The #H2IQ Hour

Today's Topic:

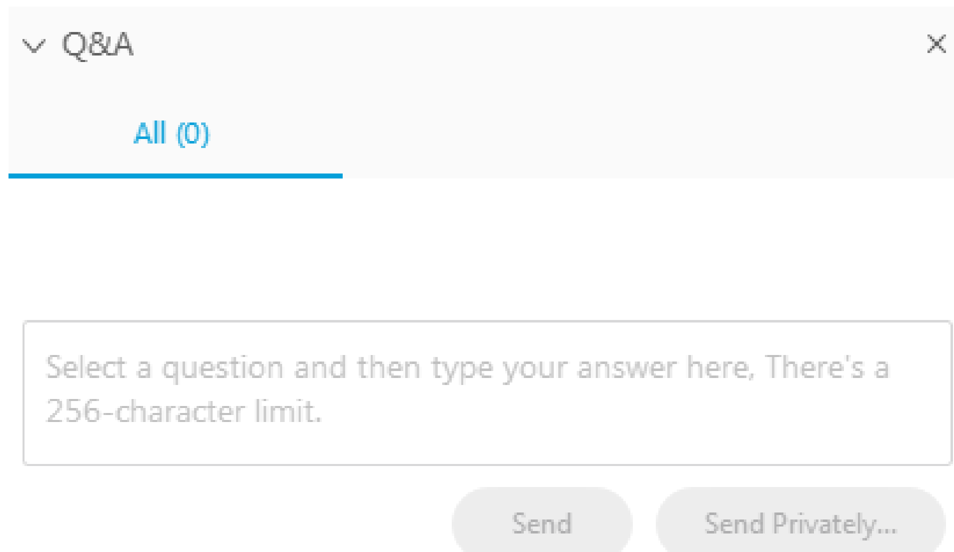
Long Duration Energy Storage Using Hydrogen and Fuel Cells

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).

INCREASE YOUR H2IQ

The #H2IQ Hour Q&A

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



StoreFAST Model Overview: Long Duration Energy Storage Using Hydrogen and Fuel Cells

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SPIA: Sam Baldwin

March 24, 2021

H2IQ Hour

Outline

- **Methods**
- Results
- StoreFAST modelling tool & demo

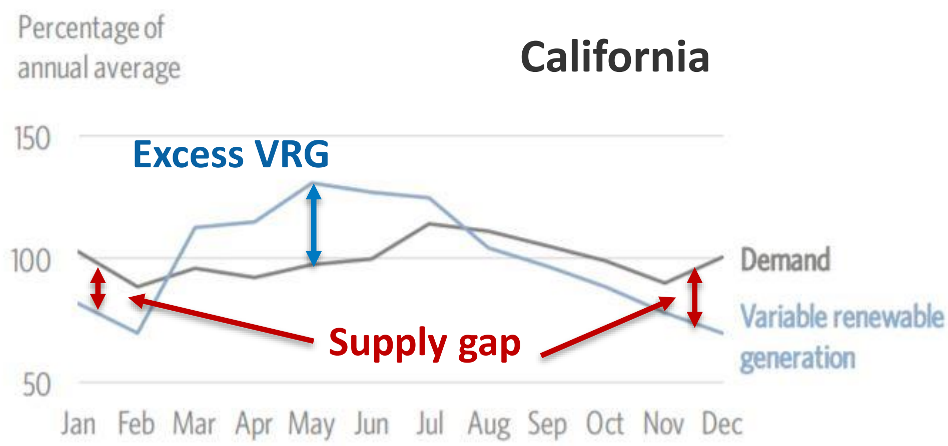
High variable renewable energy (VRE) grids will require seasonal energy storage or flexible power generation

- Exceeding ~80% VRE penetration will require seasonal energy storage or flexible low-carbon generation[1][2][3]
  - Intermittent operation with low capacity factors

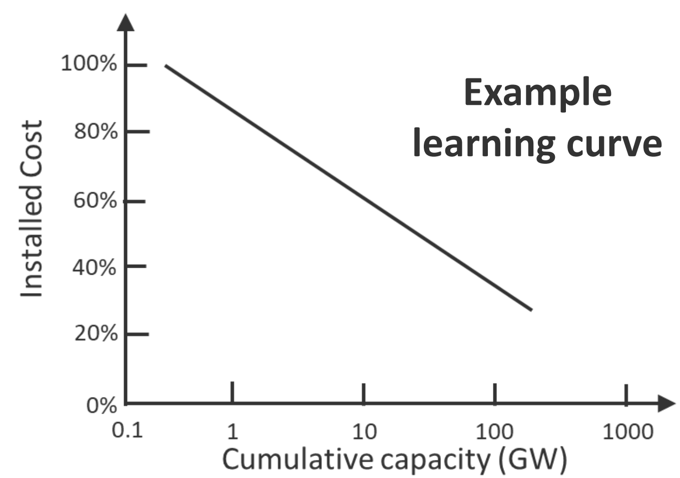
- Limitations of previous studies
  - Historic capital costs that ignore potential for future cost reductions
  - Limit storage durations to < 12 hours
  - Focus on narrow subset of technologies

- Most technologies experience cost reductions over time (learning, scale)

High VRE grid studies must use up-to-date technology costs and consider all options



Projected variable renewable generation potential and demand for a 100% VRG California grid throughout one year[4].



Generic example of a learning curve plot for a power generation technology.

[1] P. Denholm, Renewable Energy 130 (2019) 388-399
[2] M.R. Shaner, S.J. Davis, N.S. Lewis, K. Calderia. "Geophysical constraints on the reliability of solar and wind power in the United States." Energy & Environ. Sci 11 (2018) 914-925
[3] B. Pierpont. "Mind the Storage Gap: How Much Flexibility Do We Need for a High-Renewables Grid?" Green Tech Media, June 2017.
[4] B. Pierpont, D. Nelson, A. Goggins, D. Posner. "Flexibility: The path to low-carbon, low-cost electricity grids." Climate Policy Initiative, April 2017.
[5] Hydrogen Council, 2020. "Path to hydrogen competitiveness: A cost perspective."

Levelized cost of energy (LCOE) is used as a convenient metric for comparison

- **Levelized cost of energy (LCOE)**: *Unit price of energy for plant to break even at end of life*

- Considers capital costs, finances, return on equity, taxes, O&M costs, and ***energy input***
  - **Energy storage systems:** LCOE includes charging cost (electricity price ÷ RT efficiency)
  - **Power generation systems:** LCOE includes fuel cost (fuel price ÷ discharge efficiency)

- The Storage Financial Analysis Scenario Tool (StoreFAST) provides a ***general, flexible framework*** for detailed LCOE calculation and sensitivity analysis across technologies

LCOE calculation inputs
- Capital & O&M costs
- Plant size, life, efficiency
- Electricity and/or fuel cost
- Finance specifications
- Annual operation (capacity factor)

→ StoreFAST →

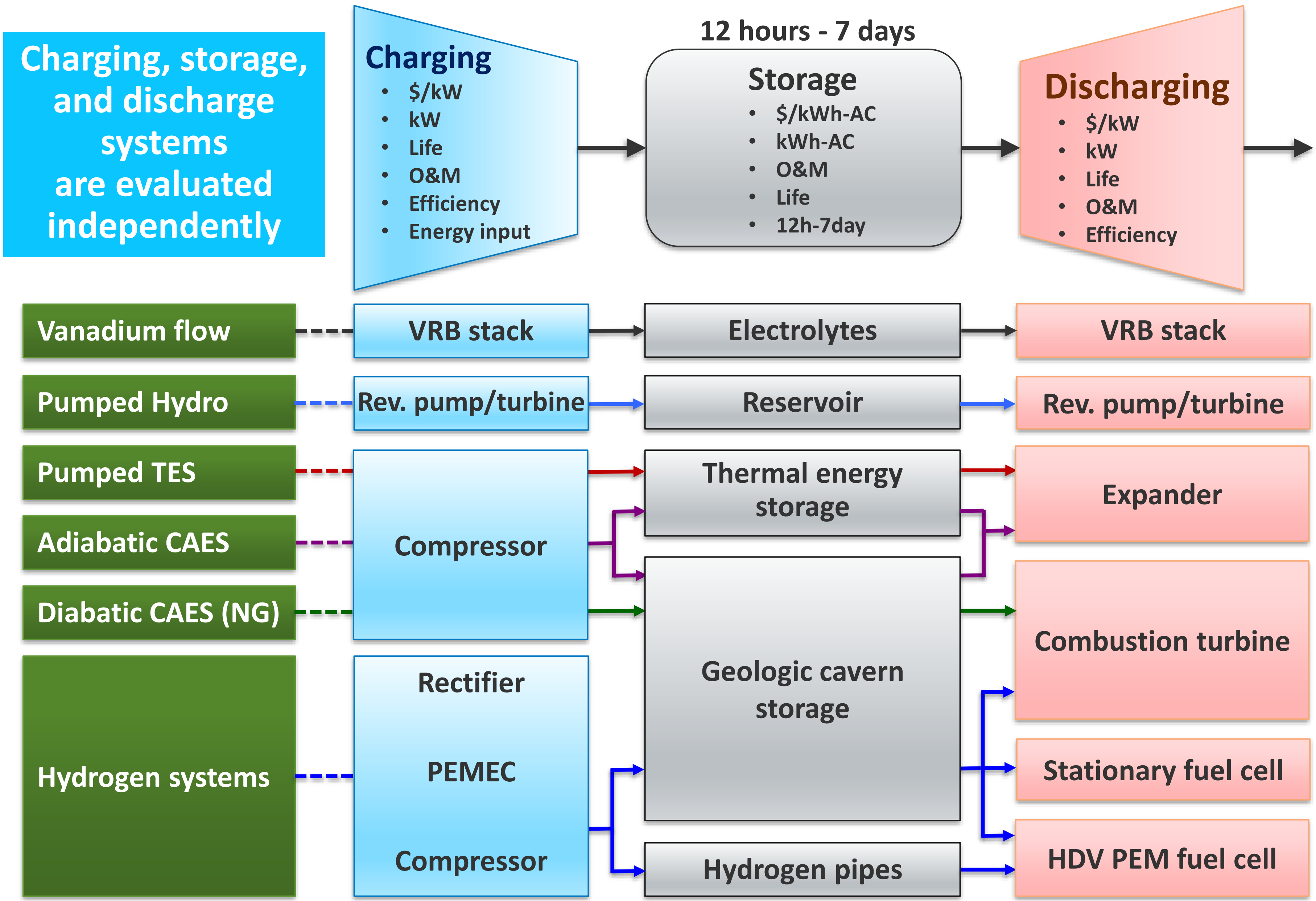
LCOE calculation outputs
- LCOE comparison
- Cost breakdown
- Sensitivity analysis
- Monte Carlo analysis

- Systems designed for **100 MW discharge capacity**
- Consider **storage durations > 12 hours**, up to 7 days

Accurately comparing LCOE requires specification of capital and operating costs, system and component performance, and plant financing

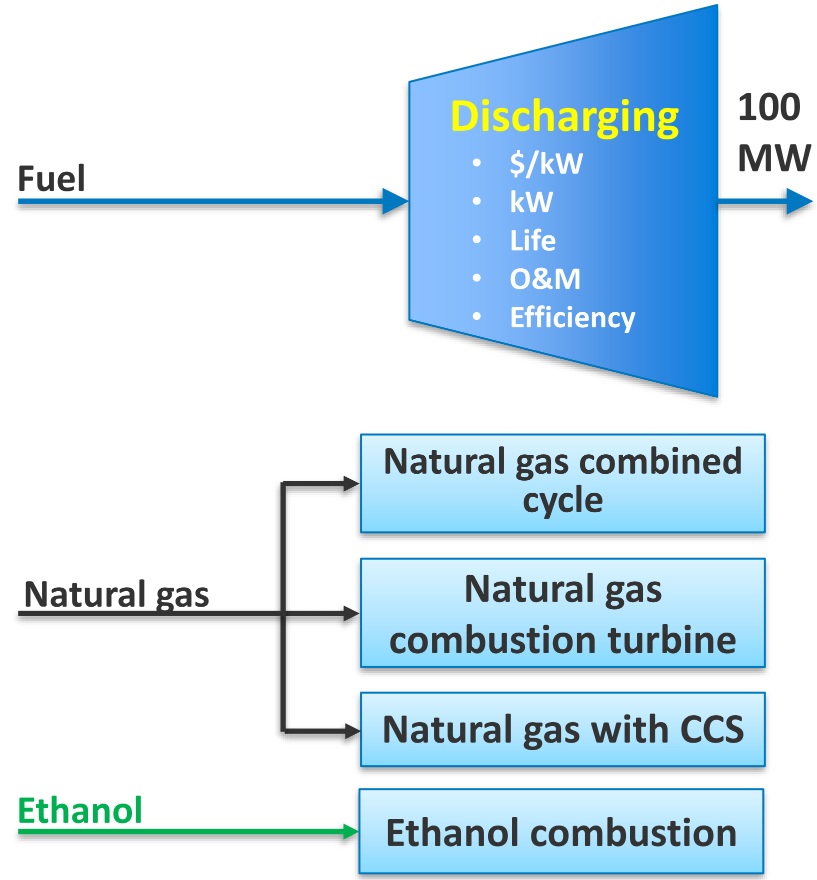
https://www.nrel.gov/storage/storefast.html

Disaggregation of Energy Storage Systems



Parametarization of Flexible Power Generators

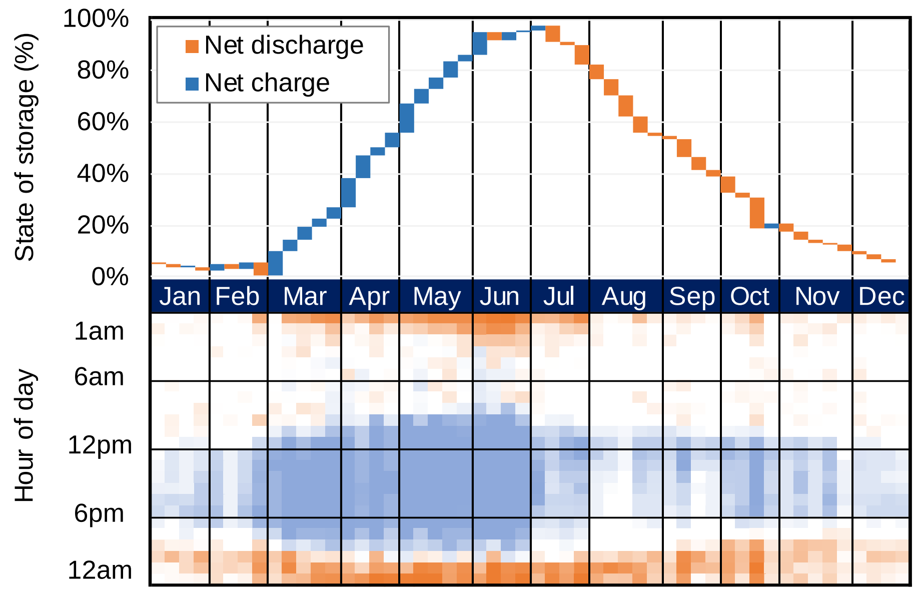
- NG-CCs and NG-CTs currently contribute toward grid flexibility
- Many studies consider natural gas with CCS for future flexible power generation systems
- Ethanol offers dispatchable renewable fuel



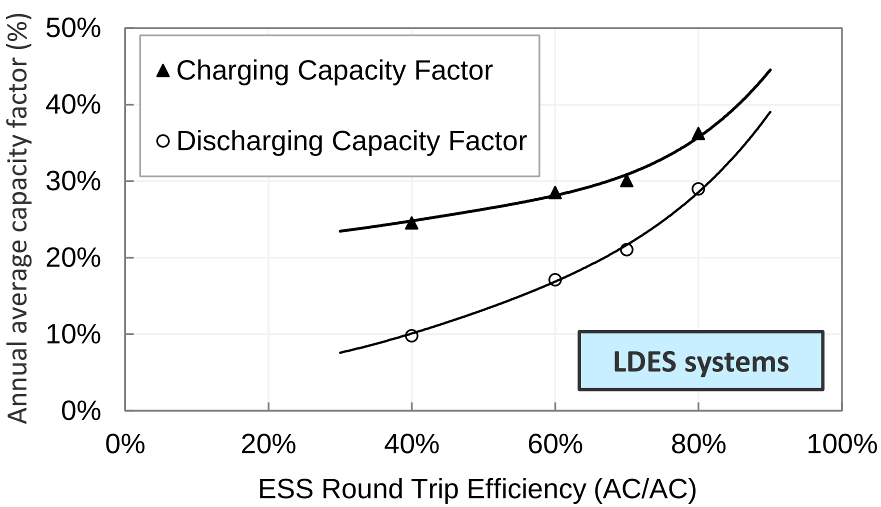
Seasonal storage technologies must be compared to dispatchable low-carbon power generation systems

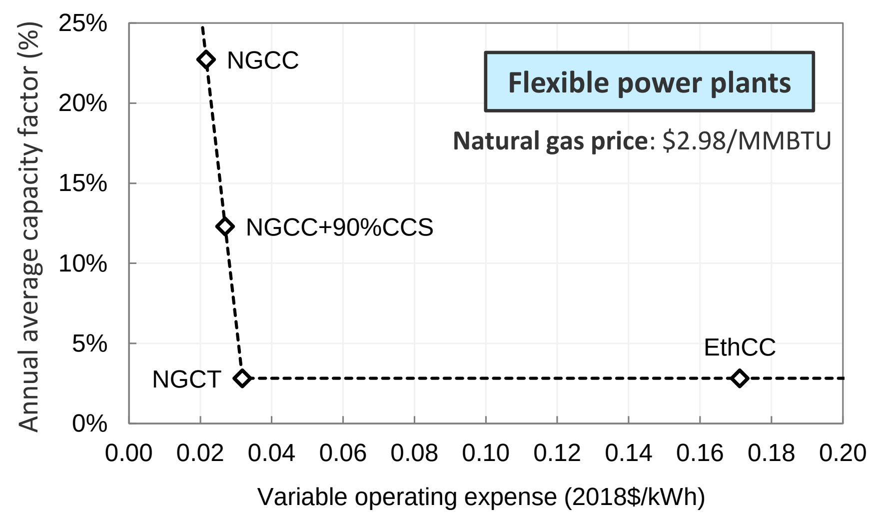
Asset utilization depends on operating costs. PLEXOS modeling used to estimate technology-specific capacity factors

- At least 5 days of storage was desired by the grid in the PLEXOS modeling
- Capacity factors are specific to region (Western U.S.) and scenario (85% VRE)
- PLEXOS NG-CC / NG-CT CFs verified with published CEC data and personal communication with a utility
- NG-CC|CCS CF is interpolated between NG-CT and NG-CC as a *f*(var OpEx)



Annual storage cycling for a LDES system with 40% round trip efficiency[5].





[5] M. Pellow, J. Eichman, J. Zhang, O. Guerra. Valuation of Hydrogen Technology on the Electric Grid Using Production Cost Modeling. (forthcoming) NREL 2020.

Outline

- Methods
- **Results**
- StoreFAST modelling tool & demo

First, let's evaluate the Current Cost scenarios

Current Costs

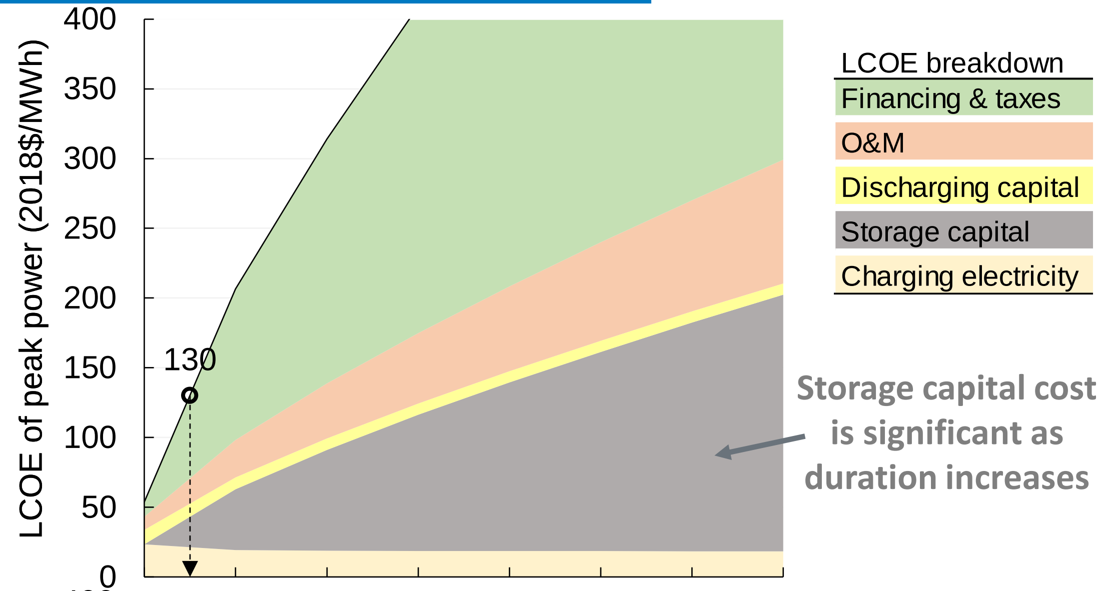
Future Costs

LCOE breakdowns illustrate importance of low storage capital cost for longer durations

Scenario:
Current Costs

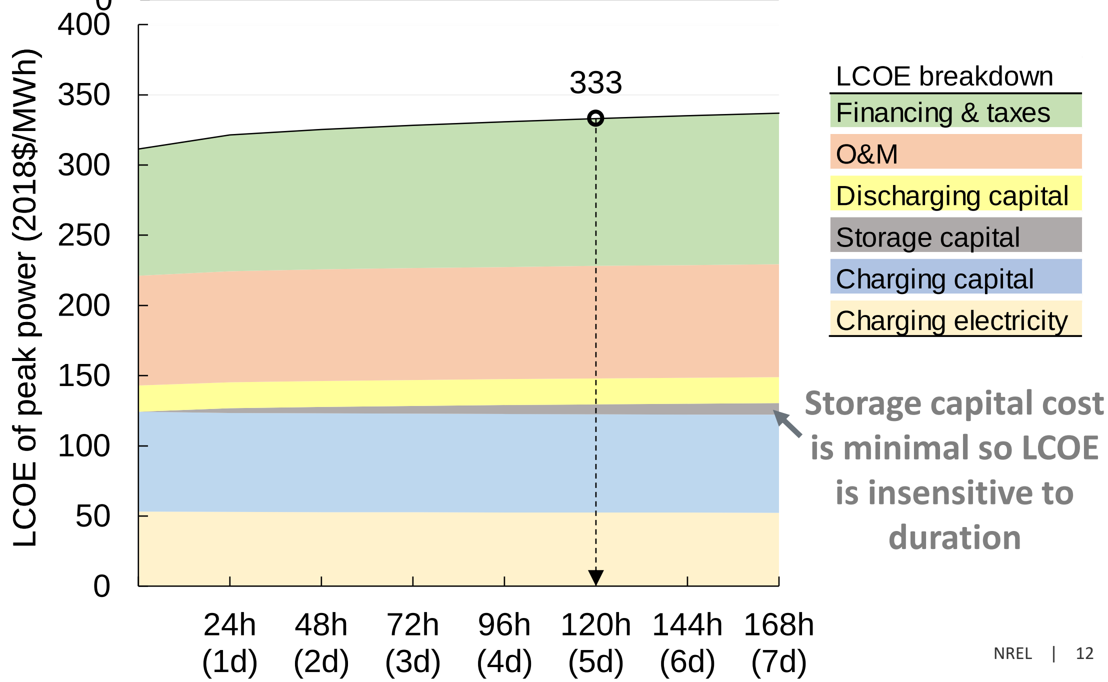
Pumped Hydro Storage (PHS)

- Significant storage capital
- Financing the large upfront capital cost is a major LCOE contribution
- O&M increases as storage capital costs increases



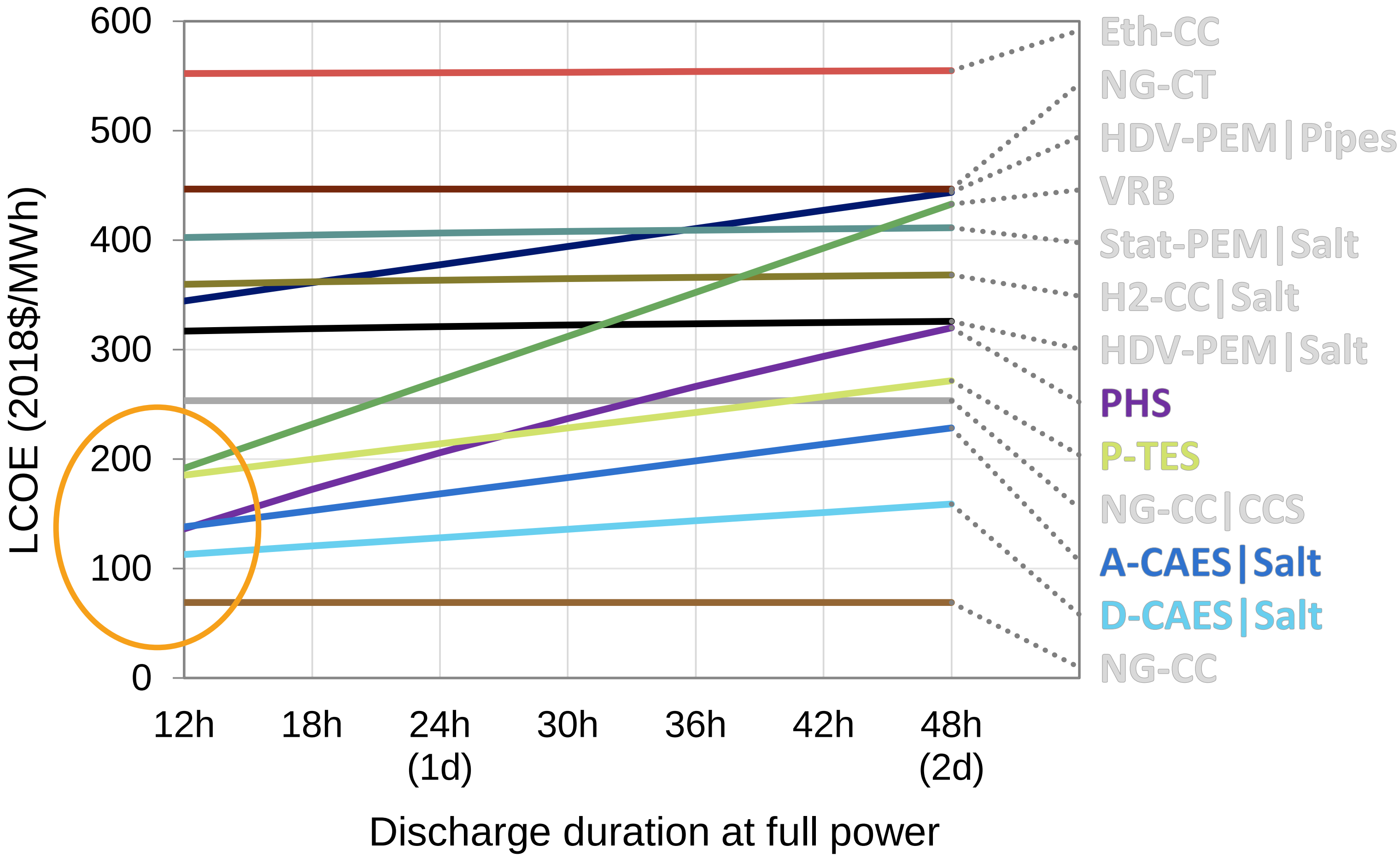
HDV-PEM|Salt

- Low storage capital costs
- Energy dense fuel
- Minimal change in LCOE as duration increases



“Calibrated CF” scenario LCOEs match expectations for 12h duration in current grid

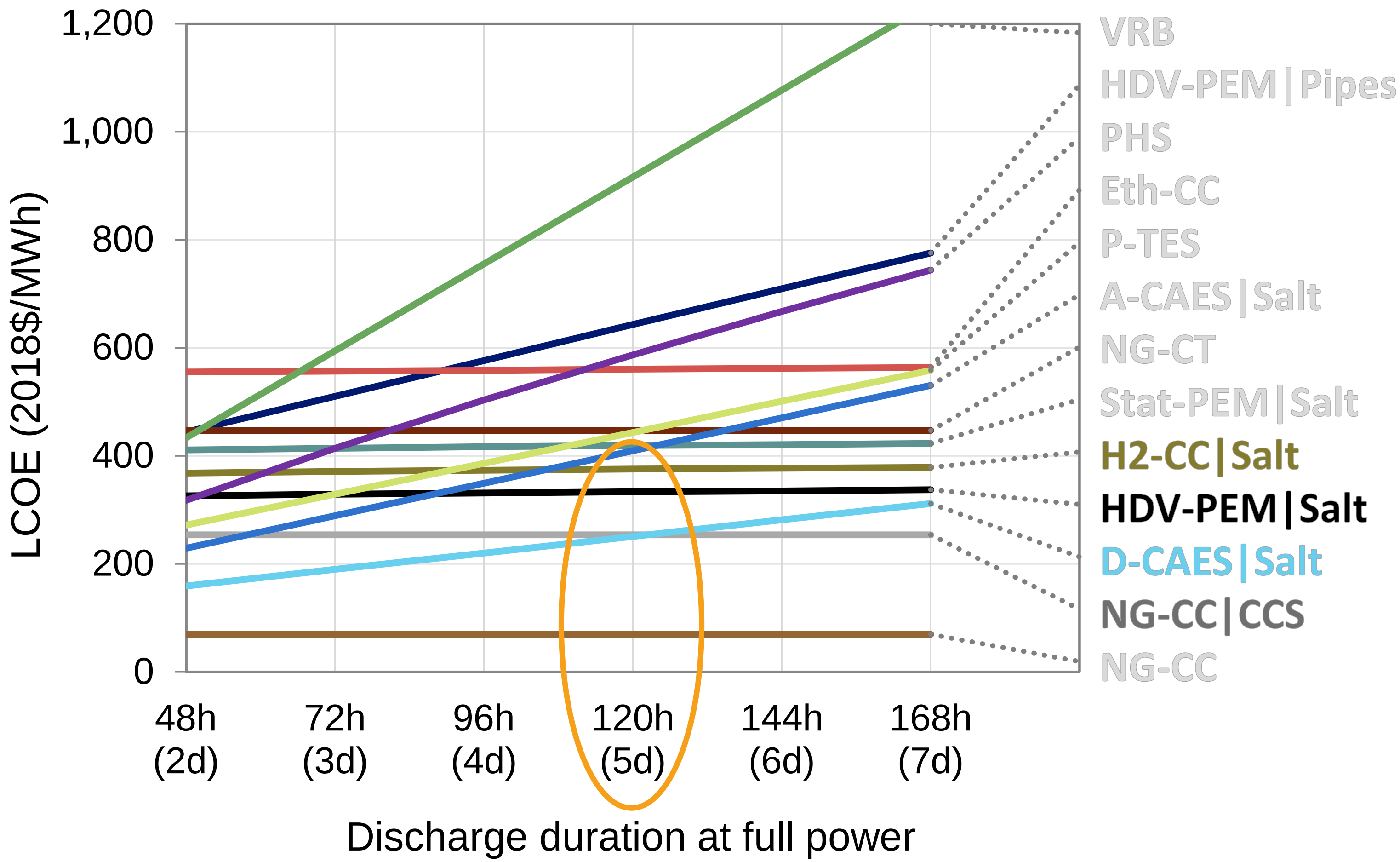
Scenario:
Current Costs



- PHS becomes the lowest cost storage at 12 hours, consistent with what is expected for that duration on today’s grid
- Vanadium flow batteries (VRB) are just above D-CAES|Salt and A-CAES|Salt at 12 hours

At 120 hours, D-CAES and NGCC|CCS are the lowest cost after NGCC

Scenario:
Current Costs



- Pumped hydro, A-CAES|Salt, P-TES, and VRB costs rise significantly with longer durations
- NG-CC, NG-CC|CCS, D-CAES|Salt, and geologic hydrogen storage are the lowest LCOE for long duration ratings

Next, let's evaluate the Future Cost scenario

Current Costs

Calibrated CF

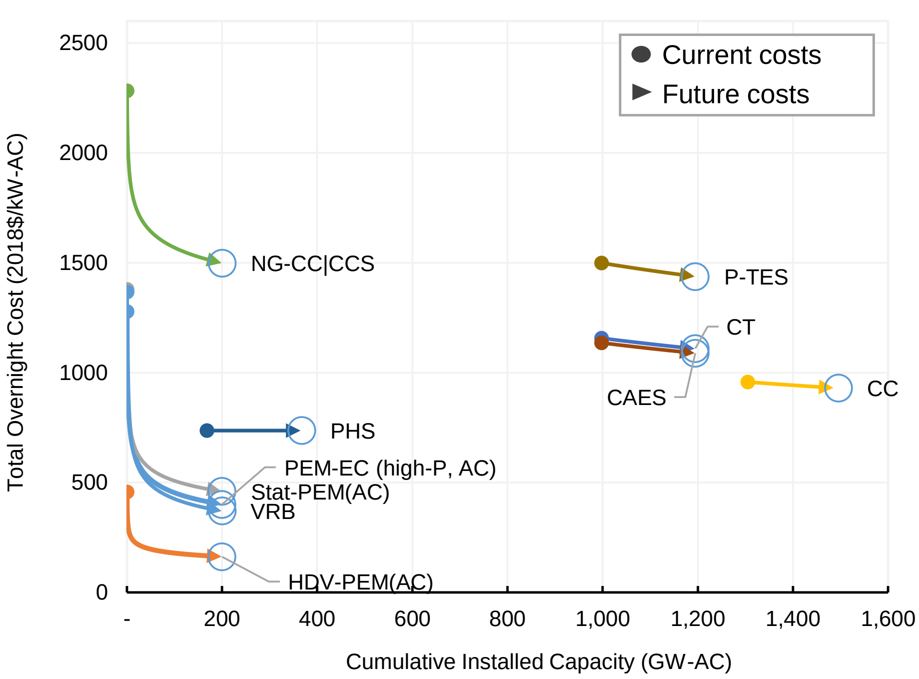
Future Costs

Calibrated CF

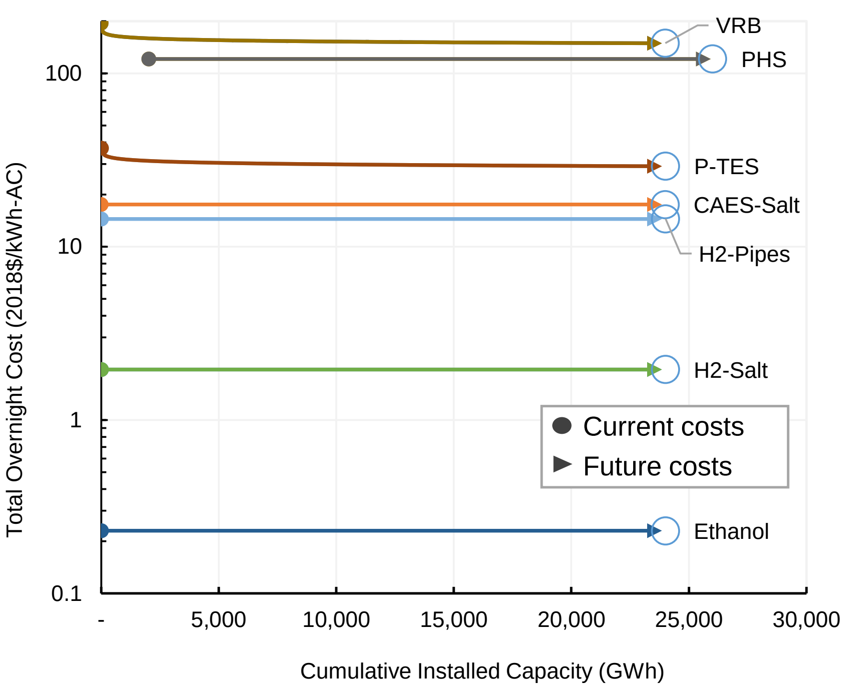
Future costs reduction

- Based from current cost & deployment
- Projected to 200 GW future capacity
- Technology learning rate

Power cost reductions

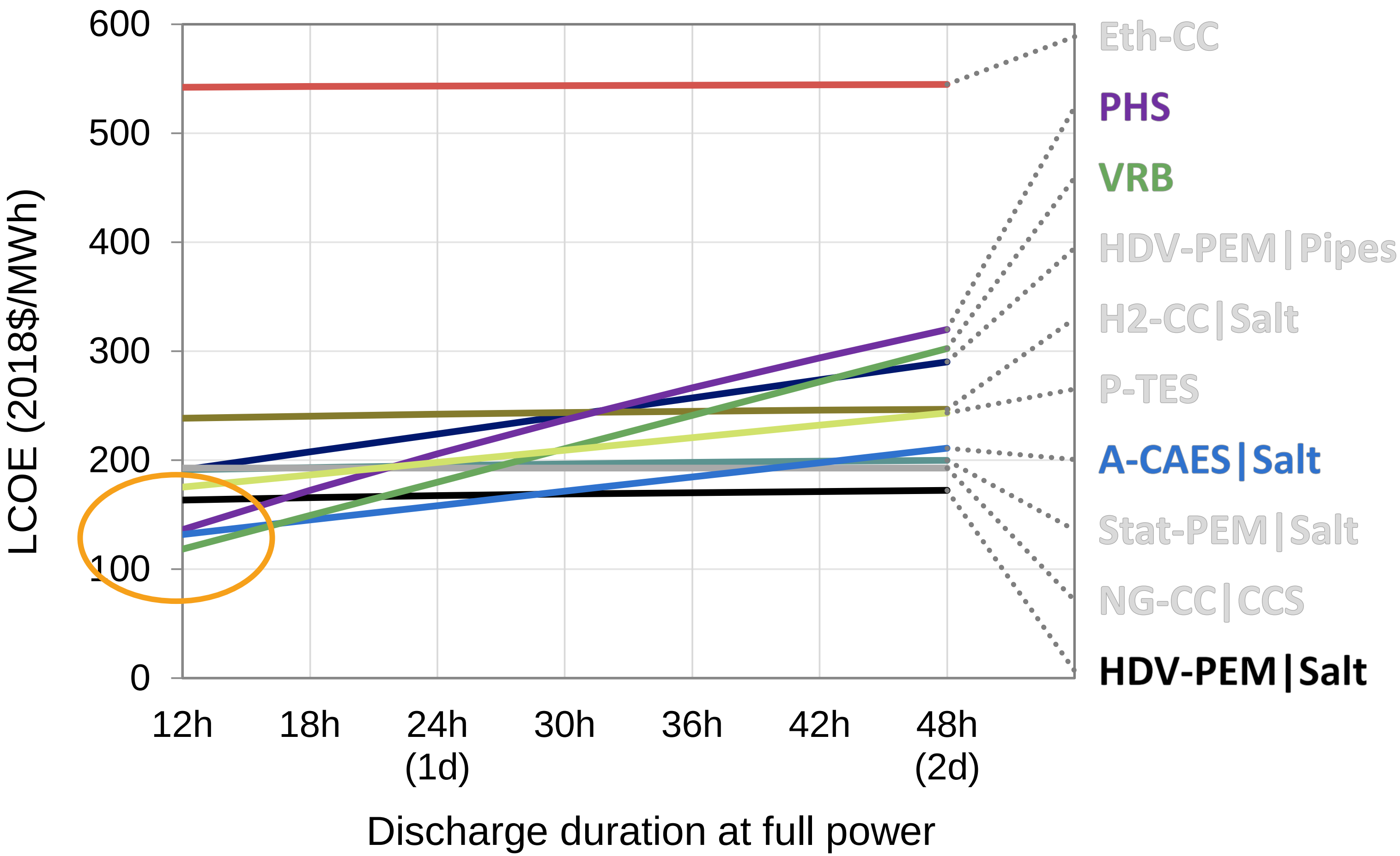


Energy cost reductions



PHS, VRB, and A-CAES are the lowest cost for a 12h storage duration

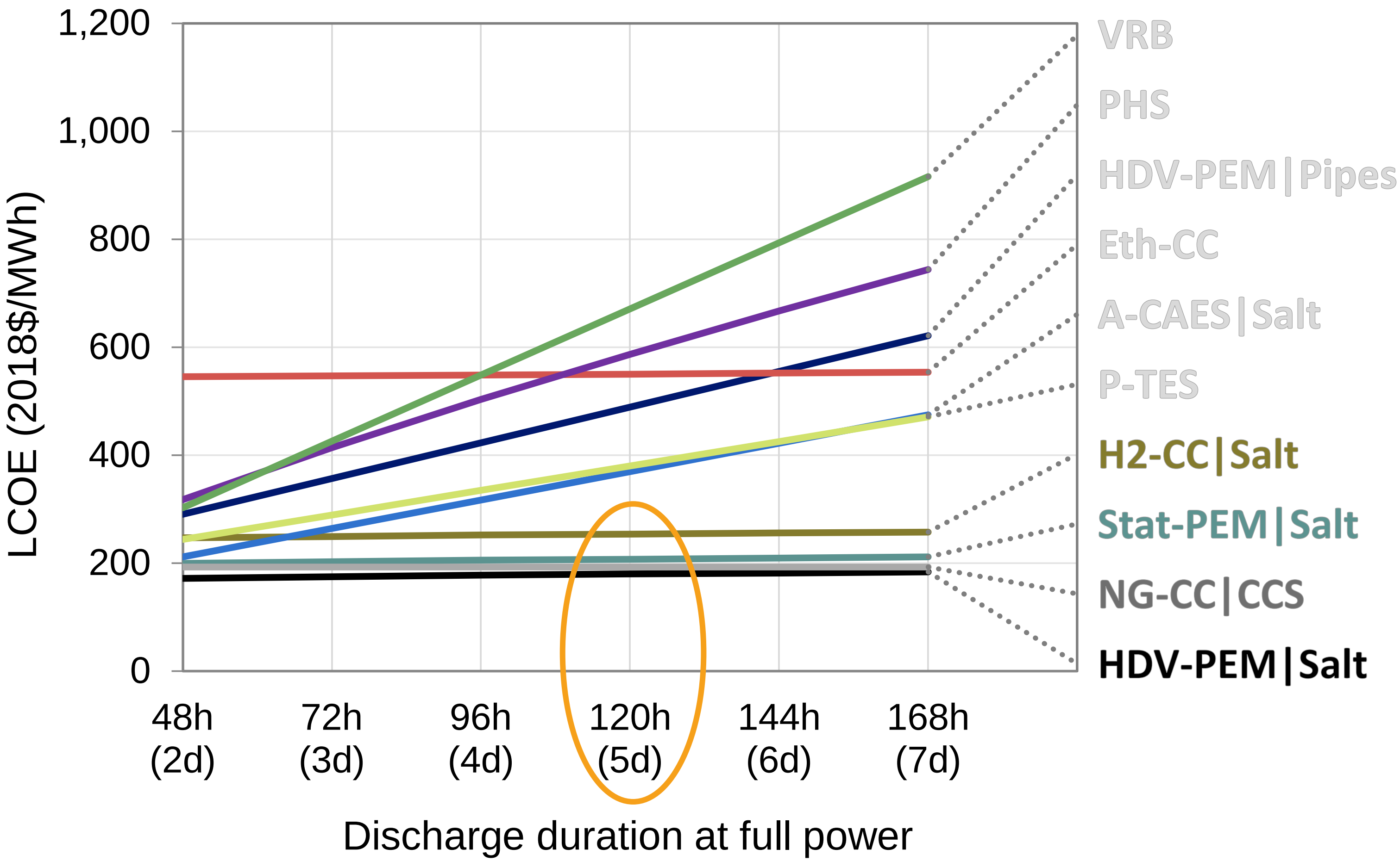
Scenario:
Future Costs



- PHS and VRB are very competitive with PHS at 12-hour storage durations if future cost reductions are achieved
- Ethanol's high variable OpEx results in a low capacity factor and high LCOE

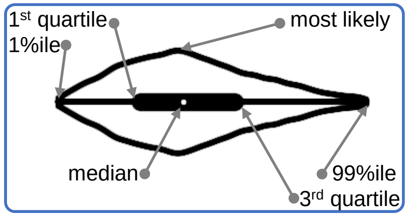
At 120 hours, HDV-PEM|Salt and NG-CC|CCS have the lowest LCOE

Scenario:
Future Costs

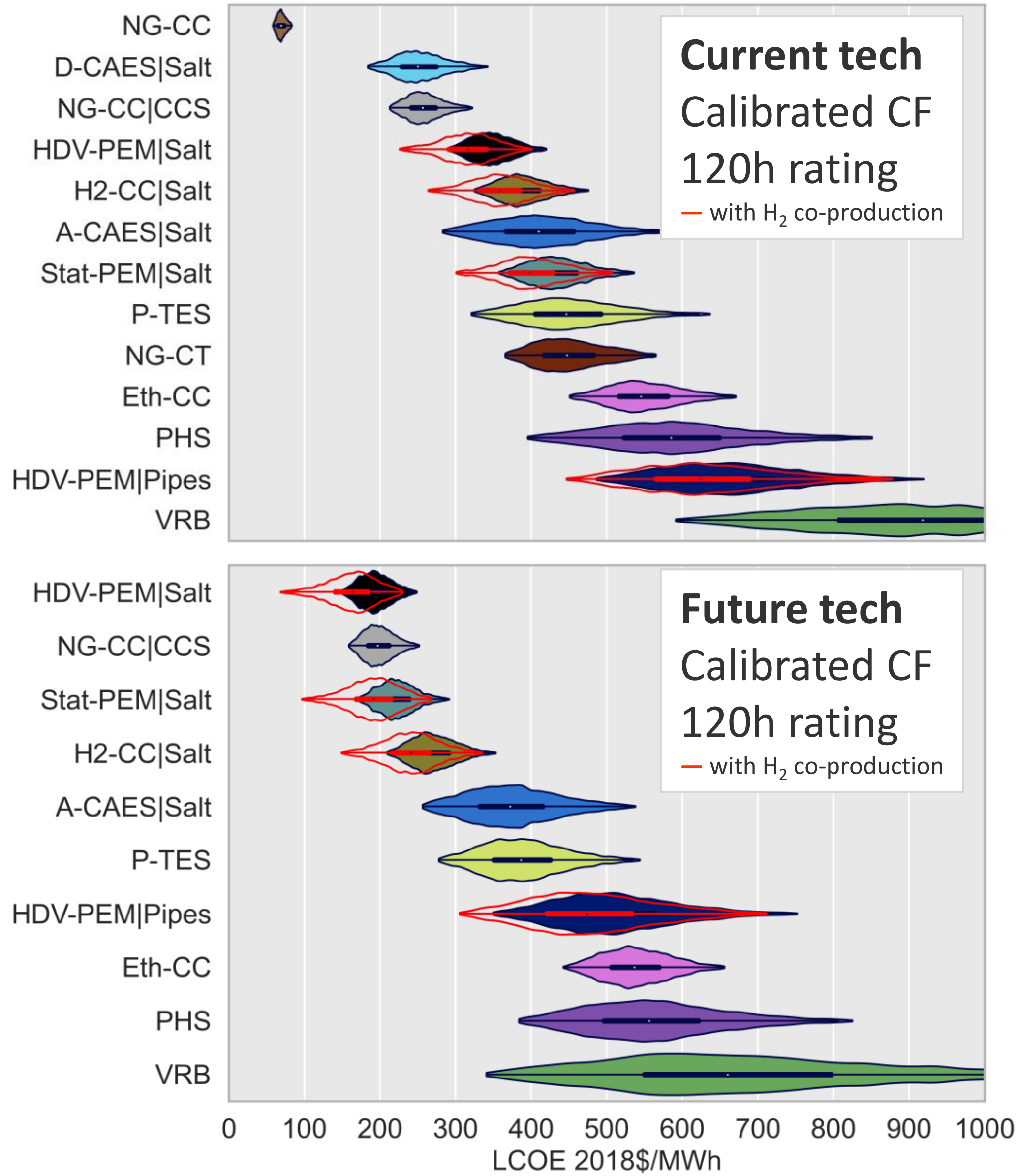


- Above 48 hours of storage, HDV fuel cells with geologic storage and NGCC|CCS have very similar LCOE due to low cost geologic storage
- HDV fuel cells provide lower capital cost with sufficient durability for this application

Geologic H_2 storage and NGCC|CCS provide lowest cost future options for 120h of flexible power



- With current costs, D-CAES and NG-CC|CCS provide the lowest LCOE
- If future capital costs are realized, geologic hydrogen and NG-CC|CCS are the most competitive
- Accounts for sensitivity to learning rate, future scale, and cost of energy input
- Without geologic storage or CCS: P-TES, Eth-CC, H_2-pipes are lowest-cost options
- Uncertainty analysis shows significant overlap in technologies



Outline

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- **StoreFAST modelling tool & demo**

Store-FAST Purpose

- Provide **consistent framework** for evaluation of utility scale flexible power
  - **Energy storage** systems
  - **Flexible power** generators
- Allow **side-by-side evaluation** of diverse technology options
- Incorporate use profiles **informed by grid models**
- Provide **risk analysis** based on for variability and uncertainty of inputs

Caveats and Limitations

- The model attributes cost to energy and hydrogen co-products only. Revenue is not modeled from other possible value streams:
  - ancillary services
  - transmission deferment
- Model reflects an 85% renewable grid scenario.
- Model can use simple amortization of any refurbishment costs (it does not perform detailed capitalization of refurbishment costs such as stack replacements, battery replacements)

Store-FAST Model Based on H2-FAST

User inputs

- **Capital costs** (charging, storage, discharging)
- **Maintenance cost** (fixed, variable)
- **System usage** (capacity factors, system life)
- **Energy use** (charging, fuel use, standing losses)
- **Energy prices** (electricity, fuel, co-product value)
- **Financial parameters** (e.g. depreciation schedule, interest rates, etc.)

Model computation framework: Generally Accepted Accounting Principles (GAAP)

- **Income statement** projections (revenues, expenses, taxes)
- **Cash flow statement** projections (cash on hand, capital expenditures, financing transactions)
- **Balance sheet** projections (assets, liabilities, equity)

Model outputs

- Levelized cost of electricity (LCOE) – total, breakdown, distribution
- Financial performance parameters (e.g. Internal rate of return, pay-back period, break-even price of hydrogen)
- Time series charts for all financial line items

Model Use Step 1: Specify Tech Values in "Technology Specifications" tab

Key global inputs for all systems

Global baseline values		References
Storage duration rating (h)	120	1
Electricity for energy storage ($/kWh)	0.020	2
Natural gas ($/MMBTU)	2.98	38
Ethanol ($/gal)	2.22	13, 39, 40
CO_2 transportation and sequestration cost ($/tonne)	65	33, 34, 35

Side by side systems

Capital costs on system level ($/kWh, $/kW)

Tech name	HDV-PEM|Salt	NG-CC|CCS	Eth-CC	PHS
Capital costs				
Charging ($/kW-AC-in)	1,673	0	0	0
Charging base capacity (kW)	1	0	0	0
Charging scaling factor	1	0	0	0
Effective storage ($/kWh-AC-out)	1.96	0	0.23	121.3
Storage base capacity (kWh)	7,050,315	0	1	12,000,000
Storage scaling factor	0.48	0	1	0.77
Storage cost recovery at end of life (%)	100%	0%	0%	100%
Discharging ($/kW-AC-out)	464	2543	1068	821
Discharging base capacity (kW)	1	1	1	1
Discharging scaling factor	1	1	1	1

Model Use Step 1: Specify Tech Values in "Technology Specifications" tab

O&M specifications fixed, variable

Tech name	HDV-PEM|Salt	NG-CC|CCS	Eth-CC	PHS
Operations & maintenance (O&M) costs				
Charging O&M				
Fixed				
O&M (labor, maintenance items) ($/kW_AC_in_y)	12.8	0	0	0
Property tax, insurance, licensing, permitting (% of cap cost)	1.50%	0	0	0
Variable				
Other ($/kWh-AC-in)	0.0013	0	0	0
Storage O&M				
Fixed				
Maintenance, property tax, insurance, licensing, permitting (% of cap cos	1.50%	1.50%	1.50%	1.50%
Discharging O&M				
Fixed				
O&M (labor, maintenance items) ($/kW_AC_out_y)	12.8	27.2	13.9	12.5
Property tax, insurance, licensing, permitting (% of cap cost)	1.5%	1.5%	1.5%	1.5%
Variable				
Other ($/kWh_AC_out)	0.0028	0.00576	0.00251	0.0003

Model Use Step 1: Specify Tech Values in "Technology Specifications" tab

Feedstock use per kWh
electricity, natural gas, ethanol, CO_2 byproduct, H_2 co-product

Other system inputs
System type, life, power generation capacity

Tech name	HDV-PEM|Salt	NG-CC|CCS	Eth-CC	PHS
System operations				
Primary energy use				
Electricity use for power generation (kWh_AC_in/kWh_AC_out)	2.86	0.00	0.00	1.23
Natural gas use for power generation (MMBTU/kWh_AC_out)	0	0.007124	0	0
Ethanol use for power generation (gal/kWh_AC_out)	0	0	0.07608	0
CO_2 to for sequestration (m.tonnes/kWh_AC_out)	0	0.000374	0	0
Standing losses & auxiliaries				
Auxiliary power (kW/kW_power_generation)	0.0%	0.0%	0.0%	0.0%
Adjustment for storage daily losses (kW/kWh_stored_energy)	0.00000	0.000	0.000	0.000
Others				
Is sytem reversible? (1=yes,0=no)	0	0	0	1
Energy storage or flexible generator (1=e.store, 2=flex.gen.)	1	2	2	1
System life (years)	30	30	30	30
System power output rating (kW-AC)	100,000	100,000	100,000	100,000

Model Use Step 1: Specify Tech Values in “Technology Specifications” tab

Other system inputs
System type, life, power generation capacity

Tech name			HDV-PEM|Salt	NG-CC|CCS	Eth-CC	PHS
H_2 coproduction parameters						
Electricity use for H_2 co-production (kWh_AC_in/kg_H_2_out)			56.4	0	0	0
Allow H2 co-production? (1=yes, 0=no)			0	0	0	0
% system idle time allowance for co-production			5%	0	0	0
Feedstock & product valuation		References				
Electricity for H_2 co-production scenarios ($/kWh)	0.035	1, 2				
Hydrogen co-production value ($/kg)	2.50	26, 42				

Model Use Step 2: Specify Sensitivities in "Sensitivity Parameters" tab

Range used for tornado charts and for triangular distributions for Monte Carlo

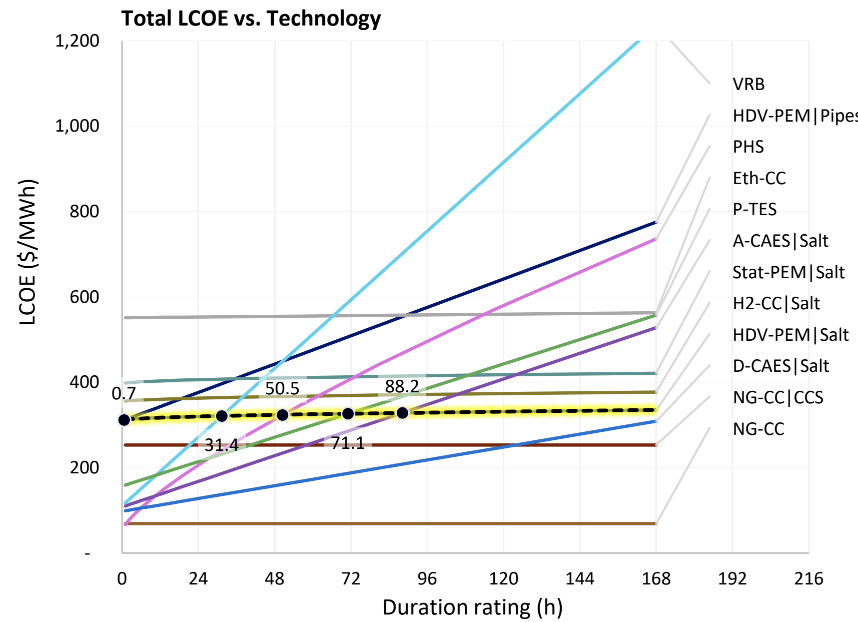
	Min	Baseline	Max	References
Storage duration rating (h)	72	120	168	1
Energy costs				
Electricity for energy storage scenarios ($/kWh)	0.010	0.020	0.030	2
Natural gas ($/MMBTU)	2.383	2.98	3.505	38
Ethanol ($/gal)	1.18	2.22	2.66	13, 39, 40
CO_2 transportation and sequestration cost ($/tonne)	27	65	125	33, 34, 35
Hydrogen coproduction related				
Electricity for coproduction scenarios ($/kWh)	0.025	0.035	0.045	1, 2
Hydrogen coproduction value ($/kg)	1.74	2.50	3	26, 42
Capital related				
Power capital ±%	-10.0%	0.0%	+10.0%	
Energy capital ±%	-10.0%	0.0%	+10.0%	
Other parameter sensitivities				
Recharge capacity factor ±%	-5.0%	0.0%	+5.0%	
Power generation capacity factor ±%	-5.0%	0.0%	+5.0%	
Relative efficiency ±%	-10.0%	0.0%	+10.0%	
System life ± years	-5	0	+5	

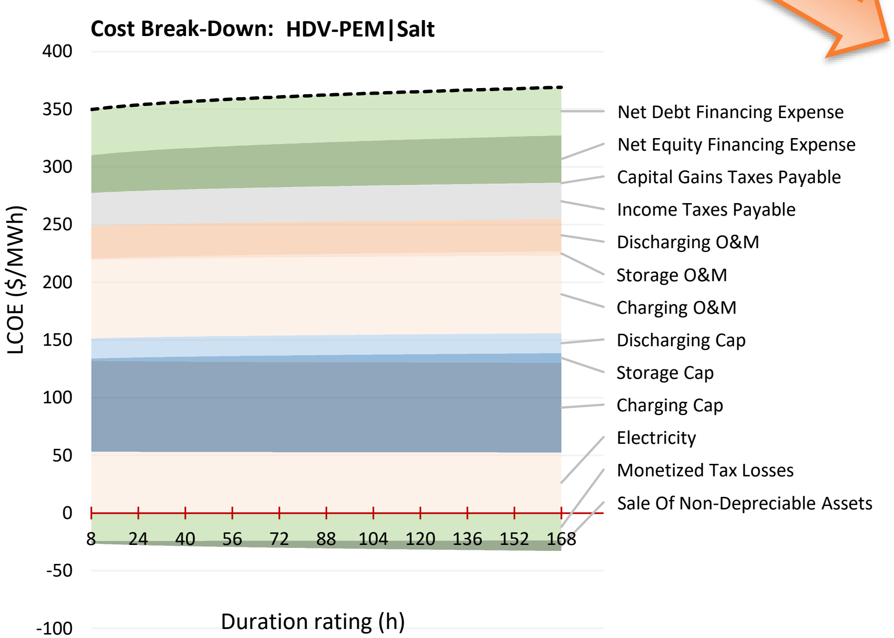
Model Use **Step 3**: Click Update Button in "Technology Specifications" tab

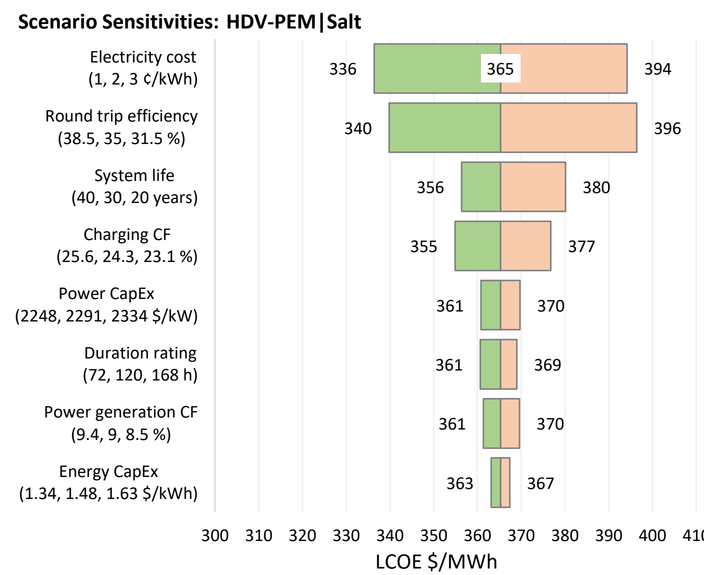
Select system to plot
HDV-PEM|Salt

LCOE @ Baseline Scenario
$365/MWh

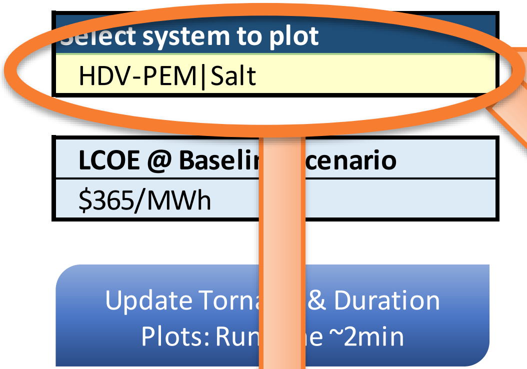
Update Tornado & Duration Plots: Run time ~2min

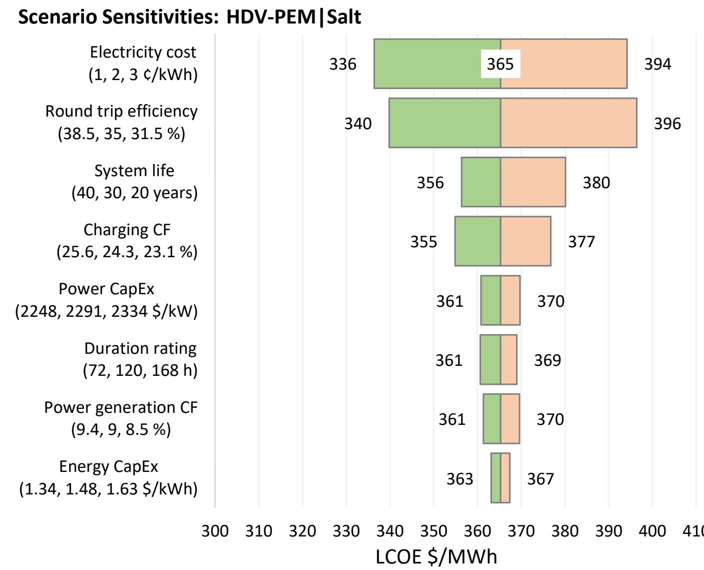




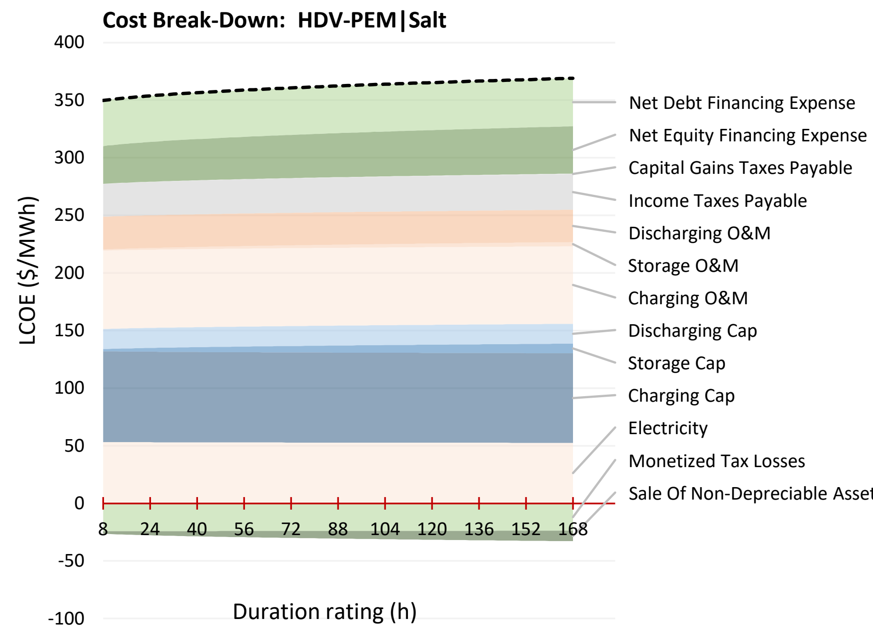


Model Use **Step 4**: Select System to Examine in “Technology Specifications” tab





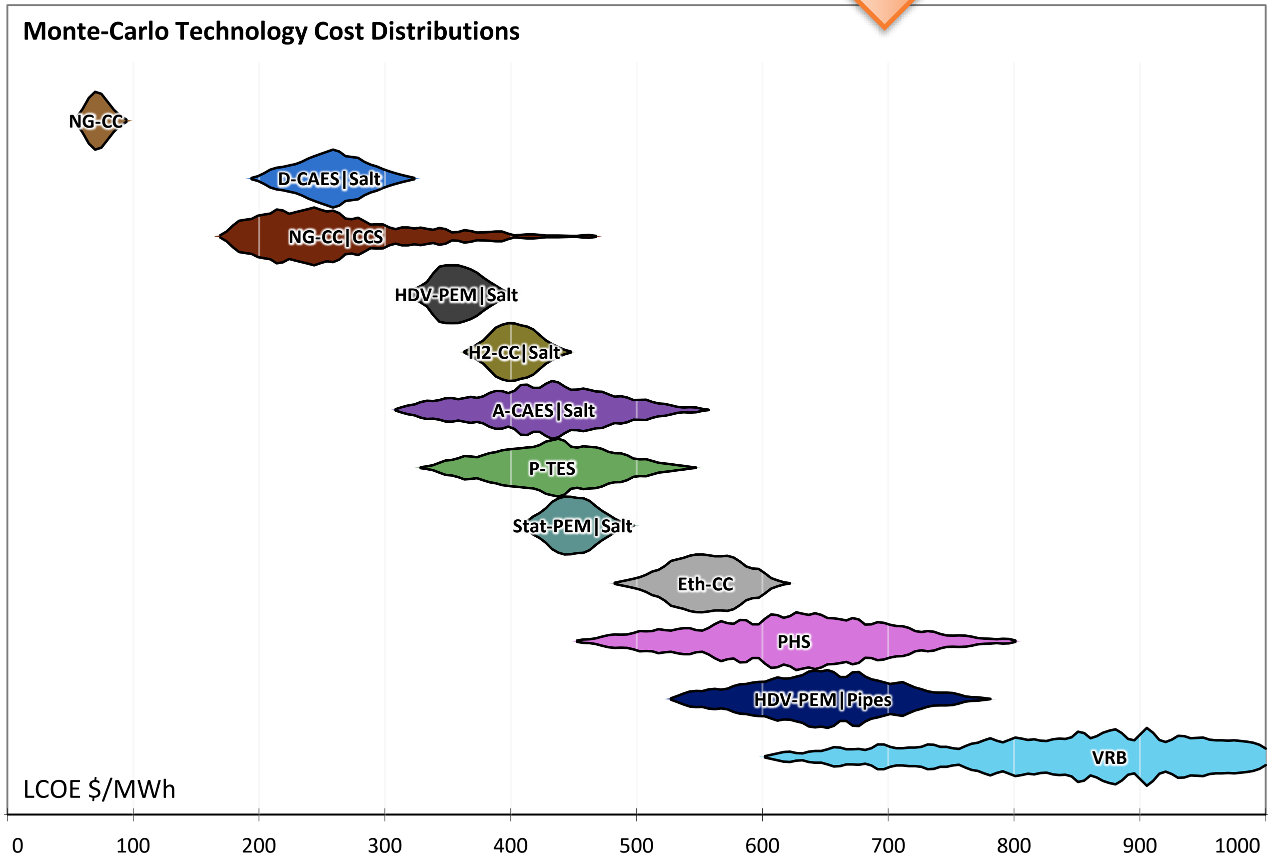
Selected system will also populate baseline details in the “Interface” and “Report Tables” tabs. (for system of baseline duration rating)



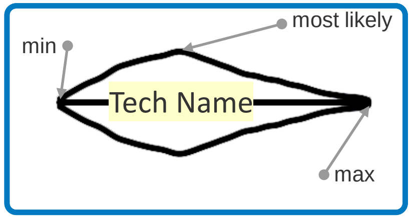
Model Use **Step 5**: Run Monte Carlo in “Sensitivity Parameters” tab

Click “Update Monte Carlo Analysis” macro button. This step takes ~30-60 min.

Update Monte Carlo Analysis
Violin Plots: **Run time ~1h**



Violin plots:
multi histogram plots



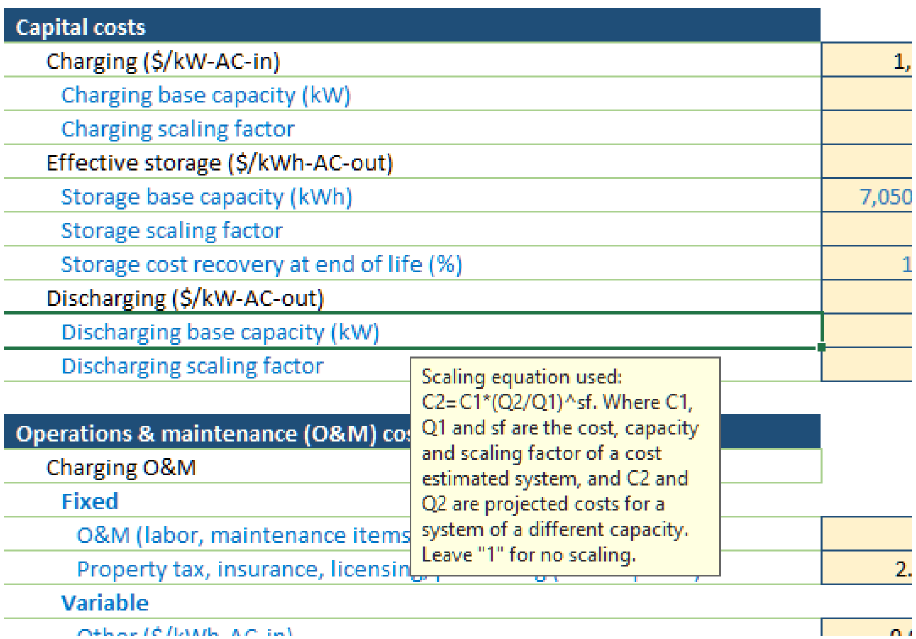
Model Is Self-Documented

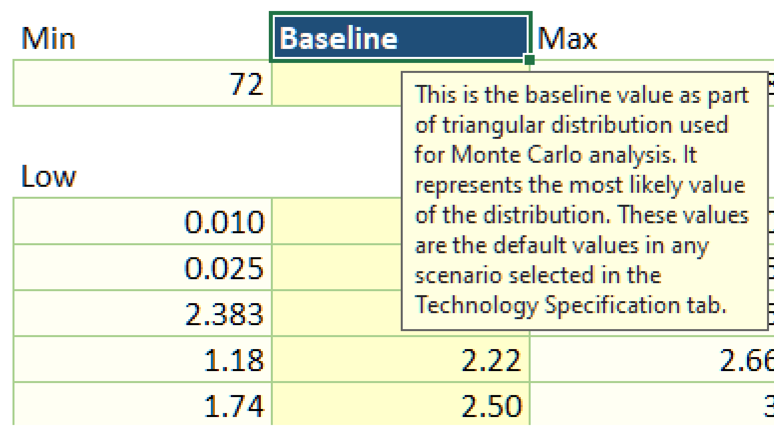
Description tab:

Tabs description

Step-by step walkthrough

All inputs include pop-up descriptions when user clicks on a cell.





Model Demonstration: Adding H_2 Coproduction

Example Compatible Systems With Model

Energy storage type	Currently in base case
Batteries (any chemistry)	
Liquid air storage	
Gravity energy storage	
Ammonia*	
Hydrogen*	√
Vanadium flow batteries	√
Pumped hydro	√
Adiabatic CAES (using thermal storage)	√
Thermal	√

*Model allows for modelling of hybrid systems e.g. energy storage with hydrogen co-production.

Example Compatible Systems With Model

Flexible generator types	Currently in base case
Conventional hydro	
Geothermal	
Turbines + renewable methane	
Nuclear (if dynamics allow)	
Turbines + CCS	√
NG-fired CAES	√
NG-fired Turbines	√
Ethanol-fired Turbines	√

Thank You

www.nrel.gov

Model link: https://www.nrel.gov/storage/storefast.html

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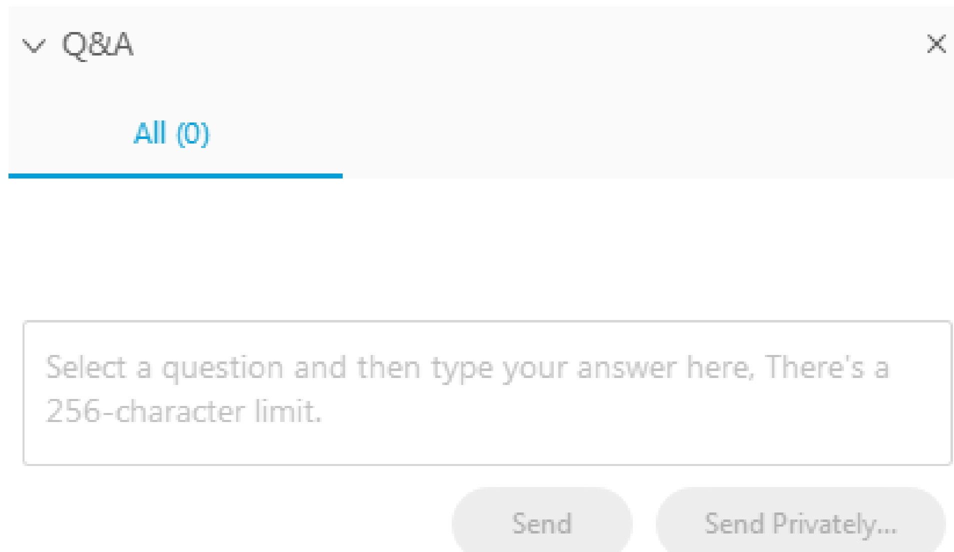
The #H2IQ Hour Q&A

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



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The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov