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CEC EPC-19-056
Assessing the Value of Long Duration Storage

Data & Scenario Selection Public Workshop

June 30, 2021

Energy+Environmental Economics

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Agenda

Time	Topic
1:00 pm - 1:10 pm	**Welcome & Project Overview** • Updated project schedule • Project objectives
1:10 pm - 1:40 pm	**Progress Updates** • Draft emerging technology review • Preliminary analytical experiments
1:40 pm - 2:15 pm	**Preliminary Analysis Scenario Design Discussion** • Bulk system scenarios • Zero-carbon microgrid scenarios
2:15 pm – 2:20 pm	**Recap of Project Schedule**
2:20 pm - 3:00 pm	**Additional Stakeholder Q&A**

Goals for Today's Workshop

+ **The focus for today's discussion is on scenario design, so we will reserve a large portion of our agenda for discussion related to that topic**

+ **The intention of the progress update sections is only to highlight & preview our ongoing work and not to provide a full discussion of assumptions, methodologies & results**
  - We will provide a more complete description of technology review & modeling work in the upcoming preliminary analysis report

+ ***We ask that questions during the workshop time focus on the Scenario Design section***
  - *If you would like to discuss any part of the Progress Updates we present today, please follow-up with the team after the workshop via email*

Project Overview

Energy+Environmental Economics

Project Objectives

1. Evaluate the tradeoffs between energy storage duration, performance and cost, against a range of resource supply options and electric load conditions for various use-cases on California's future grid.

2. Develop an updated publicly available dataset to characterize potential futures for California's grid in the context of deep decarbonization, including characterization of new energy storage and energy generation technologies.

3. Develop a publicly available modeling toolkit that extends California's capabilities to plan for a deeply decarbonized electric sector, incorporating long duration storage and new energy generation technologies into the resource mix.

Updated Project Schedule

Legend
Deliverable
Task in progress

+ **Goal is to have preliminary analysis completed approximately 3 months from today's workshop**

		2020				2021												2022					
Task	**Sub-Task**	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Baseline Data Development					Task in progress	Task in progress	Task in progress	Deliverable															
LDES Scenario Design						Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable												
Emerging Technology Review	Draft Technology Review					Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable												
	Final Technology Review											Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable
Preliminary Analysis	Preliminary Modeling Experiments					Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable												
	Preliminary Systemwide LDES Analysis										Task in progress	Task in progress	Task in progress	Deliverable									
	Preliminary Zero-Carbon Microgrid Analysis										Task in progress	Task in progress	Task in progress	Deliverable									
New Modeling Toolkit Development	New Modeling Toolkit					Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable						
	New Modeling Dataset					Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable
Final Scenario Analysis																	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Task in progress	Deliverable
Public Workshops	Introductory Public Workshops				Deliverable																		
	Data & Scenario Selection Workshop										Deliverable												
	Final Scenario Selection Workshop													Deliverable									
	Final Public Workshop																						Deliverable

Today

Where We Are in Overall Project Arc

1 Preliminary LDES analysis using existing tools

2 Refresh tools & data based on learning from Phase 1

3 Analyze LDES using New Modeling Toolkit

Define scenarios for systemwide & microgrid studies

Identify future scenarios under which to study value of long duration storage for California

1a. Analyze LDES behavior & individual value streams

- *Use existing tools to analyze operational behavior & known value streams (**RECAP**, **RESTORE**)*
- *Study techniques to reduce capacity expansion modeling complexity (**RESOLVE**, **Formware**)*

Key outputs

- *Understanding of key dispatch behaviors & LDES to capture in New Modeling Toolkit and future analyses*

1b. Study systemwide & microgrid portfolios with LDES

- *Develop CA resource portfolios under different scenarios (**Formware**)*
- *Analyze cost-effective, zero-carbon microgrid applications (**UCSD Microgrid Model**)*

Key outputs

- *Least-cost bulk system portfolios comparing LDES and other techs*
- *Least-cost microgrid portfolios comparing LDES and other techs*

Develop New Modeling Toolkit & Datasets

- *Use Phase 1 learnings to inform model enhancements needed to capture value of LDES*
- *Update datasets to complement enhanced modeling functionality (e.g., wider set of weather conditions)*

Key outputs

- *Updated modeling platform capable of representing values & system needs identified in Phase 1*

Complete final analysis in new modeling toolkit

- *Develop optimized portfolios to meet California's future energy needs that consider a broad range of options for long duration storage*

Key outputs

- *Optimized portfolios including LDES under a range of cost and duration assumptions*

Progress Updates

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Progress Updates

Draft Emerging Technology Review

Dr. John Stevens, Managing Consultant, E3
Dr. Mengyao Yuan, Senior Consultant, E3
Dr. Bill Wheatle, Consultant, E3

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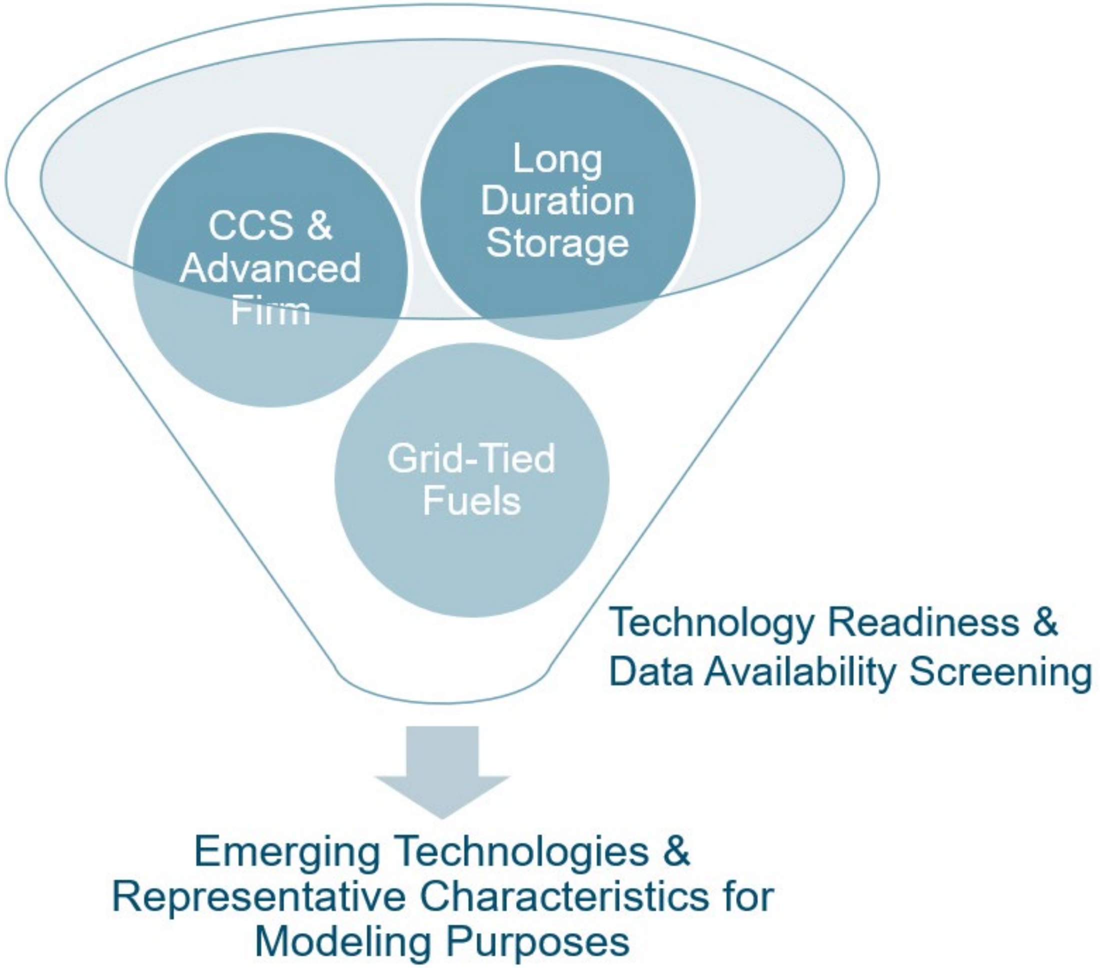
Overview

Goals for Emerging Technology Review

+ **Review emerging technologies that could lower the overall cost of deep decarbonization**
    - Technologies that can provide clean "firm" energy and/or longer-duration energy storage
+ **Generate cost and performance data to be incorporated in long-term system planning models**
    - Screen out technologies that lack sufficient technoeconomic data for modeling
    - Model results will in turn inform R&D and policymaking on these technologies
    - As we produce more modeling results, we will **compare the modeled value** of emerging technologies to cost projections



Key Technologies Reviewed To Date

- **Technology selection primarily based on technology readiness and data availability, which indicate potential for near- to medium-term deployment**
- **IEA's Technology Readiness Level (TRL) scale was used to assess market experience**
  - More details in Appendix
- **Cost and performance data are from public sources and are still under review**
  - Sources include: NREL Annual Technology Baseline (ATB), research papers, manufacturer data; E3 expertise applied to give different weights to these sources
  - Review will also document caveats, including uncertainties in costs for pre-commercial technologies (learning curve, first- vs. n-th-of-a-kind, financing costs, etc.)

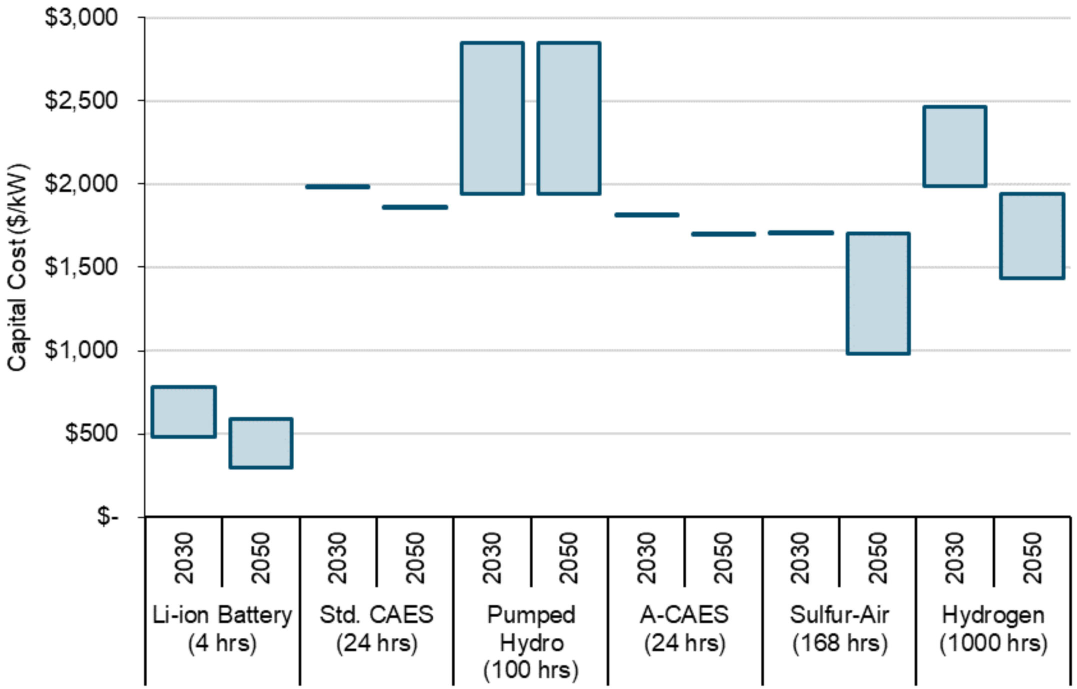
Technology	Technology Readiness Level	Storage Duration Range*
Hydrogen Storage	9	Weeks to Months
Synthetic Methane	7	Weeks to Months
Adiabatic Compressed Air Energy Storage (A-CAES)	8	Days to Weeks
Sulfur-Air Battery	5-6	Days to Weeks
Natural Gas + CCS	8	n/a
Allam Cycle	8	n/a
Bioenergy + CCS (BECCS)	7	n/a
Small Modular Reactor	7	n/a
Enhanced Geothermal	5	n/a

* Storage duration ranges are inferred from existing and proposed applications but may vary for each project depending on the specific use case and economics.

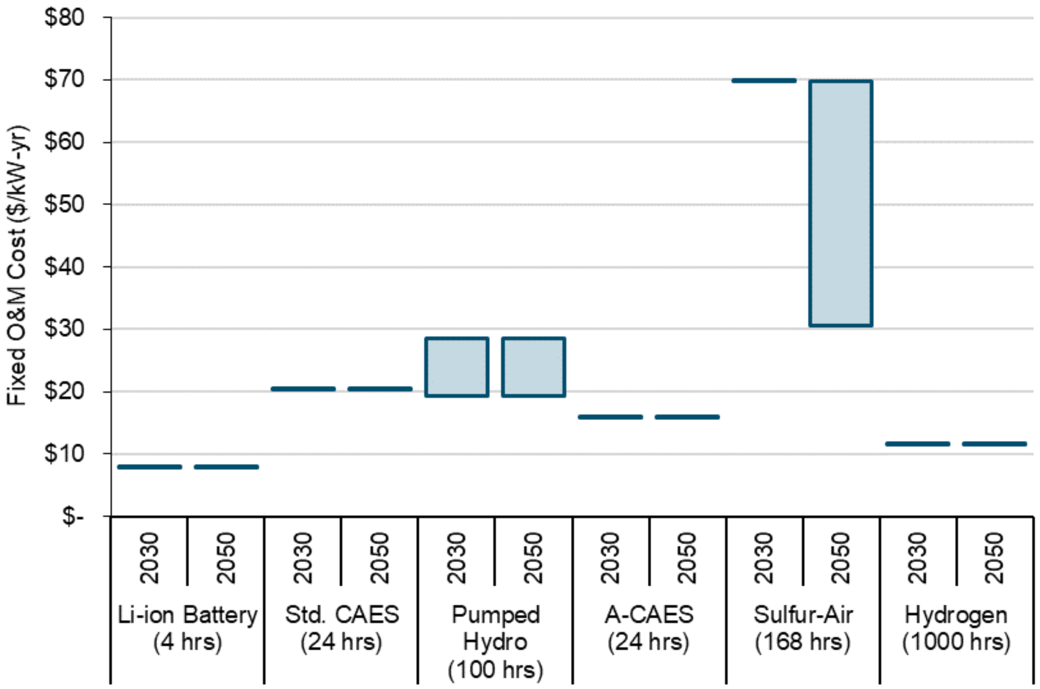
Indicative Storage Fixed Cost Projections

+ **Based on our preliminary review, we developed cost projections for key storage technologies**
+ **The team may expand the technology review to include additional storage technologies, subject to data availability & market readiness**

Installed (Capital) Cost (2019 $/kW)



Fixed O&M Cost (2019 $/kW-year)

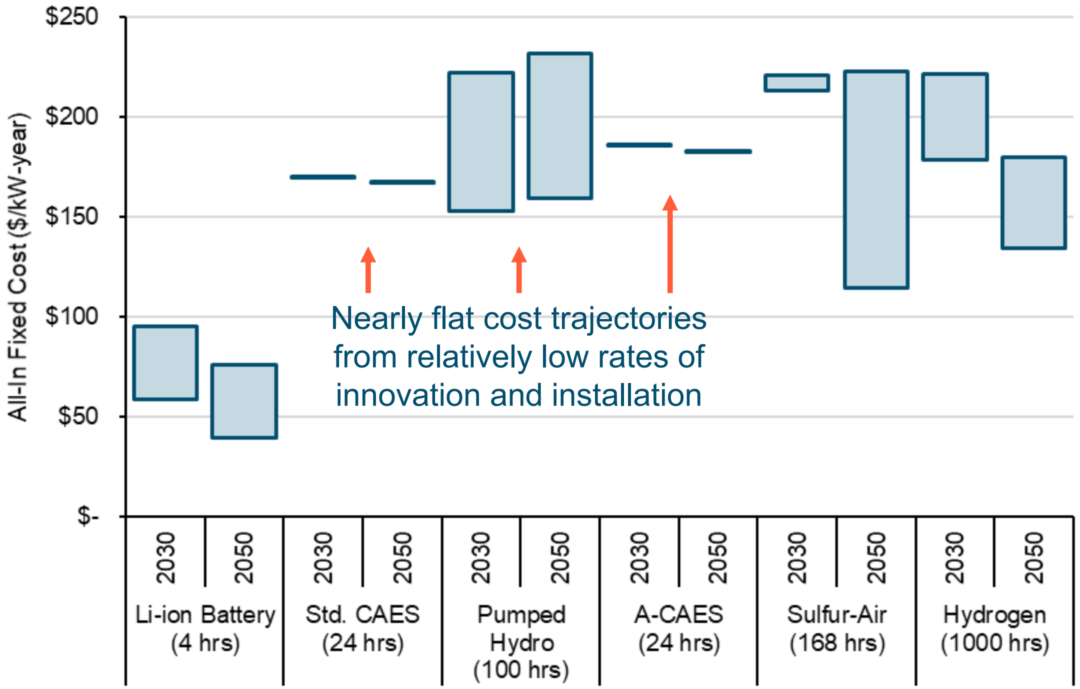


Note: Indicative durations for each technology used only for visualization purposes. Each technology has a range of potential duration configurations.

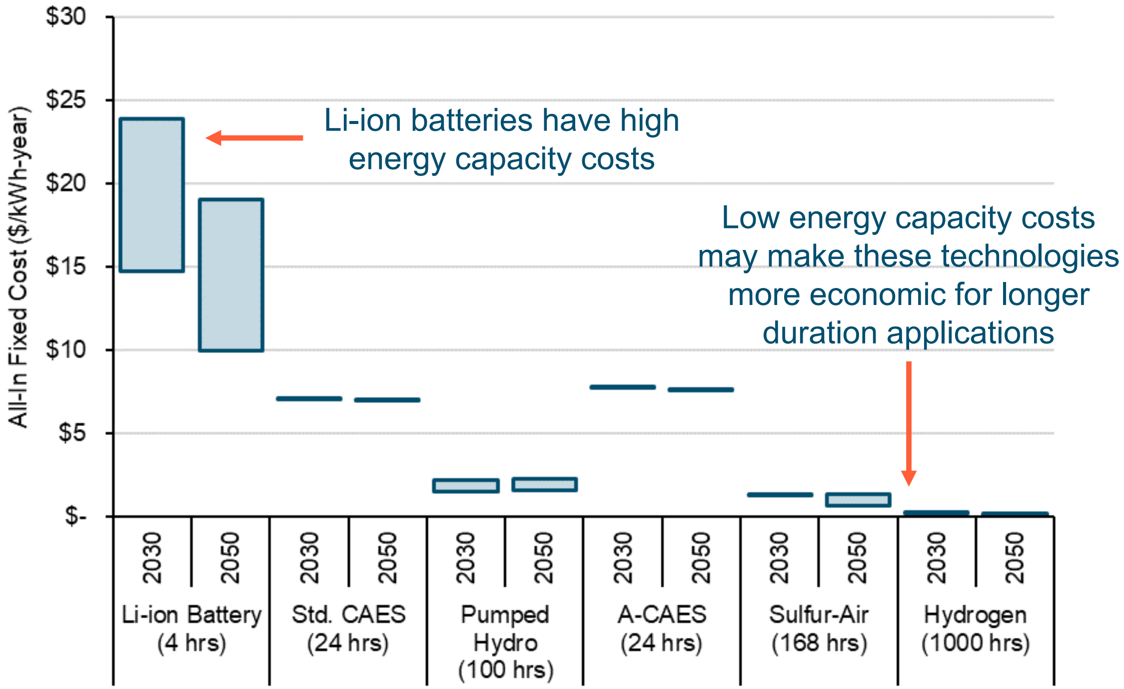
Indicative Storage Levelized Cost Projections

- **Levelization captures assumed financing costs of asset over expected lifetime**
  - Includes higher financing costs for less proven technologies & different lifetimes for different technologies
- **Levelization over energy storage capacity ($/kWh-year) highlights contrast in potentially cost-effective applications for different storage technologies**

Levelized All-In Fixed Cost (2019 $/**kW**-year)



Levelized All-In Fixed Cost (2019 $/**kWh**-year)

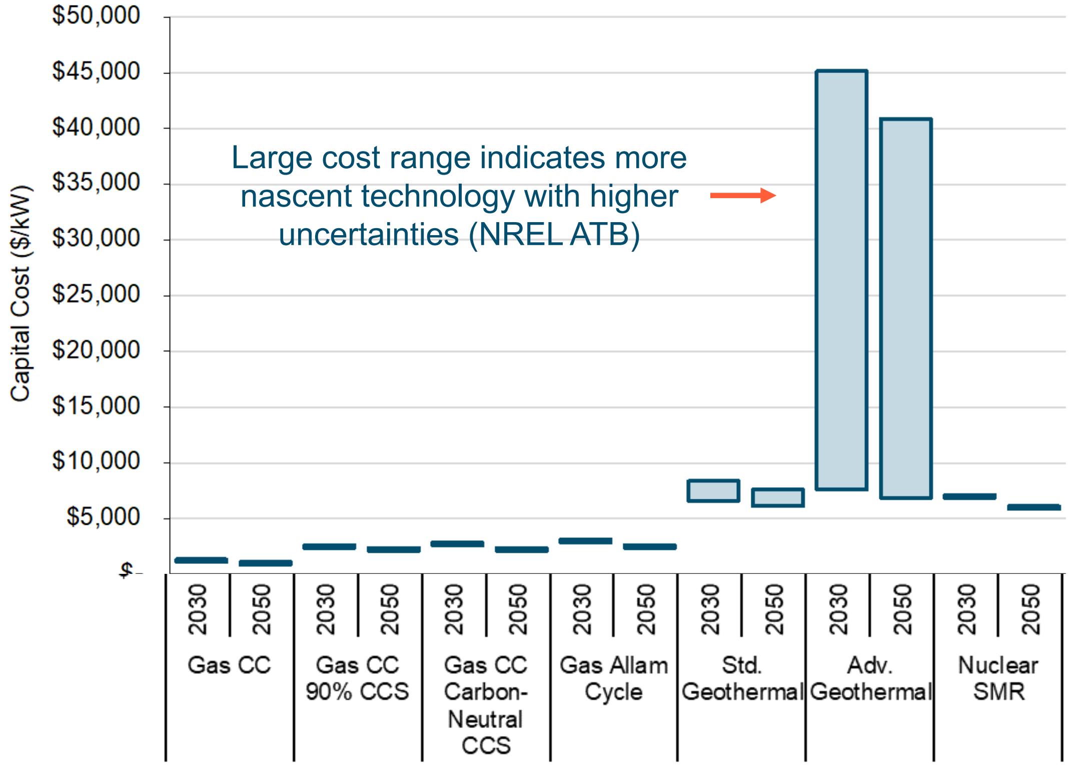


Note: Indicative durations for each technology used only for visualization purposes. Each technology has a range of potential duration configurations.

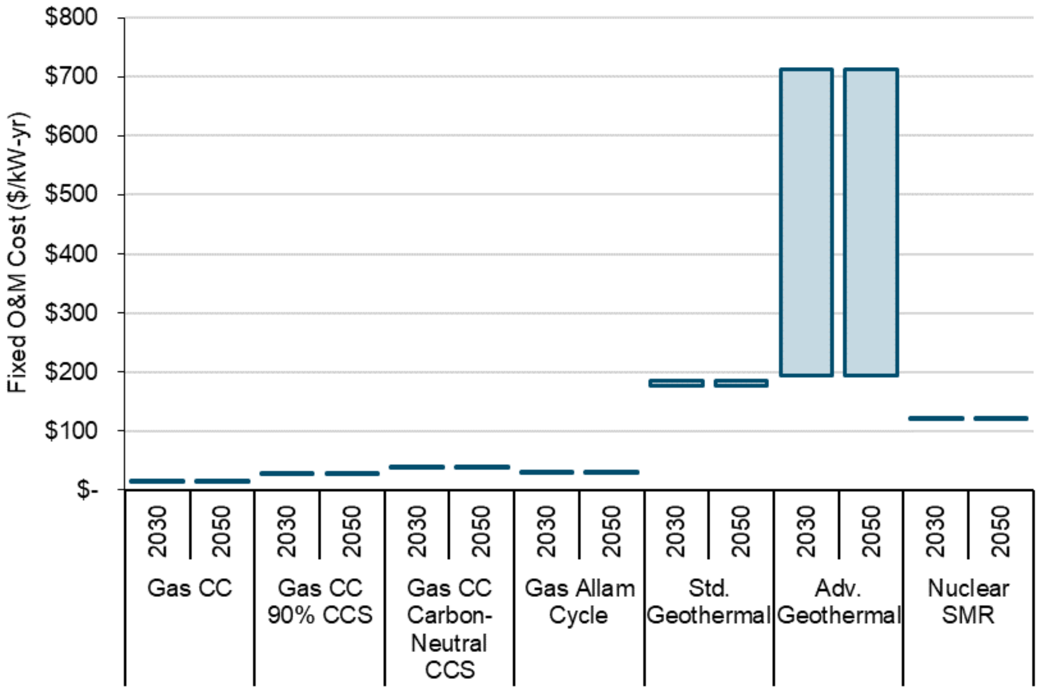
Emerging Generation Fixed Cost Projections

+ **In addition to storage technologies, we developed cost projections for new generation technologies**
  - Focus was on CCS, advanced geothermal, and advanced nuclear

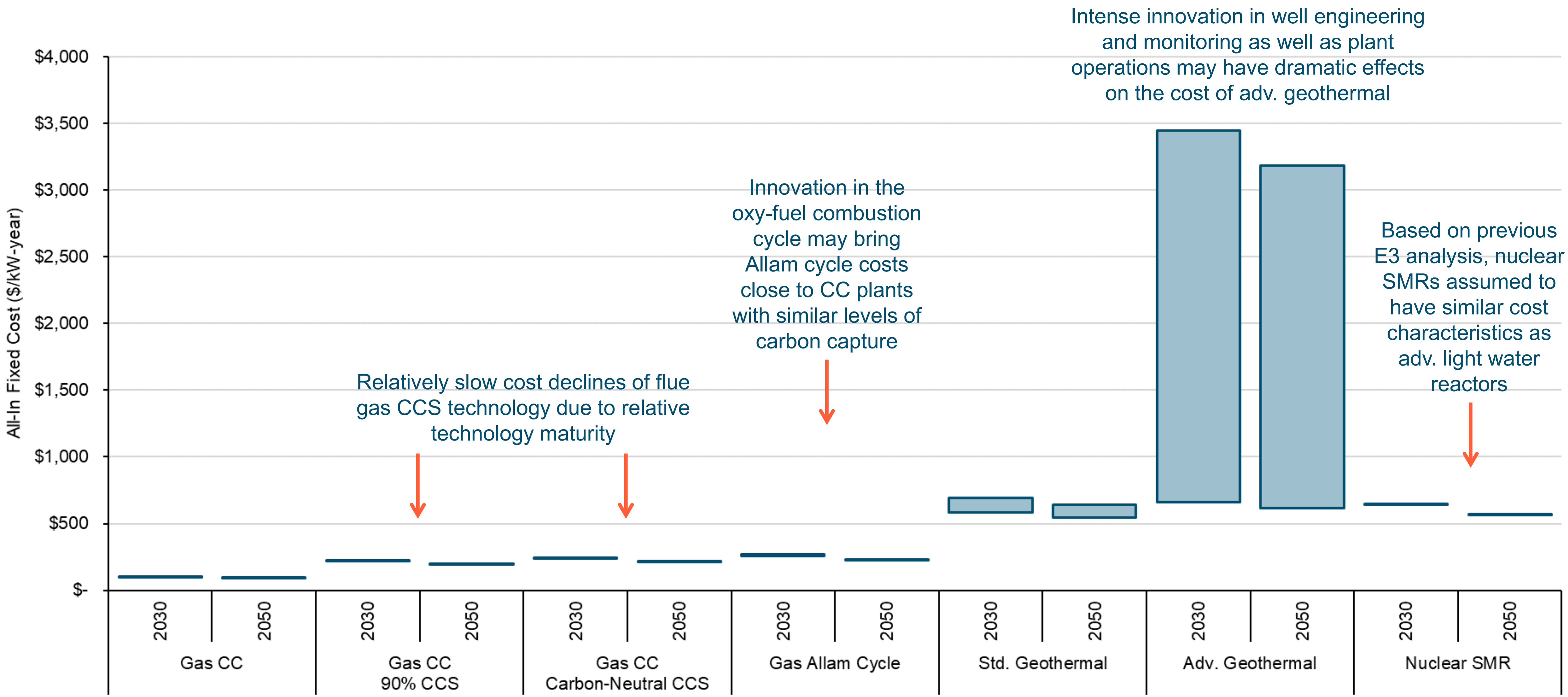
Installed (Capital) Cost (2019 $/kW)



Fixed O&M Cost (2019 $/kW-year)



Emerging Generation Levelized Cost Projections



Key Takeaways

+ **Draft technology review covers technology readiness level & cost projections for key emerging storage technologies**
  - Costs for some storage technologies may scale more slowly with duration, making them potentially useful for longer-duration storage applications
+ **Technology review also includes emerging generation technologies, which will interact with LDES in a zero-carbon resource portfolio**
  - Technologies with different cost characteristics may be operated differently and can provide different values to the system
+ **The potential value of emerging technologies is being evaluated in ongoing analysis**

+ ***We will provide updates on the technology review in future workshops***

Progress Updates

Preliminary Analytical Experiments

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Rachel Orsini, Analyst, Form Energy

Energy+Environmental Economics

Preliminary Analytical Experiments to Understand the Value of Storage Resources

To guide our upcoming analysis & model development, we conducted quick analytical experiments to highlight the kinds of behavior & values we want to consider when modeling LDES:

1. **Storage Dispatch Behavior**
   Storage technologies can simultaneously be dispatched for short- (i.e., daily) and long-duration (i.e., seasonal) arbitrage value

2. **Storage Capacity Contribution**
   Longer duration storage configurations may provide greater capacity contribution (ELCC); however, this capacity is heavily dependent on interactions with other resources in the portfolio

3. **Weather Variability**
   Capturing weather variability (both within and across years) and climate impacts is key to developing robust resource portfolios for California's decarbonized future

Cycling Behavior for Different Storage Configurations

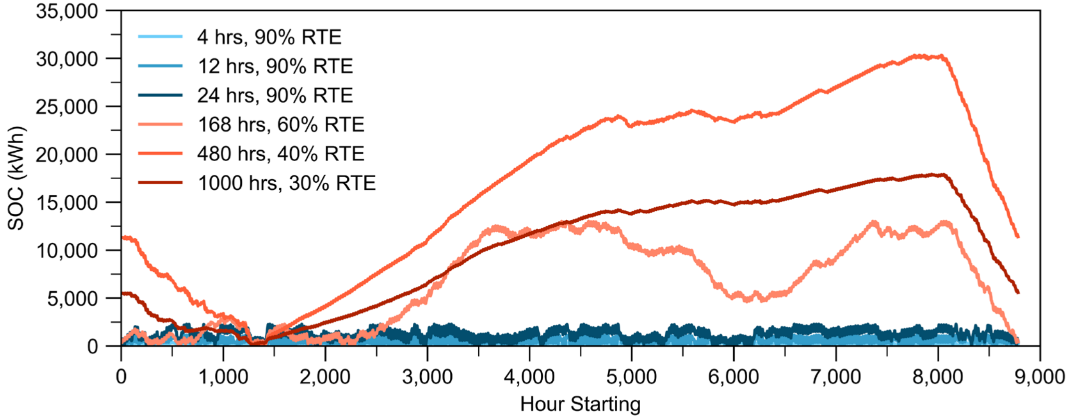
Experimental Setup & Goals

+ Using E3's RESTORE price taker model, we studied how storage of different durations & RTE would dispatch when subject to the same price signals over a full year (8760-hour)

Key Takeaways

+ Shorter duration storage respond primarily to daily & weekly price signals
+ Longer duration storage is still responsive to daily price signals, but an increasing portion of value is derived from seasonal arbitrage
  - For example: 168-hour storage resource has 2 prominent seasonal cycles across modeled year but is also cycling a noticeable amount day-to-day

Full-Year State of Charge in 2030



Resulting Discharge Cycles in 2030

Configuration	Cycles/Year
4-hour, 90% RTE	300*
12-hour, 90% RTE	300*
24-hour, 90% RTE	164
168-hour, 60% RTE	14
480-hour, 40% RTE	3
1000-hour, 30% RTE	1

* Assumed technology annual cycling limit

Allocating Storage Dispatch Value

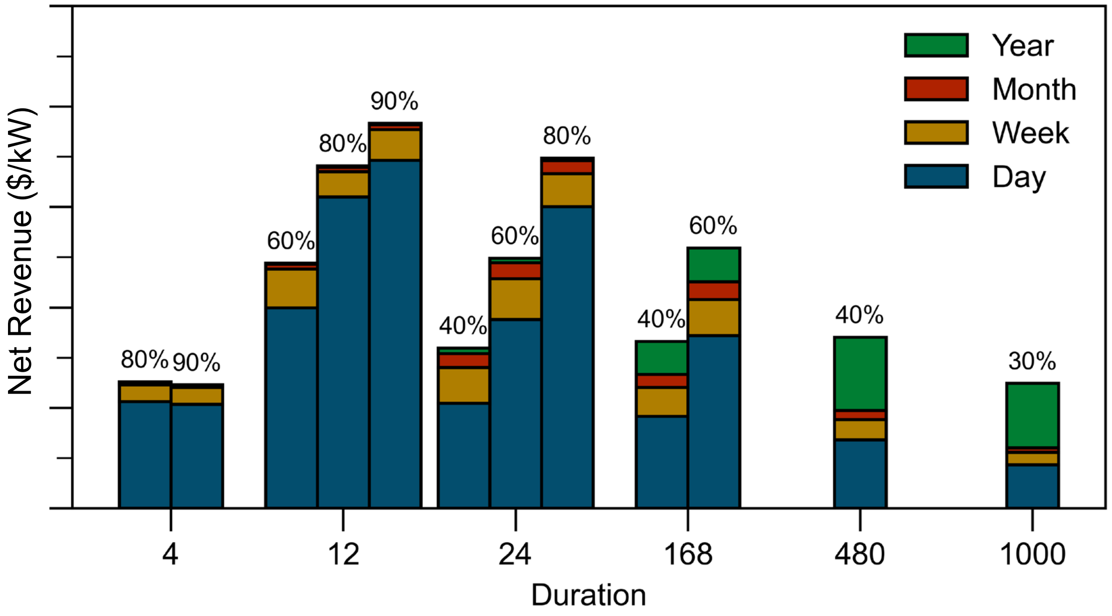
Experimental Goals

- Experiment with methods to characterize operations as daily to seasonal to understand impact of temporal sampling on modeled value

Key Takeaways

- **Long duration storage resources will typically shift energy for longer periods of time (i.e., derive value from longer-duration arbitrage)**
  - Significant increase in arbitrage value from 4- to 12-hour storage duration
- **RTE has a significant impact on arbitrage value, as less energy can be shifted to high-value times**
  - Lower RTE technologies may still be cost-effective if costs come in lower than higher RTE alternatives

Allocation of Energy Arbitrage Value

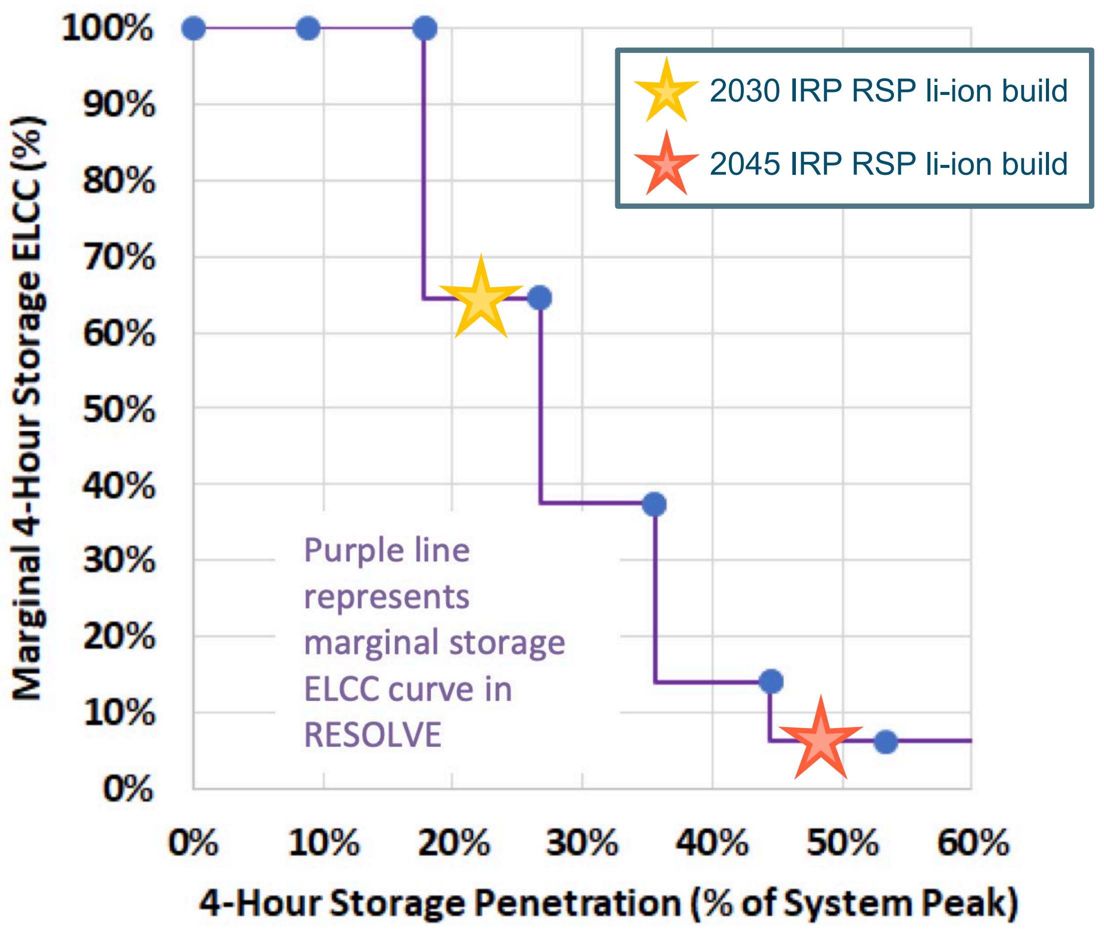


Guiding Project Question

How do we better capture the relative value associated with simultaneous daily through seasonal storage dispatch behaviors?

ELCC Context from CPUC IRP Modeling

CPUC IRP 4-Hour Storage ELCC Curve



Source: CPUC IRP Proposed Reference System Plan

- **ELCC is a metric used to quantify the <u>capacity contribution</u> of a resource toward meeting system reliability target**
  - At the highest level, achieving system reliability is about having sufficient supply to meet demand
- **The CPUC IRP used a <u>declining storage ELCC</u> curve based on SERVM LOLP modeling to represent the capacity contribution of 4-hour, lithium-ion storage**
  - By 2045, the incremental capacity contribution of 4-hour storage is modeled as <10% of nameplate capacity
- **We expect longer duration storage configurations to provide greater capacity contribution and/or decline less rapidly than 4-hour storage**

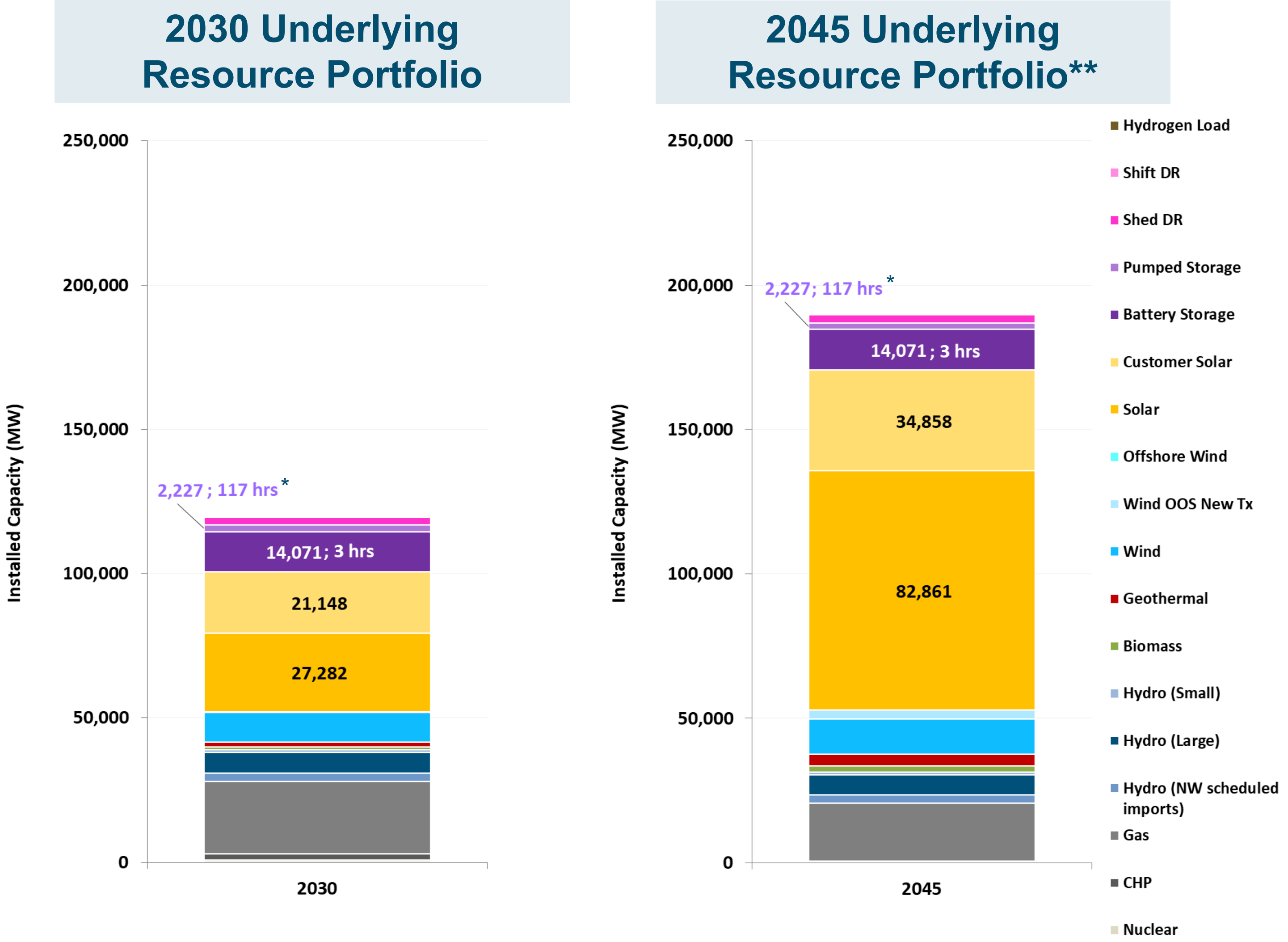
Experimental Setup

Experiment Setup

+ Using CPUC IRP RSP build as our starting point, study the incremental ELCC of various storage configurations

Experimental Goals

+ Understand how durable ELCCs for longer duration storage resources may be as load/resource balance changes
+ Understand effect of duration & RTE as two major operational characteristics on calculates storage ELCC
+ Understand interactive effects between shorter & longer duration storage resources in the same portfolio



* High average storage duration driven by existing pumped storage capacity. New pumped storage duration is modeled as 12-hour duration.
** 2045 portfolio includes all generation resources from 2019 CPUC IRP RSP but no incremental storage build after 2030

Impact of Duration & RTE on Storage ELCC

Key Takeaways

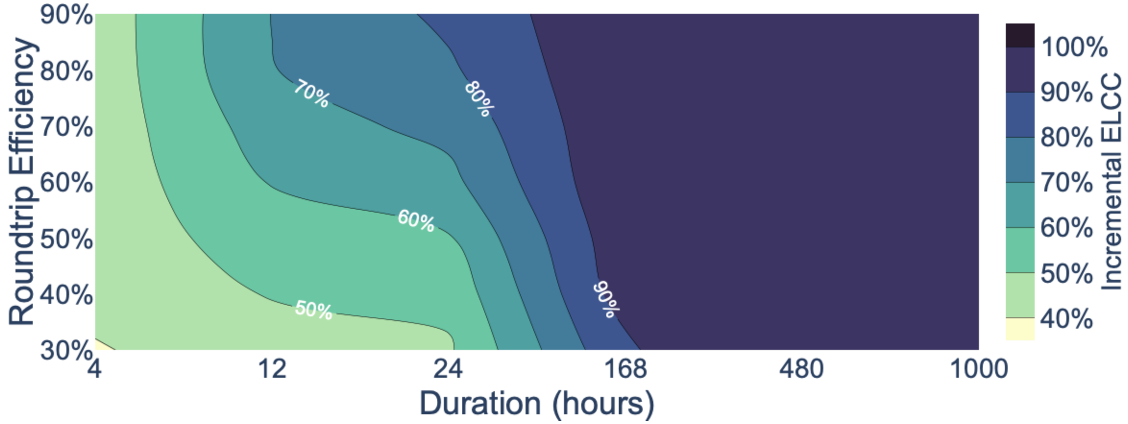
+ **In 2030, storage of at least 12-hour duration can achieve full ELCC***
    - Compared to <70% ELCC from CPUC IRP
+ **By 2045, storage of duration approaching one week needed to achieve full ELCC***
    - ELCC becomes heavily dependent on interactive effects with other dispatch-limited resources
+ **Complex effect of RTE on ELCC, driven by ability for storage to recharge after reliability events—requires further study**

Guiding Project Question
Can capacity expansion models better capture the interactive effects that affect storage capacity contribution for robust, future resource portfolios?

* Full ELCC approaches 100% subject to modeled forced outages

2030 ELCC (5 GW incremental)

2045 ELCC* (5 GW incremental)



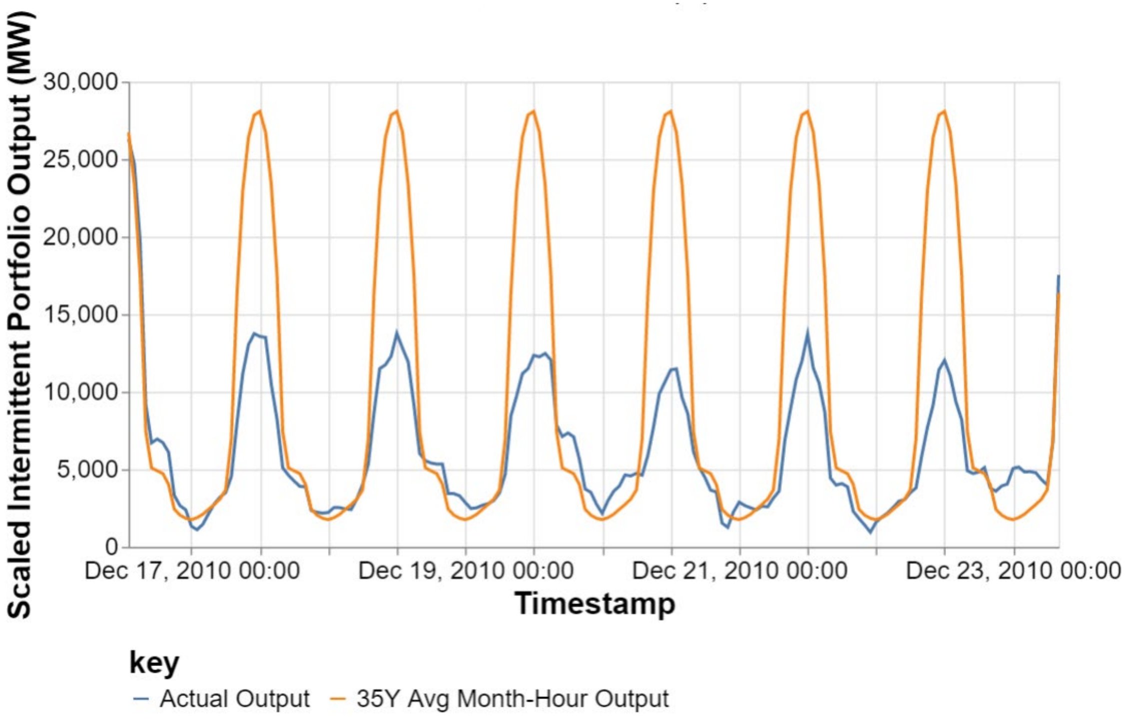
* 2045 portfolio includes all generation resources from 2019 CPUC IRP RSP but no incremental storage build after 2030 (see previous slide)

Data Analysis of CPUC IRP Modeling Data

+ **Hypothesis: future reliability risks driven by multi-day low renewable energy events**
    - Here, we define "renewable lulls" as extended events where renewable resource availability falls 25% below historical average
+ **Analysis of 35 years of SERVM resource profiles from CPUC's "Hybrid Conforming Portfolio 2030" from the 2018 IRP preferred system plan revealed data revealed:**
    - 50-hour renewables lulls occur once every 2 years
    - 100-hour renewables lulls occur once every 10 years

Guiding Project Question
Can we capture the effects of these low resource availability periods on the value & reliability contribution of future resource additions?

December 2010 Low-Renewables Event



Capacity Expansion Model Reduction Experiments

Experimental Context

- Models need to maximize detail to build robust, low-cost portfolios, while maintaining tractability
- Tractability allows modeling of a wide range of sensitivities, increasing transparency & understanding of uncertain futures

Experimental Goals

- Explore the impact of modeling tradeoffs on resource portfolio & other key reporting metrics to inform development of New Modeling Toolkit & final analysis

Key Modeling Experiments

Geographic Scope:
Explore alternative representations of WECC to unlock computational power for greater temporal or technoeconomic detail

Temporal Scope:

Explore alternative representations of time to better capture storage and renewables dynamics

Technoeconomic Detail:
Explore alternative technoeconomic and market details to unlock computational power for greater temporal or spatial detail

* Reference will be the CPUC IRP and SB100 Joint Agency Report portfolios

Key Takeaways & Upcoming Modeling Improvements

+ **Key takeaways from existing experiments to keep in mind for New Modeling Toolkit:**
  1. Emphasis on capturing both daily and longer-duration dispatch behaviors to value storage
  2. The potential multi-dimensional and time-varying considerations to correctly capture the capacity contribution of storage resources
  3. The potential importance of capturing a wider range of weather conditions for California's future resource portfolios in New Modeling Toolkit & Dataset

+ **Ongoing modeling development & analysis:**
  - Modeling the value of interannual storage (on top of within-year daily & seasonal arbitrage)
  - Modeling the value of cross-sectoral storage (i.e., electrofuels, which may be used in other sectors)
  - Developing data to study the value of locally- & distribution-sited storage resources
  - Investigating additional datasets & modeling approaches to incorporate climate impacts into our generation data to capture a wider range of plausible, future system conditions
  - As we need to higher granularity in some dimensions (e.g., storage dispatch), what other dimensions can we tradeoff to keep capacity expansion modeling useful, tractable & producing reliable resource portfolios?

Preliminary Analysis Scenario Design

Energy+Environmental Economics

Overview of Two Scenario Design Questions

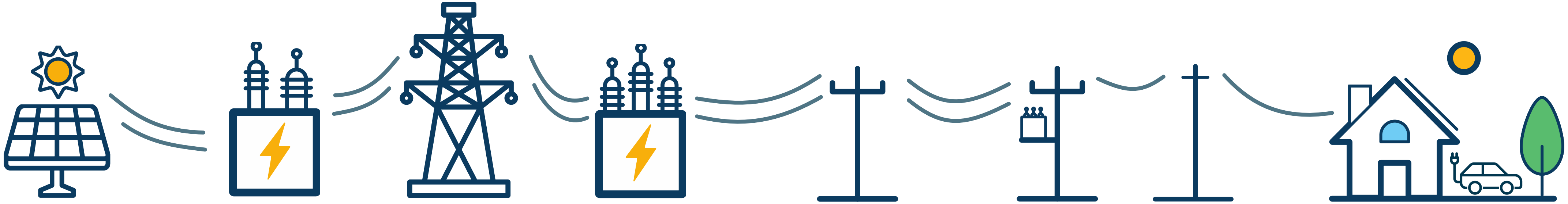
Bulk System Scenarios

How will the **speed & stringency** of economywide emissions constraints affect procurement of LDES and other emerging technologies?

As project timeline permits, we will study potential ways to better align the bulk system & microgrid perspectives

Zero-Carbon Microgrid Scenarios

How will **emissions constraints & market access** affect the economics of customer-sited LDES and zero-carbon microgrids?



Grid Location	Generation	Transmission	Distribution Substation & Circuits	Customer Microgrid
Value Stream	Energy + System Capacity + AS		+ Local Capacity + T&D Deferral	+ Bill Savings + Resiliency Value

Preliminary Analysis Scenario Design

Preliminary Bulk System Scenarios

Roderick Go, Technical Manager, E3
Jasmine Ouyang, Managing Consultant, E3
Nick Schlag, Director, E3
Amber Mahone, Partner, E3
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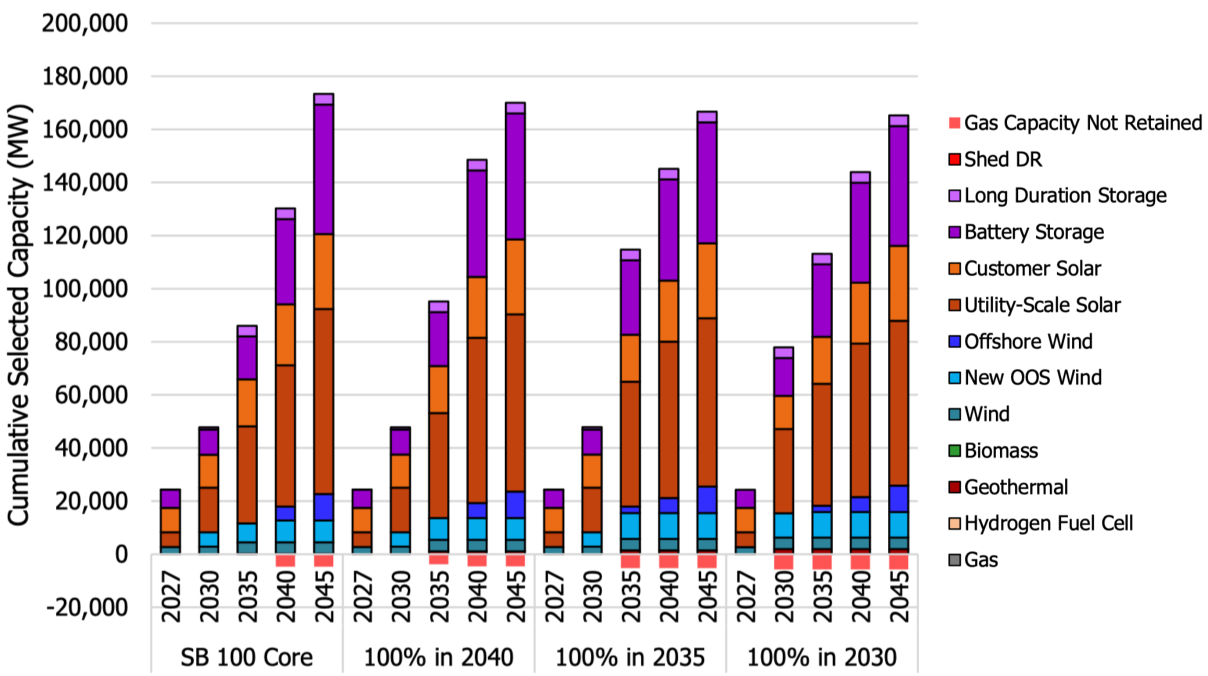
Background & Key Analytical Questions

Context for Preliminary Analysis: SB100 Cumulative Resource Additions



Source: SB100 Joint Agency Report (figure 9)

Key Analytical Questions

1. What role could LDES play in system portfolio?
   - How could the resource portfolio change with inclusion of a wider range of emerging technologies?
2. What price targets must LDES achieve in order to become key components of the overall system portfolio?
3. What modeling approaches can we use to better capture the value of LDES technologies in a capacity expansion context?

Preliminary Bulk System Scenario Design

+ **For our scenario design, we believe the primary driver for adoption of emerging technologies will be the speed of electric sector decarbonization**
  - Sensitivities will focus on drivers of the value of LDES within the resource portfolio—for example, relative to other commercialized & emerging technologies
  - Preliminary bulk system analysis will be conducted in Formware model
+ **Proposed scenarios will be consistent with economywide decarbonization pathways**

Scenario	Description
SB100 Reference Policy	Match SB100 Joint Agency Report Core Scenario (100% zero-carbon sales by 2045)
"Core" Zero-Carbon	Achieve 100% zero-carbon generation by 2045
Accelerated Zero-Carbon	Achieve 100% zero-carbon generation by 2035

Additional Sensitivities

+ **Proposed sensitivities are intended to better understand the robustness of long duration storage value within the context of each policy scenario (previous slide)**
  - We propose that some sensitivities would be performed during the final analysis due to data development required or limited impact on preliminary results

Category	Sensitivity	Description
Resource	***Existing Technologies Only***	• Only test existing resource options (e.g., in- and out-of-state renewables, OSW, geothermal, li-ion, CPUC IRP transmission assumptions)
	Emerging Technologies	• Add emerging technologies one-by-one: LDES, CCS, drop-in low carbon fuels
	No Combustion by 2045	• No combustion resources (existing or candidate) remaining on the system by 2045
Demand	***Mid Electrification***	• Consistent with High Biofuels Pathways scenario, lower building electrification potentially drives lower LDES value
	High Electrification	• Consistent with High Electrification Pathways scenario
	High DER Adoption	• Adjust loads and expected T&D upgrade costs based on higher assumed adoption of DERs
	High Load Flexibility	• Higher load flexibility shows substitutability between load flexibility and LDES technologies
Weather Year	***Wider Range of Weather Years***	• Test a wider range of weather years, which may be a driver of LDES value not captured by current modeling methodologies & datasets
	Extreme Events	• Test portfolios against a characterized set of extreme weather events (characterization in progress)

Sensitivity for Final Analysis only

Any comments on the bulk system scenarios, sensitivities & modeling experiments?

Preliminary Analysis Scenario Design

Preliminary Zero-Carbon Microgrid Scenarios

Dr. Ryan Hanna, Research Scientist, UCSD
Roderick Go, Technical Manager, E3
Jessie Knapstein, Managing Consultant, E3

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Resiliency Need & Key Analytical Questions

Resiliency Needs in California

+ California is experiencing increasing need for electric reliability, while a growing number of hazards threaten to degrade reliability
+ California has identified microgrids as a possible solution to these problems, but issues around high investment costs, use of fossil fuels, and other open questions persist (SB 1339, CPUC microgrid proceeding)

Key Analytical Questions

1. What role could LDES play in enabling zero-carbon microgrids?
2. How will policy drivers (e.g., emissions limits, new incentive programs, or new market opportunities) affect the role that LDES could play in microgrids?
3. What price targets must LDES achieve in order to become key components of microgrids?
4. How do different parameters (e.g., critical load or number of PSPS events) impact cost-effectiveness?

Preliminary Zero-Carbon Microgrid Scenario Design

+ **Scenarios define explicit choices that policymakers could take to facilitate use of zero-carbon microgrids—e.g., constraining the use of fossil fuels or expanding market opportunities for DERs during "blue sky" grid conditions**
  - Because LDES may not be economic under conditions today, it is important to understand the conditions (scenarios) in which they could be.
+ **Within each scenario we will run a number of sensitivities, to further explore variation in parameters that could impact use of LDES but lie outside the purview of policy**
  - For example, rates of PSPS, cost and performance of LDES

Scenario	Emissions Constraints	Available Revenue Streams
1. Baseline	None / CO_2 price where applicable	Utility bill savings
2. Zero-carbon	100% carbon-free	Utility bill savings
3. Zero-carbon commercialization	100% carbon-free	Utility bill savings + market participation (energy, AS, etc.)

UCSD Building Microgrid Case Studies

- **For each case study, a base (no investment) and microgrid case (with investment) are modeled**
  - Where buildings are already tied to diesel gensets for emergency backup, we will model this in the base case
  - Comparing the two gives insights about the microgrid's economics and optimal use of DERs
- **Reliability is modeled as "survivability"—a minimum requirement for islanding duration**
- **The value of resiliency is calculated as the ratio of the change in cost and change in reliability upon investing**

Building	Annual Load (GWh)	Peak Load (kW)	Average Daily Load Factor (%)	Critical Circuits Metered Separately	Average Critical Load
Biomedical Research II	7.5	1,030	92%	Yes	39%
Cellular & Molecular Medicine West	3.5	460	94%	Yes	10%
Moores Cancer Center	8.3	1,200	87%	Yes	47%
Pharmacological Sciences	6.7	1,040	88%	Yes	32%
UCSD Campus	297	47,600	94%	No	–
Other Campus Buildings	[TBD]	[TBD]	[TBD]	[TBD]	[TBD]

Focus: Separately metered critical loads will allow us to study how microgrids could serve different types of load shapes. These buildings on UCSD's campus tend to be higher load factor

Focus: Campus-level and other building data will provide a wider range of load factors.

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Any comments on the scenarios to study for zero-carbon microgrids?

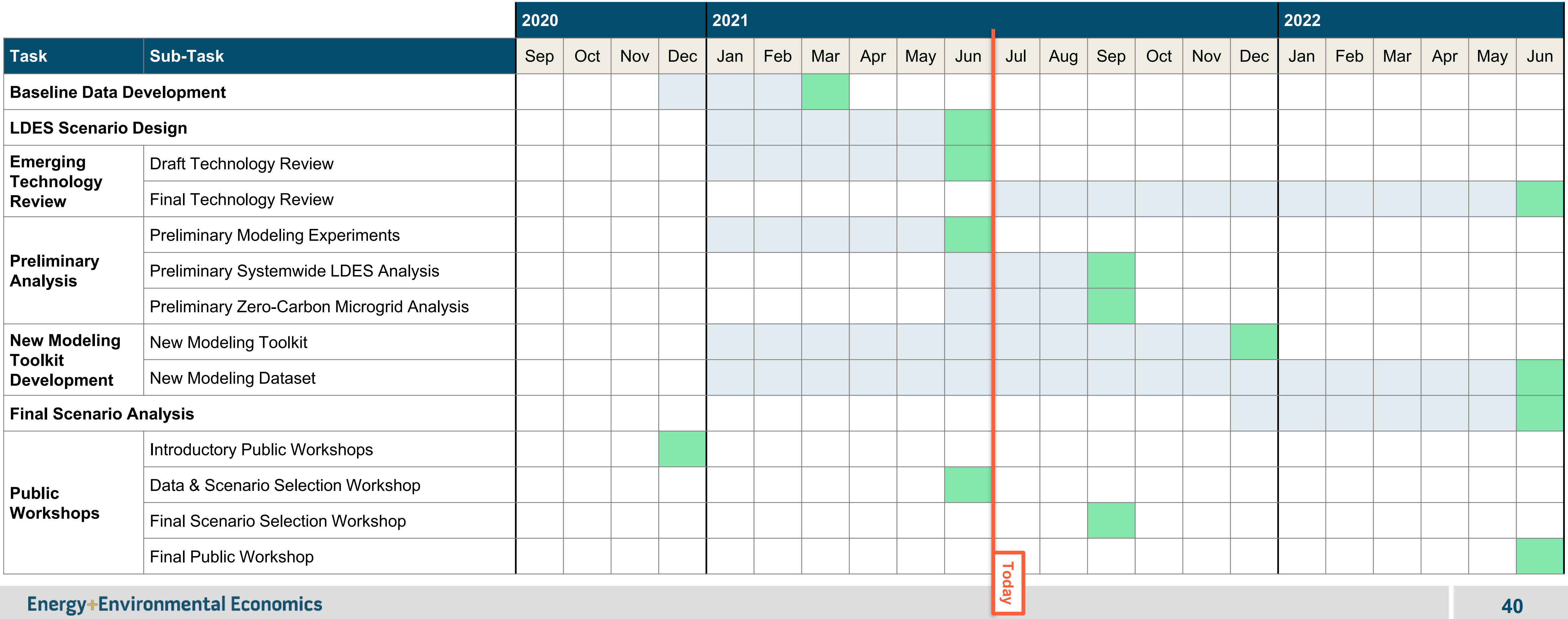
Next Steps

Energy+Environmental Economics

Updated Project Schedule

Deliverable
Task in progress

+ **Goal is to have preliminary analysis completed approximately 3 months from today's workshop**



Where We Are in Overall Project Arc

1 Preliminary LDES analysis using existing tools

Define scenarios for systemwide & microgrid studies

Identify future scenarios under which to study value of long duration storage for California

Analyze LDES behavior & individual value streams

- *Use existing tools to analyze operational behavior & known value streams (**RECAP**, **RESTORE**)*
- *Study techniques to reduce capacity expansion modeling complexity (**RESOLVE**, **Formware**)*

Key outputs

- *Understanding of key dispatch behaviors & LDES to capture in New Modeling Toolkit and future analyses*

Study systemwide & microgrid portfolios with LDES

- *Develop CA resource portfolios under different scenarios (**Formware**)*
- *Analyze cost-effective, zero-carbon microgrid applications (**UCSD Microgrid Model**)*

Key outputs

- *Least-cost bulk system portfolios comparing LDES and other techs*
- *Least-cost microgrid portfolios comparing LDES and other techs*

2 Refresh tools & data based on learning from Phase 1

Develop New Modeling Toolkit & Datasets

- *Use Phase 1 learnings to inform model enhancements needed to capture value of LDES*
- *Update datasets to complement enhanced modeling functionality (e.g., wider set of weather conditions)*

Key outputs

- *Updated modeling platform capable of representing values & system needs identified in Phase 1*

3 Analyze LDES using New Modeling Toolkit

Complete final analysis in new modeling toolkit

- *Develop optimized portfolios to meet California's future energy needs that consider a broad range of options for long duration storage*

Key outputs

- *Optimized portfolios including LDES under a range of cost and duration assumptions*

Thank You

Roderick Go, roderick@ethree.com

Energy+Environmental Economics

Appendix

Energy+Environmental Economics

Overview of Project Team & Responsibilities

+ **E3 will lead this team, leveraging expertise in deep decarbonization analyses**
  - **Amber Mahone** and **Roderick Go** will be serve as project managers
  - **Arne Olson** will be principal investigator
  - **Nick Schlag** will serve as project advisor
+ **Form Energy will provide technology expertise on their long duration storage technology and analytical support valuing long duration storage assets**
+ **UCSD CER will draw on real-world testing expertise to assess the technical characteristics of long duration storage technologies and use the UCSD campus as a case study for low-carbon microgrids based on long duration storage**

Overview of Project Team

Prime Recipient: E3

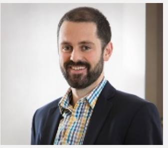
Principal Investigator

Arne Olson,
Senior Partner

Project Manager (External)

Amber Mahone,
Partner

Project Advisor



Nick Schlag,
Director

Project Manager (Internal)

Roderick Go,
Technical Manager

E3 Consulting Staff

- Jasmine Ouyang, Sr. Managing Consultant
- Jessie Knapstein, Managing Consultant
- Dr. John Stevens, Managing Consultant
- Xiaoxuan Hou, Senior Consultant
- Gabe Mantegna, Senior Consultant
- Manohar Mogadali, Senior Consultant
- Dr. Yuchi Sun, Senior Consultant
- Dr. Mengyao Yuan, Senior Consultant
- Emily Peterson, Consultant
- Vignesh Venugopal, Consultant
- Dr. Bill Wheatle, Consultant
- Charlie Gulian, Associate
- Karl Walter, Associate

Sub-Contractor 1:
University of California
San Diego Center for Energy Research

CER Center for Energy Research

Mike Ferry,
Director of Energy Storage
and Systems

Ryan Hanna,
Research Scientist

Sub-Contractor 2:
Form Energy

form energy

Dr. Marco Ferrara,
Co-Founder & SVP of Analytics and Business Development
Mateo Jaramillo,
Co-Founder & Executive Chairman
Dr. Scott Burger,
Analytics Manager
Rachel Orsini,
Analyst
Dr. Ben Jenkins,
Manager, Data and Optimization
Jason Houck,
Policy and Regulatory Affairs Lead

IEA's Clean Energy Technology Guide

- **As part of its Energy Technologies Perspective (ETP) report in 2020, IEA published a "Clean Energy Technology Guide"**
  - This guide contains over 400 clean energy technologies for achieving global net-zero emissions by mid-century
- **It utilizes an 11-point technology readiness level (TRL) scale**
- **IEA's TRL scale is adopted for E3's technology review**
  - Supplemented with E3 expertise where needed

** SDS = Sustainable Development Scenario (IEA-specific analysis).*

https://www.iea.org/articles/etp-clean-energy-technology-guide

Proposed Technology Screening Approach

Commercialized ← Emerging → Experimental

	Mature Technologies	Emerging Technologies	Experimental Technologies
Market Experience	Fully commercialized	Limited development	No development
Data: Costs	Available, documented near-term costs and established trajectories	Limited, possible near-term costs but speculative cost trajectories	Theoretical, no real-world cost data
Data: Potential	Available	Limited	Theoretical
Data: Operating Characteristics	Available	Limited	Theoretical
Examples	Solar, wind, battery storage, fossil gas CT/CCGT, biogas combustion	Gas w/ CCS, advanced nuclear (e.g., modular reactors), direct air capture, BECCS, H_2, power-to-gas (P2G), advanced geothermal, long duration storage	Nuclear fusion, solar fuels ("artificial photosynthesis")

Proposed Approach	Model in all scenarios	Model in sensitivity scenarios	Do not model due to lack of data
Impact	***Drives results + near-term decision making***	***Informs least-regrets planning, stranded asset risk***	***Informs R&D spending, pilot projects***

Energy Arbitrage Modeling Experiment

2030 vs. 2050 Forecasted Energy Prices

Raw DA Energy Prices	Year: 2030 Zone: SP15																							
$/MWh	Hour Starting																							
Month	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	$ 45	$ 45	$ 44	$ 44	$ 46	$ 46	$ 46	$ 43	$ 26	$ 18	$ 18	$ 17	$ 17	$ 17	$ 18	$ 19	$ 39	$ 46	$ 46	$ 46	$ 46	$ 46	$ 46	$ 46
2	$ 47	$ 45	$ 45	$ 45	$ 47	$ 49	$ 49	$ 40	$ 22	$ 18	$ 17	$ 17	$ 17	$ 17	$ 17	$ 19	$ 31	$ 52	$ 52	$ 52	$ 52	$ 52	$ 51	$ 50
3	$ 44	$ 44	$ 44	$ 44	$ 44	$ 45	$ 44	$ 22	$ (0)	$ (2)	$ (2)	$ (2)	$ (2)	$ (2)	$ (2)	$ (1)	$ 12	$ 43	$ 45	$ 45	$ 45	$ 45	$ 45	$ 45
4	$ 35	$ 35	$ 35	$ 35	$ 35	$ 35	$ 32	$ 7	$ 0	$ 0	$ (0)	$ (1)	$ 0	$ 0	$ 0	$ 2	$ 9	$ 33	$ 37	$ 37	$ 37	$ 37	$ 37	$ 36
5	$ 35	$ 35	$ 35	$ 35	$ 35	$ 31	$ 30	$ 9	$ 7	$ 6	$ 6	$ 5	$ 6	$ 6	$ 6	$ 7	$ 12	$ 34	$ 41	$ 43	$ 42	$ 41	$ 41	$ 40
6	$ 33	$ 33	$ 33	$ 33	$ 33	$ 29	$ 29	$ 19	$ 18	$ 17	$ 18	$ 18	$ 17	$ 18	$ 18	$ 17	$ 23	$ 36	$ 40	$ 47	$ 46	$ 40	$ 38	$ 37
7	$ 39	$ 39	$ 39	$ 39	$ 39	$ 37	$ 36	$ 28	$ 25	$ 25	$ 25	$ 25	$ 25	$ 25	$ 25	$ 26	$ 34	$ 47	$ 54	$ 61	$ 59	$ 50	$ 49	$ 48
8	$ 42	$ 42	$ 41	$ 41	$ 42	$ 42	$ 38	$ 29	$ 28	$ 29	$ 29	$ 29	$ 29	$ 28	$ 29	$ 31	$ 37	$ 49	$ 64	$ 62	$ 57	$ 49	$ 48	$ 47
9	$ 44	$ 44	$ 43	$ 43	$ 44	$ 44	$ 40	$ 27	$ 25	$ 25	$ 25	$ 26	$ 26	$ 25	$ 25	$ 30	$ 39	$ 57	$ 65	$ 63	$ 56	$ 55	$ 50	$ 48
10	$ 45	$ 44	$ 43	$ 43	$ 44	$ 45	$ 43	$ 22	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 16	$ 24	$ 39	$ 53	$ 54	$ 52	$ 52	$ 51	$ 46	$ 46
11	$ 44	$ 43	$ 42	$ 42	$ 44	$ 44	$ 44	$ 29	$ 16	$ 15	$ 15	$ 14	$ 14	$ 15	$ 15	$ 24	$ 46	$ 47	$ 47	$ 47	$ 47	$ 47	$ 47	$ 47
12	$ 47	$ 45	$ 44	$ 44	$ 47	$ 49	$ 49	$ 44	$ 32	$ 28	$ 27	$ 26	$ 26	$ 26	$ 28	$ 33	$ 52	$ 53	$ 53	$ 53	$ 53	$ 53	$ 53	$ 52

Raw DA Energy Prices	Year: 2050 Zone: SP15																							
$/MWh	Hour Starting																							
Month	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	$ 68	$ 68	$ 68	$ 68	$ 68	$ 68	$ 68	$ 61	$ 35	$ 22	$ 16	$ 13	$ 14	$ 16	$ 18	$ 28	$ 48	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67
2	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67	$ 49	$ 31	$ 26	$ 22	$ 19	$ 20	$ 22	$ 21	$ 29	$ 34	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67	$ 67
3	$ 50	$ 50	$ 50	$ 50	$ 50	$ 50	$ 50	$ 8	$ (10)	$ (14)	$ (17)	$ (19)	$ (18)	$ (17)	$ (16)	$ (13)	$ (8)	$ 47	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49
4	$ 37	$ 37	$ 37	$ 37	$ 37	$ 37	$ 37	$ (13)	$ (27)	$ (26)	$ (28)	$ (29)	$ (28)	$ (28)	$ (27)	$ (24)	$ (23)	$ 35	$ 38	$ 38	$ 39	$ 38	$ 38	$ 38
5	$ 36	$ 36	$ 36	$ 36	$ 36	$ 36	$ 35	$ (4)	$ (5)	$ (6)	$ (7)	$ (7)	$ (7)	$ (6)	$ (5)	$ (5)	$ (4)	$ 31	$ 35	$ 35	$ 35	$ 35	$ 35	$ 35
6	$ 46	$ 46	$ 46	$ 46	$ 46	$ 44	$ 44	$ 13	$ 12	$ 11	$ 10	$ 9	$ 10	$ 10	$ 11	$ 12	$ 14	$ 40	$ 49	$ 49	$ 49	$ 49	$ 49	$ 49
7	$ 56	$ 56	$ 56	$ 56	$ 56	$ 55	$ 52	$ 16	$ 16	$ 14	$ 13	$ 13	$ 13	$ 14	$ 15	$ 16	$ 16	$ 46	$ 57	$ 57	$ 58	$ 57	$ 57	$ 57
8	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60	$ 58	$ 22	$ 19	$ 17	$ 15	$ 13	$ 14	$ 16	$ 18	$ 21	$ 25	$ 59	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60
9	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60	$ 17	$ 14	$ 12	$ 8	$ 7	$ 9	$ 13	$ 15	$ 17	$ 31	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60	$ 60
10	$ 62	$ 62	$ 62	$ 62	$ 62	$ 62	$ 61	$ 13	$ 9	$ 6	$ 4	$ 2	$ 4	$ 6	$ 10	$ 13	$ 46	$ 61	$ 61	$ 61	$ 61	$ 61	$ 61	$ 61
11	$ 64	$ 64	$ 64	$ 64	$ 64	$ 64	$ 64	$ 32	$ 21	$ 12	$ 7	$ 7	$ 8	$ 12	$ 15	$ 31	$ 64	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65	$ 65
12	$ 75	$ 75	$ 75	$ 75	$ 75	$ 75	$ 75	$ 65	$ 56	$ 46	$ 42	$ 38	$ 39	$ 42	$ 47	$ 58	$ 75	$ 77	$ 77	$ 77	$ 77	$ 77	$ 77	$ 77

+ **Seasonal and intraday shifting signals remain**
+ **The maximum difference in seasonal and intraday prices increases by ~50% and ~40% respectively**
+ **Expect that seasonal shifting will play a larger role in 2050, if a LoDES technology can perform it**

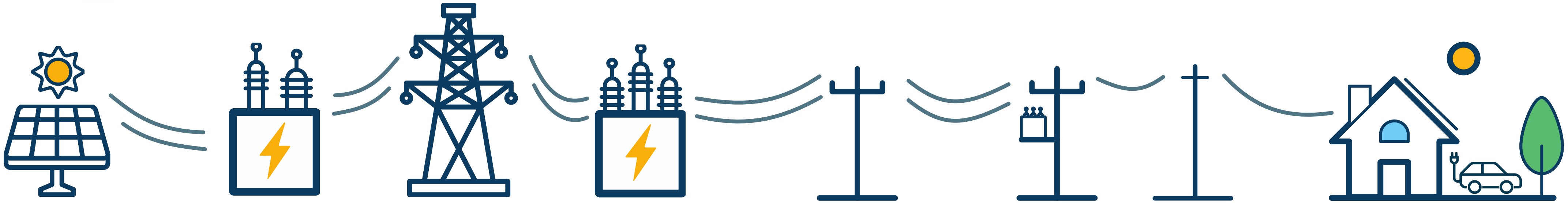
Analytical Approach

- Rather than focusing on categorizing technologies as "long" vs. "short" duration storage, we will study the applications, value streams, and operational characteristics that may drive storage procurement decisions
  1. **Energy, Capacity, and Operating Reserves**
     - How do technology characteristics affect the value proposition for meeting systemwide RA, decarbonization targets?
  2. **Transmission, Distribution & Local Reliability**
     - How do technology characteristics affect the value proposition for local reliability and T&D deferral applications?
  3. **Resiliency & Customer Benefits**
     - How do technology characteristics affect the value proposition for microgrid applications?
- We will assess other factors (e.g., renewable integration, land-use impacts) in addition to these value streams

Value stream	Category
Energy	Bulk System Values
System Resource Adequacy (RA)	Bulk System Values
Operating Reserves	Bulk System Values
Transmission Deferral	Bulk System Values
Local Capacity Requirement	Local Values
Distribution Deferral	Local Values
DG Integration & Hosting Capacity	Local Values
Local Air Quality	Local Values
Backup Power & Resiliency	Customer Values
Bill Savings	Customer Values

Analytical Approach

Tying Together Analyses at Different Scales of the Electricity System



Grid Location	Generation	Transmission	Distribution Substation & Circuits	Customer Microgrid
Value Stream	Energy + System Capacity + AS		+ Local Capacity + T&D Deferral	+ Bill Savings + Resiliency Value

Models

RESTORE	Evaluate bulk grid- and distribution-sited LDES as a price-taker, including market volatility
RECAP	Assess the effective load carrying capacity (ELCC) for system RA
RESOLVE & Formware	Evaluate impact of emerging techs on system build & operations, based on expected total system cost (without market volatility).
UCSD Microgrid Model	Evaluate economics & system reliability of LDES in a customer-sited, microgrid context

Analytical Approach

Anticipated Results for Comparison Across Baseline & Scenarios

Anticipated Result	Category
Scenario-based assumptions on load component forecasts & profiles (e.g., implied building & transportation electrification)	Bulk System
Systemwide portfolio Total Resource Cost	Bulk System
Systemwide annual GHG emissions & marginal GHG abatement cost	Bulk System
Marginal ELCC curves for storage technology alternatives	Bulk System
Achieved PRM & PRM shadow price (indicative of marginal cost to achieve System Resource Adequacy requirements)	Bulk System
Systemwide resource build (e.g., MW of renewables, LDES, etc. deployed & gas economically retired, based on expected cost projections)	Bulk System
Breakeven cost of LDES to be competitive with bulk system resource alternatives (e.g., firm, zero-carbon resources, renewables, lithium-ion)	Bulk System
Breakeven cost of LDES to be competitive with local capacity resource alternatives (e.g., firm, zero-carbon resources, renewables, lithium-ion)	Local Capacity
Potential local capacity or T&D deferral value captured (translated into a net cost reduction for DERs in capacity expansion)	Local Capacity
B/C ratio for LDES as a local capacity resource based on expected cost projections (to be developed via technology review)	Local Capacity
Customer bills & reliability metrics	Customer Microgrid
Breakeven cost of LDES to be competitive with microgrid resource alternatives (e.g., CHP, diesel, solar + lithium-ion)	Customer Microgrid
B/C ratio for LDES as a microgrid resource based on expected cost projections (to be developed via technology review)	Customer Microgrid
Scenario-based microgrid deployment & configurations, informed by cost-effectiveness analysis	Customer Microgrid
Annual GHG emissions & local air quality impacts of various microgrid configurations	Customer Microgrid
Total land use for resource build	Other Metrics
Value of “short-” (e.g., intra-day) vs. “long-duration” (e.g., seasonal) dispatch behavior for various storage alternatives	Other Metrics

Summary of Relevant Public Datasets

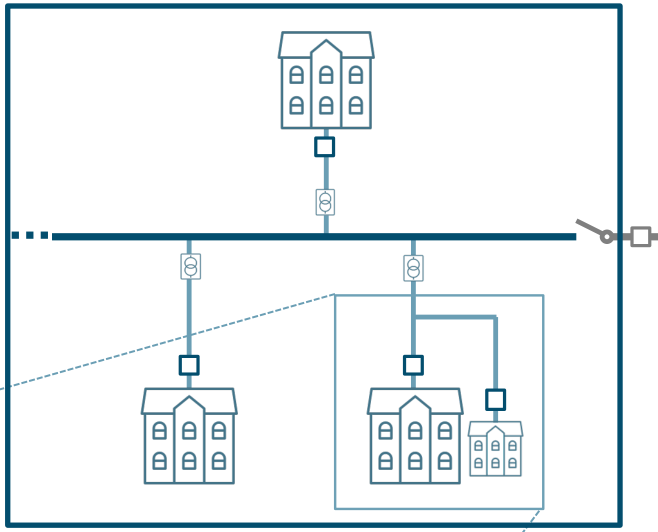
+ Many of the relevant datasets are derived from the latest publicly available CPUC IRP proceeding*

Data	Source
Load profiles	• Baseline loads: 2007-09 WECC historical load profiles • CEC 2019 California IOU Load Shape study • Building & transport electrification profiles: Modeling Assumptions for the 2021-2022 Transmission Planning Process
Load forecasts	• CA: 2019 CEC IEPR • Non-CA: WECC 2028 Anchor Data Set (ADS) Phase 2 V1.2
Baseline resources	• Supply-side: 2020 IRP baseline portfolio (based on CAISO master file, RPS contract database, WECC ADS Phase 2 v. 1.2) • Behind-the-meter: 2019 CEC IEPR
Resource costs	• 2020 NREL Annual Technology Baseline (ATB) • 2019 Lazard Levelized Cost of Storage • 2020 NREL The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032
Resource potentials	• Renewables: Black & Veatch RPS Calculator v.6.3 • Shed DR: LBNL Final Report on Phase 2 Results: 2025 California Demand Response Potential Study
Resource profiles	• NREL PVWATTSv5 calculator • NREL Wind Integration National Dataset ("WIND") Toolkit
Fuel and carbon prices	• 2019 CEC IEPR (NAMGas, Preliminary Nominal Carbon Price Projections)
Local capacity needs	• CAISO 2020-2021 TPP Appendix G: 2030 Local Capacity Technical Study
Transmission upgrade costs	• Modeling Assumptions for the 2021-2022 Transmission Planning Process
Distribution upgrade cost	• CPUC IOU Grid Need Assessment (GNA) and Distribution Deferral Opportunity Report (DDOR) filings (R.14-08-013)
Historical PSPS events	• CPUC PSPS Post-Event Reports
Utility distribution system reliability	• CPUC Annual Electricity Reliability Reports
DER equipment reliability	• Various field data sets (IEEE, Marqusee et al. 2020)

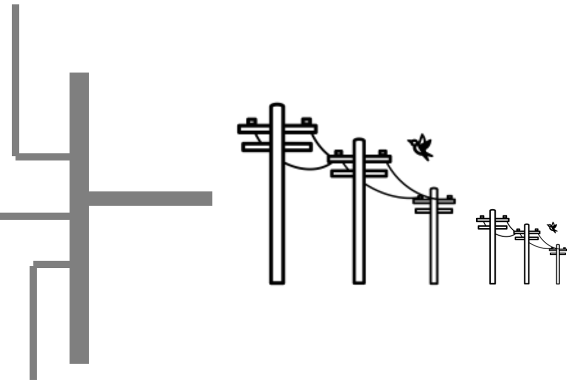
* Several datasets are in the process of being updated, and the project team plans on updating or supplementing these baseline assumptions when those datasets become available.

UC San Diego System Configuration

UCSD Campus (Metered)



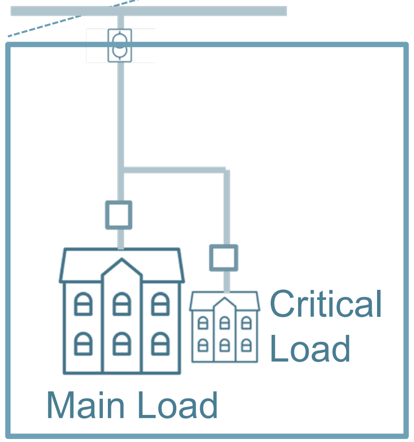
SDG&E Transmission (69 kV)



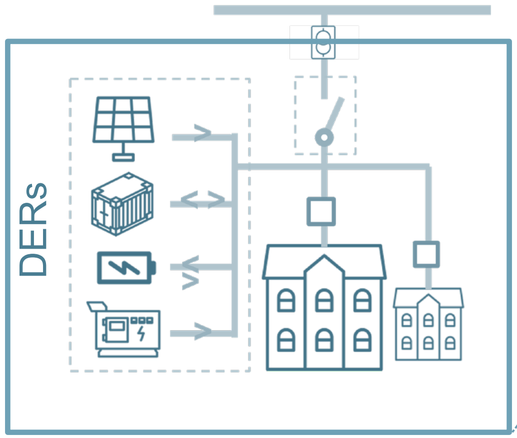
Buildings characterized by:
- Loads, critical loads
- Space (for DERs, DGPV)
- Demand for reliability

Bulk grid characterized by:
- Customer rates
- System avoided costs and/or market price streams
- Reliability metrics (SAIDI, CAIDI, PSPS)
- Marginal emissions factors

Base Case
Building without microgrid



Test Case
Investment in microgrid



Capacity Expansion Model Reduction Experiments

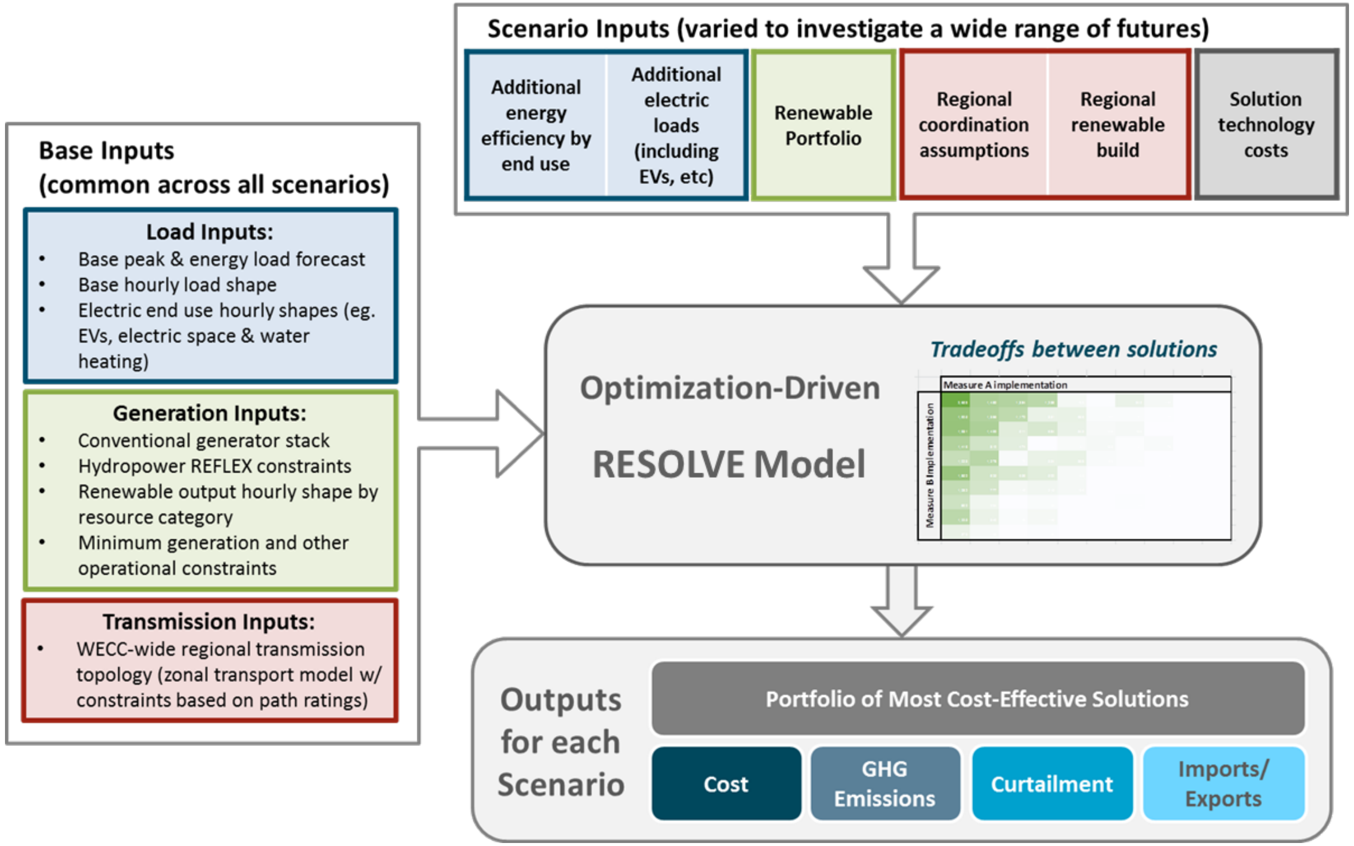
+ **In addition to previously described scenarios, we want to study what model reduction techniques are appropriate for our resource planning**

Case Name	Temporal Representation	Zonal Representation	Operating Reserves	PRM & ELCCs	Resource Tranches	Rationale
RSP Benchmark	37 rep. days	6 load zones	7 operating reserves	15% PRM + ELCCs	Aligned with IRP RSP tranches	Provide benchmark between Formware & CPUC IRP RSP/SB100 RESOLVE case
No External Zones	*[Same as Benchmark]*	**Replace non-CA zones with price streams**	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	Test if external zones can be simplified without significantly affecting portfolios
No A/S	*[Same as Benchmark]*	*[Same as Benchmark]*	**None**	*[Same as Benchmark]*	*[Same as Benchmark]*	Test impact of modeling AS on resource portfolio decisions
Reduce Resource Tranches	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	**Reduce # of renewable resource tranches**	Test if reducing # of modeled renewable tranches significantly affects portfolios
365 Day, HLH/LLH	**365 days but only 2-4 rep. hours per day**	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	Test if modeling all days but lower resolution still captures major seasonal arbitrage value for LDES
Representative Weeks	**4-6 rep. weeks**	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	*[Same as Benchmark]*	Test if modeling representative weeks captures full value of long duration storage & other long operational decision resources
8760-Hour, with PRM	**Model full 8760-hour timeseries**	*[Model simplification may be needed]*	*[Model simplification may be needed]*	*[Same as Benchmark]*	*[Model simplification may be needed]*	Test if PRM has significant impact on resource build if modeling all 8760 operational hours
8760-Hour, No PRM	**Model full 8760-hour timeseries**	*[Model simplification may be needed]*	*[Model simplification may be needed]*	**None**	*[Model simplification may be needed]*	Test if 8760-hour modeling is possible with CAISO system; additional iteration to simplify as needed
Multi-Year, No PRM	**Model full 8760-hour timeseries**	*[Model simplification may be needed]*	*[Model simplification may be needed]*	**None**	*[Model simplification may be needed]*	Test if directly modeling more operational years reduces need for PRM while maintaining reliability

RESOLVE Modeling Inputs

+ **RESOLVE is designed to allow easy scenario analysis of a variety of uncertainties**

+ **Inputs for RESOLVE include:**
  - Future resource costs (capital, interconnection, fixed & variable O&M)
  - Existing & future resource operational characteristics (heat rate, fixed generation profiles)
  - Fuel price forecasts
  - Load profiles & annual load forecasts
    - Assumed adoption & load impacts of DERs (e.g., DGPV, EV, and other flexible loads)
  - Annual GHG, RPS/CES, and PRM policy targets



Formware Overview

Inputs

Project-Specific Constraints
Site capacity, target availability, …

Sophisticated Storage Models
$/kWh, $/kW, RTE, …

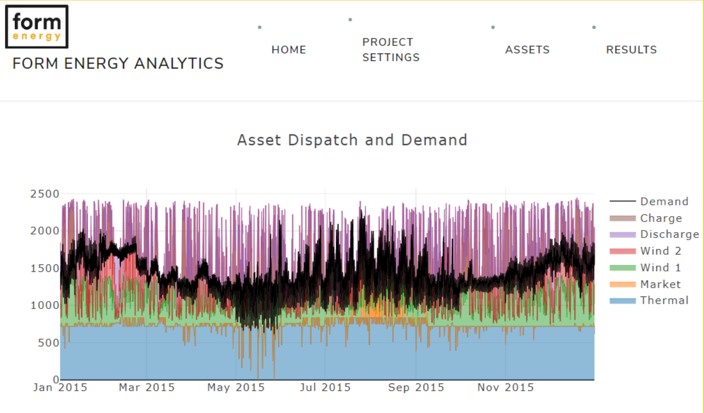
Market Conditions
PPA price, capacity prices, energy and ancillary prices, RPS, …

Grid Data
Transmission limits, load forecasts, retirements, …

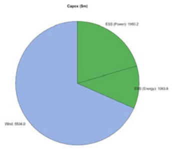
Generator Data
Capex, opex, start costs, heat-rates, fuel costs, solar & wind resource, …

Formware™ Software

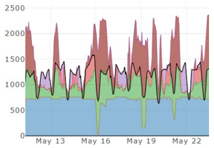
- 8760+ model captures price and resource volatility
- Multi-scenario optimization validates solution across range of conditions
- Customizable model allows Form to deliver bespoke analyses on-demand



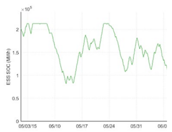
Outputs



Recommended Energy Asset Sizing
Power, energy capacity

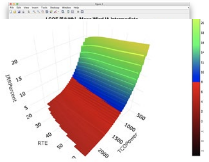


Hourly Operational Profiles
8760+ by energy asset



Storage "Duty Profile"
Cycles/yr, peak power

Project Financials
LCOE, FCF, IRR



Sensitivity Analysis
Risks and trade-offs from input uncertainties