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# Energy Storage Analysis

Chad Hunter, Evan Reznicek, Michael Penev, Josh Eichman, Sam Baldwin
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Project ID SA173

# *Overview:*
# Hydrogen grid energy storage analysis

| Timeline | Barriers (4.5) |
|---|---|
| Start: October 2019<br>End: June 2020<br><br>50% complete | **A. Future Market Behavior**<br>• Assessing competitiveness of hydrogen for grid storage<br>**C. Inconsistent Data, Assumptions & Guidelines**<br>• Consistent modeling methodology using established DOE cost/price and performance targets<br>**D. Insufficient Suite of Models and Tools**<br>• Develop hydrogen grid storage techno-economic tool |
| **Budget** | **Partners** |
| Total Project Funding: $155k<br><br>• FY20: $155k<br><br>Total DOE funds received to date: $50k | ***Project Management***<br>EERE Strategic Priorities and Impacts Analysis (SPIA)<br><br>***Collaborators and Peer Reviewers*** *(alphabetical)*<br>Ballard, Bioenergy Technology Office, Fossil Energy, NREL (Paul Denholm, Wesley Cole), Office of Electricity, Solar Energy Technology Office, Water Power Technology Office |

# *Relevance (1/3):* HFTO Systems Analysis Framework

**Hydrogen Grid Energy Storage Analysis Integrates System Analysis Framework:**

- Leverages and expands existing systems analysis models
- Systems analysis approach uses DOE cost and performance targets

- H2@Scale
- SPIA/HFTO hydrogen energy storage
- ANL bulk hydrogen storage analysis
- PNNL hydrogen grid integration tool

- DOE Fuel Cell Technologies Office
- DOE Strategic Priorities and Impacts Analysis
- Hydrogen storage analysis community

### Analysis Framework
- Cost estimation (LCOE)
- Energy resource utilization
- $H_2$ technology financial analysis

### Models & Tools
- H2A
- H2FAST
- HDSAM
- ReEDS
- PLEXOS
- RODeO
- FECO2CCS

- HFTO Program Targets

### Studies & Analysis
- Hydrogen storage market analysis
- Framework implementation

### Outputs & Deliverables
- Reports
- Hydrogen Storage Cost Calculator
- Public insights into market potential

**Acronyms**

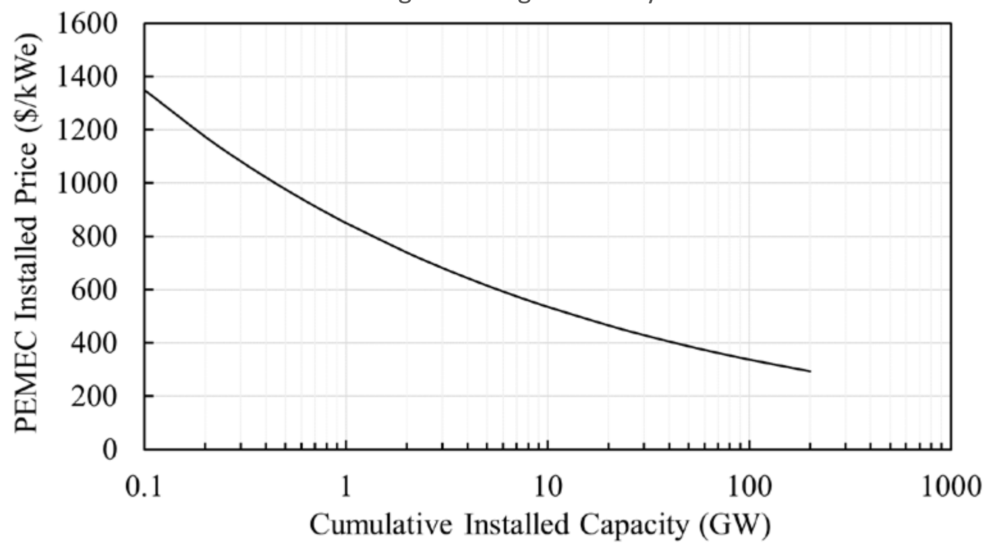
**H2A:** Hydrogen Analysis
**H2FAST:** Hydrogen Financial Analysis Scenario Tool
**HDSAM:** Hydrogen Delivery Scenario Analysis Model
**ReEDS**: Regional Energy Deployment System
**RODeO**: Revenue Operation and Device Optimization
**LCOE:** Levelized Cost of Electricity/Energy
**FECO2CCS:** FE/NETL CO2 Saline Storage Cost Model

# ***Relevance (2/3)***: High variable renewable energy (VRE) grids will require seasonal energy storage

- Exceeding 80% VRE penetration will require seasonal energy storage or flexible low-carbon generation[1][2][3]
- Electrolyzer and fuel cell costs could decline significantly in the future
- M/HDV fuel cells may have adequate durability (20-25k hours) to support energy storage applications
- Producing hydrogen for multiple end-uses (transportation, industry, storage) could improve economic viability

**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].




Projected PEM electrolyzer installed price [5].


[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."

# *Relevance (3/3):* This project synthesizes and compares LDES and peak power technology costs

**Project Objectives:**

1. Review literature to ***characterize current and future costs*** for LDES systems and flexible power generation technologies

2. Provide ***detailed cost and performance data*** for a subsequent project utilizing grid capacity expansion modeling and dispatch optimization

3. Perform a case study ***comparing levelized cost of energy*** of promising long duration storage concepts

4. Evaluate the potential benefit of ***co-producing hydrogen*** for grid storage *and* transportation, industry, etc.

5. Develop an ***online hydrogen storage cost calculation tool*** for interested stakeholders, policy makers, etc.

# *Approach (1/5)*: Levelized cost of energy (LCOE) serves as a convenient benchmark

- **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 Hydrogen Financial Analysis Scenario Tool (H2FAST) enables detailed LCOE calculation and sensitivity analysis

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

→ H2FAST →

**LCOE calculation outputs**
- LCOE comparison
- Cost breakdown
- Sensitivity analysis

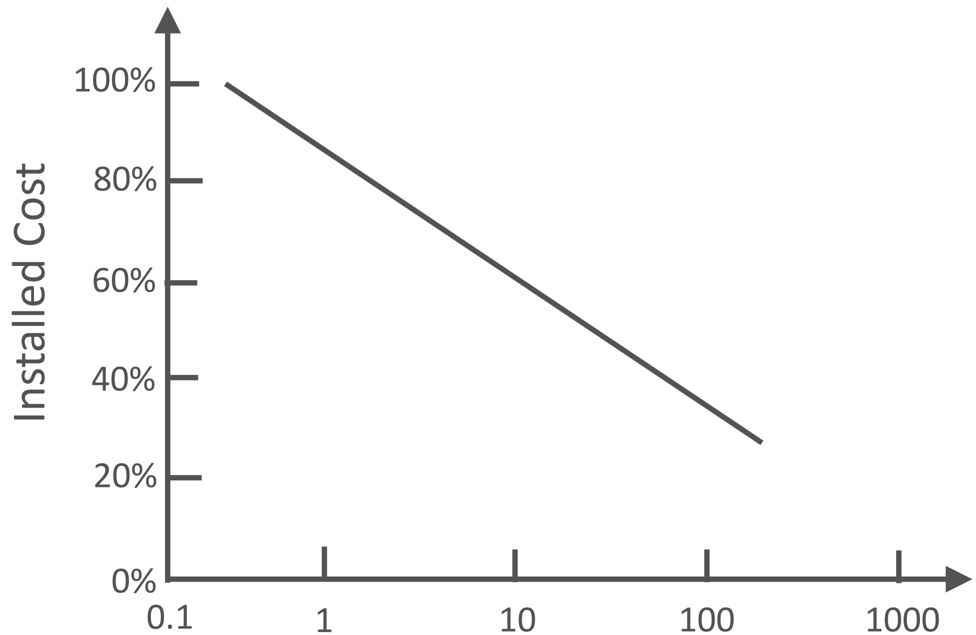
- Systems designed for **100 MW discharge capacity**
- Consider **storage durations > 24 hours**, up to 7 days

**Systematic comparison of LCOE requires specification of capital and operating costs, system performance, and plant financing**

# ***Approach (2/5)***: Current and future costs estimated from literature using learning rates

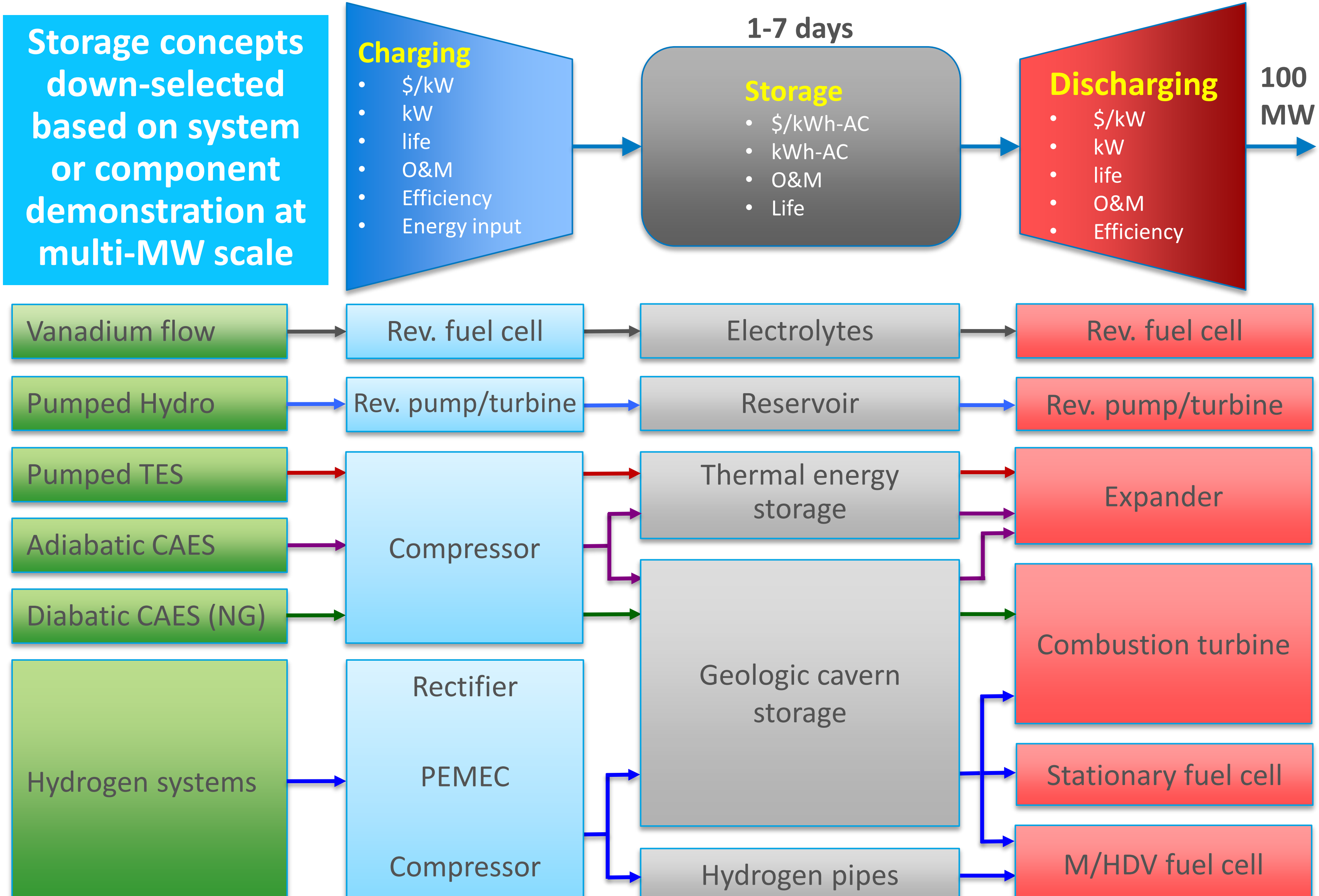
- **Current cost scenario:** How do today's technologies compare?
  - Costs and capacities retrieved from literature
  - Low or unknown capacity: assume 100 MW (first LDES plant)
- **Future cost scenario:** How will technologies compare in a high VRE penetration grid?
  - **Learning by doing:** cost reduces with cumulative experience
  - **Learning rate:** % cost reduction with each doubling of capacity
  - Assume 200 GW of additional capacity for each technology

**"Learning by doing" provides a way to estimate future costs consistent with historic data**



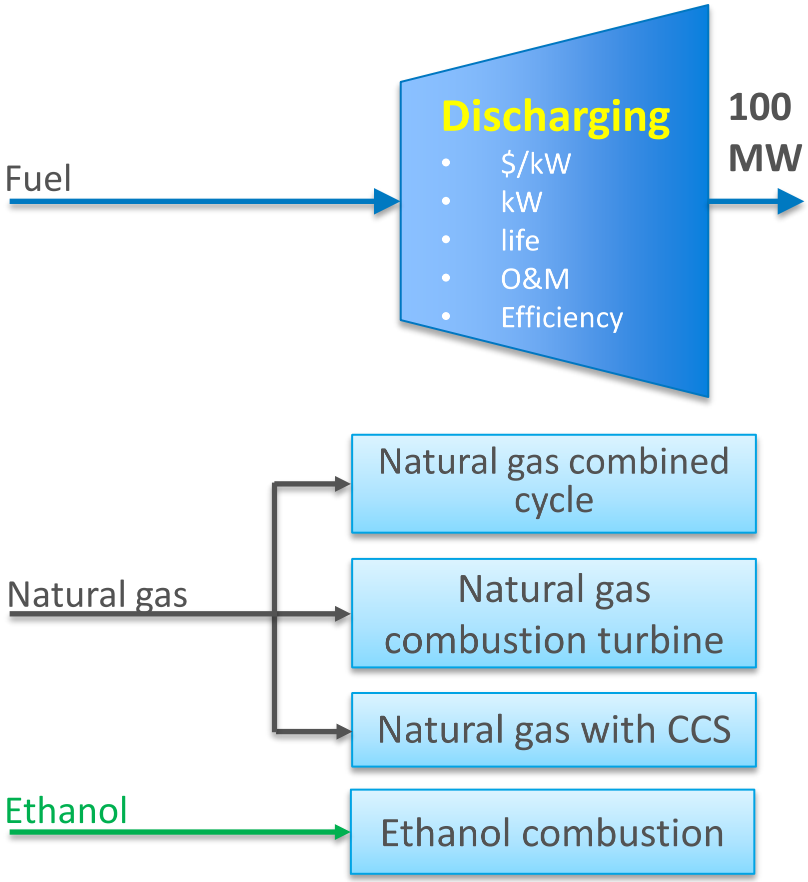

Generic example of a learning curve plot for a power generation technology.

# *Approach (3/5)*: Charging, storage, and discharge systems are evaluated independently



# *Approach (4/5)*: Flexible power generation will compete with seasonal energy storage

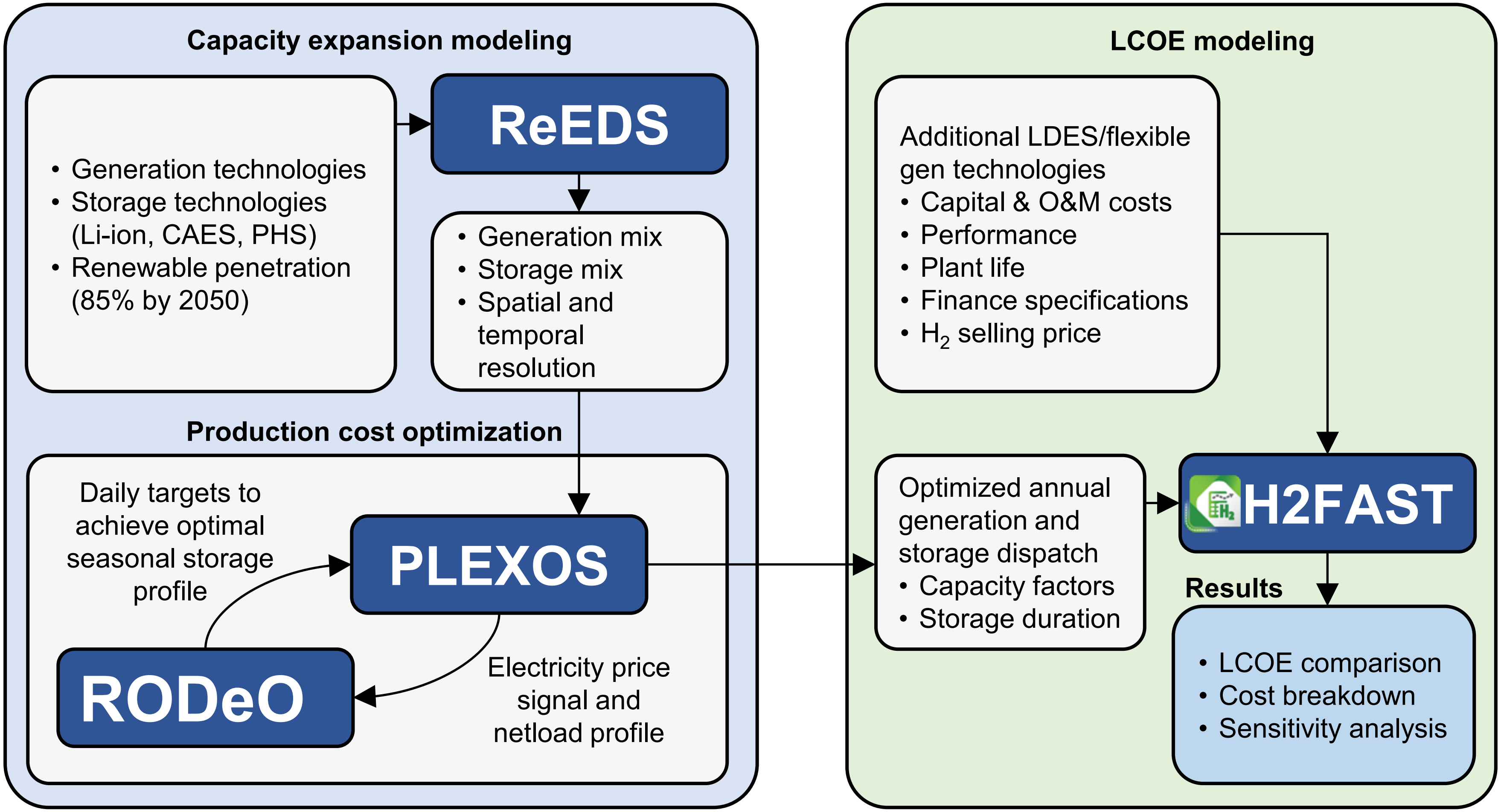
- NGCCs and NGCTs currently contribute toward grid flexibility
- Many studies consider natural gas with CCS for future flexible power generation systems
- Ethanol offers dispatchable renewable generation
- Life cycle assessment is key to assess supply chains and environmental impact – *beyond current scope*




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

# *Approach (5/5)*: Storage duration and capacity factor are informed by production cost modeling

**Exogenous Analysis by Eichman et al.** [5] | **This Analysis**




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

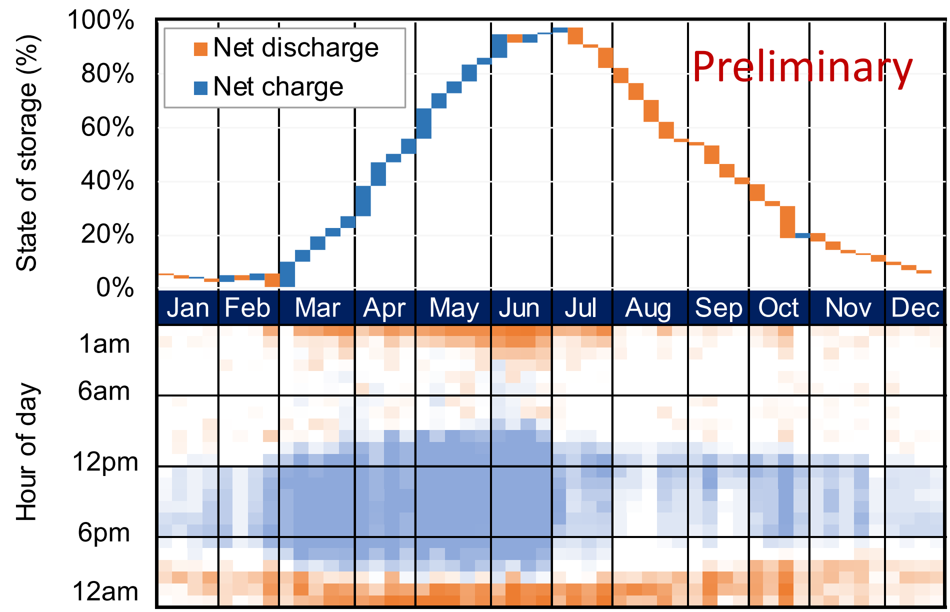
# ***Accomplishments and Progress (1/8)***: Capacity factor is a function of efficiency and/or total operating cost

**Different capacity factors stem from differences in operating costs**

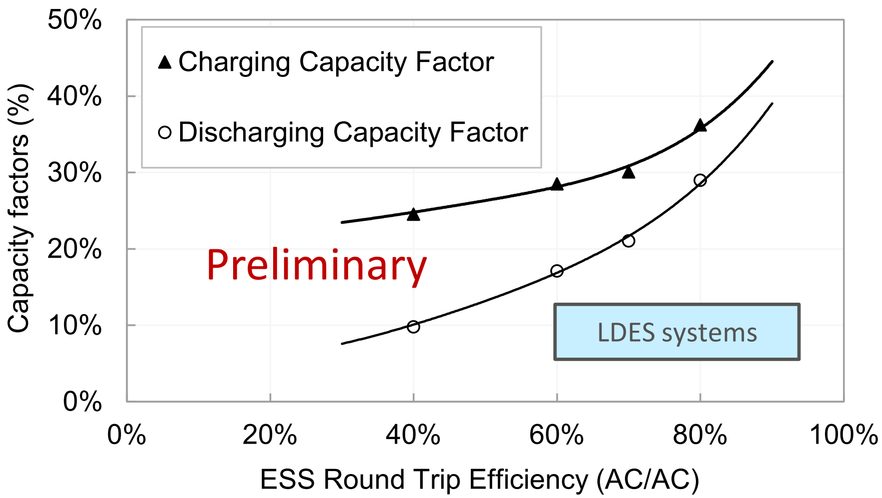
- High efficiency → low OPEX → high CF
- Low efficiency → high OPEX → low CF

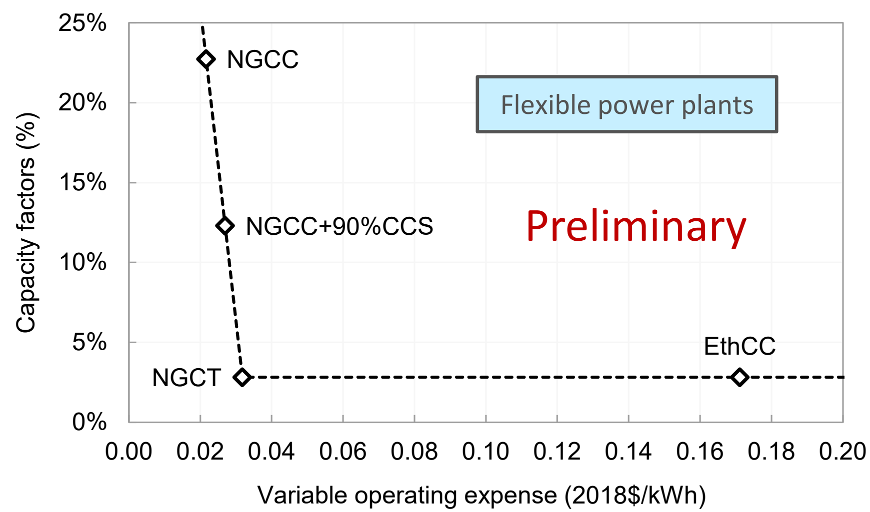
- Capacity factors are specific to region (Western U.S.) and scenario (85% ren.)

- **Electricity price:** 2 ¢/kWh ± 50%
- **Natural gas price**: $2.98/MMBTU ± 20%




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.

# *Accomplishments and Progress (2/8)*: Several technologies may experience significant cost reductions

**Hydrogen storage has low efficiency, but potential for low power and geologic storage costs in the future**

Preliminary

| Power Technology | Learning rate (%) | Current cost ($2018/kW) | Future cost ($2018/kW) |
|---|---|---|---|
| Pumped hydro | 0% | 821 | 821 |
| Combustion turbine | 15% | 1,289 | 1,047 |
| PEM Electrolyzer | 13% | 1,503 | 326 |
| Stat. PEMFC | 6.5% | 1,114 | 713 |
| M/HDV PEMFC | 14% | 439 | 187 |

Preliminary

| Technology | RTE (%) |
|---|---|
| Pumped hydro | 80% |
| Vanadium redox | 75% |
| A-CAES | 65% |
| Pumped TES | 52% |
| Hydrogen storage | 35% |

Preliminary

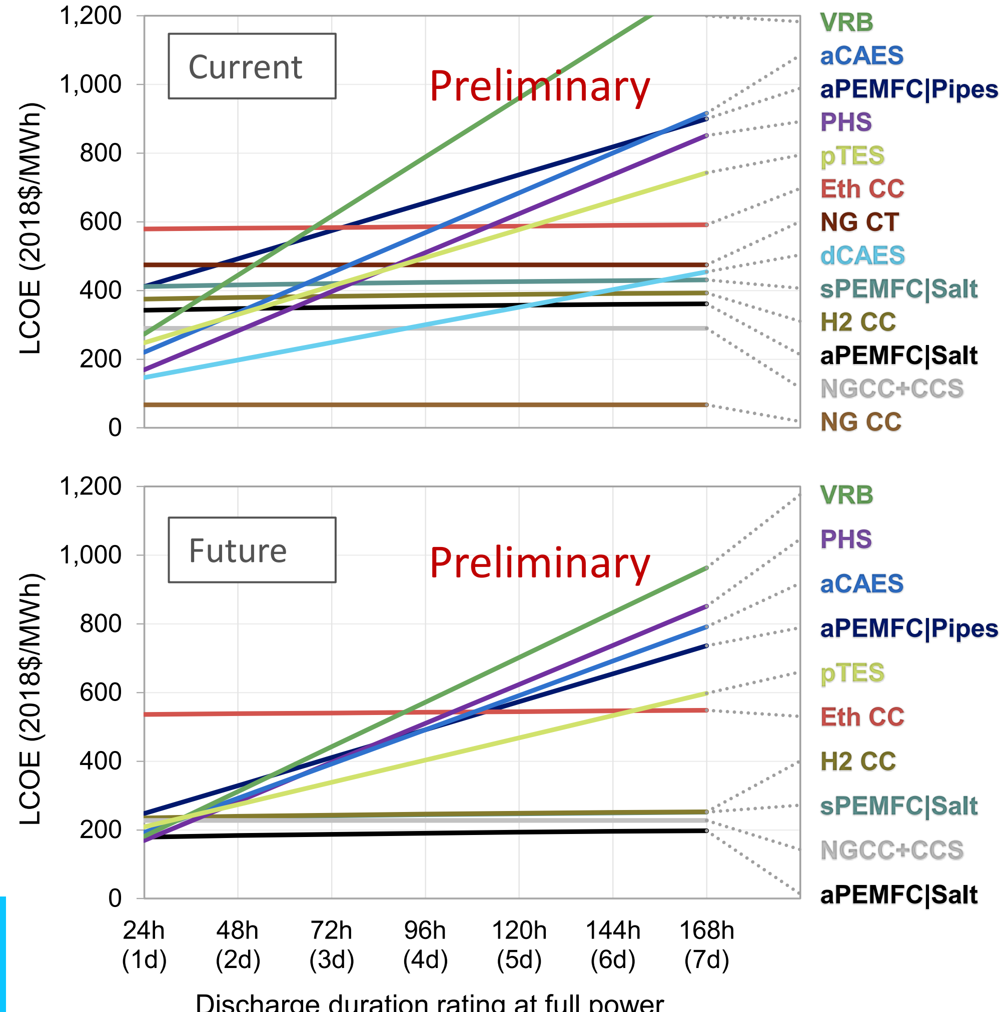
| Storage Technology | Learning rate (%) | Current cost ($2018/kWh-AC) | Future cost ($2018/kWh-AC) |
|---|---|---|---|
| Pumped hydro | 0% | 123 | 123 |
| CAES cavern | 0% | 19 | 19 |
| Thermal energy storage | 0-4% | 37* | 29* |
| Hydrogen pipes | 0% | 29 | 29 |
| Hydrogen cavern | 0% | 1.9 | 1.9 |

References available at end of presentation

# *Accomplishments and Progress (3/8)*: LCOE as a function of storage duration rating

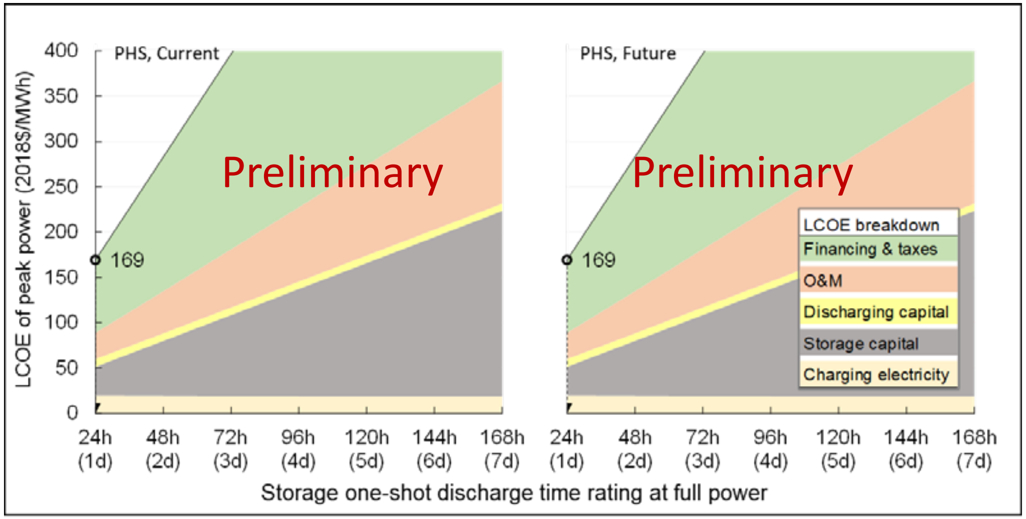
- PHS, CAES, VRFB, and pTES
  - Low cost at low storage duration ratings
  - Cost is highly sensitive to duration rating
- Geologic $H_2$ and natural gas
  - Cost is independent of storage duration rating
  - Competitive at all duration ratings in future scenario
- Ethanol: Higher cost than $H_2$ and NG due to low CF

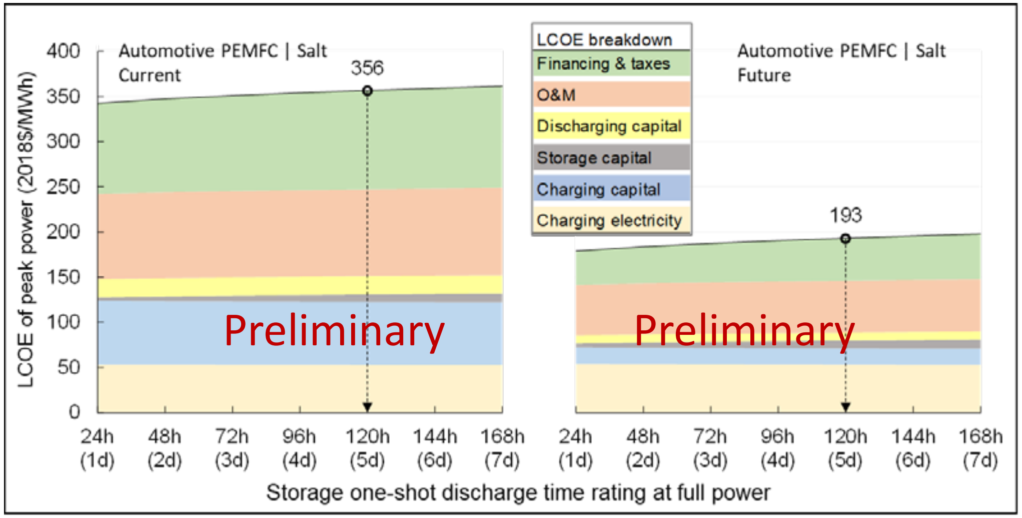
**Geologic H2 storage and flexible generation systems achieve lowest LCOE for long duration ratings**



# *Accomplishments and Progress (4/8)*: Cost breakdown of most competitive technologies

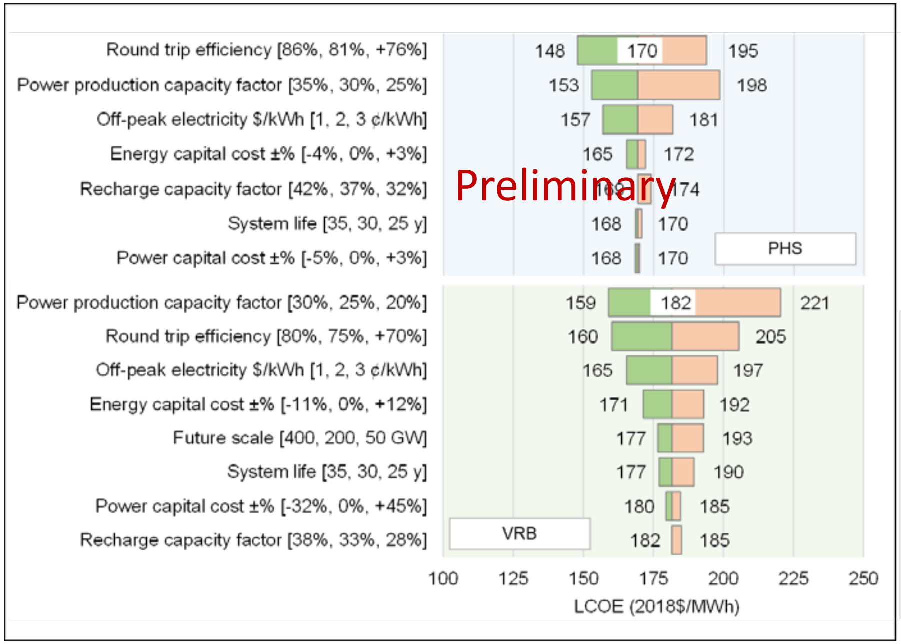
- PHS (lowest LCOE at 24 hours)
  - Significant storage capital, O&M, and financing
  - No significant learning
- Geo-$H_2$ with M/HDV FCs (lowest LCOE at 120 hours)
  - Higher charging costs due to lower efficiency
  - High O&M due to stack replacements
  - Capital costs and financing reduce in future

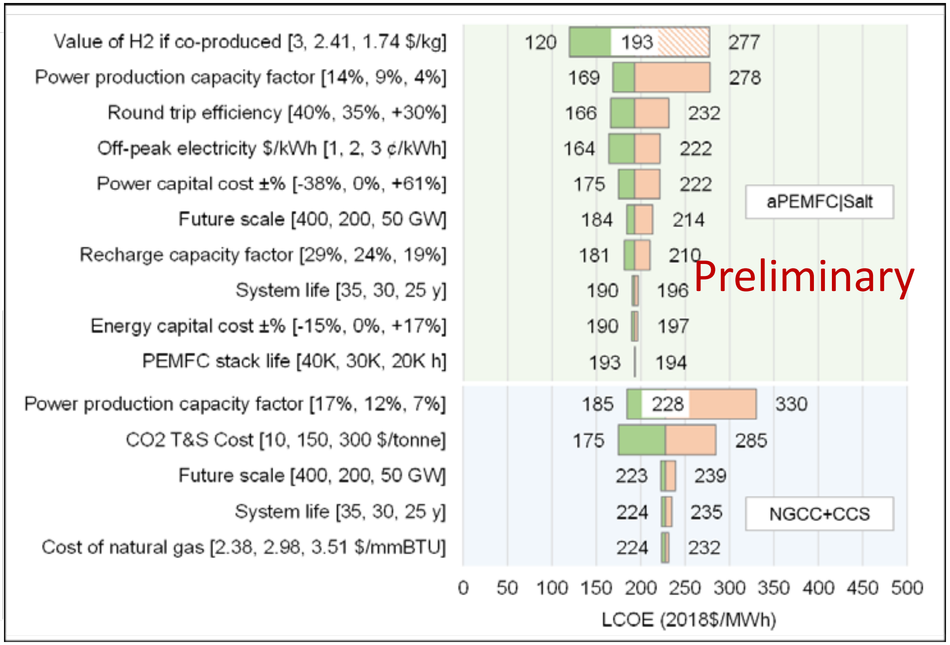



**Capital, O&M, and financing costs comprise largest contributions to hydrogen LCOE**

# *Accomplishments and Progress (5/8)*: Sensitivity analysis illustrates the most influential parameters




- PHS and VRFB (lowest cost 24-hour technologies)
  - Power production CF, efficiency, and electricity price are highly influential
  - Learning rate, future capacity, and system life are less influential
- Geo-H2 with M/HDV PEMFC and NGCC+CCS (lowest cost 120-hour technologies)
  - Geo-H2 influenced by H2 coproduction sales price and capacity factor
  - CCS is influenced by capacity factor and T&S cost

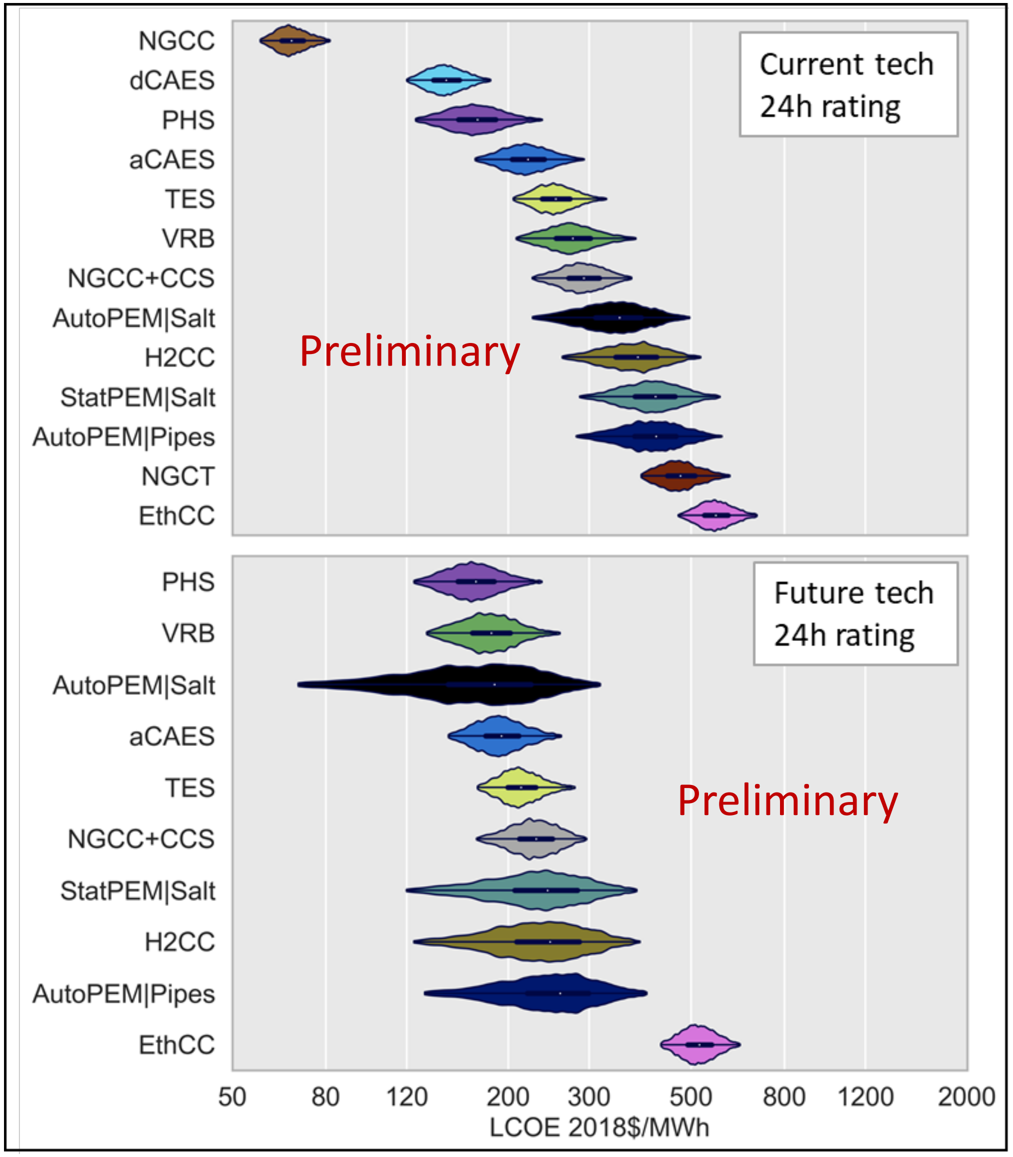
**LCOE is highly sensitive to parameters that influence capital cost and charging costs**

# *Accomplishments and Progress (6/8)*: LCOE comparison – 24 hour storage duration

- Assigned triangular distribution to each sensitivity parameter
- Performed Monte Carlo uncertainty analysis
- Thickness of each "violin" indicates probability of that LCOE value

- Current cap costs: CAES, PHS, TES, VRFB lowest cost at 24 h
- Future cap costs: Many systems have competitive cost
- Hydrogen coproduction and sales could reduce LCOE

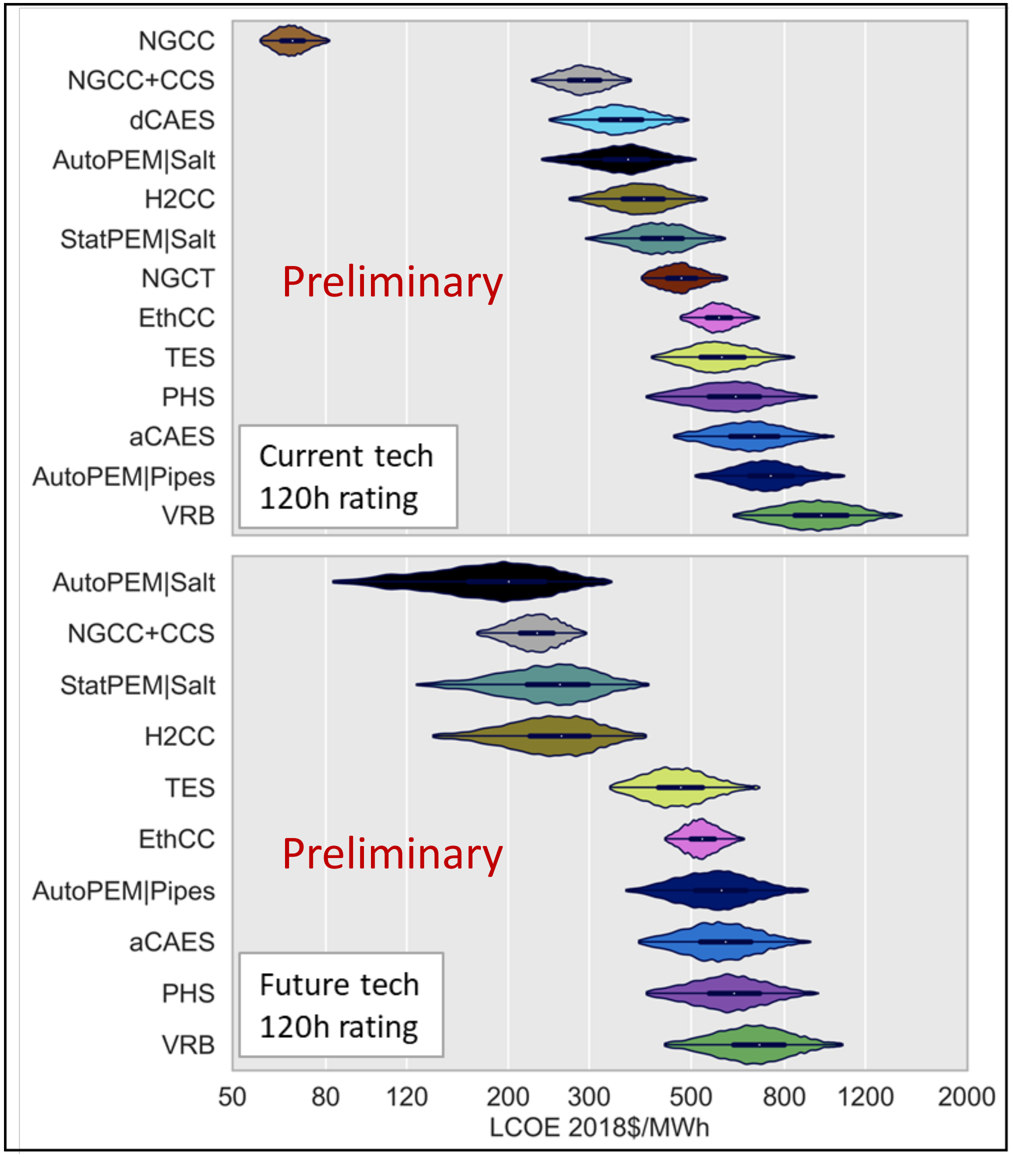
**Many technologies could compete in the future 24-hour energy storage market**



# ***Accomplishments and Progress (7/8)***: LCOE comparison – 120 hour storage duration

**Geo-H2 and natural gas are lowest-cost options for long durations of flexible power**

- With current cap costs, geo-H2 and natural gas are lowest-cost options
- With future cap costs, geo-$H_2$ and CCS establish a solid lead
- Without geo-storage or CCS: TES, ethanol, $H_2$-pipes are lowest-cost options
- Deployment of systems will likely depend on local resources and factors not captured here



# ***Accomplishments and Progress (8/8):*** *Development of a hydrogen energy storage cost calculation tool*

- Existing tools lack hydrogen storage as an option

- Desirable tool capabilities
  - Specification of hydrogen storage costs and performance
  - Independent modeling of charging and discharging systems
  - Simulation and/or optimization of annual system performance
  - Available free online

- Existing NREL tools that could be modified
  - Hydrogen Financial Analysis Scenario Tool (H2FAST)
  - Renewable Energy Integration and Optimization (REopt)
  - System Advisor Model (SAM)
  - Revenue Operation and Device Optimization (RODeO)

**The hydrogen energy storage cost calculation tool will allow custom investigation of economics for specific scenarios of interest to technology stakeholders**

# Responses to Reviewers’ Comments

This project was not reviewed at the 2019 AMR.

# Collaboration and Coordination

**National Laboratories**

- Argonne National Laboratory
- Pacific Northwest National Laboratory

**Office of Energy Efficiency and Renewable Energy**

- Fuel Cell Technologies Office
- Strategic Priorities and Impact Analysis
- Water Power Technologies Office
- Solar Energy Technologies Office
- Bioenergy Technology Office

**Other DOE Offices**

- Office of Electricity Delivery & Energy Reliability
- Office of Fossil Energy

**Industry**

- Xcel Energy

**Peer Reviewers**

- Paul Denholm
- Wesley Cole
- Ballard
- Others at NREL

# Remaining Challenges and Barriers

**Cost and learning rate data**

- Coordination across multiple DOE offices to align on the state-of-the-art technology cost and performance data
- Uncertainty in technology learning rates and operating costs

**Modeling**

- Understanding how to model LDES for planning and operations
- LCOE doesn't tell the whole story – need capacity expansion modeling and operations modeling
- Determining the actual value of storage duration and/or grid flexibility
- Need for dynamic models coupling multiple-sectors together to understand the impact of cross-sectoral spillover of learnings on hydrogen technologies
- Assessing regional variation in feedstocks and resources

**Market Design**

- Investment signals: resource adequacy rules prevent LDES implementation
- Operations signals: how to design future market products to appropriately value storage

# *Proposed Future Work*

- Quantify future international capacity potential of each technology system
- Evaluate regional availability of geologic storage for hydrogen, air, and carbon dioxide
- Incorporate cost and performance data into detailed analyses of high VRE penetration grids
  - Regional Energy Deployment System (ReEDS) capacity expansion model
  - PLEXOS production cost model

***Any proposed future work is subject to change based on funding levels***

# *Summary*

- LDES and/or flexible power generation are necessary to enable high VRE penetration grids
- This study provides detailed cost and performance data for LDES and renewable/low-carbon power generation technologies
- Hydrogen fuel cells and electrolyzers have potential for significant cost reductions
  - Electrolysis costs could reduce by 78% in future scenario
  - M/HDV fuel cells could reduce by 57% in future scenario
  - LCOE of M/HDV PEMFC with cavern storage could reduce by 38% in future scenario
- Developing electrolysis systems for both energy storage and hydrogen sales may improve the economic viability of hydrogen storage for the grid
  - Co-production could reduce LCOE by 20%
  - Requires higher hydrogen price than that of steam-methane reforming

# Acronyms & Key Definitions

| | |
|---|---|
| aCAES | adiabatic compressed energy storage |
| aPEMFC | automotive PEM fuel cell |
| CAES | compressed air energy storage |
| CCS | carbon ($CO_2$) capture and sequestration |
| CF | capacity factor |
| ESS | energy storage system |
| EthCC | ethanol (fueled) combined cycle |
| GW | gigawatt (power) |
| H2CC | hydrogen (fueled) combined cycle |
| LCOE | levelized cost of energy/electricity |
| LDES | long duration energy storage (system) |
| M/HDV | medium/heavy duty vehicle |
| MMBTU | million British thermal units |
| MW | megawatt (power) |
| NGCC | natural gas combined cycle |
| NGCT | natural gas combustion turbine |
| O&M | operations & maintenance (excluding fuel) |
| OPEX | operating expenses |
| PEM | proton exchange membrane |
| PEMEC | PEM electrolyzer |
| PHS | pumped hydro storage |
| pTES | pumped thermal energy storage |
| sPEMFC | stationary PEM fuel cell |
| T&S | transportation and storage (of $CO_2$) |
| TES | thermal energy storage |
| VRB | vanadium redox (flow) battery |
| VRE | variable renewable energy |
| VRG | variable renewable generation |

**Storage duration rating**: time to deplete energy storage from its maximum operating charge level to minimum operating charge level while producing power at nameplate capacity.

**Charging capital cost ($/kW):** overnight installed cost for all equipment associated with charging of storage divided by the maximum AC power consumption during storage charging.

**Storage capital cost ($/kWh):** overnight installed cost for all equipment associated with storing energy divided by the potential AC energy which can be produced by downstream power generation equipment while storage is discharged from its maximum operating charge level to its minimum operating charge level.

**Discharging capital cost ($/kW):** overnight installed cost for all equipment associated with converting stored energy to AC power to the electric grid.

# Thank You

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