The #H2IQ Hour

Today's Topic:

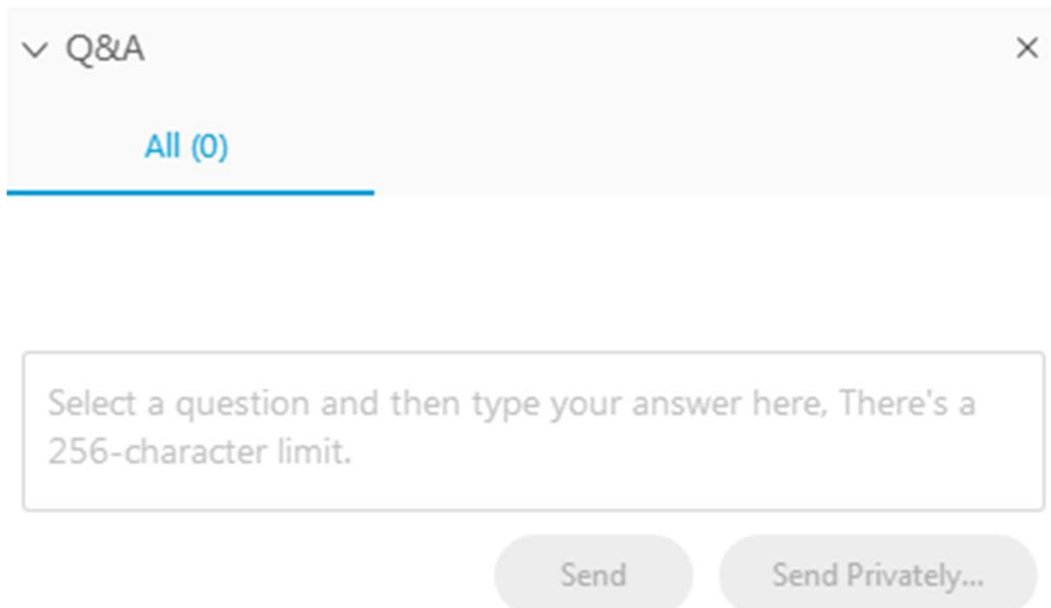
Concentrated Solar Power as a Pathway for Electrolytic Hydrogen Production

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

The #H2IQ Hour Q&A

INCREASE YOUR H2IQ

Please type your questions into the **Q&A Box**



Concentrated Solar Power as a Pathway for Electrolytic Hydrogen Production

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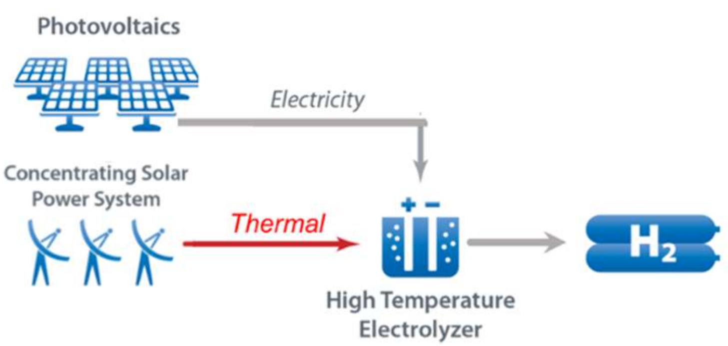
H2IQ Meeting

4/27/2022

Table of Contents

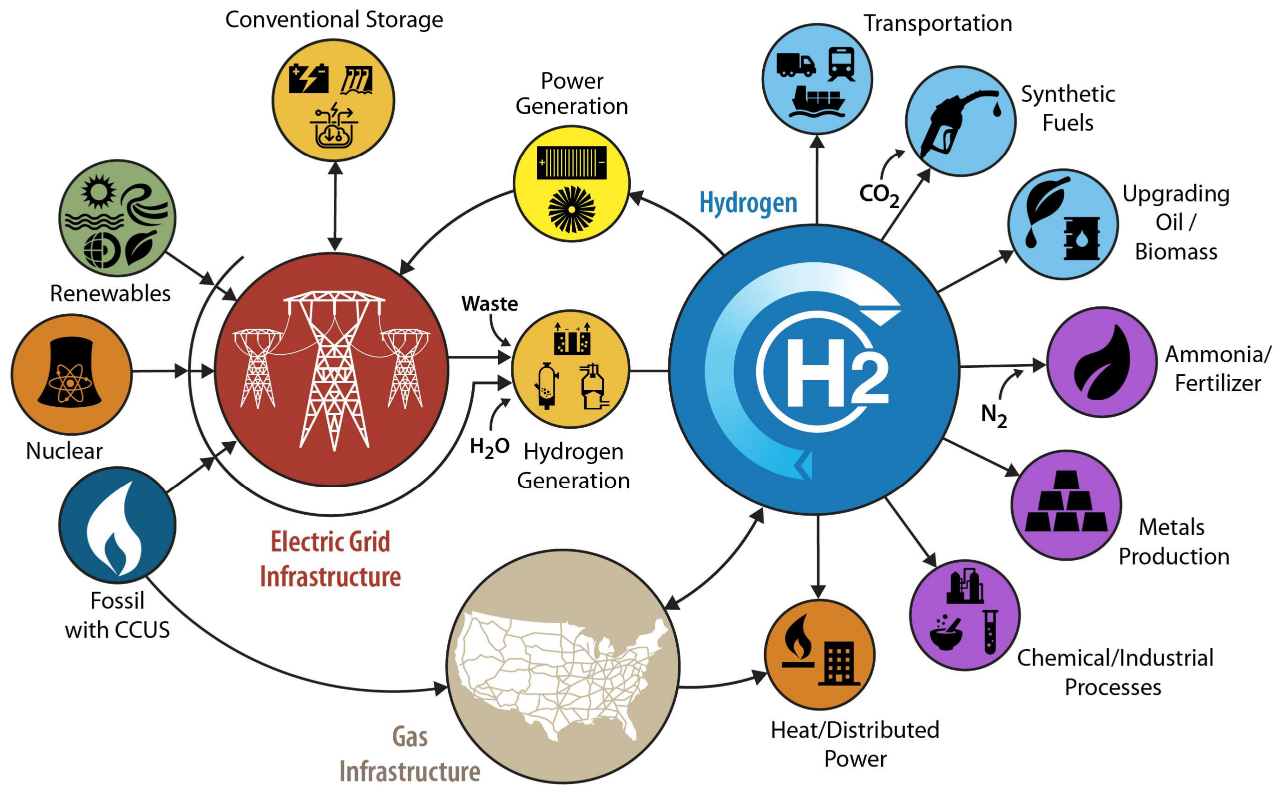
Solar Energy and the Hydrogen Future



What is the opportunity space for solar hydrogen systems? Can we get to \$2/kg H_2?

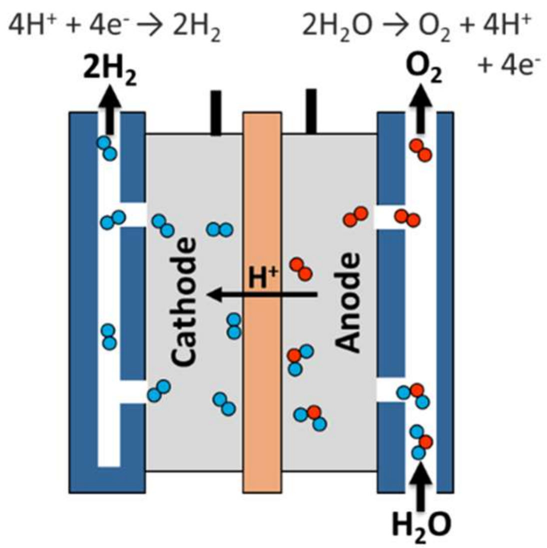
Would using concentrating solar heat with PV and higher efficiency HTSEs be a more efficient and cost-effective alternative to PV solar hydrogen systems?

Can we answer these questions by connecting industry-standard solar simulation environments to HFTO hydrogen analyst tools?



Technologies Overview

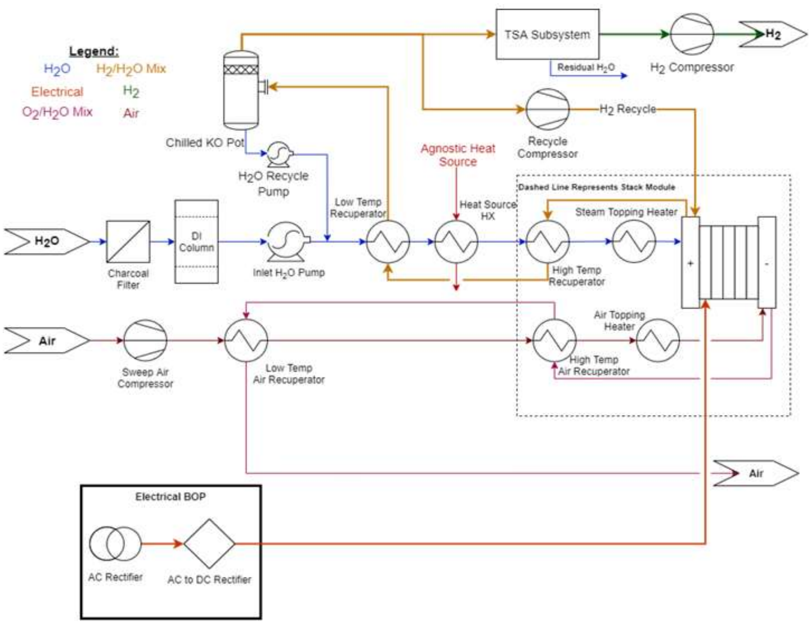
Low Temperature Electrolyzers – Polymer Electrolyte Membrane (PEM)



- Water reacts at the anode to produce protons which combine with electrons at the cathode to produce hydrogen gas
- PEM electrolyzer cells consist of several components: membrane electrode assemblies, current collectors and separator plates.
- The cells are arranged in series to form a stack and multiple stacks are combined to form a module which is typically in the multi – MW scale

PEM Electrolysis System	Stack Purchase Cost ($/kWDC$_{Stack}$)	BOP Mechanical, Electrical ($/kWDC$_{Stack}$)	Installation Factor	H_2 Prod Efficiency Stack (kWh$_{DC}$/kg H_2)	Voltage Eff (% LHV)	Replacement Frequency (years)	BOP Load (kWh$_{AC}$/kg H_2)
H2A (Future Central)	143	23.02, 68.00	1.10	47.8 @ 80°C	69.6 @ 80°C	10	2.1
H2A (Current Central)	342	36.19, 82.00	1.12	50.4 @ 80°C	65.9 @ 80°C	7	2.45

High Temperature Electrolyzers



- Water electrolysis at elevated temperatures (700 to 1000 °C).
- At elevated temperatures a greater proportion of electrolysis energy can be supplied by heat, which is cheaper than electricity while the total electrolysis energy requirement remains approximately constant
- Improved reaction kinetics at higher temperatures increases the overall system efficiency

	Uninstalled Costs ($/kWDC)			
Scenario	HTSE Stack	Electrical/Grid Connections	Water/Gas Feed and HX system	Purification and Compression
2020	190	119	65	51
2050	100		257	

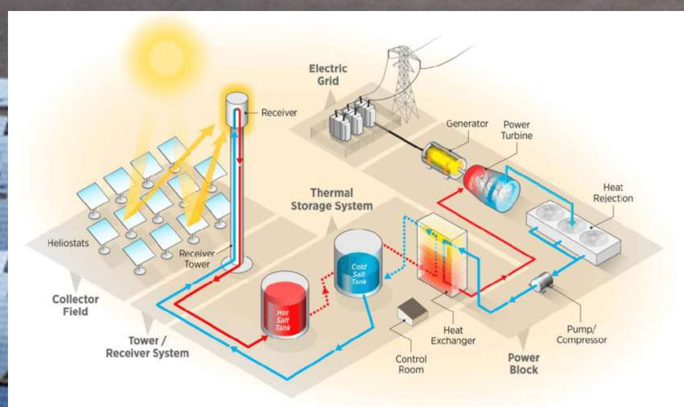
Electrical Load (kWh/kgH_2)	Thermal Load ($kWhth/kgH_2$)	Standby Electrical Load	Standby Thermal Load	Intermediate Load Efficiency	BOP Efficiency ($kWhe/kg H_2$)
36.80	6.40	0.9% Nominal	19% Nominal	Linear Interp.	2.56

CSP Power Tower

Electricity sent to power grid

Steam drives turbine to generate electricity

Irradiance reflected to receiver by tracking mirrors



Fluid exchanges heat to steam

Fluid pumped into receiver atop tower

Concentrated irradiance heats fluid

Tanks store hot fluid

credit: Jamey Stillings

Systems Overview

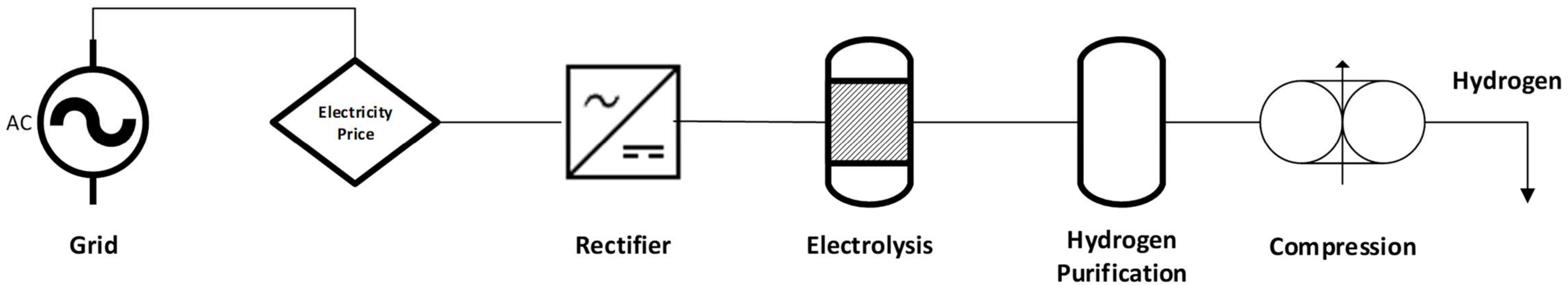
System 1: Grid-LTE

System 2: PV-LTE-batteries

System 3: MSALT–HTSE

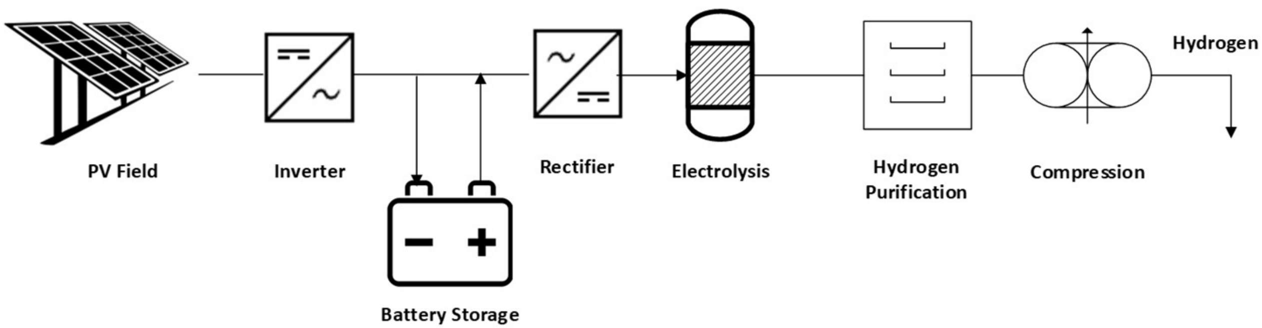
System 4: PV-MSALT-HTSE

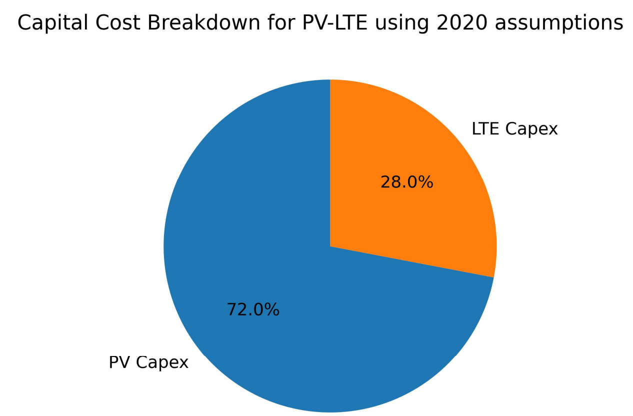
Baseline System: Grid-LTE



- Simplified block flow diagram of System 1 (baseline grid model)
- Electrolyzer turns on and off based on electricity price threshold or capacity factor target

Baseline Systems: PV-LTE



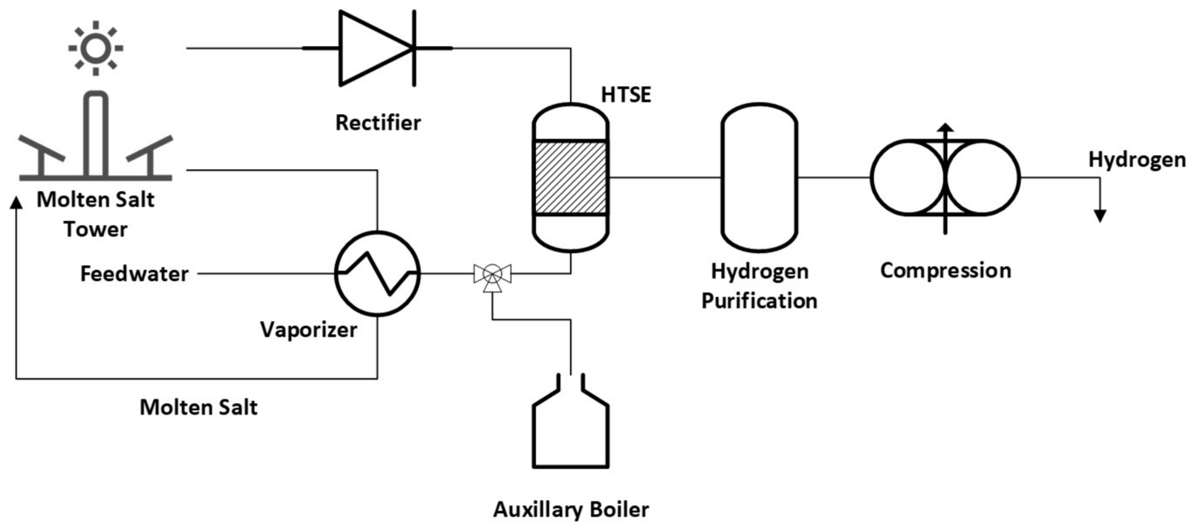


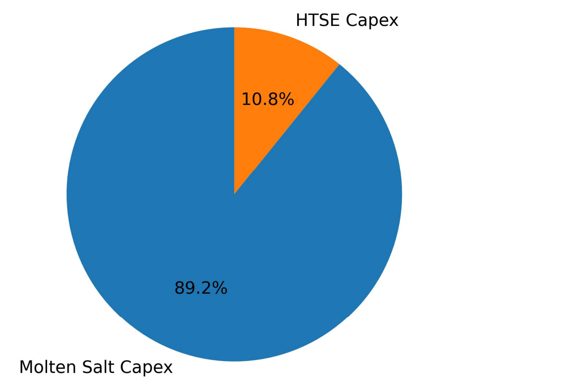
System 2: Islanded PV-LTE with Power Electronics and Optional Battery Storage

- Default SAM 1-axis PV with inverter and optional lithium Ion NMC battery storage
- Battery dispatched to store excess PV electricity and discharge when electrolyzer is underutilized
- Costs from ATB scenarios or DOE targets (Earthshot)

Scenario	Hrs Storage	Tracking	DC to AC Ratio	Installed Cost	Fixed Cost
2020	0-10	1 Axis	1.34	\$1.377/ Wac	\$23/kw-yr
2050	0-10	1 Axis	1.34	\$0.776/ Wac	\$17/kw-yr

Baseline System: MSALT-HTSE



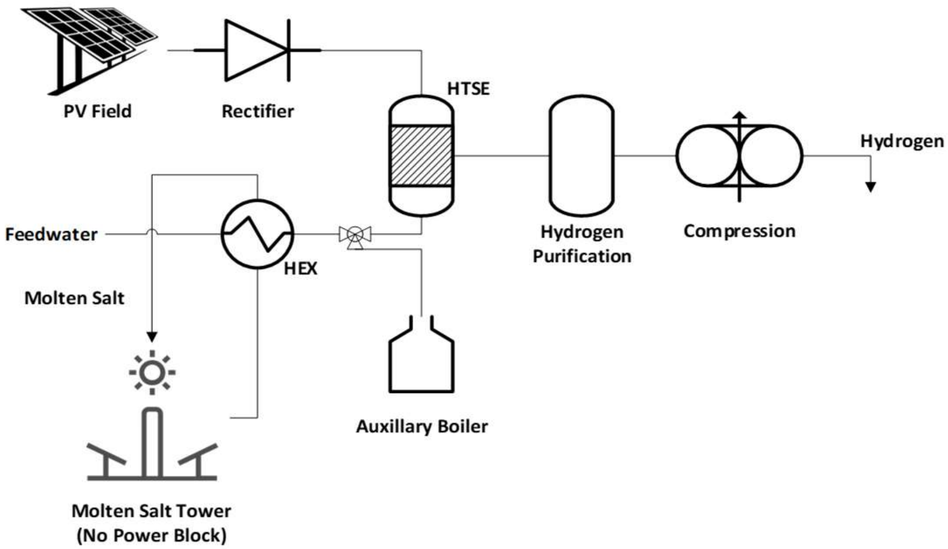


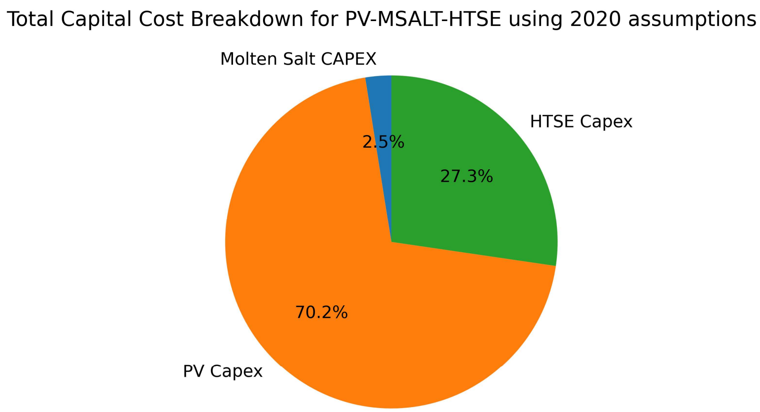
System 3: Islanded Hybrid Power Tower coupled to HTSE

- Molten salt tower producing heat and electricity with two-tank thermal storage coupled to HTSE
- Small grid connection and auxiliary boiler for HTSE standby
- Heat from the tower is used to vaporize feedwater

Scenario	PC Efficiency	HTF	Storage Hrs	Total Installed Cost	Variable Cost	Fixed Cost	Loop Outlet HTF Temp
2020	0.412	Salt	8-12 hrs	$6,573 / kW	$3.5/MWh	$66/kw-yr	574°C
2050	0.412	Salt	8-12 hrs	$4,213 / kW	$2.9/MWh	$50/kw-yr	574°C

Baseline System: PV-MSALT-HTSE



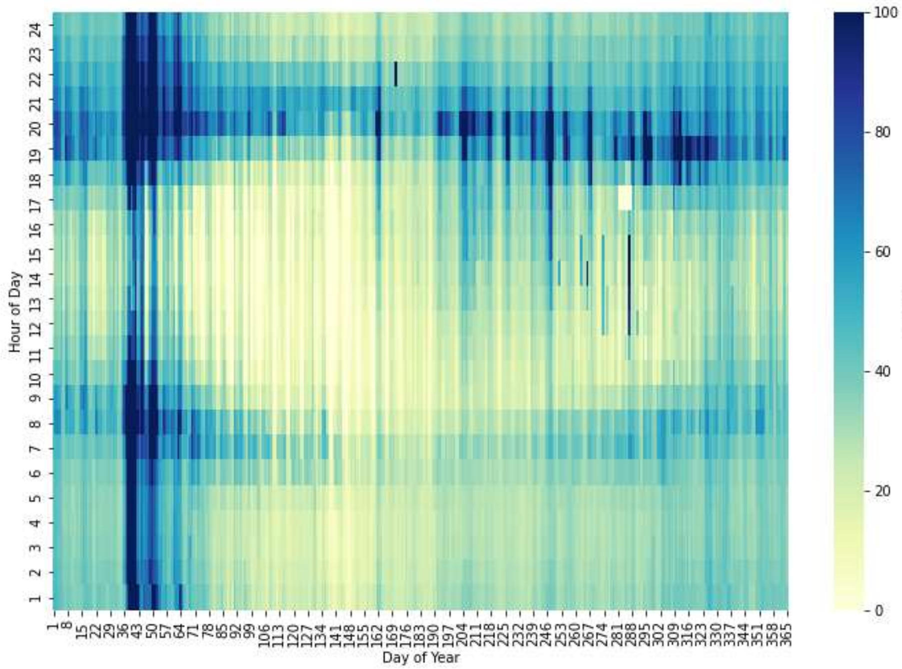


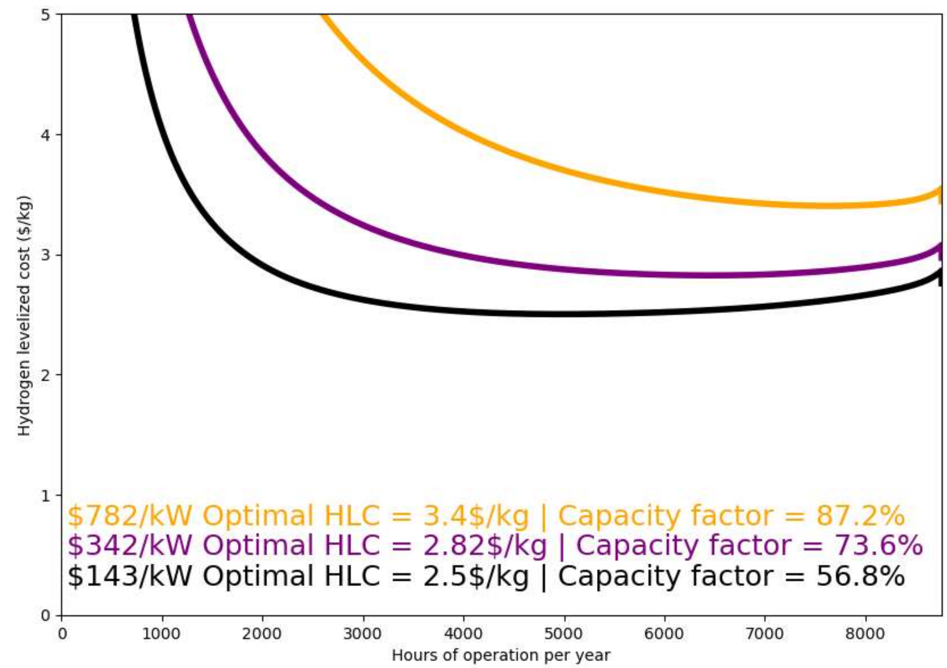
System 4: Islanded Heat Only Salt Tower or Parabolic Trough with PV and Batteries coupled to HTSE

- Tower or parabolic trough system (optional storage) is used to provide heat while PV and batteries provide electricity to the HTSE
- Heat from concentrating solar is dispatched to match the PV generation profile in the ratio required by the HTSE
- Adjusted salt tower cost curve (Sargent and Lundy 2003) :

2020$ = (600000 + 17.72 * (height_meters^2.392)) * (596.2/355)

Grid-Connected LTE System Achieves Minimum Hydrogen Levelized Costs of 2.50 to 3.40 $/kgH_2$





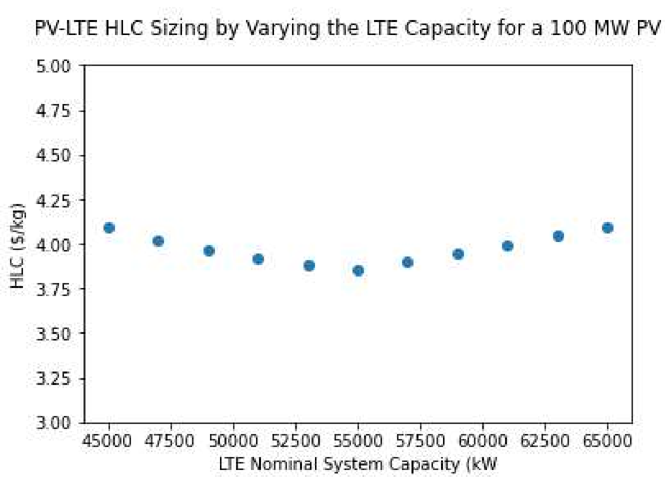
- H2A current central electrolyzer HLC curves using a LMP curve for Daggett, CA in 2019
- The optimal capacity factor increases with stack purchase costs

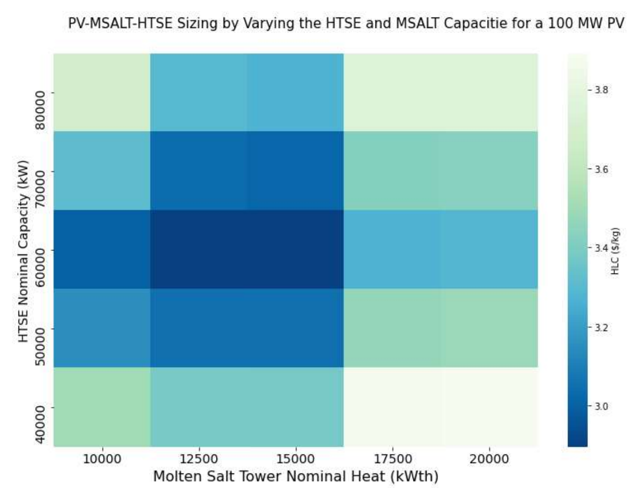
Optimal System Configurations involves some Heat Trimming

Grid search sizing is used to find the lowest cost system configuration

Ex: Varying the electrolyzer capacities relative to solar system capacities (see table for Daggett)

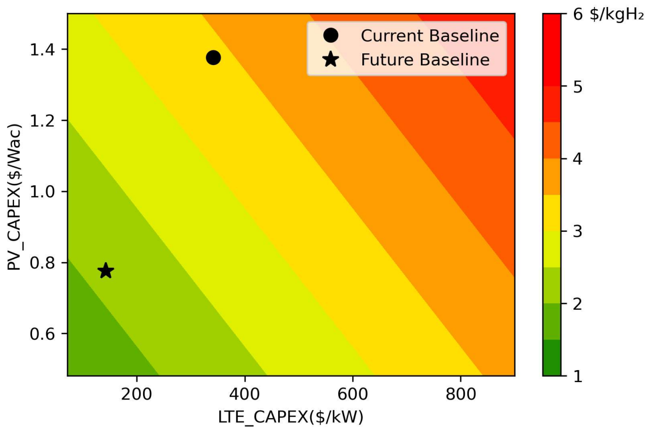
System	System Capacities	CAPEX	HLC ($/kg H_2)	Energy Trimmed
Grid-LTE	131 MW LTE with 20 $/MWh Price Adder	342 $/kW	2.82	Negligible
PV-LTE	100 MW PV | 55 MW LTE	1.38 $/Wac | 342 $/kW	3.86	Negligible
MSALT-HTSE	115 MWe/25 MWth Tower | 130 MW HTSE	6573 $/kW | 425 $/kW	3.68	Negligible electricity | 17% of heat
PV-MSALT-HTSE	100 MW PV | 15 MWth Tower | 60 MW HTSE	1.38 $/Wac | Cost Curve | 425 $/kW	2.90	8% of electricity | 20% of heat





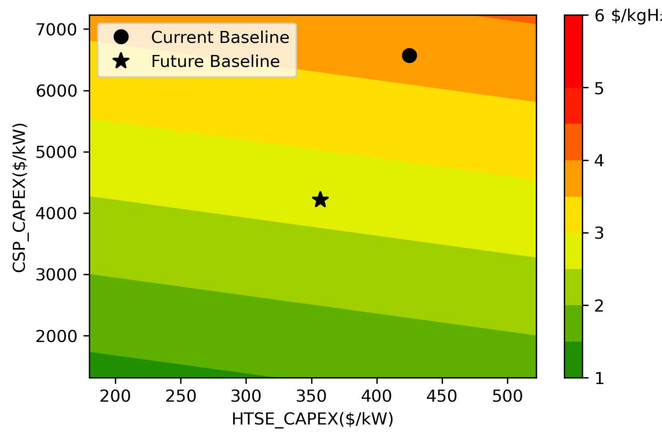
2 $/kg H_2 Achieved with Aggressive Cost Reductions

2: PV-LTE



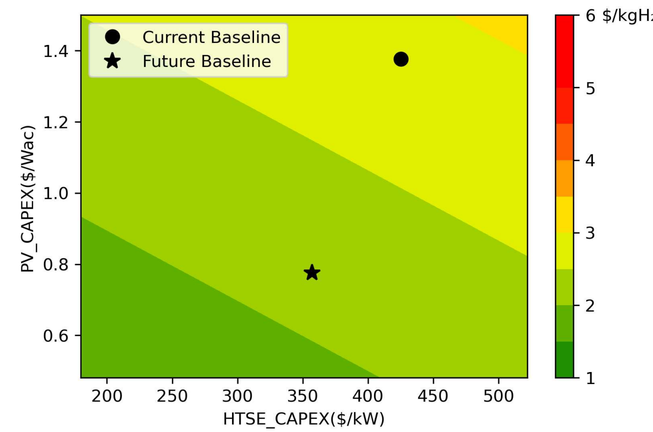
- 2020 scenario at Daggett, CA for a 100 MW PV system and 55 MW LTE system without battery storage
- ~2.13 $/kg H_2 is achievable at future baseline values of 0.776 $/Wac PV and 143$/kW stack purchase costs

3: MSALT-HTSE



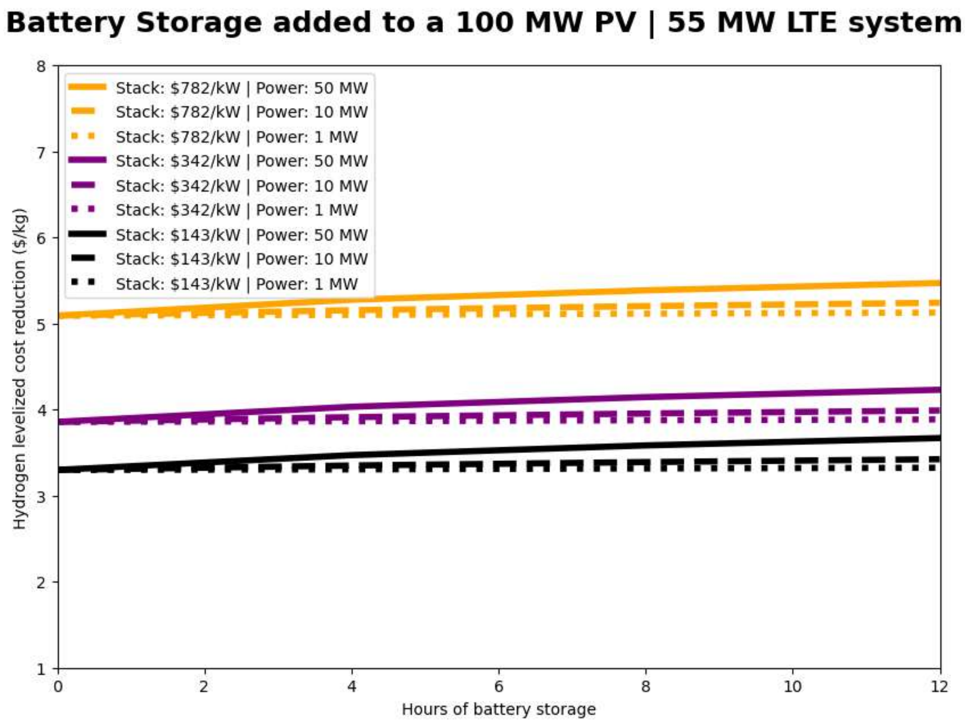
- 2020 Scenario at Daggett, CA for a 115 MWe/25 MWth Molten Salt Tower system and 130 MW HTSE system with 10 hours of thermal storage
- HLC of 2.68 $/kg H_2 is obtained using future baseline values

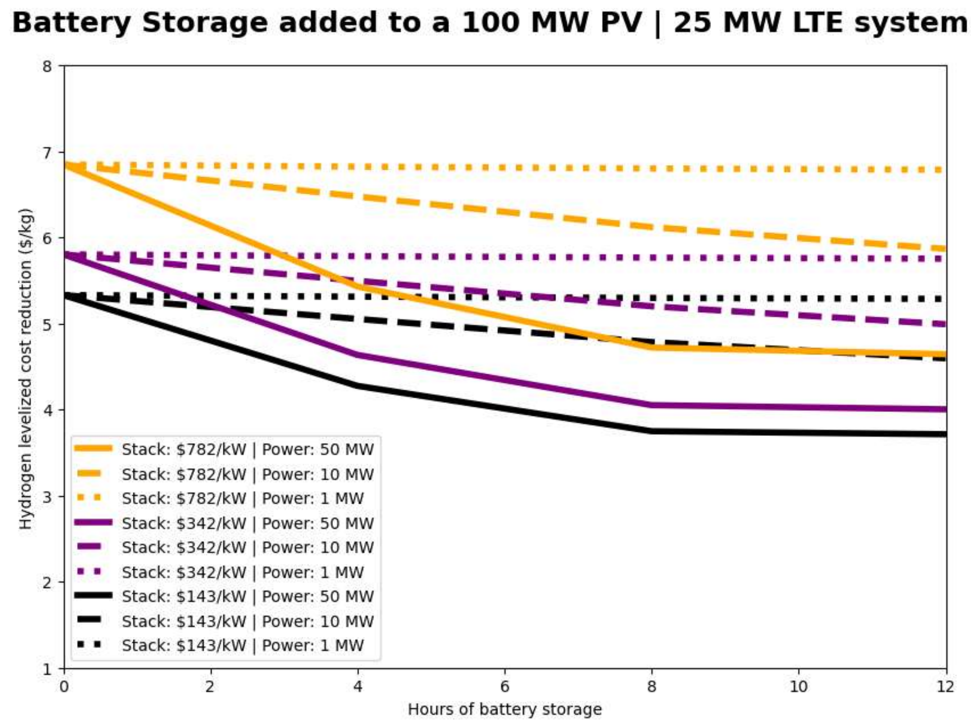
4: PV-MSALT-HTSE



- 2020 Scenario at Daggett, CA for a 100 MW PV System, Molten Salt Nominal Thermal Power of 15 MWth and 70 MW HTSE system
- HLC of \$2.15 kg/H_2 obtained for future baseline values

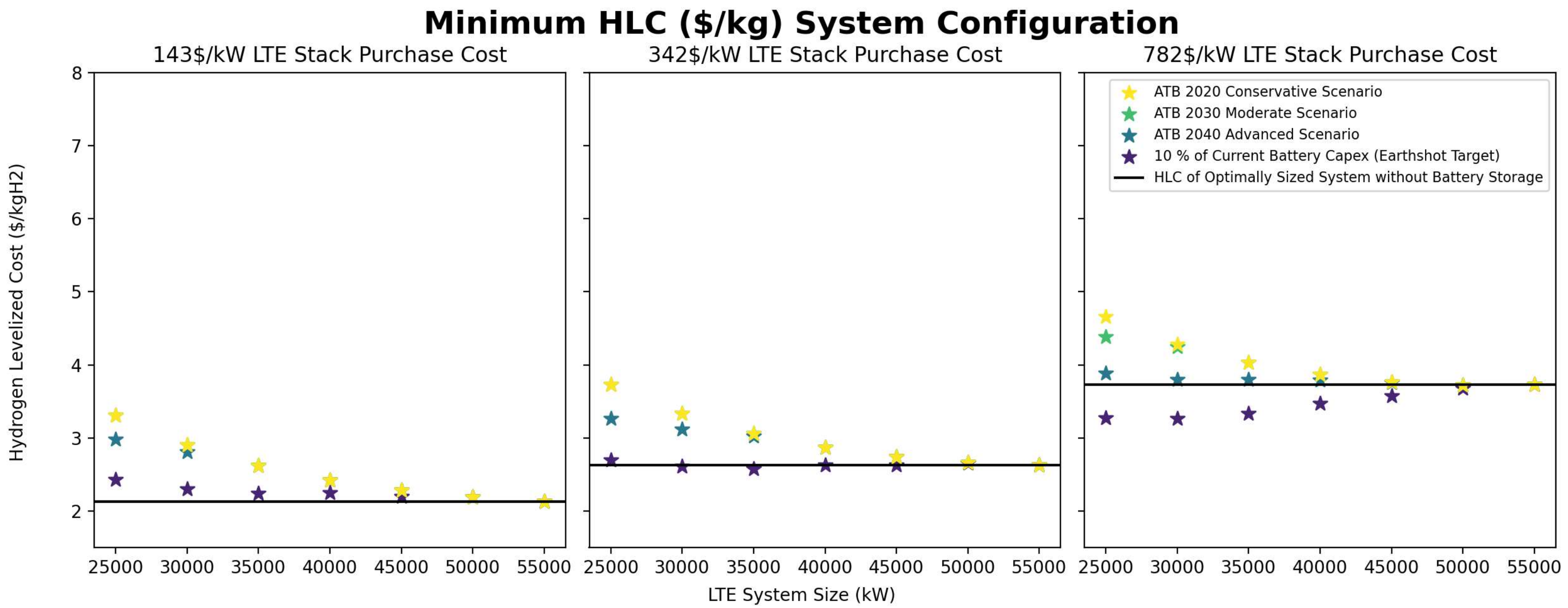
Higher Power Batteries Improve HLCs for Systems with Higher PV:Electrolyzer Ratios





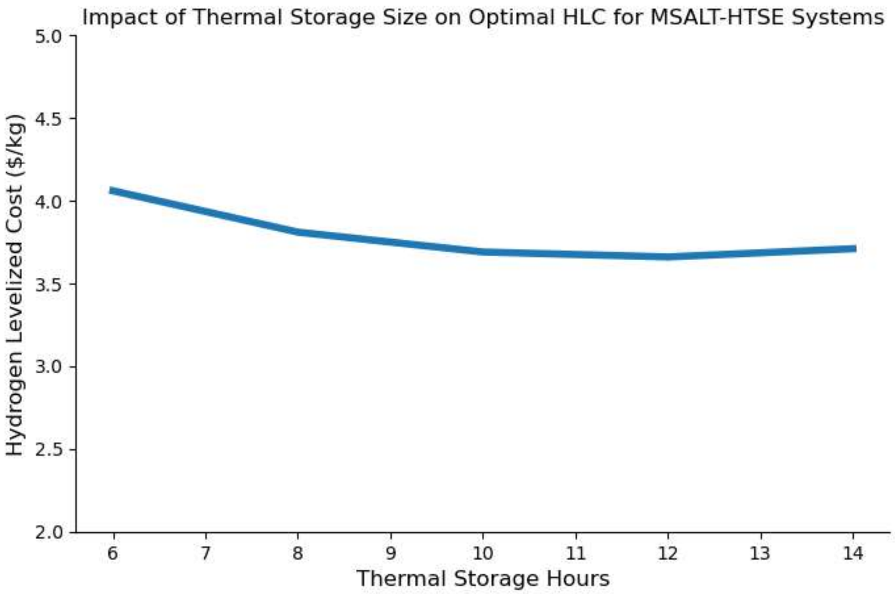
- Increasing battery power and storage hours up to 50 MW and 12 hours respectively improves the HLC only for LTEs sized significantly below the optimal LTE size without battery storage given 90% cost reductions in batteries
- Increasing battery bank power drives lower HLCs with increasing storage only reducing the HLCs given sufficient power

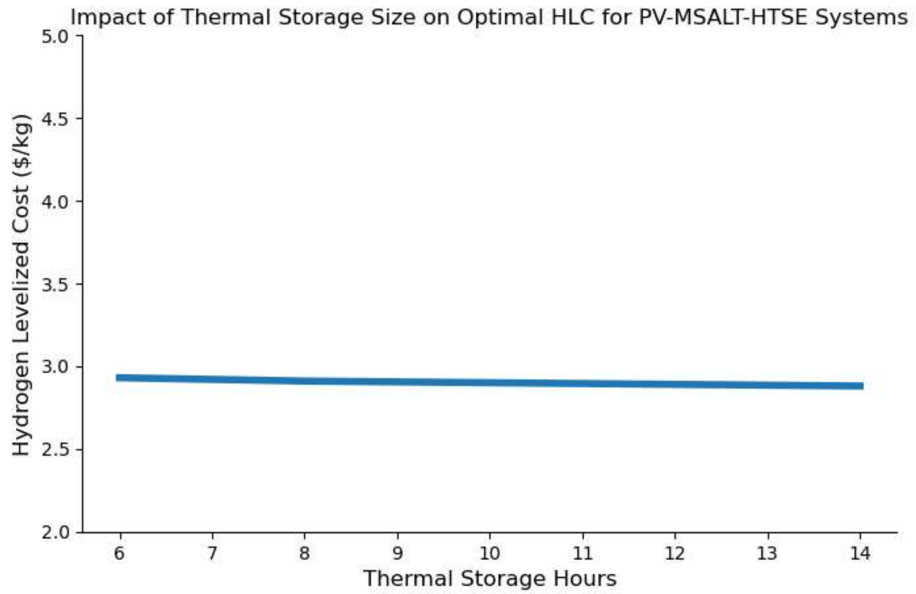
Battery Storage Reduces HLCs when Stack Costs are High and Battery Costs are Low



- The lowest HLC PV-LTE Battery configuration for each LTE system size and stack purchase cost combination is identified
- Battery storage achieving DOE Earthshot CAPEX targets is the only simulated scenario that can noticeably reduce HLCs below PV-LTE systems without battery storage

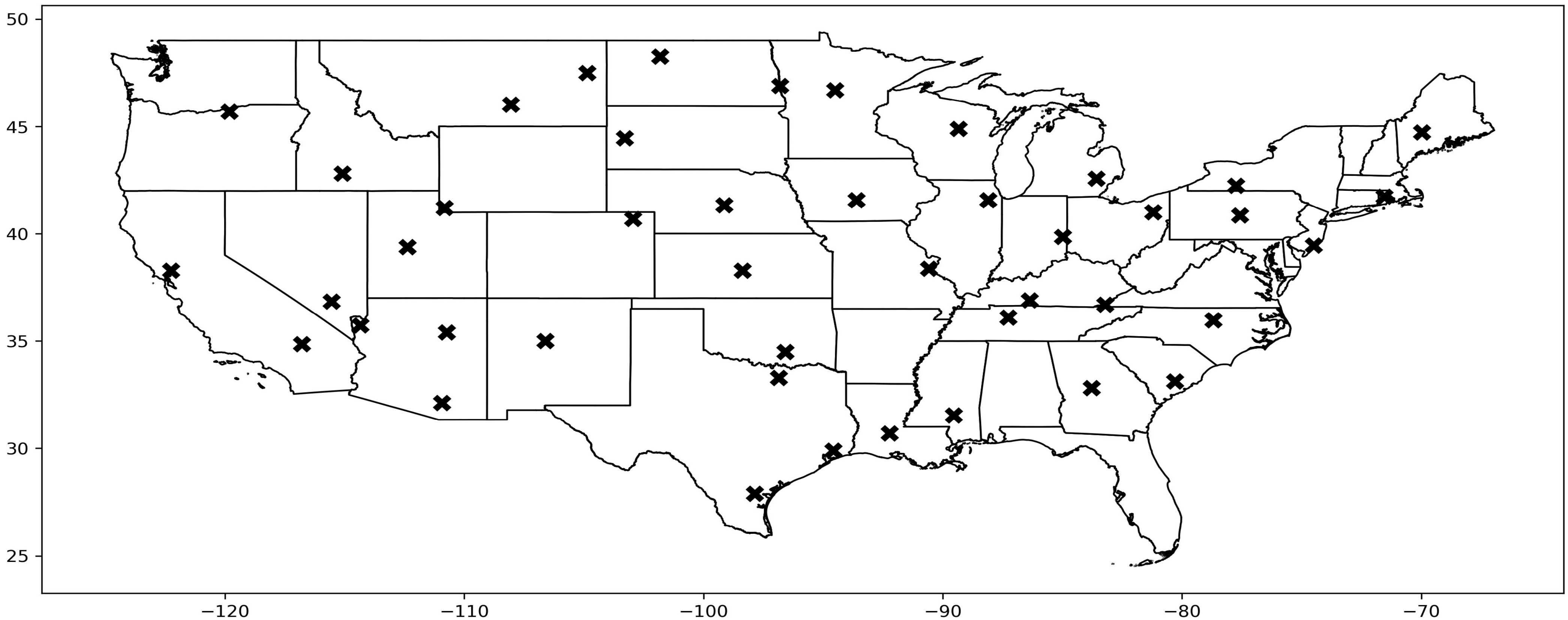
Thermal Storage Beyond 6hs for Tower Systems has Negligible Impact on HLCs





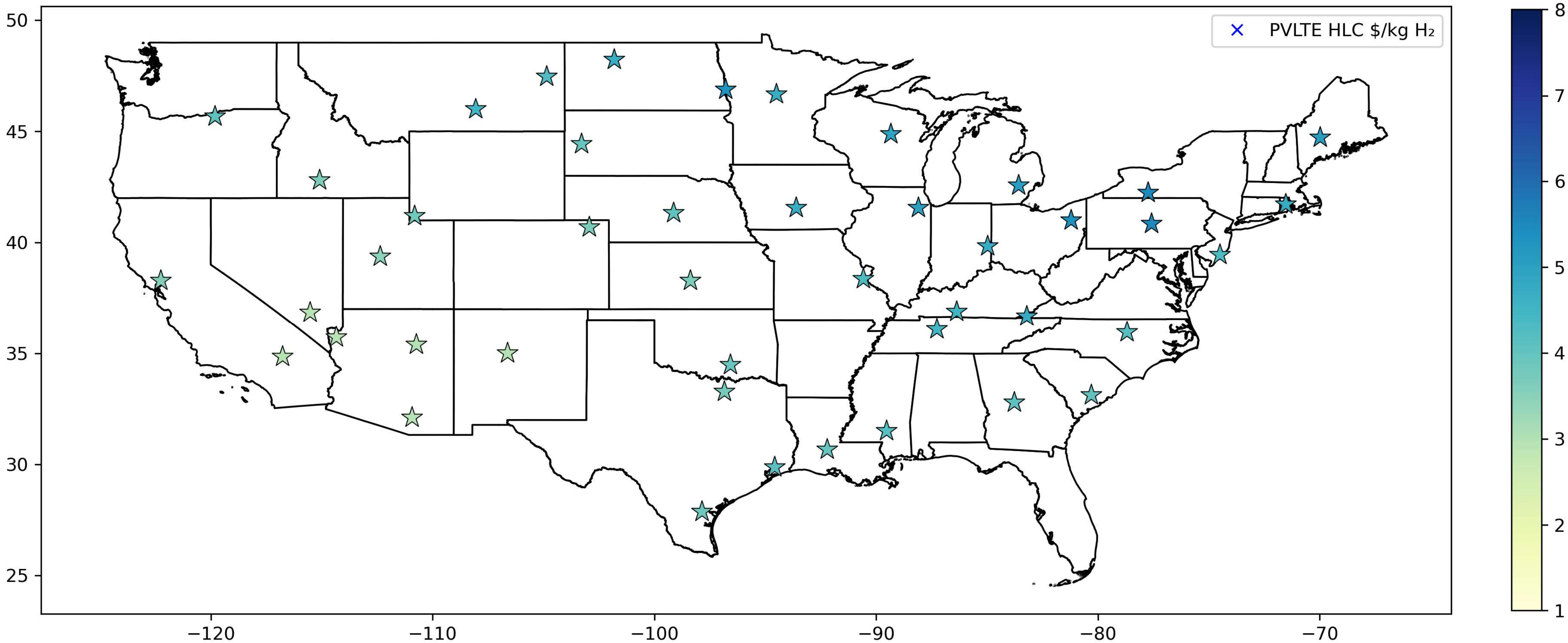
- Towers in MSALT-HTSE systems are dispatched to a constant load as per nominal HTSE operating condition ; increasing storage hours improves the capacity factor of the HTSE with negligible improvements above 10 hours of storage
- Towers in PV-MSALT-HTSE systems are dispatched to match the PV generation in the ratio required by the HTSE ; thermal storage has negligible impact due to differences in PV vs tower generation

Location Results



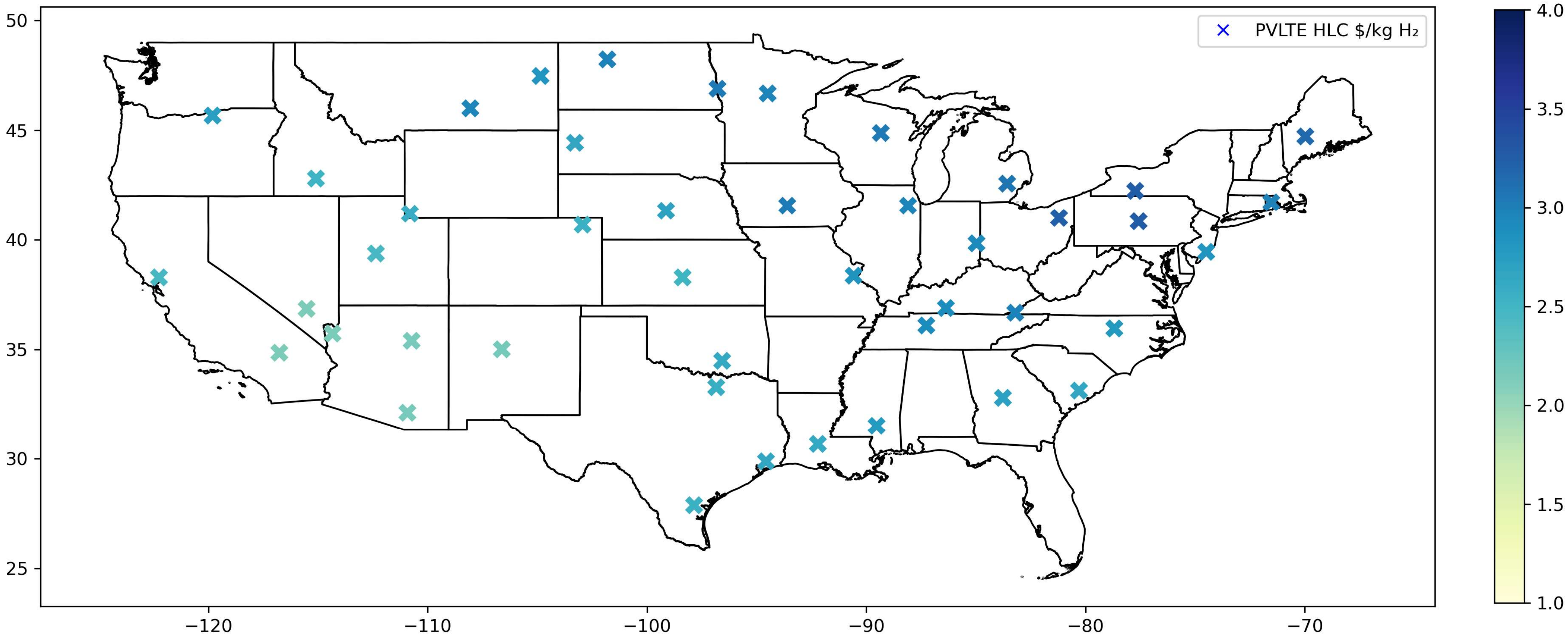
Locations Selected for the Analysis

- Variability in solar resource and geography
- Proximity to essential infrastructure



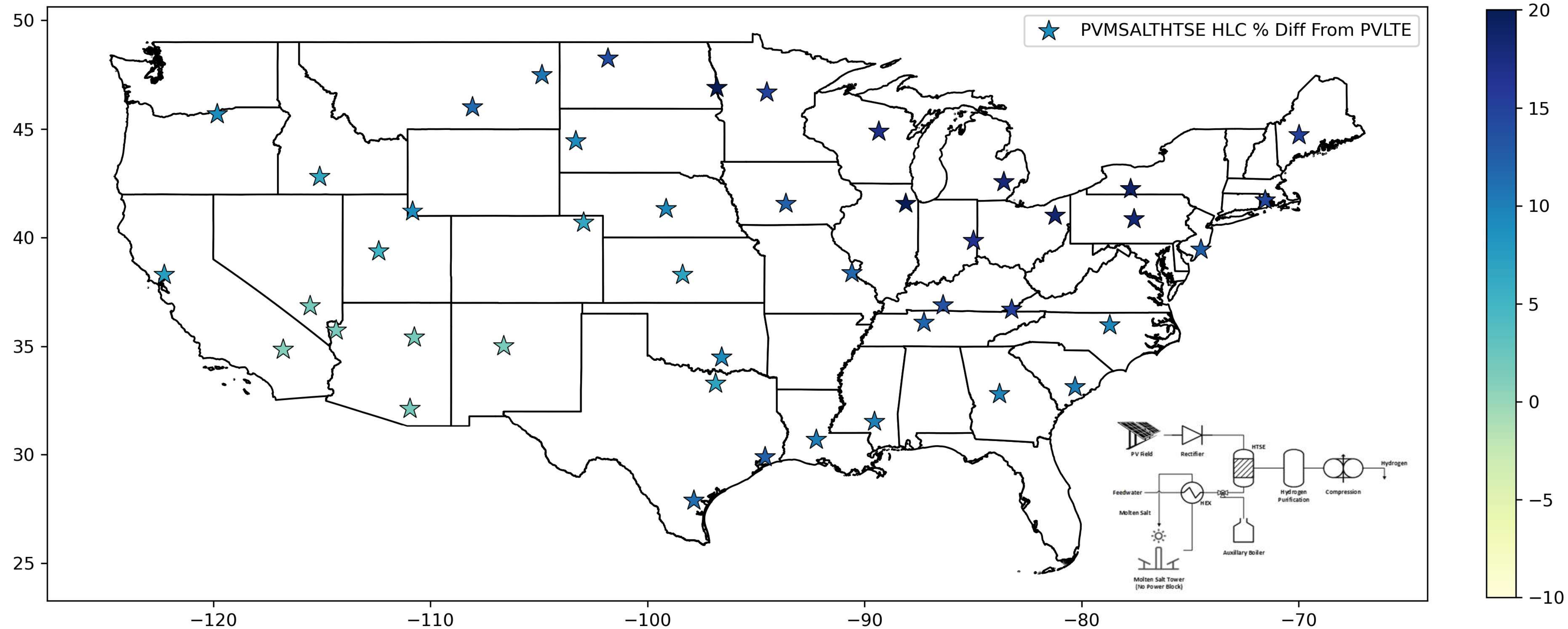
PV-MSALT-HTSE has the Lowest HLC across all Locations in 2020

- Relatively cheap PV and HTSE costs result in low HLC of PV-MSALT-HTSE
- HLC varies from 2.90 to 5.49 \$/kgH_2



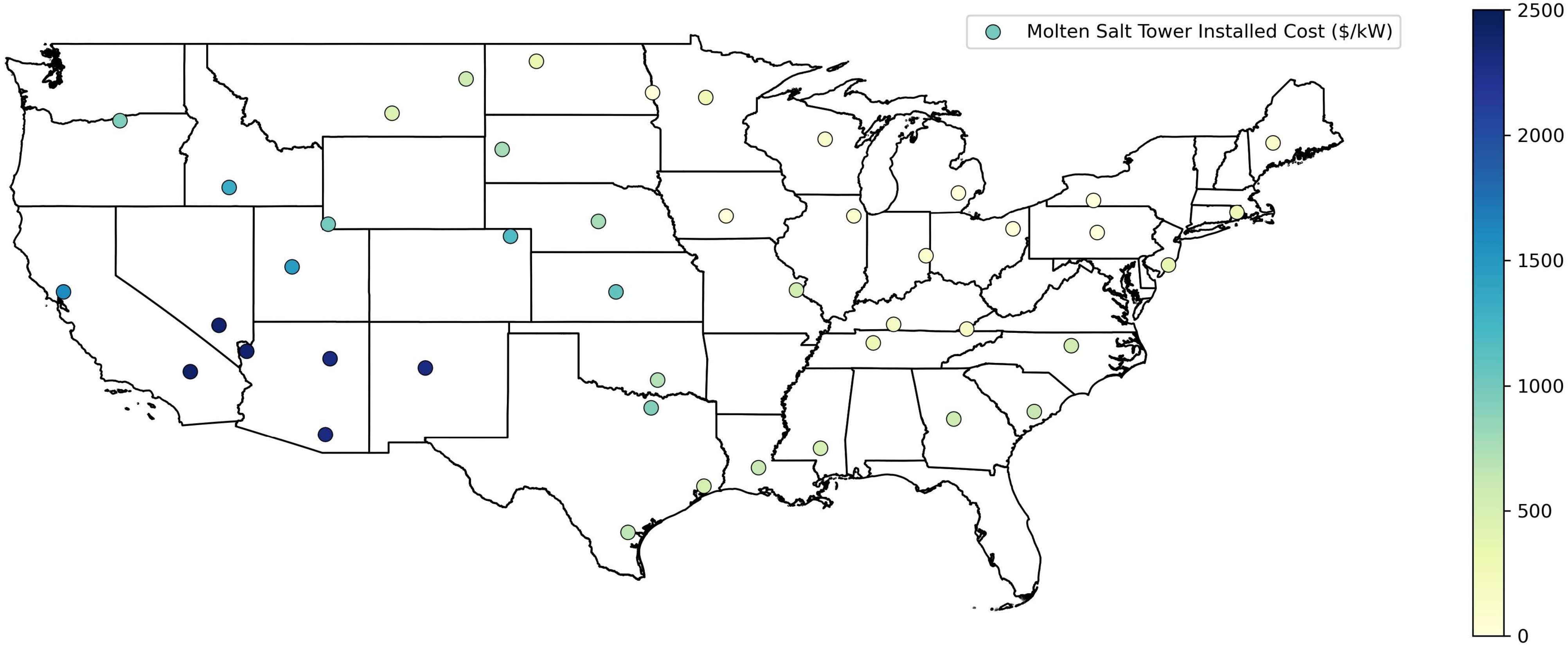
PV-LTE has the Lowest HLC across all Locations in 2050

- PV-LTE is the lowest cost system due to reductions in LTE (342 to 143$/kW) and PV (1.39 to 0.776 $/Wac) costs
- HLC varies from 2.13 to 3.25 $/kg H_2



HLC % Difference between PV-MSALT-HTSE and PV-LTE in 2050

PV-MSALT-HTSE system HLCs range from 1% higher in excellent resource location to 22% higher in poor resource locations



$2/kg H_2 for MSALT-HTSE systems in 2050

- MSALT-HTSE systems can achieve 2$/kg H_2 in 2050 if salt tower costs are 2500 $/kW or below including the power block

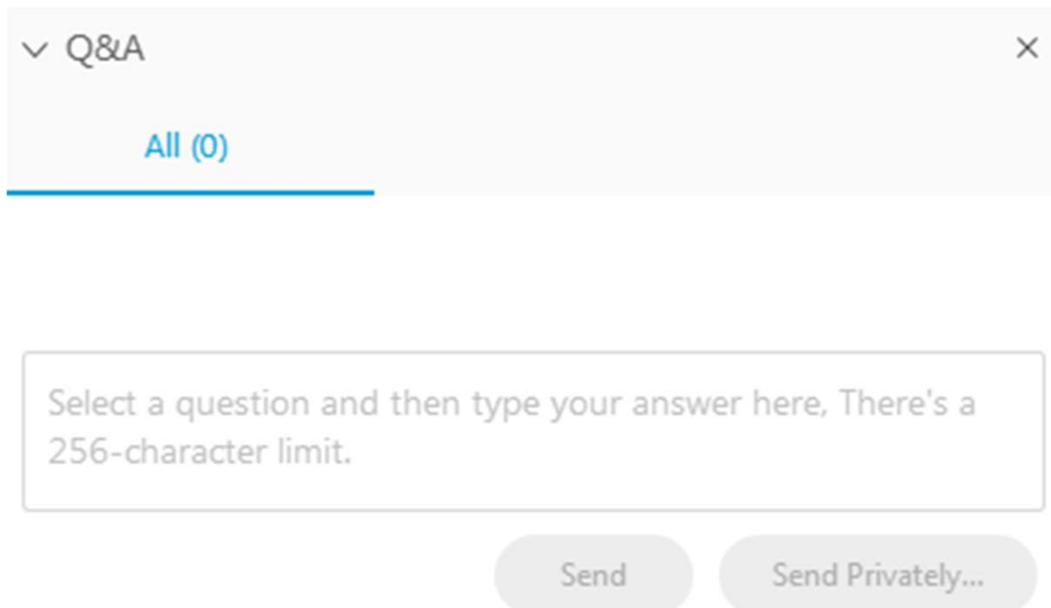
Conclusions

- SAM has been improved and now includes both low- and high-temperature electrolysis
- Optimal system configurations involve some heat trimming
- Aggressive cost reductions are needed for all systems to achieve $2/kg target in Daggett, CA
- PV-MSALT-HTSE system has the lowest HLC across the country under current technology assumptions
- PV-Battery-LTE system becomes the lowest HLC option across the country in the future due to assumed reductions in LTE and PV costs
- MSALT-HTSE system can achieve 2$/kg H_2 in excellent resource location in 2050 if salt tower costs are 2500 $/kW or below

Thank You

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov

Supporting Slides

Potential Follow on Work

A method for simulating technologies together using shared site data (i.e., solar resource, market grid prices, and land boundaries)

Modeled Technologies:

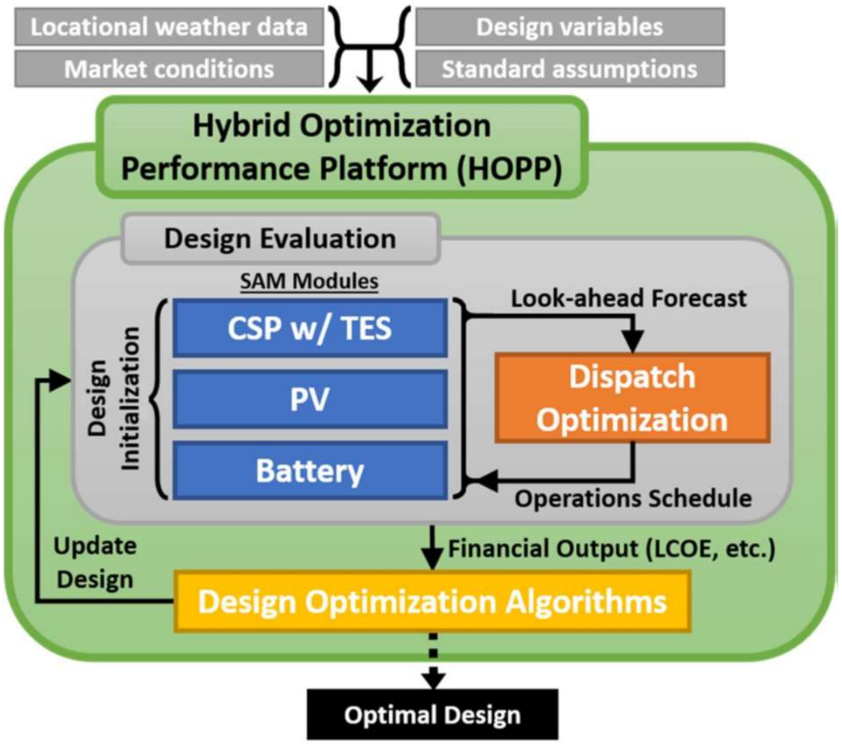
- Parabolic trough concentrating solar power (CSP)
- Power tower CSP
- Photovoltaics arrays (PV)
- Lithium-Ion batteries
- Wind farms

Dispatch Optimization: Revenue maximizing

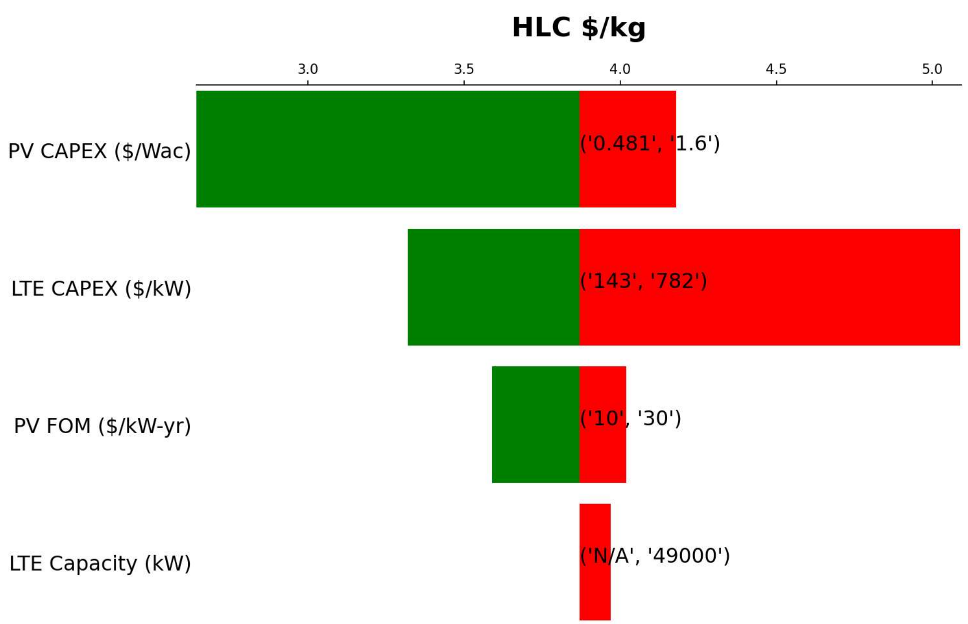
Design Analysis:

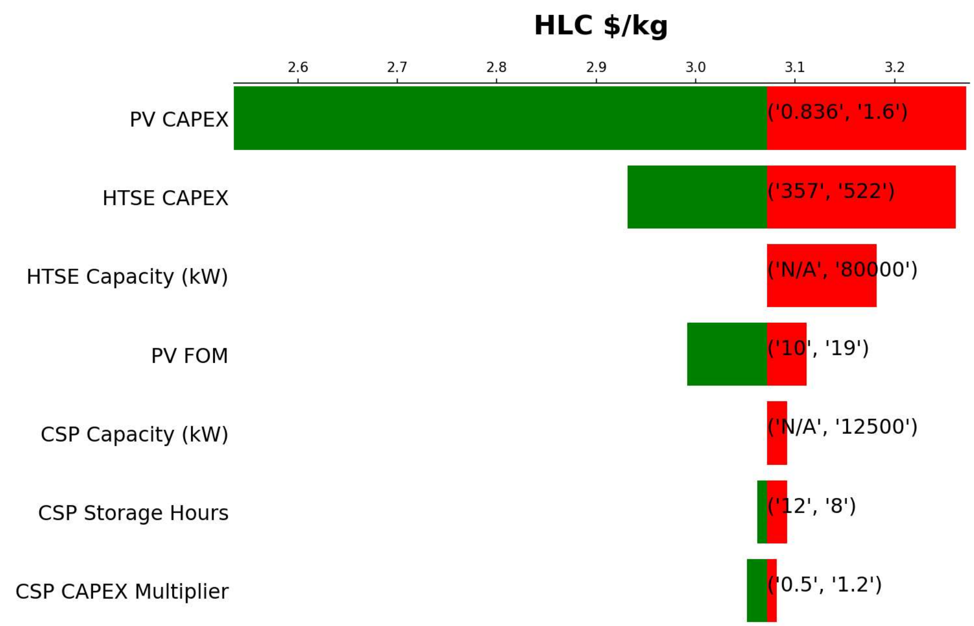
- Sampling Design Space
- Single-Objective Optimization (untested)
- Pareto Analysis (untested)

GitHub Branch: [WB_CSP_dispatch_design]



Tornado Plots for Well Sized System Configurations in Daggett, CA

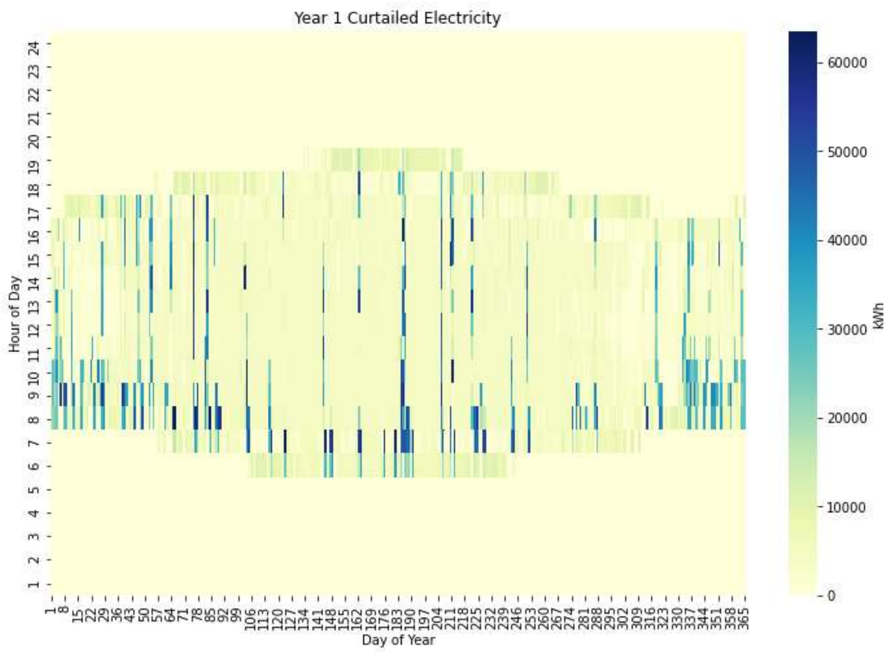


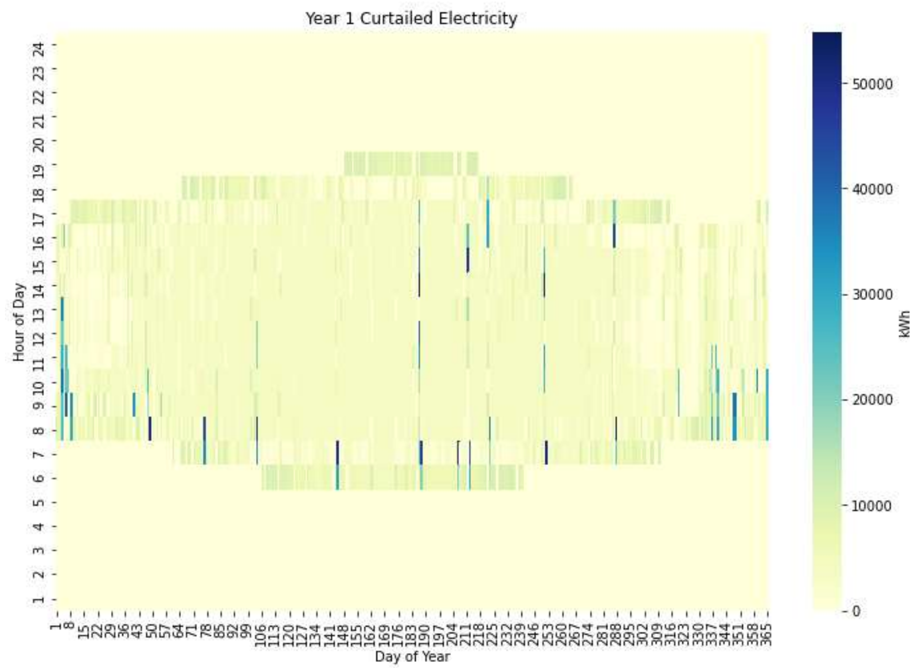


- 2020 scenario at Daggett, CA for a 100 MW PV system and 55 MW LTE system without battery storage
- Key cost drivers are LTE purchase costs and PV installed costs

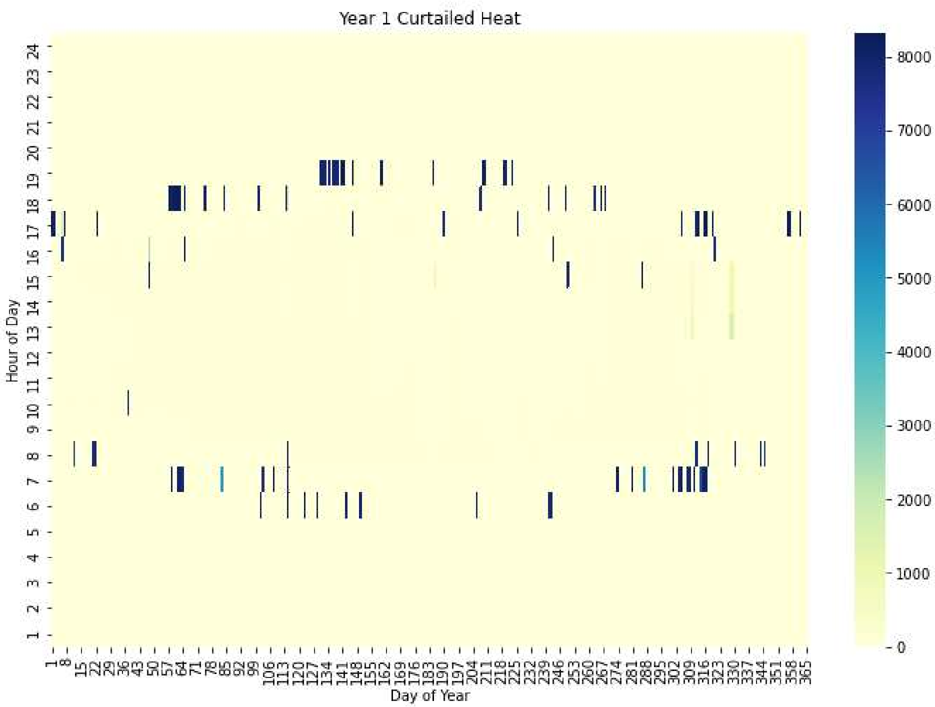
- 2020 Scenario at Daggett, CA for a 100 MW PV System, Molten Salt Nominal Thermal Power of 15 MWth and 70 MW HTSE system
- Key cost drivers are PV installed costs and HTSE purchase costs

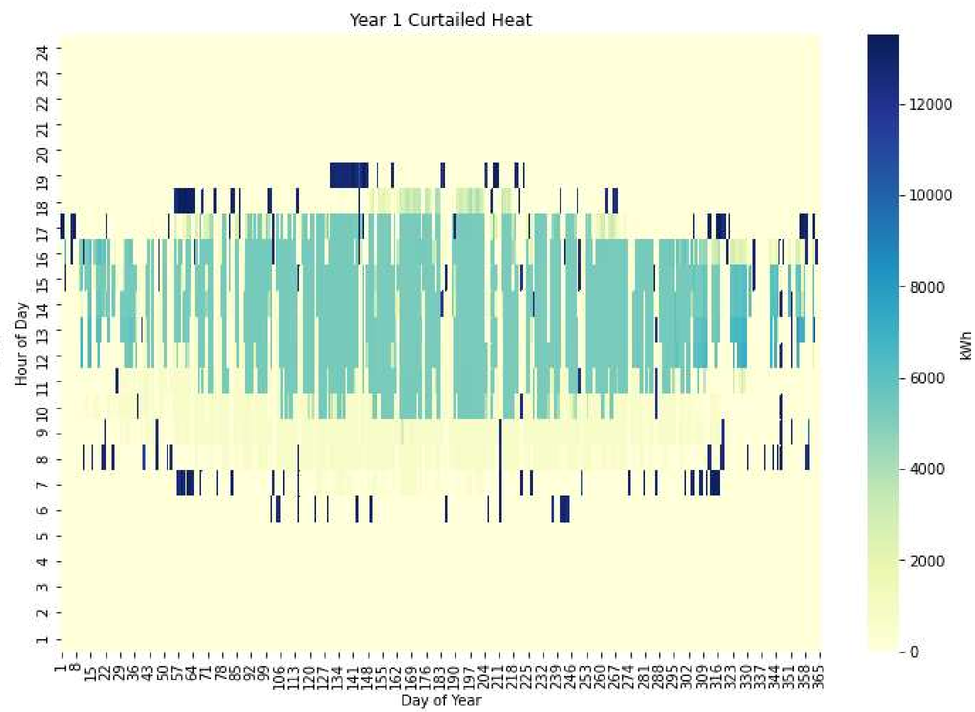
Tower Thermal Capacity 10000 -15000 MWth Electricity Curtailment





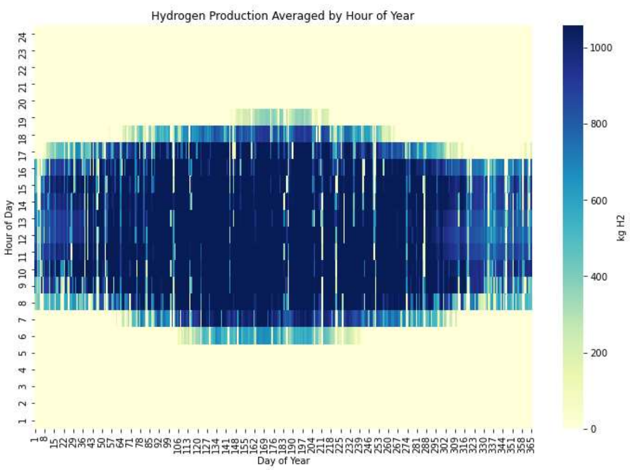
Tower Thermal Capacity from 10000 -15000 MWth – Heat Curtailment





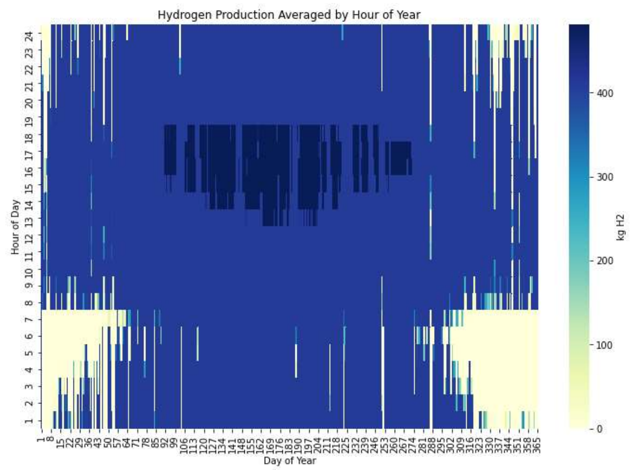
Hourly Hydrogen Production in Year 1

PV coupled to LTE without batteries



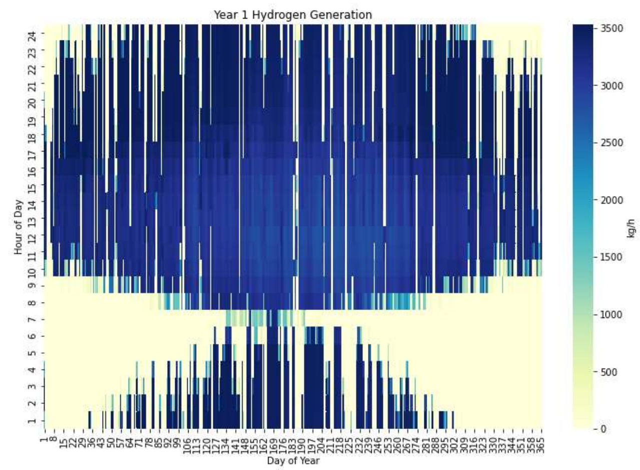
Capacity factor of 39% obtained for a 55 MW LTE system coupled to 100 MW PV @ Daggett

PV coupled to LTE with batteries

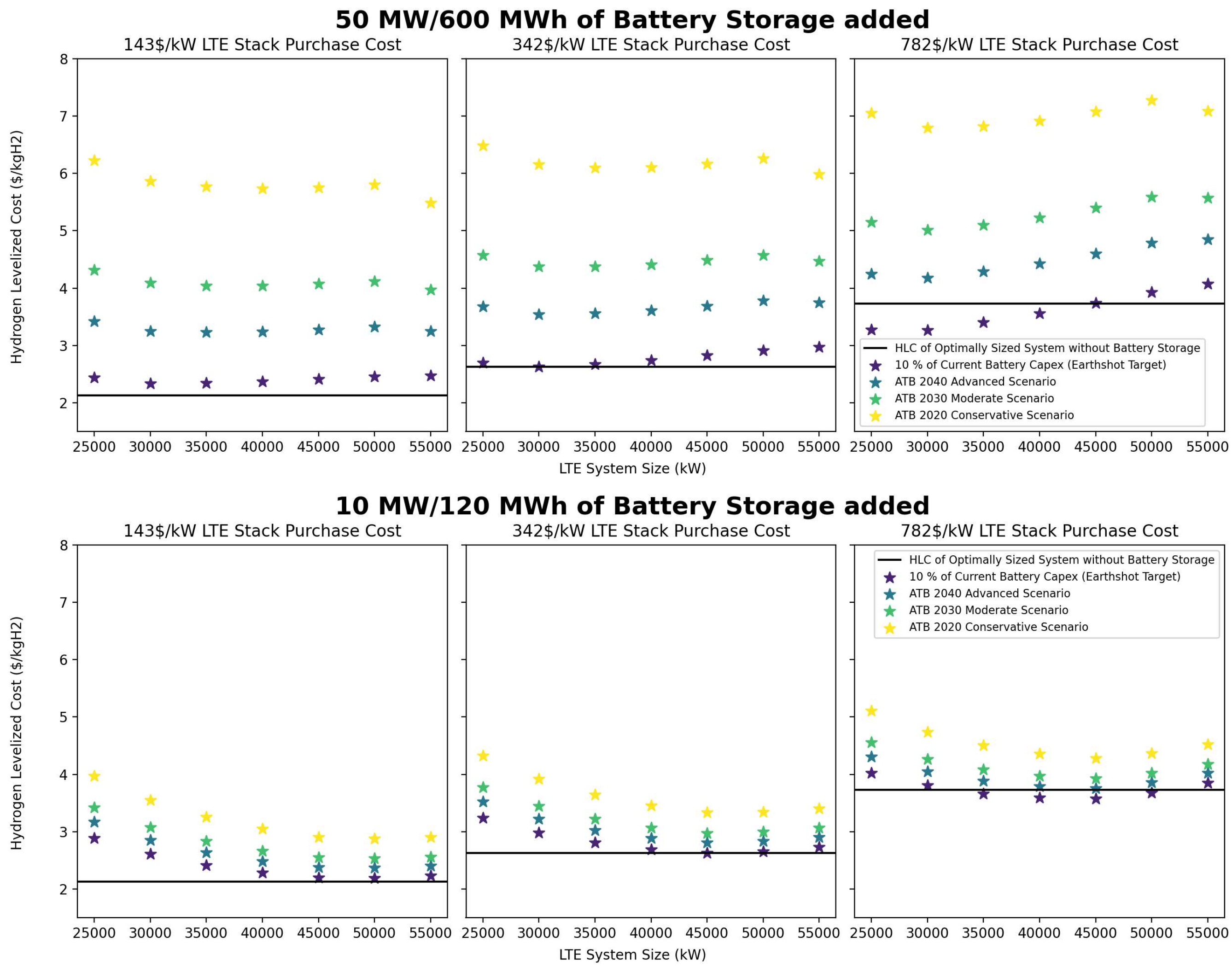


Capacity factor of 76% obtained for a 25 MW LTE system coupled to 100 MW PV with 50 MW/600 MWh of battery storage @ Daggett

Hybrid Salt Tower coupled to HTSE



Capacity factor of 58% obtained for a 130 MW HTSE system coupled to a molten salt tower providing 115 MWe and 25 MWth with 12 hours of thermal storage @ Daggett



- Larger battery systems have promising impacts on HLCs only at vastly reduced battery costs (Earthshot targets)
- Smaller battery systems can extend the electrolyzer capacity factor without significantly impacting the HLCs for two cost scenarios