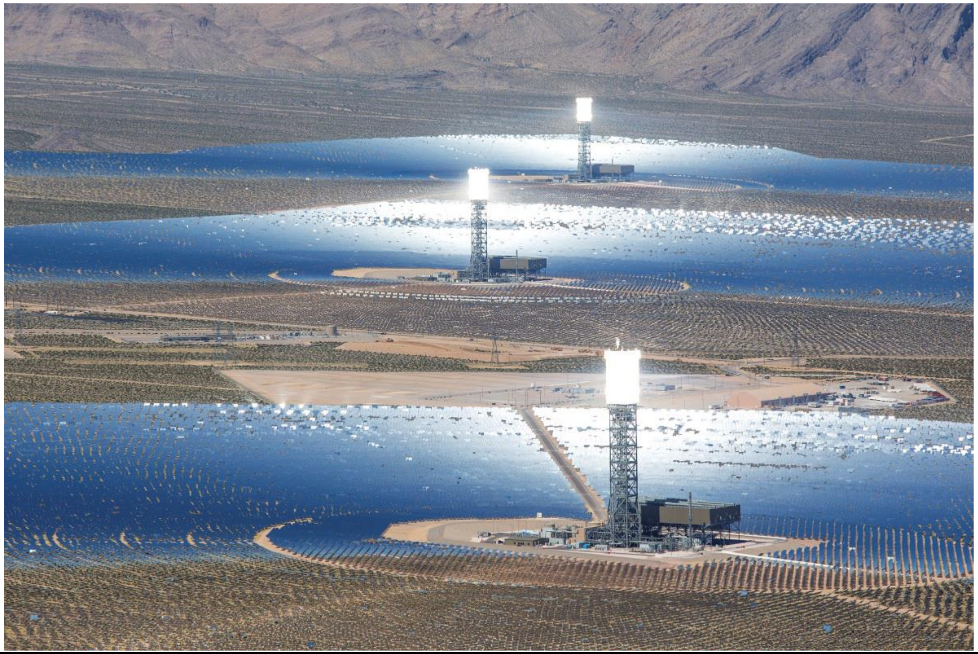
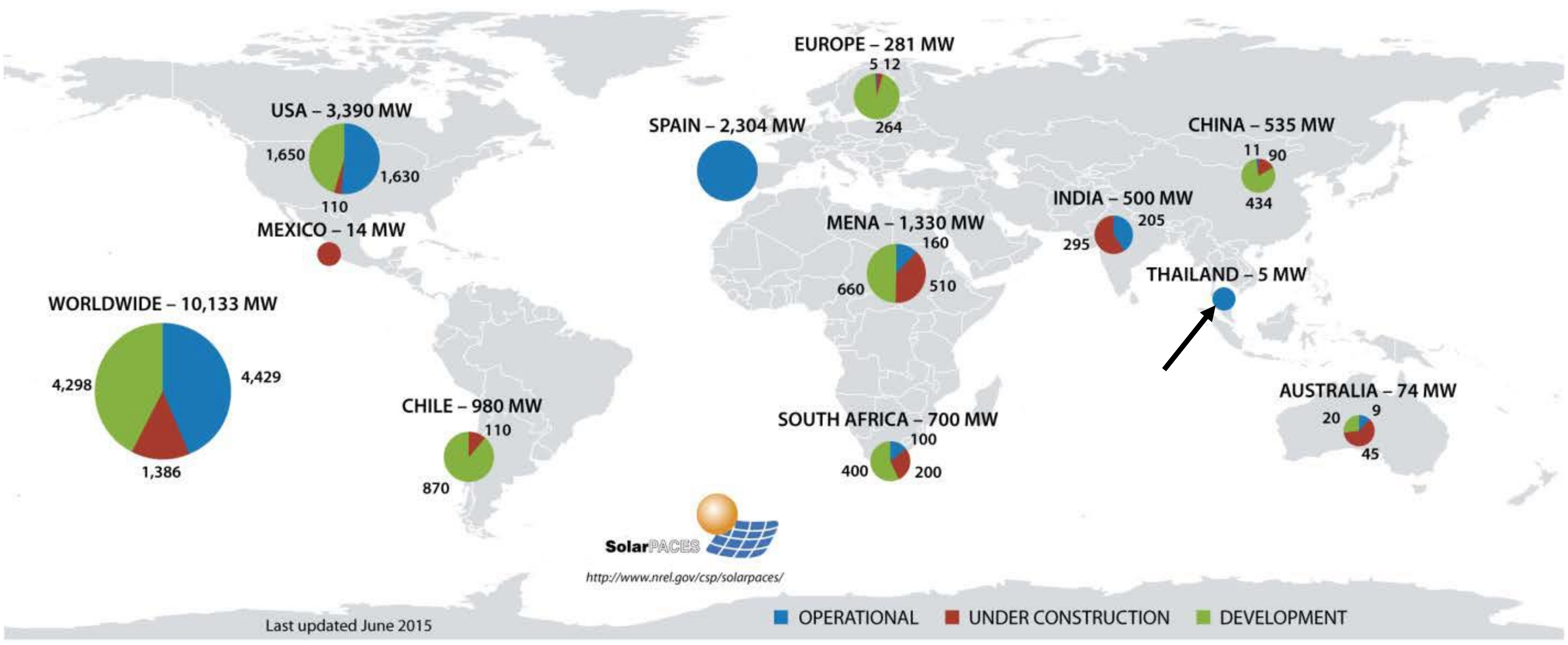


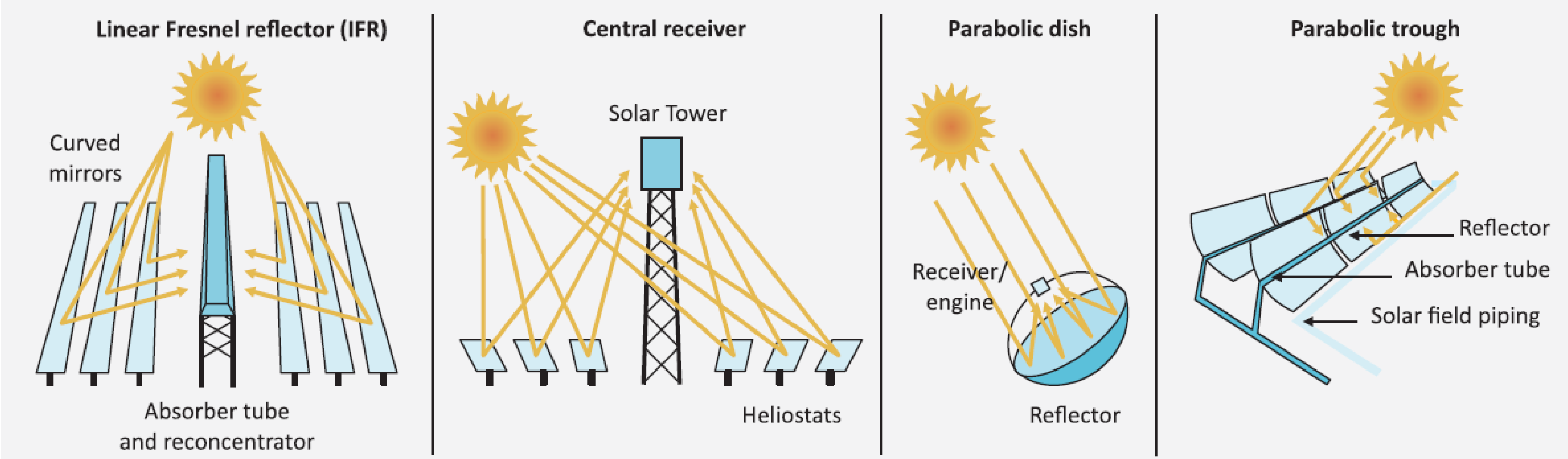
Image: US Department of Energy

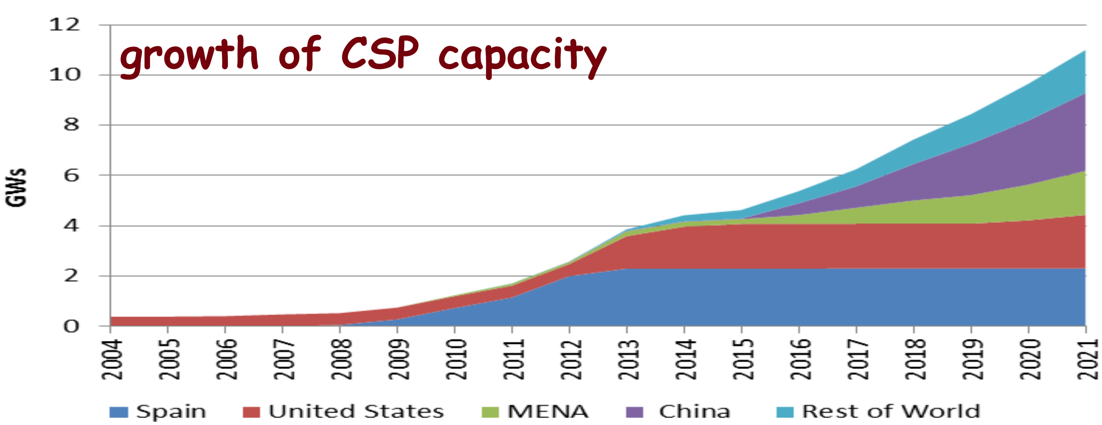


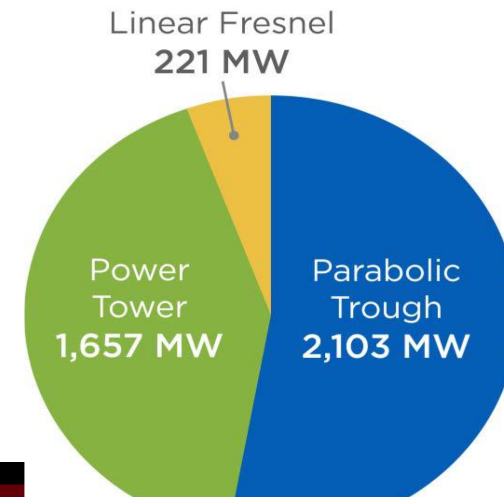
Cumulative CSP capacity by country and status (operational, under construction, development)



Types of CSP system: how they collect solar energy







Collector Field

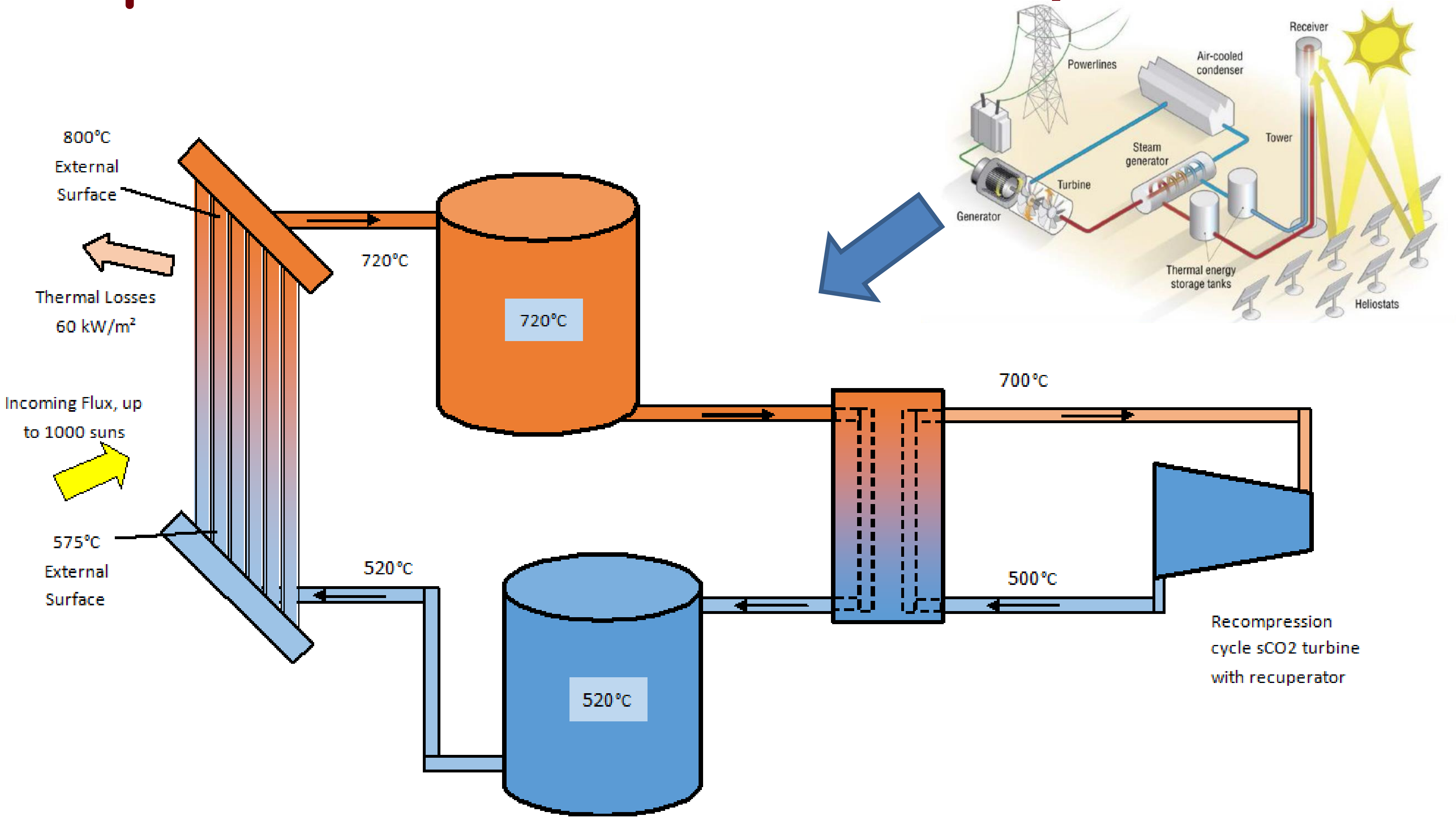
- Cost <$75/m²
- Concentration ratio >50
- Operable in 35-mph winds
- Optical error <3.0 mrad
- 30-year lifetime

	Molten Salt	Falling Particle	Gas Phase
Receiver *Cost < $150/kWth* *Thermal Efficiency > 90%* *Exit Temperature > 720°C* *10,000 cycle lifetime*	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Most challenging to achieve high thermal efficiency	• High-pressure fatigue challenges • Absorptivity control and thermal loss management
Material & Support *Cost < $1/kg* *Operable range from 250°C to 800°C*	• Potentially chloride or carbonate salt blends; ideal material not determined • Corrosion concerns dominate	• Suitable materials readily exist	• Minimize pressure drop • Corrosion risk retirement
Thermal Storage *Cost < $15/kW$_{th}$* *99% energetic efficiency* *95% exergetic efficiency*	• Direct or indirect storage may be superior	• Particles likely double as efficient sensible thermal storage	• Indirect storage required • Cost includes fluid to storage thermal exchange
HTF to sCO_2 Heat Exchanger	• Challenging to simultaneously handle corrosive attack and high-pressure working fluid	• Possibly greatest challenge • Cost and efficiency concerns dominate	• Not applicable

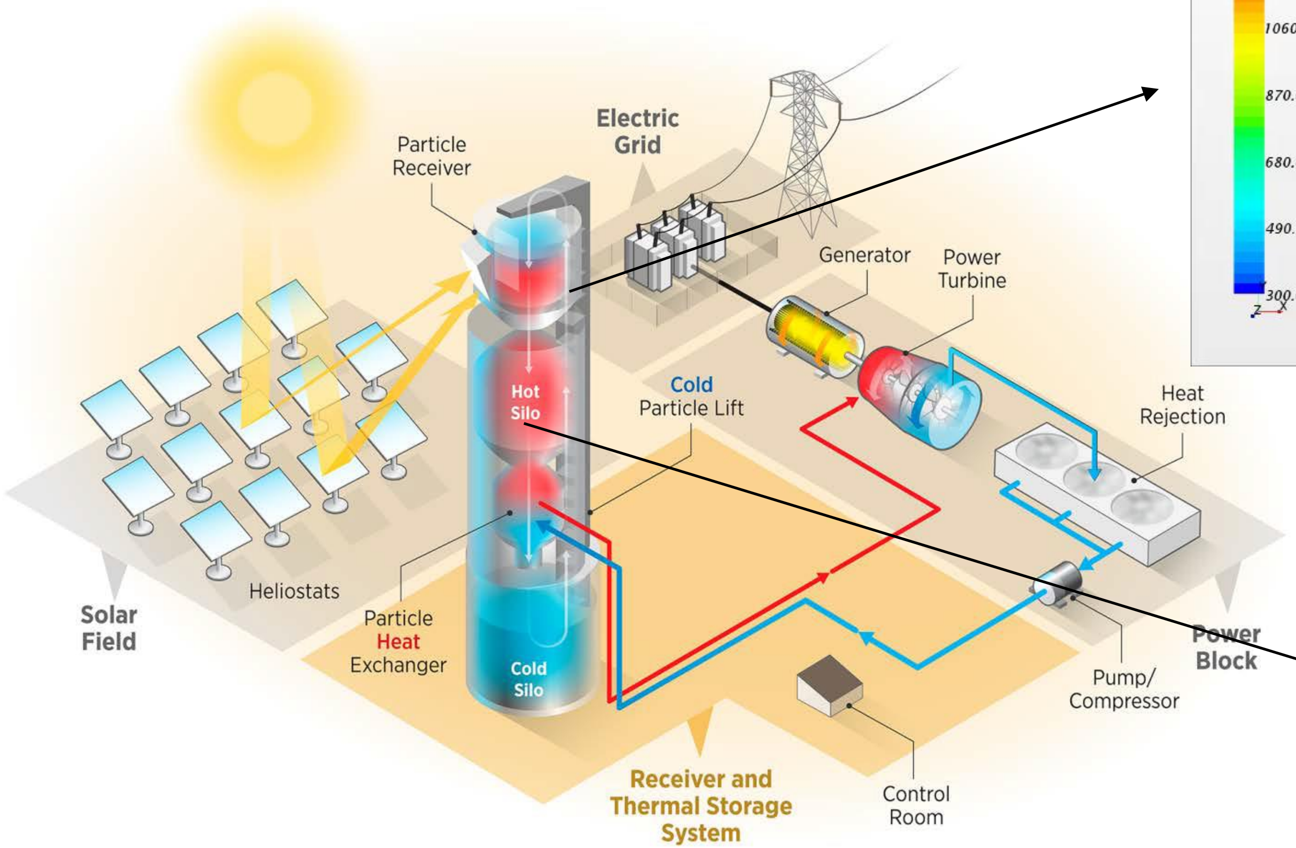
Supercritical CO_2 Brayton Cycle

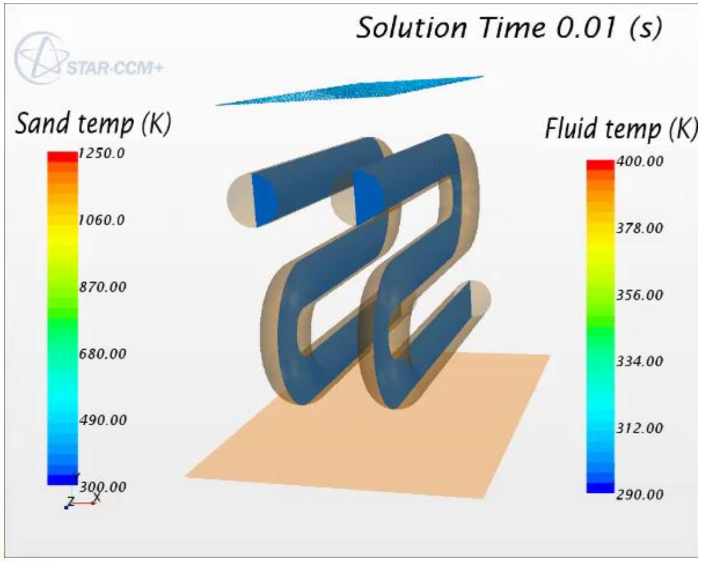
- Net thermal-to-electric efficiency > 50%
- Power-cycle system cost < $900/kW$_e$
- Dry-cooled heat sink at 40° C ambient
- Turbine inlet temperature ≥ 700°C

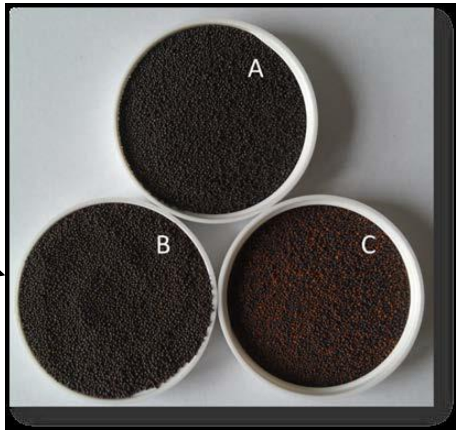
High temperature molten salt loop schematic with potential surface and fluid temperatures.

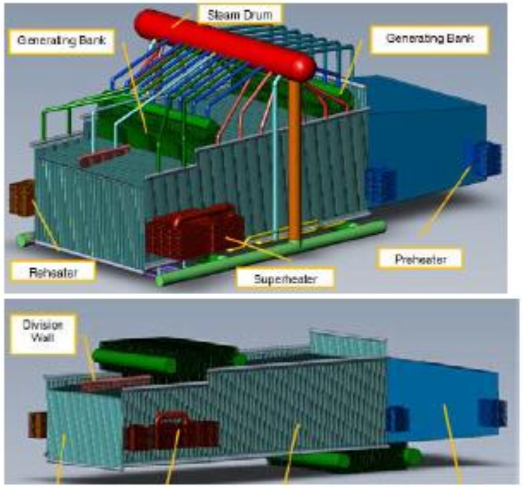


Falling-particle receiver system with integrated storage and heat exchange for a power cycle

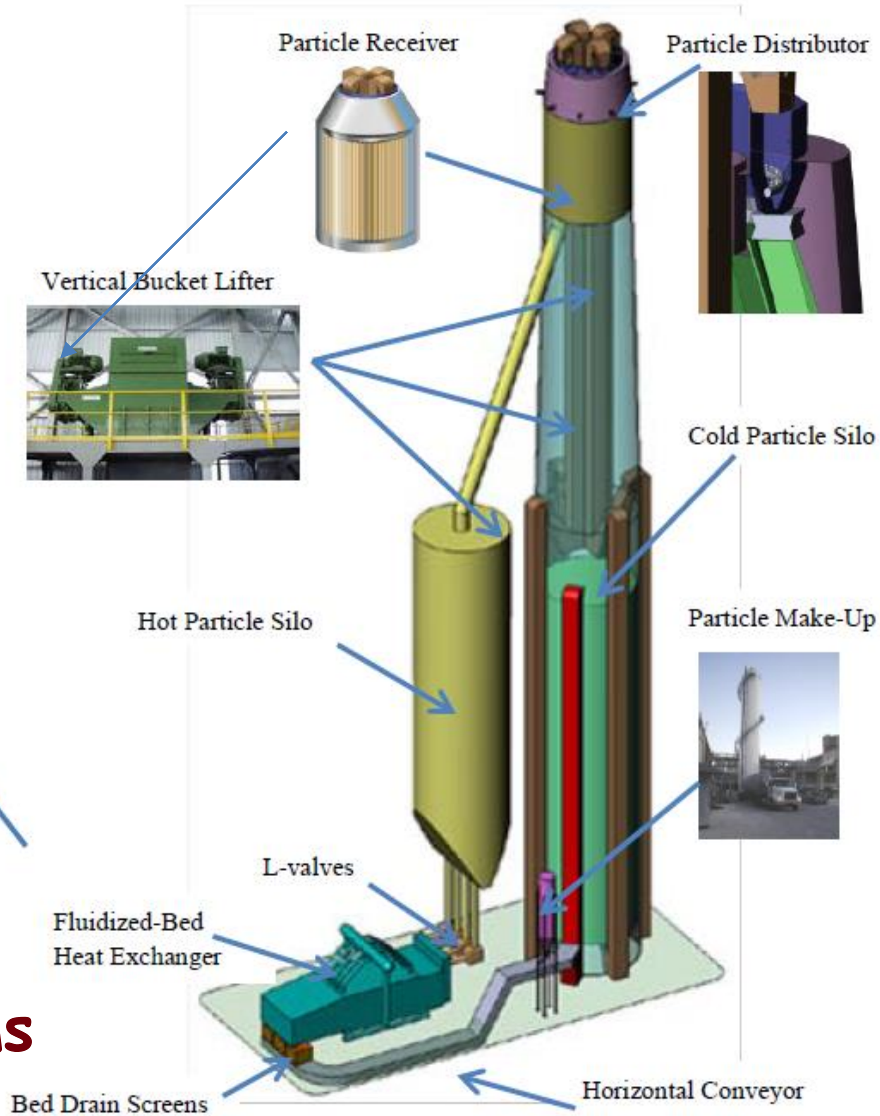






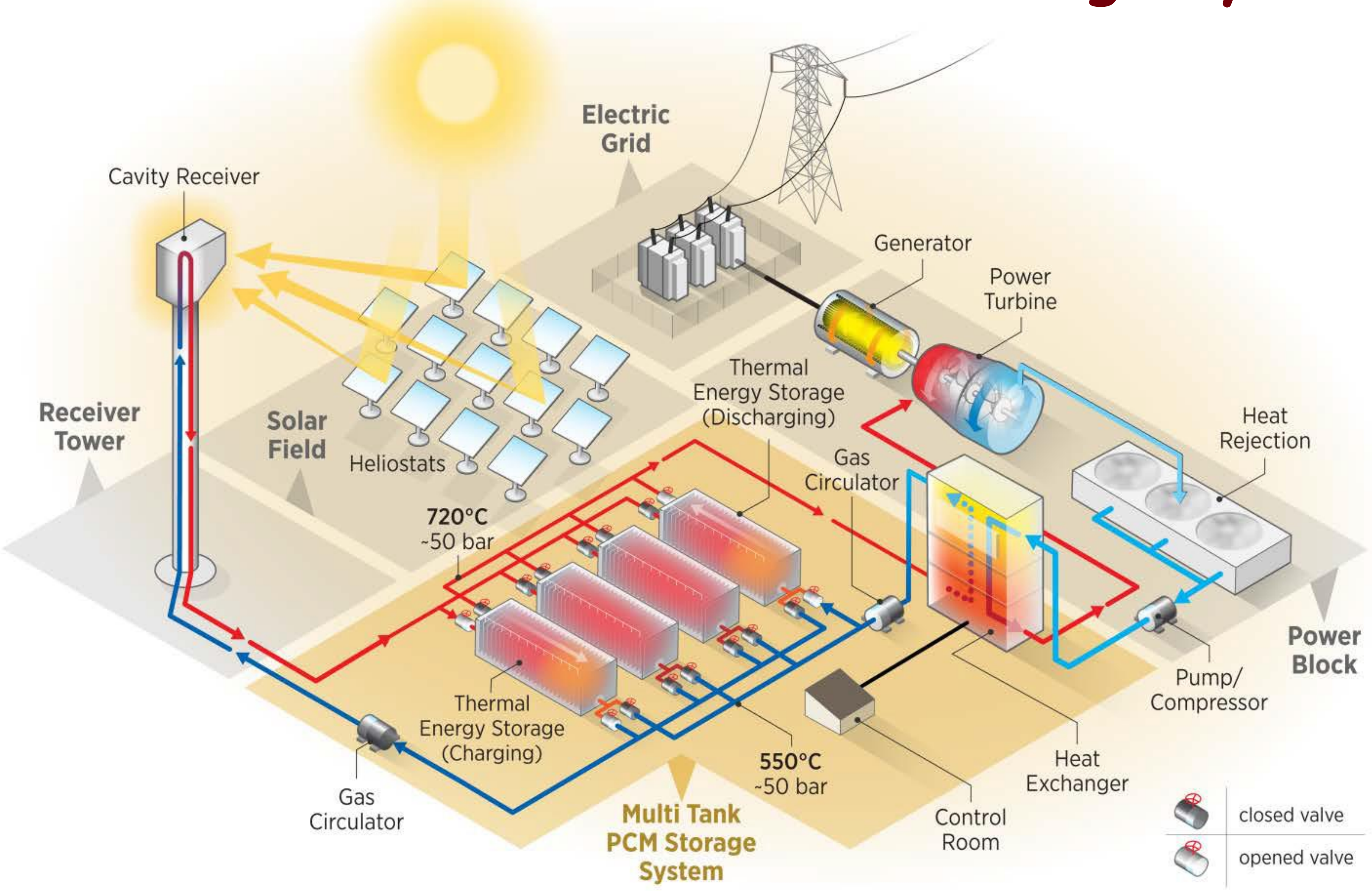


Steam fluidized-bed heat exchanger



Major components of the particle-based CSP systems

Conceptual design of gas-phase receiver system with a modular PCM thermal storage system.



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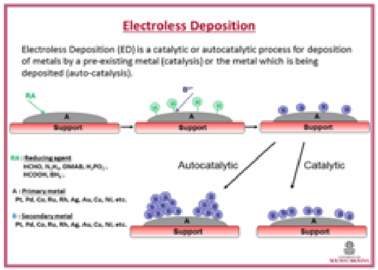
High temperature reactor catalyst material development for low cost and efficient solar driven sulfur-based processes

1647-1547

Claudio Corgnale / Greenway Energy

Technology Summary

- Development and testing of a new catalytic material to decompose sulfuric acid. This will result in:
    1. Limiting the catalyst deactivation by using very small particles of a high surface free energy core metal with a catalytically-active outer metal shell (60% less than the current catalyst).
    2. Decreasing the material cost, with lower Pt content
    3. Increasing the nominal catalyst activity (30% higher than the current catalyst activity).
- Simulation, design, construction and testing of a lab scale decomposition reactor.
- Process modeling of the integrated solar driven H_2 production plant, with objective of demonstrating potential to:
    1. High solar to hydrogen efficiency (≥ 20%)
    2. Low production cost (≤ 2 \$/kg)



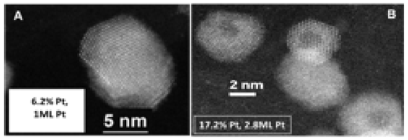
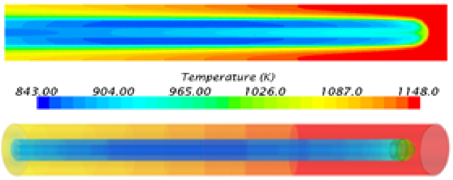


Figure A. HAADF images of (A), 0.9 ML deposition of Pt and (B), 2.7 ML deposition of Pt on Pd core particles of a 30 wt% Pd/C base catalyst.



Key Personnel

William Summers, Prabhu Ganesan (Greenway Energy); John Monnier, Sirivatch Shimpalee, John Regalbuto, John Weidner (University of South Carolina)

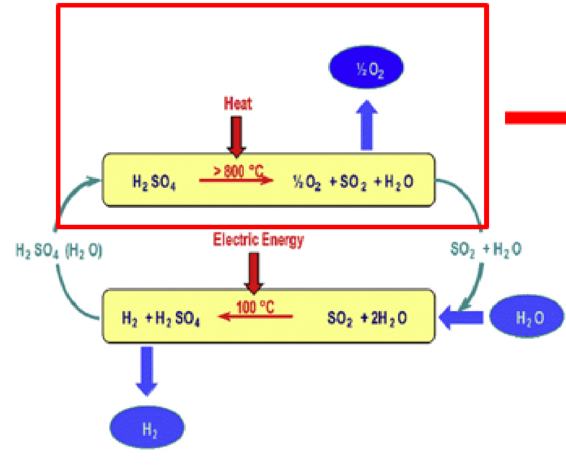
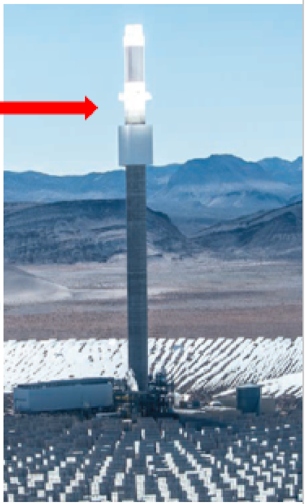


Fig. 1 – Hybrid Sulfur cycle simplified schematic.

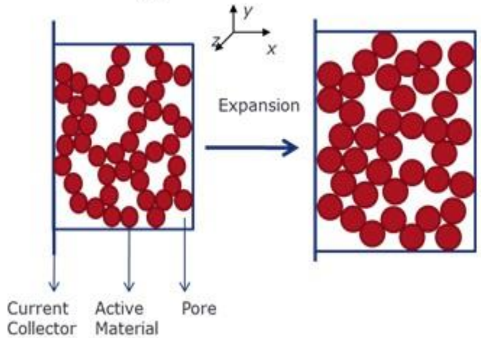


- High efficiency hydrogen production (driven by solar source), reaching solar to hydrogen η ≥ 20% (DOE target = 20%)
- Low cost hydrogen production (driven by solar source) ≤ 2 \$/kg_{H2} (DOE target = 2\$/kg_{H2})
- The proposed solar driven hydrogen production process, operating at T max ≈ 750-850 °C, can be integrated with other primary sources

Novel sulfuric acid decomposition catalyst for low cost H_2 production cycles

Battery Research at USC

Modeling Volume Change in Porous Electrodes



Solid volume: $V^0(1-\varepsilon^0)$

$$\frac{\partial(1-\varepsilon)}{\partial t} + \nabla\cdot[(1-\varepsilon)\boldsymbol{v}] = \frac{-s\hat{V}}{n\mathcal{F}}j$$ [1]

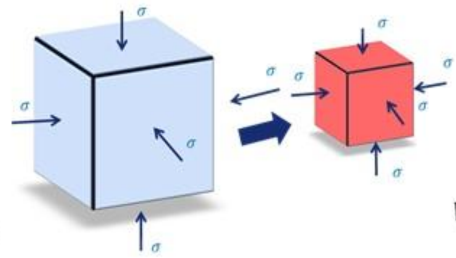
Rate of change of solid volume — Displacement of solid volume within the electrode — Rate of production of solid volume

Defining the gradient of velocity as rate of change of volumetric strain

$$\nabla\cdot\boldsymbol{v} = \frac{\partial\left(\frac{\Delta V}{V^0}\right)}{\partial t} = \frac{\partial\varphi}{\partial t}$$

Therefore,

$$\frac{\partial(1-\varepsilon)}{\partial t} + \boldsymbol{v}\cdot\nabla(1-\varepsilon) + (1-\varepsilon)\frac{\partial\varphi}{\partial t} = -\frac{s\,\hat{V}}{n\mathcal{F}}j$$



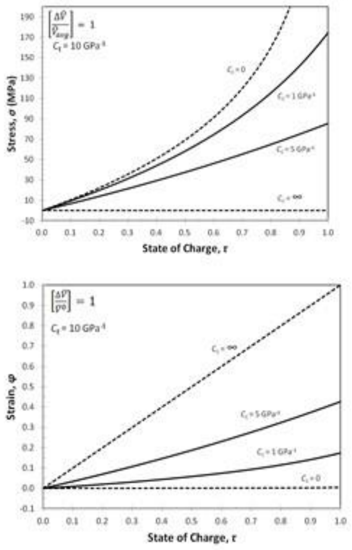
Taking into consideration rock mechanics, the compressibility of the bulk can be written:

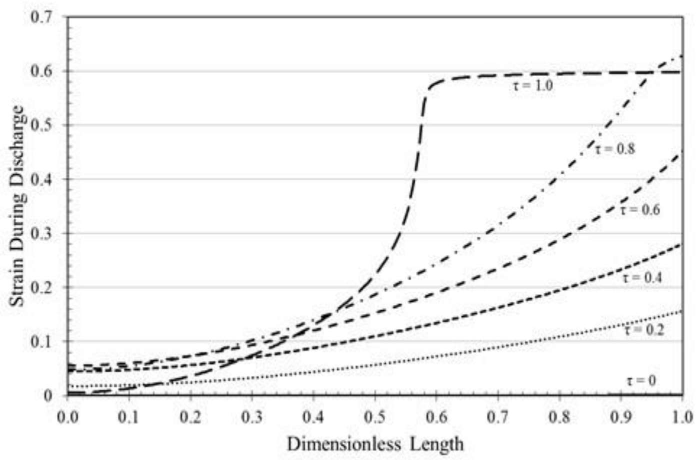
$$C_E = -\frac{1}{V_m}\frac{dV_m}{d\sigma}$$

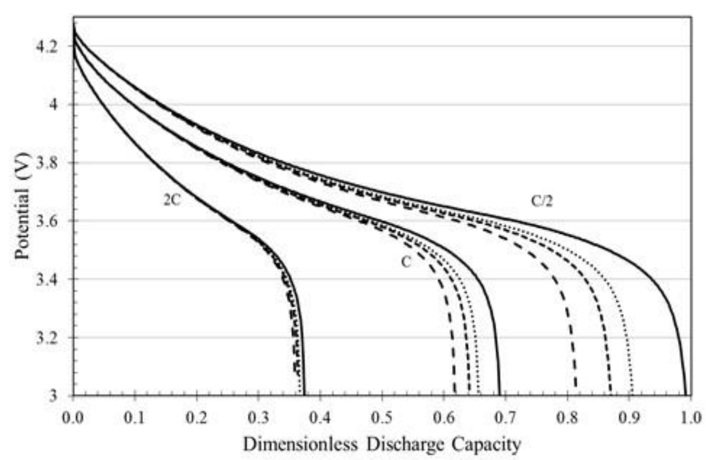
$$V_m = V_m^0(1+\varphi)$$

Electrode Strain: $\varphi = e^{(-\gamma\bar{\sigma})} - 1 + \left[\frac{\Delta\hat{V}}{\hat{V}_{avg}}\right]\tau$

Casing Strain: $\varphi_{avg} = \varphi_c = C_C\sigma$



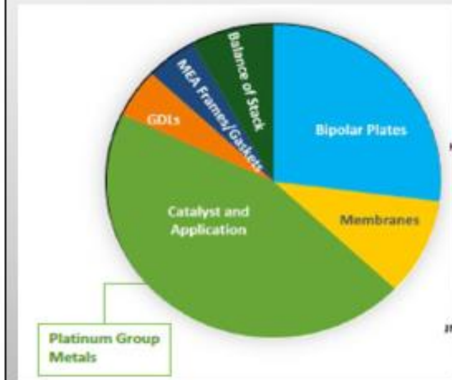


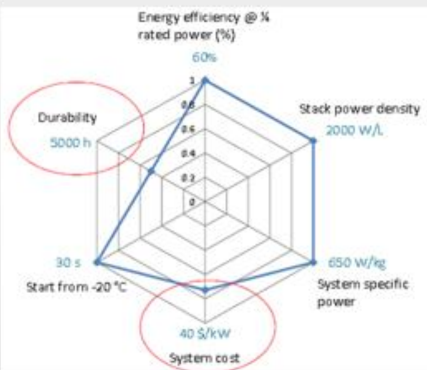


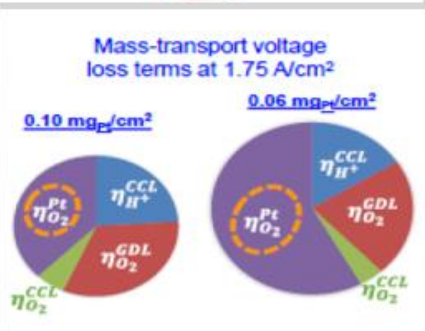
Transport Study in PEM Fuel Cells

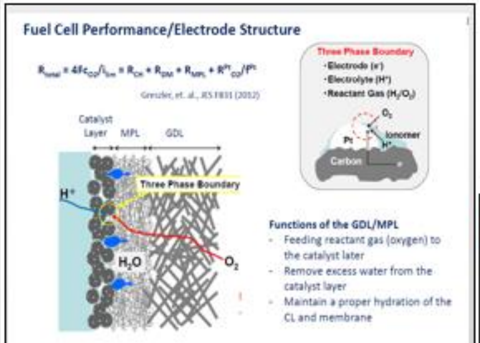
UNIVERSITY OF SOUTH CAROLINA

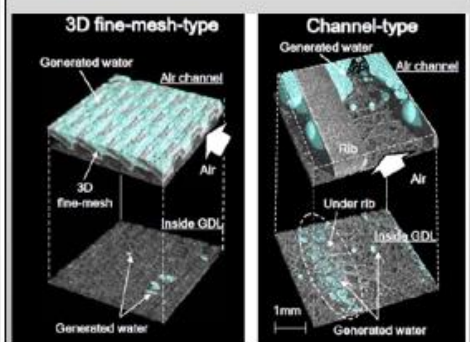
Pongsarun Satjaritanun, Sirivatch Shimpalee and John W. Weidner





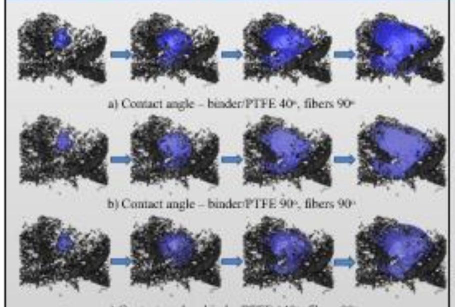






GDL: gas diffusion layer

Micro-structure of GDL and PTFE

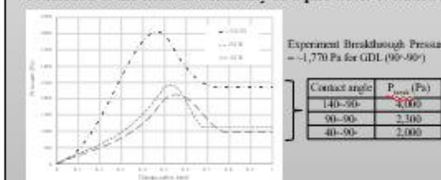


a) Contact angle – binder/PTFE 40°, fibers 90°

b) Contact angle – binder/PTFE 90°, fibers 90°

c) Contact angle – binder/PTFE 140°, fibers 90°

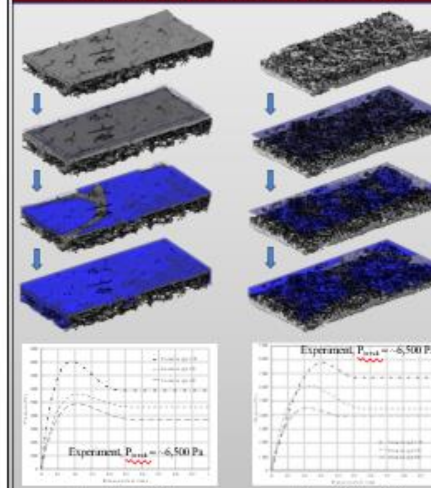
Prediction of the effect of wettability on liquid water evolution



Contact angle	P_{break} (Pa)
140–90	4,000
90–90	2,300
40–90	2,000

The effect of wettability of water breakthrough pressure (Pa) for original binder/PTFE dispersion.

Micro-structure of SGL 25BC

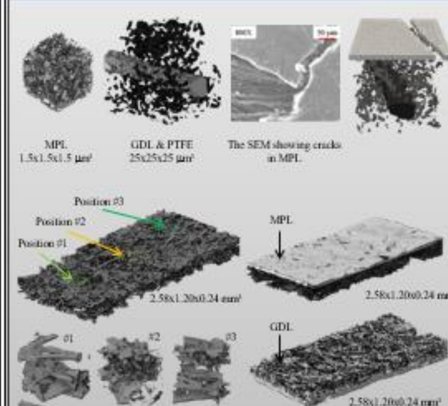


a) From MPL to GDL

b) From GDL to MPL

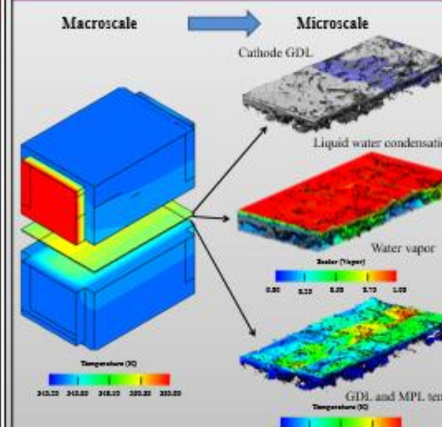
The effect of wettability on water breakthrough pressure (Pa): a) liquid water will push from the MPL thru GDL and b) liquid water will push from GDL thru MPL

Nano X-ray Computed Tomography



3D rendered image from Micro Computed Tomography of SGL 25BA. Locations 1, 2 and 3 were selected for water breakthrough predictions.

Multi-Scale Modeling



Predictions show temperature distribution of macroscale fuel cell and liquid water, water vapor, and temperature distributions of microscale GDL/MPL

Acknowledgement

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SunShot U.S. Department of Energy

ATPAC The Association of Thai Professionals in America and Canada

MOST Ministry of Science and Technology of Thailand

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