Emerging resources: Resource alternatives for energy storage

Public webinar

April 23, 2024

PUGET SOUND ENERGY

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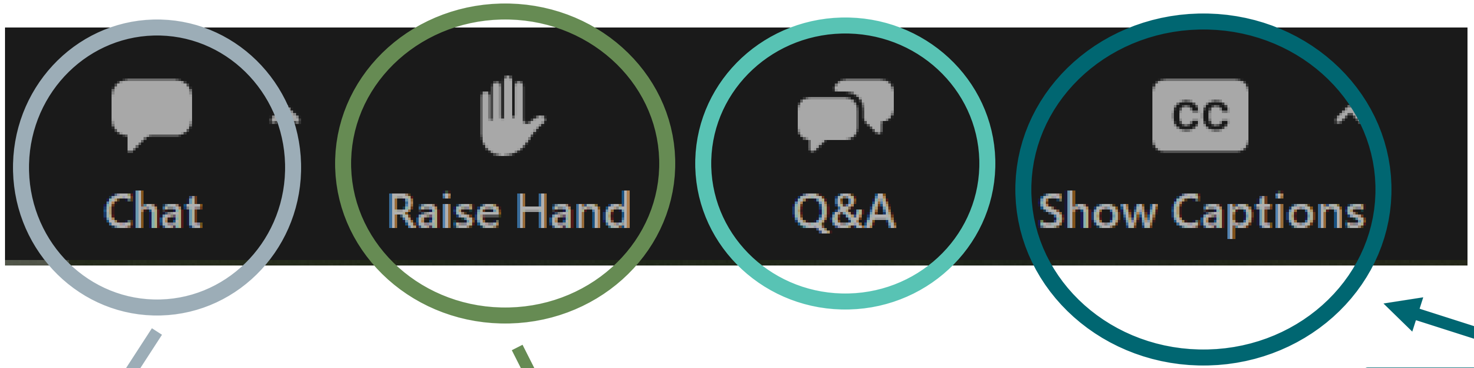

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During the public comment period, raise your hand if you would like to make a verbal comment

Facilitator requests

- Engage constructively and courteously towards all participants
- Respect the role of the facilitator to guide the group process
- Avoid use of acronyms and explain technical questions
- Use the Feedback Form or email irp@pse.com for additional input to PSE
- Aim to focus on the webinar topic
- Public comments will occur after PSE's presentations

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Safety moment

Outdoor hiking safety

- Research before you go (weather, trail conditions, permits etc.)
- Pack a map
- Bring extra food and water
- Keep your pet safely on a leash (if pets allowed)
- Leave wildlife and plants alone

PUGET SOUND ENERGY

Today's speakers

Sophie Glass

Facilitator, Triangle Associates

Kara Durbin

Director, Clean Energy Strategy, PSE

Elizabeth Hossner

Manager, Resource Planning and Analylsis, PSE

Prantik Saha

Black and Veatch

Michael Eddington

Black and Veatch

Malcolm McCulloch

Manager, New Products and Services, PSE

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Agenda

Time	Agenda Item	Presenter / Facilitator
1:00 p.m. – 1:05 p.m.	Introduction and agenda review	Sophie Glass, Triangle Associates
1:05 p.m. – 1:10 p.m.	Engagement roadmap and public feedback questions	Kara Durbin, PSE
1:10 p.m. - 1:15 p.m.	Energy storage overview	Elizabeth Hossner, PSE
1:15 p.m. – 2:05 p.m.	Energy storage technologies	Prantik Saha, Black and Veatch Michael Eddington, Black and Veatch
2:05 p.m. – 2:20 p.m.	Spotlight on Vehicle to Grid (V2G) and Vehicle to Everything (V2X)	Malcolm McCulloch, PSE
2:20 p.m. – 2:30 p.m.	Next steps and public comment opportunity	Sophie Glass, Triangle Associates
2:30 p.m.	Adjourn	All

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Engagement roadmap and public feedback questions

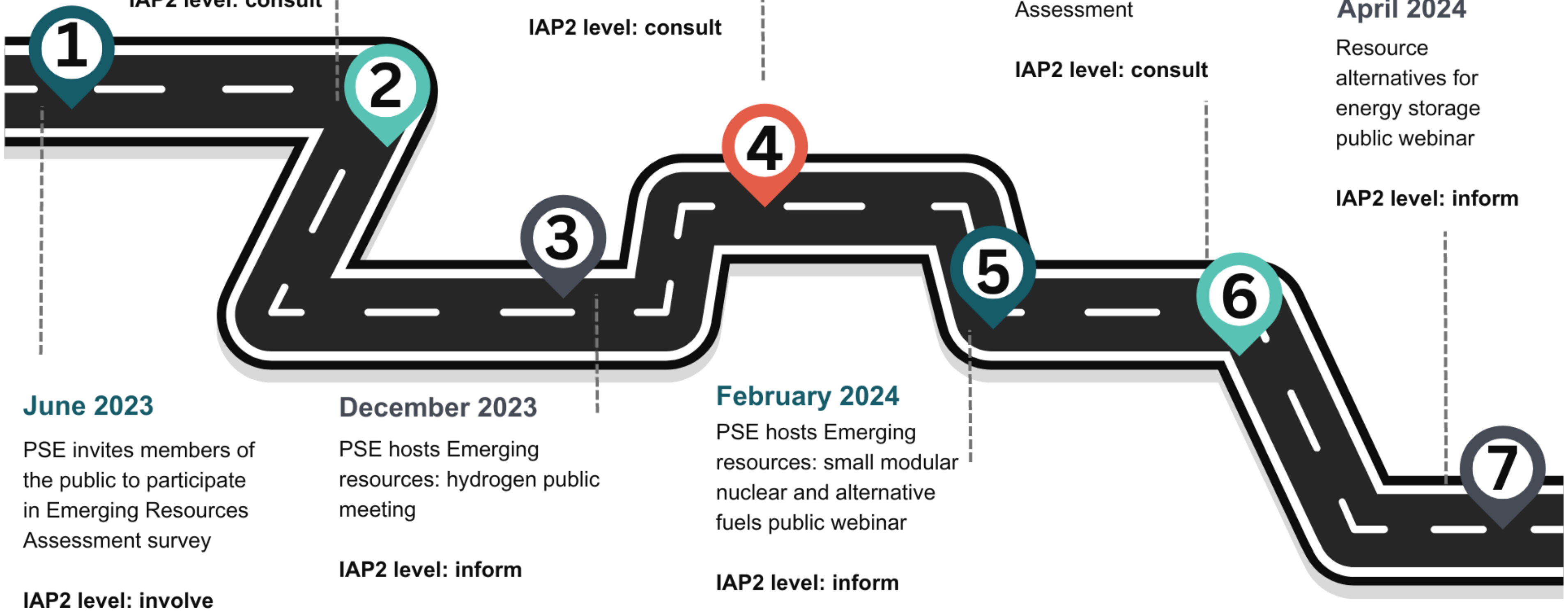
Kara Durbin, PSE

IAP2 Spectrum

	INFORM	CONSULT	INVOLVE	COLLABORATE	EMPOWER
PUBLIC PARTICIPATION GOAL	To provide the public with balanced and objective information to assist them in understanding the problem, alternatives and/or solutions.	To obtain public feedback on analysis, alternatives and/or decision.	To work directly with the public throughout the process to ensure that public concerns and aspirations are consistently understood and considered.	To partner with the public in each aspect of the decision including the development of alternatives and the identification of the preferred solution.	To place final decision-making in the hands of the public.
PROMISE TO THE PUBLIC	We will keep you informed.	We will keep you informed, listen to and acknowledge concerns and aspirations, and provide feedback on how public input influenced the decision.	We will work with you to ensure that your concerns and aspirations are directly reflected in the alternatives developed and provide feedback on how public input influenced the decision.	We will look to you for advice and innovation in formulating solutions and incorporate your advice & recommendations into the decisions to the maximum extent possible.	We will implement what you decide.

INCREASING IMPACT ON THE DECISION

Emerging resources engagement roadmap (“involve”)



June 2023

PSE invites members of the public to participate in Emerging Resources Assessment survey

IAP2 level: involve

September 2023

PSE asks for public feedback on future IRP public webinar topics and files 2025 IRP work plan

IAP2 level: consult

December 2023

PSE hosts Emerging resources: hydrogen public meeting

IAP2 level: inform

January 2024

PSE discusses Emerging Resources Assessment overview in RPAG meeting and asks for public feedback

IAP2 level: consult

February 2024

PSE hosts Emerging resources: small modular nuclear and alternative fuels public webinar

IAP2 level: inform

March 2024

Resource alternatives RPAG meeting to discuss Emerging Resources Assessment

IAP2 level: consult

April 2024

Resource alternatives for energy storage public webinar

IAP2 level: inform

Feedback questions

- What risks and rewards for energy storage should PSE keep in mind?
- Can you identify some examples of energy storage projects at other utilities that you think are good ones for PSE to consider?

Submit feedback via Q&A box, public comment, Feedback Form, or irp@pse.com

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Energy storage overview

Elizabeth Hossner, PSE

April 23, 2024

Electric resource planning

What is the purpose of the IRP?

- Establish the resource need
- Resources identified are not a resource acquisition shopping list
- Separate acquisition and evaluation process are used to select and acquire specific resources to meet capacity and energy needs, and CETA requirements

What is a generic resource?

- A place holder to help with evaluations, sizing, and creating a plan to meet future needs

What is an emerging resource?

- Technology that appears likely to be viable on the timeline required in the IRP

Today's objective: learn about generic energy storage options to be modeled (e.g., batteries)

What is energy storage?

- Variety of technologies that allow energy to be stored for future use
- Typically stores excess energy produced during off-peak time that would otherwise go unused
- Storage can be called upon during peak use times and can reduce the need for other peaking capacity (e.g., natural gas peaking plant)

- Durations (how long the system can provide power) and capacities (how much energy the system can store) varies
- Includes:
  - Various types of batteries
  - Mechanical, compressed air, and hydro systems

Feedback on storage resources – 2023 and 2025

2023

- ✓ Model varying battery configurations and durations
- ✓ Model BESS
- ✓ Explore gravity storage

2025

- ✓ Storage technologies:
  - Model Li-ion batteries
  - Expand battery storage
  - Model established technologies for generic resources for batteries
- ✓ Explore vehicle to grid technology

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Technology Readiness Level (TRL)

- TRL 1 • Basic principles observed and reported
- TRL 2 • Technology concept and/or application formulated
- TRL 3 • Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 4 • Component and/or breadboard validation in a laboratory environment
- TRL 5 • Component and/or breadboard validation in a relevant environment
- TRL 6 • System/subsystem model or prototype demonstration in a relevant environment
- TRL 7 • System prototype demonstration in an operational environment
- TRL 8 • Actual system complete and qualified through test and demonstration
- TRL 9 • Actual system proved through successful mission operations

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Energy Storage Technology

- **Short Duration (2-8 hours):**
  - Lithium-ion Battery (TRL 9)
  - Sodium Battery (TRL 7-9)
- **Medium Duration (8-24 hours):**
  - CAES (TRL 6-9)
  - Pumped Hydro TRL (8-9)
  - Other Mechanical Storage TRL (6-9)
  - Flow Battery TRL (7-9)
- **Long Duration (24 + hours):**
  - Iron-Air Battery (TRL 7)

Energy storage technology

Black and Veatch

April 23, 2024

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Short duration storage (2-8 hour): Lithium-ion and sodium-sulfur battery storage

Prantik Saha, Black & Veatch

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Short duration energy storage

What is it?

- **2-8 hours of energy storage**
- Most deployed storage today (25+ GWh in operation globally)
- Highest technology readiness level
- Many commercial lithium-ion battery vendors available today
- High project level experience decreases project development and financing risks

What did we study?

- Compared technical considerations and readiness for the two (2) major sub-categories
- Discussed safety concerns for both

Sub-categories

- **Lithium-Ion Battery (4 hr)** – Lithium-nickel-manganese-cobalt oxide (NMC) and Lithium ferrous phosphate (LFP) chemistries used for energy storage
- **Sodium-sulfur Battery** – Sodium-sulfur battery uses metallic sodium and sulfur in molten state and solid-state ceramic electrolyte. Requires high temperature (> 300 C) for efficient operation.

Short Duration

Battery comparison

Technology	Geological requirements	Scalability	Deployment
Lithium-ion battery	Flat land	<1 MW to 100+ MW exists in 1-hour to 4-hour capacities	Operational: The Edwards & Sanborn solar + storage facility in California 3200+ MWh **Li-ion BESS** online in 2024. It's the biggest in the US.
Sodium-sulfur battery	Flat land	<1 MW to 100+ MW exists in 1-hour to 4-hour capacities	Operational: 108 MW 6-hour **Sodium-Sulfur** project in Abu Dhabi, UAE, is operational since 2019.

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Short Duration

Safety concerns – lithium and metal-ion

Technology	Safety concerns
Lithium-ion battery	▪ Fire hazard due to **thermal runaway;** occurs due to external shorting or internal shorting via formation of lithium dendrite inside battery cells. o Of the two most common chemistries, lithium-nickel-manganese-cobalt oxide (NMC) is more fire-prone than lithium ferrous phosphate (LFP) due to lower thermal runaway temperature. o Next generation of lithium-ion batteries are working on reducing the thermal runaway occurrence by improving design such as using liquid-cooled system and confining thermal runaway. ▪ **Emission of several toxic and flammable gases** like hydrogen, hydrogen fluoride, ethylene, etc. ▪ **Electrolyte spill** also occurs during fire.
Sodium-ion battery	▪ Fire can be caused by **exposure** of highly reactive metallic sodium and sulfur at high temperature ▪ The cell container gets **corroded** fast because of the highly reactive nature of sodium and sulfur at high temperature ▪ In case of a **thermal runaway**, it may be difficult to keep the temperature from rising due to the high amount of heat released during operation ▪ **Molten metal**, if spilled, is highly reactive and can pose significant risk

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Medium duration storage (8-24 hour): Compressed air & mechanical energy storage

Prantik Saha & Michael Eddington, Black & Veatch

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Mid Duration

Medium duration energy storage (MDES)

What is it?

- **8-24 hours of energy storage**
- Grids require energy storage for up to a day when daily renewable power generation is low or zero, such as, at night.
- Used primarily for energy shifting purposes and not for grid ancillary services such as frequency regulation. Can also be used for blackstart applications depending on the response time of the storage technology.

What did we study?

- Compared technical aspects and readiness of the sub-categories

Sub-categories

- **Compressed air energy storage (CAES)**
- **Pumped hydro energy storage (PHES)**
- **Mechanical energy storage**
- **Flow batteries**

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Mid Duration

Compressed air energy storage (CAES)

What is it?

- Stores low-cost off-peak energy as compressed air or other gas
- Utilizes underground or above ground storage
- Compressed gas is released, heated, and directed into expansion turbine
- Cost-effectiveness limited by availability, design & size

Sub-categories

- **Adiabatic** – Stores heat from compression process and upon extraction of compressed air from storage, recovers stored heat prior to expansion
- **Diabatic** – Compressed stored air heated by combusting natural gas or hydrogen using conventional combustion turbines
- **Isothermal** – Heat removed continuously from air during compression process and added continuously during expansion; no combustion process needed

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Mid Duration

Compressed air energy storage (CAES)

Geological requirements	Technology / subcategory maturity	Scalability	Deployment
Salt caverns created by solution mining most common	TRL 9 **Diabatic**	100+ MW projects exist	Operational: 290 MWe project in Huntorf, Germany since 1978 110 MWe plant near McIntosh, Alabama, USA since 1991
Storage created by mining caverns into hard rock formations available in WA State	TRL 8 **Adiabatic / Advanced Adiabatic (AA)**	Sufficient demonstration to scale up to the 100 MW size or larger	Operational (2017): 60 MWe 5-hour Jiangsu Jintan AA-CAES Demonstration Project in China In Development (by Hydrostor): 500 MWe 8-hours Willow Rock Energy Storage Center in Kern County, CA,USA
None	TRL 6 **Isothermal**	Still in pilot / demonstration stage	Pilot Plant (2013): SustainX Inc 1.5 MWe 4-hour plant in Seabrook, New Hampshire, USA

Data derived primarily from Sandia National Laboratories, DOE Global Energy Storage Database, https://sandia.gov/ess-ssl/gesdb/public/, and Momentum building for Hydrostor's Willow Rock Energy Storage Center, March 4 2024, https://hydrostor.ca/momentum-building-for-hydrostors-willow-rock-energy-storage-center-as-company-reaches-key-permitting-and-interconnection-milestones/

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Mid Duration

Mechanical energy storage (MES)

What is it?
Surplus energy on the grid is used to drive a mechanical process to store energy and then releases / converts the stored energy to electricity during peak periods

What did we study?
Based on the expected scale and application of energy storage needed, further evaluation considered liquid air energy storage and gravitational potential energy storage

Sub-Categories

- **Flywheels**
- **Hydraulic accumulators**
- **Liquid air energy storage (LAES)**
- **Gravitational potential energy storage**
- **Spring energy / mechanical battery storage**
- **Kinetic energy storage with rail systems**

* Pumped hydro is MES however PSE already has adequate information, so it was not included in the study.

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Comparison of selected MES sub-categories

Technology	Geological Requirements	Technology / Subcategory Maturity	Scalability	Deployment
Mechanical energy storage	Specific to site and technology design criteria	**Liquid air energy storage (LAES)** TRL 8	5 MW to 200 MW+	Demonstration project: Commercial 5 MW 3-hours Under construction: Carrington 50 MW 6-hours in Manchester, UK 200 MW 12.5-hours in Yorkshire, UK
		Gravity-based rail, block or piston TRL 6 to 9		Under construction: 5 MW 15-min Advanced Rail Energy Storage (ARES) in Nevada, USA 25 MW 4-hours Energy Vault

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Mid Duration

Liquid air energy storage (LAES) – TRL 8

What is it?

Thermo-mechanical storage that uses electricity to liquify cool air and store in an insulated, unpressurized vessel; liquid air is then warmed to convert back to a gaseous state to operate a turbine and generate electricity.

- Can utilize waste heat for the liquefaction and expansion processes improving efficiency
- Conceptually suitable for large grid-scale storage and offers duration storage of 10 hours

Advantages

Simplicity of the technology, scalability, flexibility, high energy density and attractive costs

Challenges

Infrastructure requirements for storage and handling of liquid air

Status

Near to market and currently prepared to be deployed in various locations

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Gravitational potential energy storage – TRL 6-9

What is it?

Converts stored energy into kinetic energy to generate electricity

- ❖ Rail, block and piston-based systems are advantaged over some other types as there is little to no self-discharge of stored energy, increasing efficiency
- ❖ Broad-based application: renewable shifting, peak capacity reduction, transmission and distribution grid investment deferral, and frequency regulation

Advantages

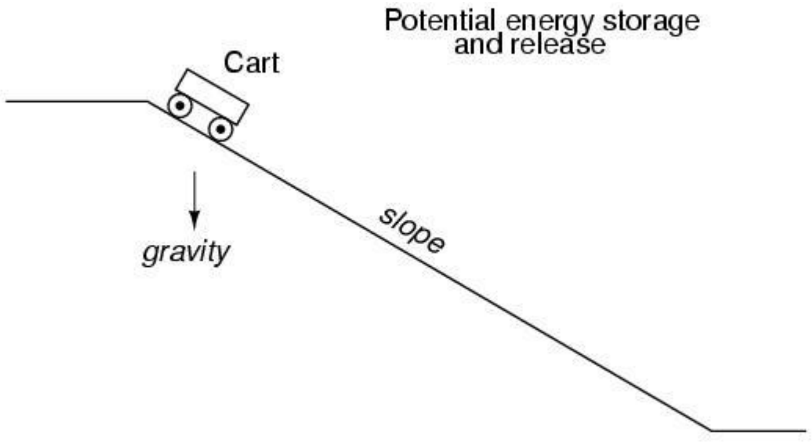
Potentially large grid-scale storage capacity with low environmental impact

Challenges

Site-specific requirements, safety concerns, and need for significant elevation differences

Status

Early-stage demonstration deployment phase, with commercial projects announced but not yet constructed



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Flow batteries (FB)

What is it?

- Stores energy in electrolytes using Vanadium Redox, Iron-Chloride, Zinc-Bromide or Metal Coordination electrolytes.
- Like Li-ion BESS products, they come as containerized solutions.

What did we study?

- Compared technical aspects and readiness of the sub-categories

Sub-categories

- **Vanadium redox**
- **Iron**
- **Zinc bromide**
- **Metal coordination complex**

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Comparison of flow battery sub-categories

Geological requirements	Technology / subcategory maturity	Scalability	Deployment
None Large footprint (vs Li-Ion)	**Vanadium Redox FB** TRL 9	Most operational projects are in 10s of MW scale. Bigger projects (100s of MW) are in construction.	Operational: 200 MW 4-hour project in Dalian, China. Operational since 2022. Largest operational flow battery project in the world.
	Iron FB TRL 8		Under Construction: 200 MW 10-hour project in Sacramento, CA, USA
	Zinc-Bromide FB TRL 7	Pilot projects at 2 to 10 MW scale underway	Under Construction: 2 MW 10-hour project in CA, USA
	Metal-Coordination Complex FB TRL 7		Pilot Project: 5 MW 8-hour project in Alberta, Canada

The difference primarily comes from the electrolytes used, e.g., vanadium-based electrolytes for vanadium FBs, iron-chloride for iron FBs etc.

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Safety concerns – sodium-ion and flow

Technology	Safety concerns
Sodium-ion battery	▪ Fire hazard due to **thermal runaway** can occur ○ High operating temperature increases risk of thermal runaway; low reactivity of sodium compared to lithium makes the overall risk much lower ▪ Ceramic electrolyte is a solid-state ion conductor; **no** chemical spill or gas emission risk ▪ **Molten metal** can be a potential source of risk.
Flow battery	▪ Do not have any significant fire hazard like lithium-ion batteries ▪ **Vanadium oxide** used in vanadium flow batteries is highly acidic; it is **very corrosive** if spill occurs ▪ Iron flow battery uses iron chloride as the electrolyte which is safer than vanadium oxide ▪ **Bromine-based electrolytes** that are used in zinc-bromide batteries are **very corrosive**

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Long duration energy storage (LDES; 24-100 hour): metal-air and flow battery storage

Prantik Saha, Black & Veatch

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Long duration energy storage (LDES)

What is it?

- **24+ hours of energy storage**
- Days long energy storage systems can perform various functions
- Grids require days-long energy storage for resilience, when the daily renewable power production profile is not consistent. Wind power farms in US Midwest tend to have this daily inconsistency.
- Can perform as a backup power supply too.

What did we study?

- Technical considerations and readiness for the one major sub-category

Sub-categories

- **Iron (Fe)-Air Batteries** – These batteries are strong contenders of 24+ hour storage durations

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Characteristics for iron-air battery

Technology	Geological requirements	Technology / subcategory maturity	Scalability	Deployment
Iron-air battery	None Large footprint (vs Li-Ion)	TRL 7	Up to 10 MW most common currently	Under Construction: 10 MW 100-hour **Iron-Air** battery pilot projects in Colorado and Minnesota, USA

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Safety concerns for iron-air battery

Technology	Safety concerns
Iron-air battery	▪ Metal-air batteries do <u>not</u> pose any significant safety or fire hazards ▪ An alkaline **electrolyte** is used which is **mildly corrosive** ▪ Ceramic electrolyte is a solid-state ion conductor with **no** chemical spill or gas emission risk

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Spotlight on V2G and V2X

Malcolm McCulloch, PSE

April 23, 2024

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Vehicle-to-everything (V2X) overview

Opportunity

Customer adoption of **EVs** is **growing rapidly** which promotes **two-way flows of energy** and offer opportunities for utilities and customers to **work together** and innovate to meet rising demand.

Desired Outcome

Identify and evaluate the technical feasibility, operational requirements, and interconnection protocols, as well as to engage with customers and interested parties to assess the benefits, barriers, and market readiness for V2X.

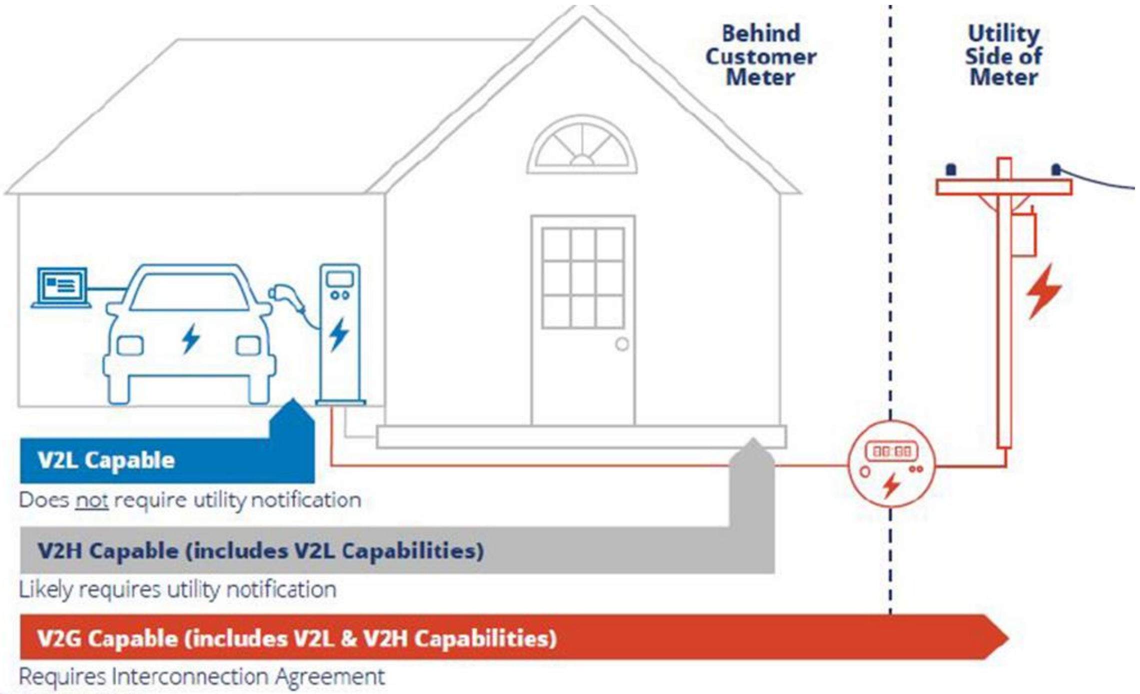
Customer benefits

- Back-up power during outages
- Compensation for PSE's use of EV battery capacity
- Possible demand charge reduction

System benefits

- Capacity resources
- Load balancing & grid stability
- Distribution equipment upgrade deferral

V2X configurations



Source: SEPA. (2023).

Definitions

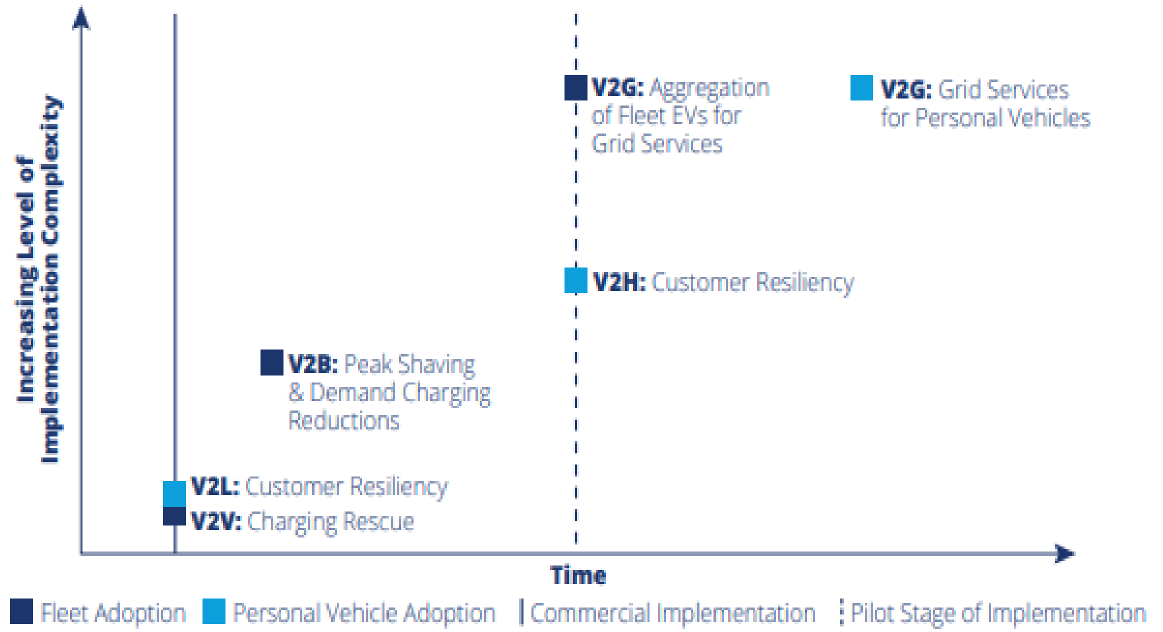
Vehicle-to-Home/Building (V2H/V2B): involves using an EV to provide supplementary power to a building.

Vehicle-to-Grid (V2G): actively injecting electricity back into the grid and requiring utility approval in the form of interconnection agreements.

V2X market readiness

- Limited availability of bidirectional vehicles and chargers
- Implementation complexity due to lack of standardization and interoperability across market actors
- Customer willingness to adopt unclear, but new V1G programs (EV/EVSE direct load control) may serve as proxy to induce scale
- Higher incremental costs for equipment and interconnection increases barrier to entry

Figure 2. Stages of Mass-Market Customer Adoption of Different V2X Use Cases



Source: SEPA, 2022

V2X technology demonstration strategy

Vehicle-to-Home (V2H)

- **Scope:** Up to 10 installations with bi-directional EVs.
- **Outcomes:** Establish technical requirements, qualified equipment lists, integration with VPP, demand reduction potential, customer preferences, and interaction w/ EV DR, Residential BESS, and TOU programs

Vehicle-to-Building (V2B)

- **Scope:** Up to 4 bi-directional fleet vehicles stationed with mix of L2 & DCFC at fleet facilities.
- **Outcomes:** Establish technical requirements, qualified equipment lists, integration with VPP, demand reduction potential, customer preferences, and interaction w/ demand charge rates, Business DR, and Commercial BESS programs

Vehicle-to-Grid (V2G)

- **Scope:** Up to 2 electric School District customers (4 electric buses combined) with existing bi-directional capable medium/heavy duty electric school bus & ability to install bidirectional high capacity L2 or DCFC EVSE.
- **Outcomes:** Establish technical requirements, qualified equipment lists, integration with VPP, interconnection standards, demand reduction potential, dispatchable capacity potential, customer preferences, future compensation models, and interaction w/ demand charge rates, Business DR, and Commercial BESS programs

V2X technology demonstration roadmap

Next Steps

- Conduct market and customer research
- Define equipment protocols and interconnection standards
- Develop VPP and related technology partnerships
- Initiate customer journey & product development process
- Facilitate interested party engagement
- Establish feasibility and equity scoring to refine product concepts
- Identify potential demonstration sites & conduct enrollment
- Dispatch V2H/V2B/V2G sites during peak event

Next steps

Sophie Glass, Triangle Associates

Additional resources

- December 7, 2023 Emerging Resources: Hydrogen public webinar recording and presentation
- January 12, 2024 Emerging Technology Assessment overview RPAG meeting recording and presentation
- February 27, 2024 Emerging Resources: Small Modular Nuclear and Alternative fuels public webinar recording and presentation
- March 25, 2024 Emerging Technology Assessment and Resource Alternatives RPAG meeting recording and presentation

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Upcoming activities

Date	Activity
April 30, 2024	Feedback form closes for this webinar
May 9, 2024	Local and regional delivery infrastructure needs public webinar
May 14, 2024	Western Resource Adequacy Program (WRAP) overview RPAG meeting

Email us at irp@pse.com

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Leave a voice message at 425-818-2051

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Public comment opportunity

Please raise your “hand” if you would like to provide comment.

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Thanks for joining us!

Appendix

Acronyms

Acronym	Meaning
AA	Advanced adiabatic
ARES	Advanced rail energy storage
BESS	Battery energy storage system
CAES	Compressed air energy storage
CCA	Climate Commitment Act
CEIP	Clean Energy Implementation Plan
CETA	Clean Energy Transformation Act
IAP2	International Association of Public Participation
IRA	Inflation Reduction Act
IRP	Integrated Resource Plan
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelized cost of energy
LDES	Long duration energy storage
Li	Lithium ion
LFP	Lithium ferrous phosphate

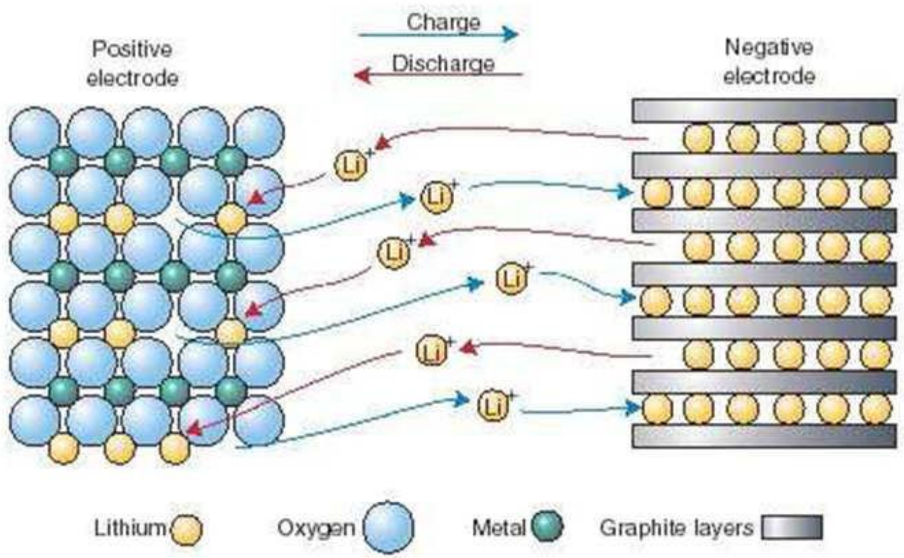
Acronyms

Acronym	Meaning
MES	Mechanical energy storage
MW	Megawatt
Mwe	Megawatt electric
MWh	Megawatt hour
NMC	Nickel-manganese-cobalt oxide
NREL ATB	National Renewable Energy Laboratory Annual Technology Baseline
O&M	Operations and maintainence
PHES	Pumped hydroelectric storage
RA	Resource adequacy
RPAG	Resource Planning Advisory Group
TIC	Total installed cost
TRL	Technology readiness level
V2G	Vehicle-to-grid
V2X	Vehicle-to-everything

Short Duration

Lithium Ion Battery

Source: PG&E; Moss Landing Battery Energy Storage



Source: LFP batteries; https://www.lythbattery.com/lifepo4-battery-vs-lead-acid-battery/

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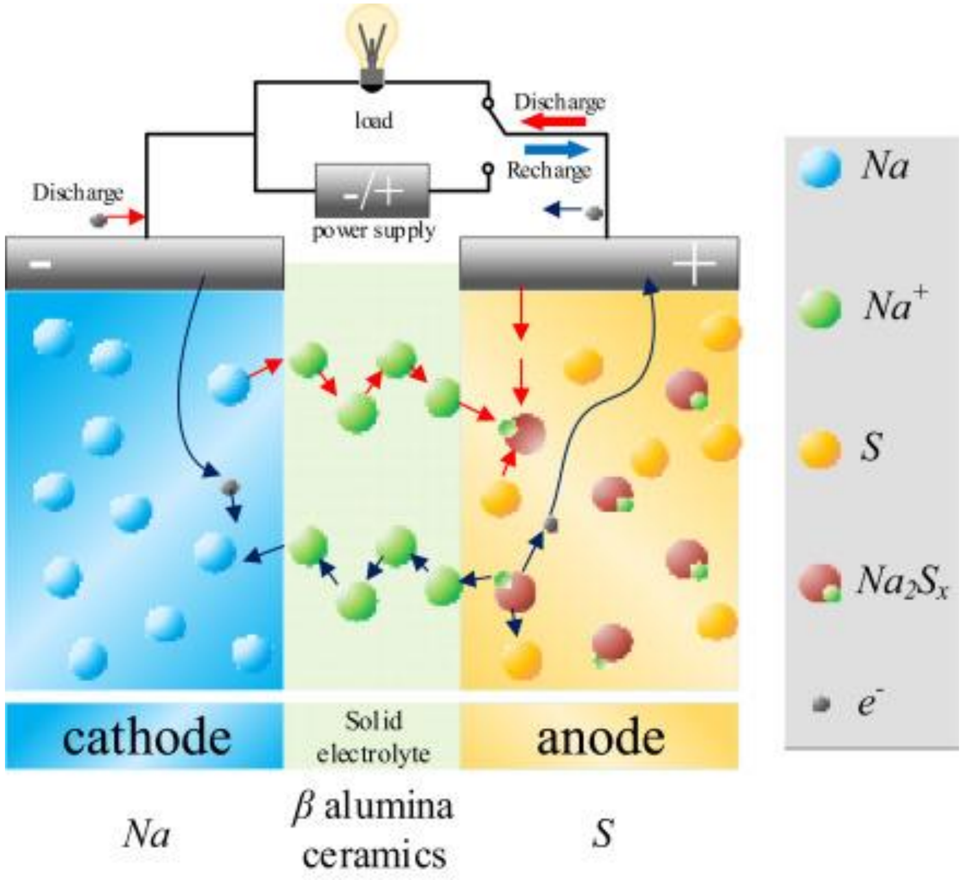
Short Duration

Sodium sulfur battery



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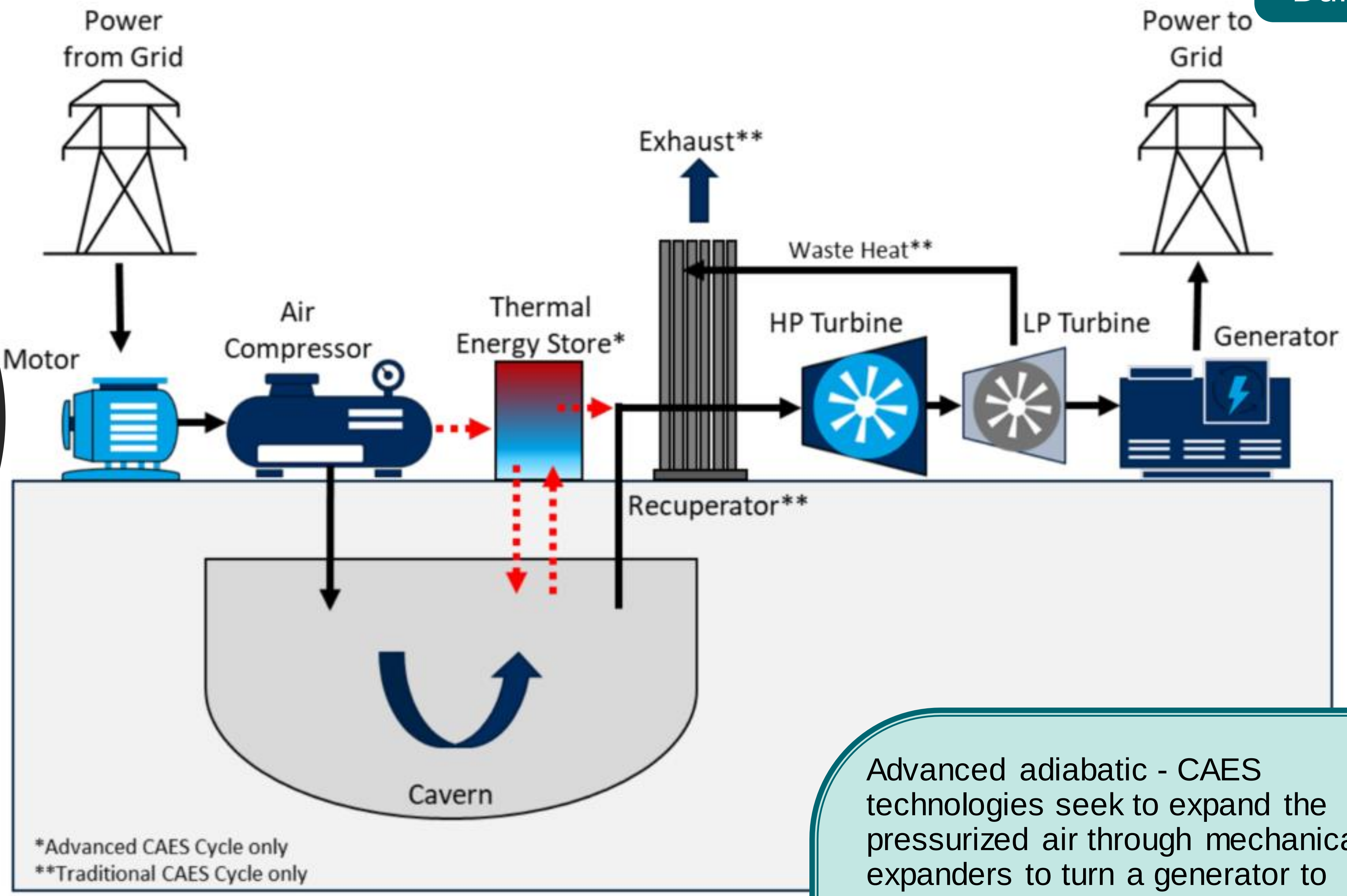
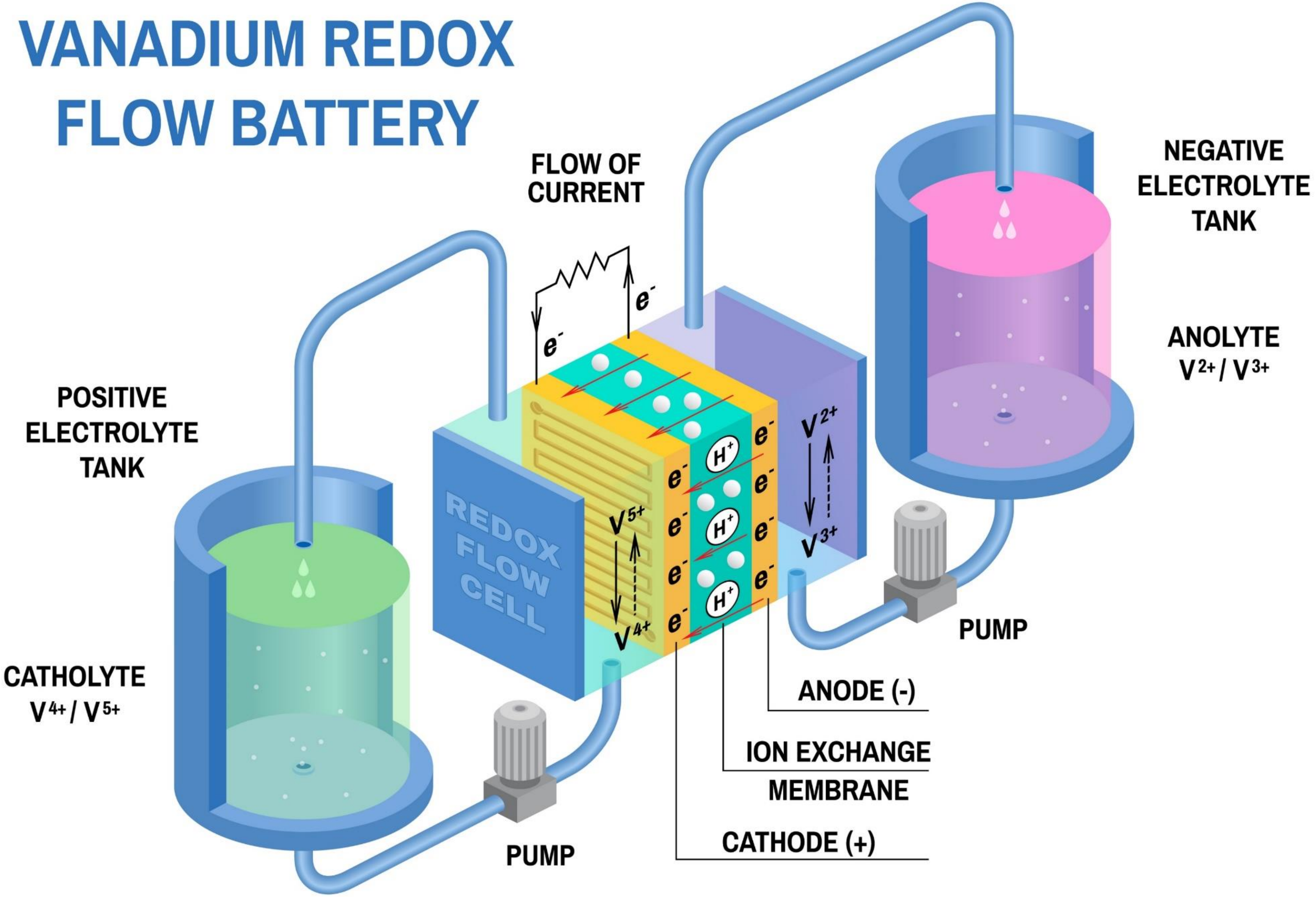
Mid Duration

10-hour advanced adiabatic - CAES selected for further characterization



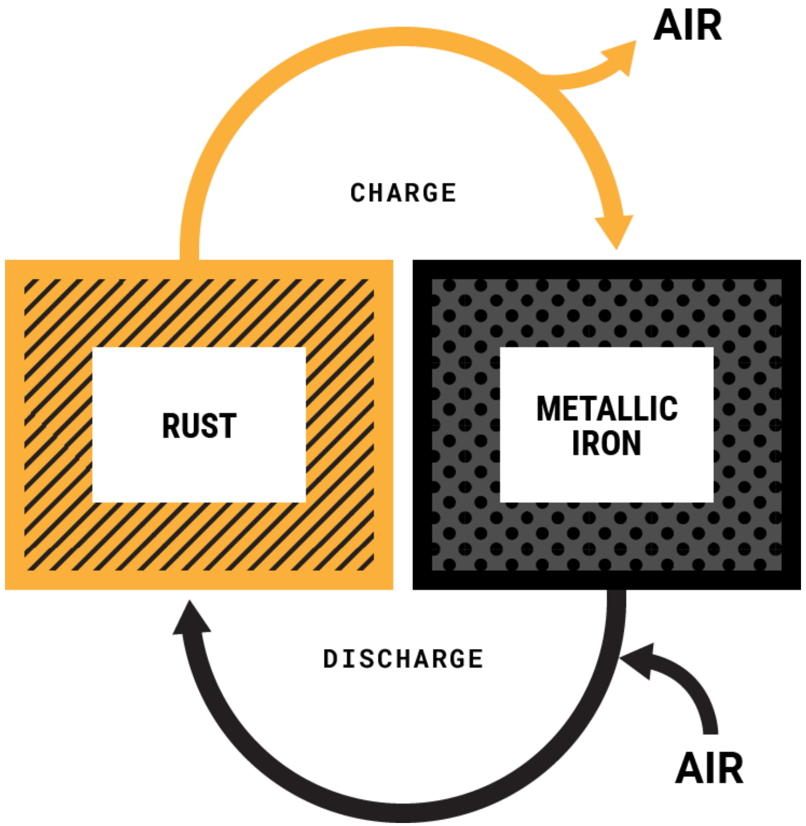
Advanced adiabatic - CAES technologies seek to expand the pressurized air through mechanical expanders to turn a generator to provide carbon-free electricity

VANADIUM REDOX FLOW BATTERY

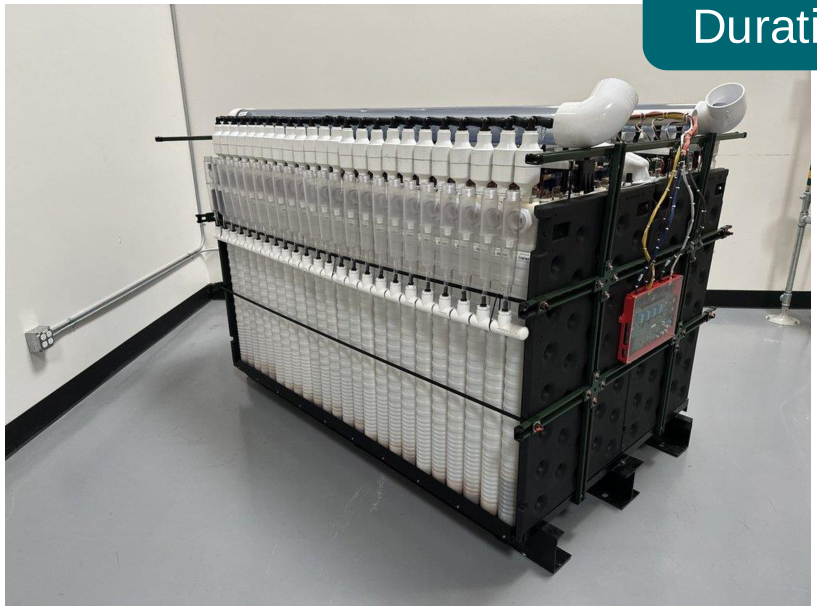


Long Duration

Form Energy's Iron-Air Battery



The iron-air battery cycle. Image courtesy of Form Energy.



Form Energy's 2023 iron-air battery module prototype. Image courtesy of Form Energy

An artist rendering of a 56 megawatt energy storage system, with iron-air battery enclosures arranged next to a solar farm. Image courtesy of Form Energy.

Supply-side resource alternatives for the 2025 IRP

Energy Storage

- Short duration (Lithium-Ion 4 hour)
- **Medium duration (CAES 8-hour) - Emerging**
- **Long duration (Iron-Air 100-hour) - Emerging**

Wind

- Onshore wind
- **Offshore wind - Emerging**
- Hybrid and co-located with energy storage and solar

Solar Photovoltaic (PV)

- Utility scale
- Hybrid and co-located with energy storage and wind

Non-Emitting Baseload

- **Small Modular Reactor (SMR) - Emerging**

Combustion Turbine (peaker)

- Natural Gas with R99 backup
- **Hydrogen/NG blend with R99 backup - Emerging**
- R99

Distributed Energy Resources

- Solar
- Energy storage

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Storage technology comparisons

Technology		Advantages	Disadvantages	TRL	Previously Modeled
Short Duration (2-8 hrs)	Lithium-ion	• Most readably available today • Reliable with long lifespan and little to no maintenance required • High power and energy density	• Thermal runaway risk - fire hazard • Higher degradation compared to some other energy storage technologies	9	Yes
	Sodium-sulfur	• High temperature battery made of molten sodium and sulfur. Requires high temperature for operation (> 300 C) • Ceramic electrolyte used as a solid-state ion conductor	• Molten metal can cause fire upon exposure to air • Require high temps to operate	9	No
Medium (Mid) Duration (8-24 hrs)	Compressed Air Energy Storage (CAES)	• No battery pack required • Little to no metals used • Caverns used for CAES systems - less of an eye-sore	• Limited by availability of caverns and/or size requirements for above-ground storage vessels • Diabatic CAES (TRL 9) heats stored air by combusting natural gas, process produces significant emissions	6-9	No
	Pumped Hydro (PHES)	• Low operating costs and long life • Water supply and flood control • Limited CO^2 emissions	• Limited by geography and water supply • High start-up costs	8-9	Yes
	Other Mechanical Storage	• Potential for large-scale energy storage with long lifespans • Potential for longer storage durations • Siting flexibility (with some options) • Potential fast response time	• Some techs requires specific infrastructure and/or siting requirements • Challenges in maintaining efficiency over long periods	6-8	No
	Flow Battery	• Power and energy are separated, enabling independent scaling. Energy storage can be increased simply by expanding the electrolyte capacity • No significant fire hazards	• Vanadium and Bromide based flow batteries are both corrosive and acidic • Wholesale price of vanadium often fluctuate	7-9	No
Long Duration (24+ hrs)	Metal Air Battery	• Low materials cost and supply chain issues due to use of earth-abundant materials • No significant health or safety hazards	• Very few technology providers at the moment • Low roundtrip efficiency and high degradation	7	No