ELECTRIC POWER RESEARCH INSTITUTE

Environmental Aspects of Utility-Scale Energy Storage Systems

An Environmental, Health & Safety Comparison Across Commercially Available Technologies

Technical Update

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NOTE

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Abstract

This report evaluates the environmental, health and safety (EH&S) aspects associated with six types of utility-scale energy storage systems (ESS). The main objective was to conduct a literature review to support development of a framework for comparing the EH&S impacts associated with commercially-viable ESS technologies. The ESS technologies included in this evaluation were: lithium-ion batteries (LIB), vanadium redox flow batteries (VRFB), sodium-sulfur (NaS) batteries, flywheels, compressed air energy storage (CAES), and pumped hydro energy storage (PHES). The EH&S impact ratings are done at a high level to support relative comparisons across all six ESS technologies and are not meant to inform site-specific decisions. Information gathered during the literature review was organized into a tabular format to support the subjective ratings created across nine EH&S categories during both normal operations and abnormal/emergency conditions. Results from this exercise, which was meant to serve as a starting point for future investigation and to evolve and improve over time, reveal differences in EH&S impacts. Battery technologies tend to have low land use intensity (LUI), air and water impacts while potential impacts exist for fires, hazardous materials, and resource extraction. Flywheels, CAES and PHES require more land area, and project development can have substantial and irreversible impacts on water resources (i.e., hydrology and runoff), land/soil resources, and ecological resources. Additional research is needed to further refine the methodology and metrics used to screen the EH&S impacts of each ESS technology.

Keywords

Energy storage
Lithium ion battery
Vanadium redox flow battery
Compressed air energy storage
Flywheel energy storage
Environmental impacts

EXECUTIVE SUMMARY

Deliverable Number: 3002016593
Product Type: Technical Update
Product Title: Environmental Aspects of Utility-Scale Energy Storage Systems: An Environmental, Health and Safety Comparison Across Commercially Available Technologies

PRIMARY AUDIENCE: Electric utility companies interested in owning and operating energy storage facilities, or in procuring energy storage services through power purchase agreements

SECONDARY AUDIENCE: Energy, environment and sustainability stakeholders interested in energy storage

KEY RESEARCH QUESTIONS

This report compiles and compares information on the environmental, health and safety (EH&S) aspects of six types of utility-scale energy storage systems: lithium ion batteries, vanadium redox flow batteries, sodium sulfur batteries, flywheels, compressed air energy storage, and pumped hydro energy storage.

RESEARCH OVERVIEW

The project investigates the following research questions:

1) What are the major environmental, health and safety EH&S impact categories for commercially available energy storage technologies?
2) How can utility-scale storage technologies be compared across major EH&S impact categories?
3) Which storage technologies have the lowest/highest impact in each of the major EH&S impact categories?

EXECUTIVE SUMMARY

KEY FINDINGS

- A framework was created to consistently compare metrics derived from a qualitative assessment of impacts derived from a literature review. Each EH&S impact category has a set of 2-8 questions that generally involve a yes/no answer, followed by a more subjective rating of the magnitude on a scale from 1-10. The results were normalized and assigned a “low”, “medium”, or “high” ratings that reflect two scenarios: normal operations and abnormal events.
- The EH&S categories used were: Emissions & Air Quality; Water Consumption & Quality; Land Use, Soil & Geology; Fire Effects; Hazardous Materials; Noise & Vibration; End-of-Life Management; Resource Extraction; and Wildlife & Habitat.

WHY THIS MATTERS

This project was intended to provide a high-level comparison of EH&S impacts associated with building, operating and decommissioning different types of utility-scale energy storage systems that are commercially available, or likely to be so over the next 3-5 years. The intent was to review potential impacts whose characterization will evolve and improve over time as new information is collected.

HOW TO APPLY RESULTS

The results can be used as a compact reference guide and educational resource for utility staff but should not be used as a substitute for assessment of project-specific impacts. The results are a starting point for future research investigations, and could be evolved and improved over time.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Interested parties can attend the EPRI Advisory Meetings for Program 197, Environmental Aspects of Fueled Distributed Generation and Energy Storage. In 2020, these will be held by Webex on September 16 and 17th, from 2:30-4:30 pm Eastern each day.

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PROGRAM: P197 Environmental Aspects of Fueled Distributed Generation and Energy Storage

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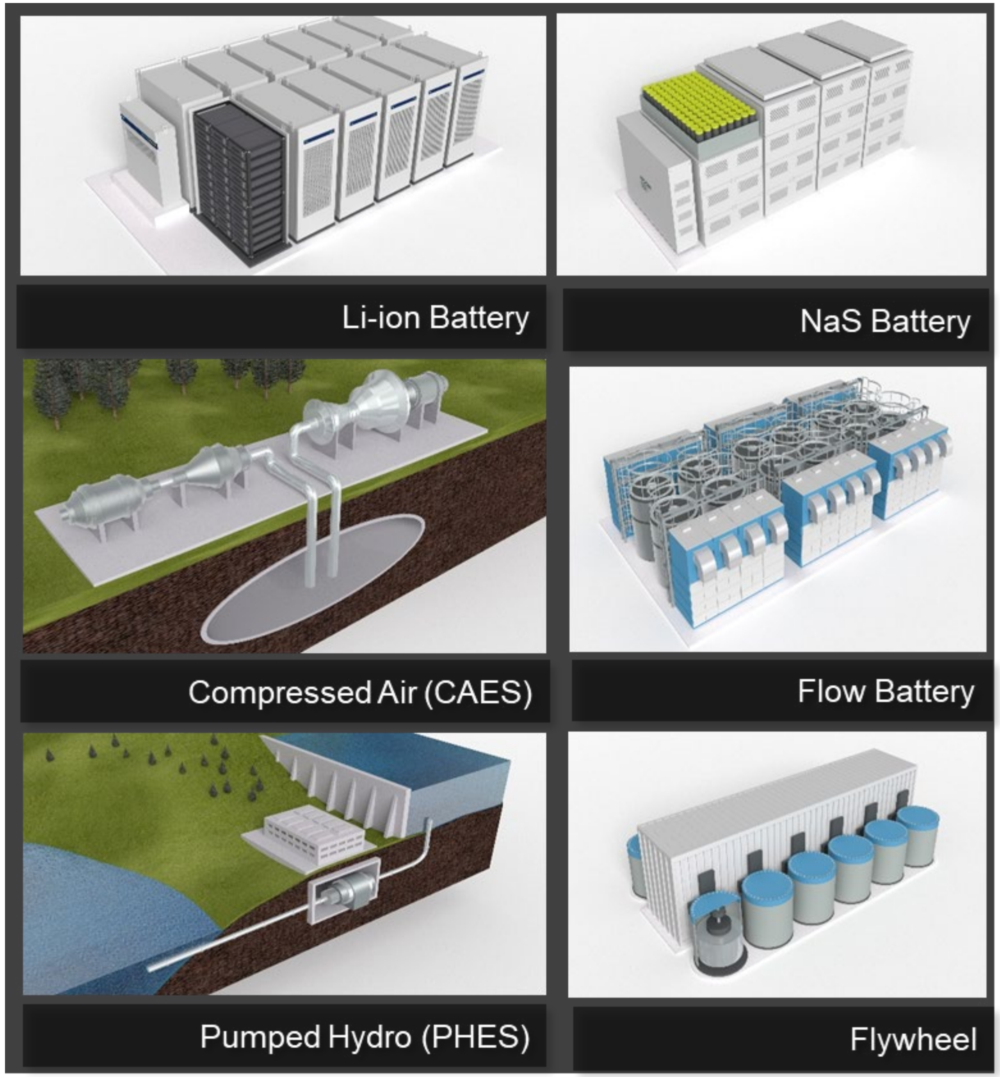


Li-ion Battery
NaS Battery
Compressed Air (CAES)
Flow Battery
Pumped Hydro (PHES)
Flywheel

INTRODUCTION

Project Background

This project was intended to provide a high-level comparison of environmental, health and safety impacts associated with building, operating and decommissioning different types of utility-scale energy storage systems (ESS) that are commercially available, or likely to be so over the next 3-5 years. The approach was intended to review potential impacts whose characterization will evolve and improve over time as new information is collected. Thus, the results can be used as a compact reference guide and educational resource for utility staff, but should not be used to assess project-specific impacts.

The six technologies included in this project are: lithium-ion batteries (LIBs) without distinction on specific chemistries, vanadium redox flow batteries (VRFB), sodium-sulfur (NaS) batteries, flywheels (FESS), compressed air energy storage (CAES), and pumped hydro energy storage (PHES). These technologies represent the majority share of existing energy storage capacity and are expected to remain the dominant technologies in the near to medium term.

The project investigates the following research questions:

1) What are the major environmental, health and safety (EH&S) impact categories for commercially available ESS technologies?
2) How can utility-scale ESS technologies be compared across major EH&S impact categories?
3) Which ESS technologies have the lowest/highest impact in each of the major EH&S impact categories?

Methodology for Impact Comparisons

- **Literature review performed**
  - Information was collected from published literature, such as specific research assessments and environmental life cycle assessments (LCA), as well as white papers, manufacturer information and other sources. This review informed the range of media and metrics that could be used in the tabulations, and the values assigned to the metrics.
- **Commonalities across each impact category definition**
  - Each category considers impacts during the construction and operational phase of the ESS project lifecycle.
  - Each category (except Fire Effects, Resource Extraction, End-of-Life and Wildlife and Habitat) includes separate ratings for normal and abnormal conditions
  - Indirect impacts (i.e., emissions associated with charging and discharge strategies) are not considered
- **The tabulation framework is meant to provide a high-level classification of ESS technologies without performing a detailed hazard risk assessment or environmental impact study which would vary depending on project size, design, and location. Ratings (low/moderate/high) are based on comparisons against the maximum possible score for each impact category (low = 0-25% of max score, moderate = 25-50% of max score, high = 50% or higher).**

Methodology for Impact Comparisons

- **Simple Metric Tabulation Used for Each Impact Category**
  - Example: Does the technology emit criteria air pollutants (Yes/No)?
  - A “yes” answers results in “1” while a “no” answer result in “0”
  - Rate the severity of the impact (i.e., criteria air pollutants) on a scale from 1-10
  - Weight of this question in the overall score (0-100%)
- **Each EH&S impact category has a set of 2-8 questions that generally involve a yes/no answer, followed by a more subjective rating of the magnitude on a scale from 1-10.**
- **Each question is normalized to a 0-1 scale. Score from each question is summed for total**
- **Category scores for a particular technology <u>do not</u> influence scores in other categories (i.e., the water consumption & quality score does not affect the wildlife impact score)**

Develop a consistent metric-based approach to compare qualitative impacts

Environmental Impact Category Descriptions

ENV Category	Category Definition & Description
Emissions & Air Quality	Direct emissions of gases regulated under the Clean Air Act including; criteria air pollutants, toxic/hazardous air pollutants (HAPs), and greenhouse gases (GHG) from combustion, other industrial processes, or from flooded reservoirs for PHES. Impacts associate with abnormal conditions may include combustion gases produced during fire events, spills, or other emergency conditions. There is no risk probability associated with abnormal events, rather the ratings are based on the assumption that an emergency event has occurred to represent a worst-case scenario.
Water Consumption & Quality	Direct consumption and evaporation of water during normal operations (i.e., cooling water intake and evaporation) and discharge of toxic and/or non-toxic liquid effluent during normal operations. Also incorporates changes from construction activities. Impacts from abnormal events are related to spills of hazardous materials that could impact ground and surface water in the absence of primary and/or secondary containment systems. Impacts to aquatic habitats, plant and animal species are not considered in this category but are included in the Ecological & Habitat Impacts category.
Land, Soil & Geology	Direct impacts caused by project construction and operations on soil at the project site, land use intensity (LUI) based on total project footprint, and subsurface geology. Considers whether construction and normal operation of each ESS technology results in a direct impact on soil, land and geological resources regardless of geographic setting and other project variables. Tabulation includes consideration of land clearing, grading, and underground trenching/drilling required to establish a viable project.
Fire Effects	Direct EH&S issues that arise during fires stemming from ESS failures or external heat sources. Includes emissions of flammable or toxic gases from off-gas or combustion, the release of flammable or toxic liquids, and whether emergency first responders require special training or protective equipment beyond standard practices. No attempt was made to quantify the probability of an fire event occurring as the impact ratings simply reflect the impacts associated with a fire event during/after it has occurred.

Environmental Impact Category Descriptions

ENV Category	Category Definition & Description
Hazardous Materials	Direct EH&S issues that arise from use of hazardous materials during normal operations, or release of hazardous materials during abnormal conditions. Includes the need for special requirements for first responders. Impact ratings are influenced the NFPA 704 hazard rating system where a 0-4 scale indicates the hazard level associated with flammability, chemical instability (i.e., corrosive/explosive), and health (human toxicity).
Noise & Vibration	Direct issues present during normal operations, or caused during abnormal conditions. Includes noise levels experienced by on-site workers and off-site receptors, as well as vibration impacts that may affect surrounding buildings and other infrastructure. Examples may include sound produced from ESS equipment (i.e., VRFB electrolyte pumps or HVAC systems) beyond standard electrical components (such as inverters, transformers and switchgear). Vibration impacts may also include the need for drilling and other sub-surface work during project development and construction.
Resource Extraction	Direct issues present during raw material mining, refining and transportation are considered in this category, which is not split into normal/abnormal conditions. The metrics do not attempt to quantify the cost of these activities or the quantities of different materials produced. Metrics are informed by a literature review of environmental lifecycle assessments (LCA).
End of Life	Direct issues present during end-of-life (EoL) decommissioning, recycling and disposal. The metrics do not attempt to quantify the cost of these activities, but rather are focused on the difficulty/availability of low-impact EoL strategies. The ability to return an ESS project site to its pre-development state is a component of the tabulation methodology. Metrics are informed by a literature review of lifecycle assessments (LCA) for various ESS technologies but this is an emerging area of research that would benefit from future study.
Wildlife & Habitat	Direct terrestrial, avian or aquatic mortality and morbidity associated with normal operation of energy storage equipment. Includes impacts resulting from land use change during/after construction of the ESS project that affect habitat size and quality. For example, wind turbine operation presents an unavoidable fatality risk to birds and bats who might collide with spinning rotor blades. LUI is used as a proxy for the magnitude/severity of habitat impacts. Landscape-level changes caused by project development (i.e., developing a new reservoir for pumped hydro) are also considered.

ENERGY STORAGE TECHOLOGY OVERVIEW

Energy Storage Overview: Battery Technologies

ESS Technology	Lithium-ion Battery (LIB)	Vanadium Redox Flow Battery (VRFB)	Sodium-Sulfur (NaS)
Description	LIBs are currently more mature than other ESS options, with extensive deployments and well-established supply chains. The most frequently deployed LIB chemistries are lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP). Offer high energy and power density which can lead to fire and safety risks. Other potential impacts from a life cycle perspective include resource extraction or rare earth minerals and end-of-life disposal.	Vanadium Redox Flow Batteries (VRFB) are the most advanced in terms of commercial availability. Other flow batteries being demonstrated at smaller scale include zinc-air, zinc-bromine, and iron-based chemistries. Electricity is generated by the flow of a liquid electrolyte through porous membranes. This requires the use of pumps which draw a parasitic load and reduce round trip efficiency. VRFBs have lower energy and power density than LIB and NaS and have lower fire risks.	Large-scale sodium sulfur (NaS) batteries were developed in Japan and are used much more widely there than other countries although several MW-scale demonstration projects have been deployed in the US. NaS batteries use molten metal electrolytes that require temperature regulation equipment to maintain high operating temperatures which has safety implications. Sodium is highly reactive with water and a range of toxic gases can be produced if a fire occurs.
Round Trip Efficiency	**85%**	**70-75%**	**80-90%**
Capacity Range	kW to MW scale; typically 2-4 hour discharge	100's kW to MW scale; typically 4-8 hour discharge	100's kW to MW scale; typically 6-10 hour discharge
Commercial Readiness	**HIGH**: Large-scale deployment underway	**MEDIUM**: Few utility applications of VRFB	**LOW**: Few NaS projects in the US; widespread in Japan

Modified from EPRI Energy Storage Technology & Cost Assessment (Report 3002013957, 2018)

Energy Storage Overview: Non-Battery Technologies

ESS Technology	Flywheel	Compressed Air Energy Storage (CAES)	Pumped Hydro Energy Storage (PHES)
Description	Energy is stored in weighted rotors that spin at extremely high speeds. Energy storage capacity is dependent on the flywheel geometry, material density, and angular velocity. While there is no fire or hazardous material risk, catastrophic rotor failures could cause severe damage to the facility and nearby structures. Uses are typically restricted to power quality and uninterruptable power supply (UPS) applications.	Ambient air is compressed and stored under pressure in an underground cavern. When electricity is required, the pressurized air is heated and expanded using natural gas in a turbine coupled to a generator. CAES functions like a natural gas-fired power plant but with 40-60% lower emissions. Only suitable for specific locations and geological conditions. Produced water containing heavy metals and other contaminants may need to be stored/shipped for treatment.	Energy is stored in the form of potential energy in an upper reservoir that drives hydroelectric turbines in a spillway leading to the lower reservoir. Reversible flow turbines are used to pump water from the lower to upper reservoir during charging periods. Only suitable for specific locations and geological conditions where an upper and lower reservoir can be created. Development can cause significant and irreversible changes to local ecosystems and hydrology.
Round Trip Efficiency	**85-95%**	**~50%**	**70-80%**
Capacity Range	100's kW to MW scale; typically sec/min discharge	100+ MW scale; hours to weeks (long) duration	10's to 100+ MW scale; hours to days (long) duration
Commercial Readiness	**LOW**: Only a few MW scale projects are operational in the US	**VERY LOW**: Only two CAES projects globally	**HIGH**: Multiple GW of capacity installed since1930's

Modified from EPRI Energy Storage Technology & Cost Assessment (Report 3002013957, 2018)

SUMMARY OF ENVIRONMENTAL, HEALTH AND SAFETY CONSIDERATIONS

Results by EH&S Category: Normal Conditions

EH&S Category	LIB	VRFB	NaS	Flywheel	CAES	Pumped Hydro
Emissions & Air Quality	Low	Low	Low	Low	Moderate	Low
Water Consumption & Quality	Low	Low	Low	Low	Moderate	Low
Land Use, Soil & Geology	Low	Low	Low	Moderate	High	High
Hazardous Materials	Low	Low	Moderate	Low	Moderate	Low
Noise & Vibration	Low	Low	Low	Low	High	Moderate
Resource Extraction	High	Moderate	Low	Low	Low	Low
End of Life	Moderate	Low	Moderate	Moderate	High	High
Wildlife & Habitat	Low	Low	Low	Moderate	High	High

Results by EH&S Category: Abnormal Events

EH&S Category	LIB	VRFB	NaS	Flywheel	CAES	Pumped Hydro
Emissions & Air Quality	Moderate	Low	Moderate	Low	Moderate	Low
Water Consumption & Quality	Low	Low	Low	Low	Moderate	Moderate
Land Use, Soil & Geology	Low	Low	Low	Moderate	High	High
Fire Effects	High	Low	High	Low	High	Low
Hazardous Materials	Moderate	Moderate	High	Low	Moderate	Low
Noise & Vibration	Low	Low	Low	High	High	High

What are Abnormal Conditions?

An “abnormal” condition was defined for this study as a general term to describe rare events such as ESS failures (i.e., battery short circuit), fires (either self-ignited or external), hazardous material releases (gases or liquid spills), or mechanical failures (i.e., flywheel rotor burst). Severe weather and natural disasters are outside the scope of this analysis. Normal operations were separated from abnormal conditions to prevent confusion about how an abnormal event probability and resulting impacts would be “weighted” into a composite score with impacts from normal operating conditions. No attempt was made to quantify the risk probability associated with abnormal events.

Results by EH&S Category: Normal & Abnormal

EH&S Category	LIB	VRFB	NaS	Flywheel	CAES	Pumped Hydro
Emissions & Air Quality	Low (M)	Low (L)	Low (M)	Low (L)	Moderate (M)	Low (L)
Water Consumption & Quality	Low (L)	Low (L)	Low (L)	Low (L)	Moderate (M)	Low (M)
Land Use, Soil & Geology	Low (L)	Low (L)	Low (L)	Moderate (M)	High (H)	High (H)
Fire Effects	(H)	(L)	(H)	(L)	(H)	(L)
Hazardous Materials	Low (M)	Low (M)	Moderate (H)	Low (L)	Moderate (M)	Low (L)
Noise & Vibration	Low (L)	Low (L)	Low (L)	Low (H)	High (H)	Moderate (H)
Resource Extraction	High	Moderate	Low	Low	Low	Low
End of Life	Moderate	Low	Moderate	Moderate	High	High
Wildlife & Habitat	Low	Low	Low	Moderate	High	High

DETAILED ENVIRONMENTAL, HEALTH AND SAFETY CONSIDERATIONS

Emissions & Air Quality (Normal Operations)

ESS Technology	Rating	Description of Impacts
LIB	Low	There are no direct emissions associated with LIBs during normal operating conditions.
VRFB	Low	There are no direct emissions associated with VRFB during normal operating conditions.
NaS	Low	There are no direct emissions associated with NaS during normal operating conditions.
Flywheels	Low	There are no direct emissions associated with flywheels during normal operating conditions.
CAES	Moderate	Current CAES technologies heat pressurized air by burning natural gas to drive expansion turbines similar to traditional natural gas-fired power plants. While fuel combustion causes CO_2 and NOx emissions, emissions from a CAES plant can be 40-60% lower than traditional plants.
Pumped Hydro	Low	There are no direct emissions associated with PHES during normal operating conditions.

Emissions & Air Quality (Abnormal Event)

ESS Technology	Rating	Description of Impacts
LIB	Moderate	LIBs can emit a variety of toxic gases during fire events. Gases detected during fire tests include; hydrogen fluoride (HF), hydrogen sulfide(H_2S), phosphoryl fluoride (POH_3), SO_2, CO and VOCs from plastic casings.
VRFB	Low	There are no flammable chemicals involved with VRFB and the liquid electrolyte has some fire resistance. Emissions from electrical components (e.g. SF_6 from switchgear, transformers, etc.) are the same as traditional generation assets.
NaS	Moderate	NaS batteries can emit a variety of toxic/hazardous gases during fire events. Reactions between sodium and water are highly exothermic and can produce hydrogen gas and sodium hydroxide. Combustion in air can also produce H_2S and sodium poly-sulfides.
Flywheels	Low	There are no combustion gases involved with normal flywheel operations. Emissions from electrical components (switchgear, transformers, etc.) are the same as traditional generation assets.
CAES	Moderate	The presence of natural gas pipelines and combustion equipment at CAES facilities present a fire and explosion risk. However, these hazards are similar to those at traditional gas-fired power plants and there is a low risk of toxic/hazardous gas emissions during a fire event.
Pumped Hydro	Low	There are no combustion gases involved with normal PHES operations. Emissions from electrical components (e.g. SF_6 from switchgear, transformers, etc.) are the same as traditional generation assets.

Water Consumption & Water Quality (Normal Operations)

ESS Technology	Rating	Description of Impacts
LIB	Low	There are no direct water consumption requirements for LIBs during normal operations unless the packaged system includes a liquid cooling system and/or water-based fire suppression system.
VRFB	Low	There are no direct water consumption requirements for VFRBs during normal operations. VFRBs do not require fire suppression systems so water supply for sprinkler systems is not required.
NaS	Low	There are no direct water consumption requirements for NaS batteries during normal operations. Fire suppression must NOT use water to avoid severe exothermic reactions with the sodium electrolyte.
Flywheels	Low	There are no direct water consumption requirements for flywheels during normal operations unless the packaged system includes a liquid cooling system and/or water-based fire suppression system for other electrical components.
CAES	Moderate	CAES facilities may utilize water for cooling of compression turbines similar to systems used at traditional gas-fired power plants. Wastewater may also be produced from the air compression basin (similar to oil/gas drilling) that will need to be injected in disposal wells, or treated for reuse or disposal.
Pumped Hydro	Low	Large water volumes are circulated through hydroelectric turbines, but not consumed. Water evaporation can impact availability. Reservoirs impact water quality from sedimentation captured, low dissolved oxygen levels and temperature changes. Intakes pose a threat to aquatic species. PHES facility development has a substantial impact on hydrology and streamflow.

Water Consumption & Water Quality (Abnormal Event)

ESS Technology	Rating	Description of Impacts
LIB	Low	LIBs have a minimal risk of spill hazard due to the absence of liquids. It is possible some water quality risks exist when large volumes of water is used to cool/extinguish LIB fires, but this is an area that requires additional testing and research.
VRFB	Low	VRFBs use a liquid electrolyte that is considered corrosive and therefore requires primary and secondary containment systems. The electrolyte contains ~60% water, ~25% sulfuric acid, and ~15% vanadium that is deemed non-toxic because of the low concentrations of vanadium.
NaS	Low	Sodium metal reacts violently with water or halon compounds and fires should be extinguished with select dry chemicals. Extreme caution should be taken to contain any electrolyte material that leaks from cracked casings to avoid contact with water.
Flywheels	Low	Flywheels do not utilize any hazardous chemicals so there is minimal risk of spills impacting water quality outside of lubricants used in electrical components that are common at traditional generation assets.
CAES	Moderate	While a fire emergency would not present significant hazards to water quality, the potential for wastewater spills could pose a significant hazard to both surface and groundwater quality depending on the spill volume and proximity of nearby water bodies.
Pumped Hydro	Moderate	The potential for wastewater spills could pose a hazard to both surface and groundwater quality depending on the spill volume and proximity of nearby water bodies. The potential need to refill water levels due to loss from an abnormal event could require extensive supply.

Land Use, Soil & Geology (Normal and Abnormal Event)

ESS Technology	Rating	Description of Impacts
LIB	Low	Utility scale LIB systems are typically packaged in modular shipping containers (usually 20/40 x 8 x 9.5ft) with high power and energy density per acre of land. Containers can be easily placed alongside existing utility infrastructure with minimal grading/earthmoving during construction.
VRFB	Low	Utility scale VRFB systems are typically packaged in modular shipping containers (usually 20/40 x 8 x 9.5ft) similar to LIB units. Energy capacity is dictated by the volume of electrolyte so the geographic footprint can be larger than LIBs but land use intensity is comparable.
NaS	Low	Utility scale VRFB systems are packaged in modular shipping containers similar to LIB units with comparable land use intensity per MW/MWh. The high temperature and other safety risks require an additional security perimeter/fencing to protect public safety.
Flywheels	Moderate	While individual flywheel units are quite compact, utility-scale flywheel projects may require more land than battery storage technologies. Some flywheel projects may also be installed below grade with higher construction impacts.
CAES	High	CAES projects require substation land area and subsurface geological formations with high land use intensity and construction impacts. For example, a DOE assessment of one 300MW CAES facility in California estimated 18 acres for generation equipment and ~230 acres for the air compression wells.
Pumped Hydro	High	PHES projects require substation land area for the upper/lower reservoirs, specific geological conditions, and underground excavation for the generator house and water pipelines. Construction impacts for PHES projects are substantial as creating new reservoirs will flood existing lands resulting in irreversible land use change and habitat loss.

Fire Effects (Abnormal Events)

ESS Technology	Rating	Description of Impacts
LIB	High	When LIB cells are exposed to high temperatures or other failure modes, they can generate heat at a faster rate than they are able to dissipate it, presenting a thermal runaway risk. LIB fires can emit toxic/hazardous gases and are difficult to extinguish without cooling the LIB cells, posing a re-ignition risk.
VRFB	Low	VRFB have lower fire risk than LIB and NaS batteries due to the use of inflammable liquid electrolytes. Typical fire prevention and safety measures for electrical components (inverters, switchgear, transformers etc.) should be installed in accordance with appropriate standards.
NaS	High	Sodium metal is highly reactive, and if ignited, is classified as a Class D fire. As such, it reacts violently with water or Halon compounds and instead should be extinguished with select dry powder chemicals. The high operating temperature could also pose an ignition risk for dry vegetation.
Flywheels	Low	Flywheels do not utilize flammable chemicals and therefore have a low fire risk compared to LIB, NaS and CAES. Typical fire prevention and safety measures for electrical components (inverters, switchgear, transformers etc.) should be installed in accordance with appropriate standards.
CAES	High	CAES fire hazards are similar to those presented by natural gas-fired power plants that are driven by leaking, damaged or malfunctioning fuel supply components. While CAES relies on a combustible fuel, the risks are well understood and do not present unique challenges for first responders.
Pumped Hydro	Low	PHES do not utilize flammable chemicals and therefore have a low fire risk. Typical fire prevention and safety measures for electrical components (inverters, switchgear, transformers etc.) should be installed in accordance with appropriate standards.

Hazardous Materials (Normal Conditions)

ESS Technology	Rating	Description of Impacts
LIB	Low	Under normal operating conditions, containerized LIBs should not impose a serious risk to human health or the environment as hazardous materials will be safely contained by the battery enclosure.
VRFB	Low	Under normal operating conditions, containerized VRFBs should not impose a serious risk to human health or the environment as hazardous materials will be safely contained by the battery enclosure and electrolyte tanks.
NaS	Moderate	Under normal operating conditions, containerized NaS batteries should not impose a serious risk to human health or the environment as hazardous materials will be safely contained by internal cells, a "safety" tube and sand filler meant to neutralize sodium/sulfur reactivity.
Flywheels	Low	Flywheels do not utilize any hazardous, corrosive, or flammable materials outside of certain lubricants used in other standard utility equipment (inverters, transformers, switches, etc.). They do not present a risk to human health or the environment under normal operating conditions.
CAES	Moderate	There are no unique hazardous materials risks at CAES facilities beyond what are common at natural gas-fired power plants. However, wastewater may be produced during compression cycles (similar to fracking wastewater) that may contain heavy metals and other toxic chemicals.
Pumped Hydro	Low	There are no unique hazardous materials risks at PHES facilities beyond oils/lubricants commonly used for maintenance at hydroelectric power plants.

Hazardous Materials (Abnormal Events)

ESS Technology	Rating	Description of Impacts
LIB	Moderate	Concerns have been expressed about fluoride-based electrolyte salts and solvents. Lithium and li-ion cells are Class 9 hazardous materials, which are require certain standard packaging and labeling. Toxic/hazardous gases can be emitted from LIB fires. LIBs are a Class 9 Hazmat in 49 CFR Part 100-185.
VRFB	Moderate	The VRFB liquid electrolyte is corrosive and secondary containment is typically designed into the system. Standard corrosive PPE is required for liquid handling. Vanadium mixed into the liquid electrolyte is deemed non-toxic due to low concentration levels.
NaS	High	Sodium reactions with water are highly exothermic (usually explosive) and produce hydrogen gas and sodium hydroxide among other toxic gases. Sodium reactions with sulfur produce highly corrosive sodium polysulfides that can erode metal battery cell casings and produce chromium sulfide.
Flywheels	Low	Flywheels do not utilize any hazardous, corrosive, or flammable materials outside of certain lubricants used in other standard utility equipment (inverters, transformers, switches, etc.).
CAES	Moderate	There are no unique hazardous materials risks at CAES facilities beyond what are common at natural gas-fired power plants. However, wastewater may be produced during compression cycles (similar to fracking wastewater) that may contain heavy metals and other toxic chemicals.
Pumped Hydro	Low	PHES do not utilize any hazardous, corrosive, or flammable materials outside of certain lubricants used for routine maintenance of hydroelectric turbines and other standard utility equipment (inverters, transformers, switches, etc.).

Noise & Vibration (Normal Conditions)

ESS Technology	Rating	Description of Impacts
LIB	Low	The lack of moving/rotating components in LIBs means they do not produce substantial noise/vibration. HVAC equipment may produce intermittent noise in some modular designs. Electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
VRFB	Low	VRFBs do not produce substantial noise/vibration except for electrolyte pumps and HVAC equipment that produce intermittent noise in some modular designs. Electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
NaS	Low	The lack of moving/rotating components in LIBs means they do not produce substantial noise/vibration. HVAC equipment may produce intermittent noise in some modular designs and electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
Flywheels	Low	Flywheels utilize heavy rotors spinning at extreme speeds to store kinetic energy. Imbalances in the flywheel rotor can lead to catastrophic failure events where projectiles can destroy the flywheel housing, and cause damage/injury to nearby people and property.
CAES	High	Noise from a CAES facility would be similar to an natural gas-fired power plant which require substantial setbacks from residential/commercial buildings. Compression of the underground storage formation may also produce geological impacts and vibration that must be understood.
Pumped Hydro	Moderate	Noise from a PHES facility would be similar to a traditional hydroelectric power plant which require substantial setbacks from residential/commercial buildings. Noise and vibration from hydroelectric turbines will be minimized due to installation in subsurface housings, but workers will require hearing protection in certain areas.

Noise & Vibration (Abnormal Events)

ESS Technology	Rating	Description of Impacts
LIB	Low	The lack of moving/rotating components in LIBs means they do not produce substantial noise/vibration. HVAC equipment may produce intermittent noise in some modular designs. Electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
VRFB	Low	VRFBs do not produce substantial noise/vibration except for electrolyte pumps and HVAC equipment that produce intermittent noise in some modular designs. Electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
NaS	Low	The lack of moving/rotating components in LIBs means they do not produce substantial noise/vibration. HVAC equipment may produce intermittent noise in some modular designs and electrical components (inverters, transformers, switches, etc.) may also cause noise similar to other utility assets.
Flywheels	High	Flywheels utilize heavy rotors spinning at extreme speeds to store kinetic energy. Imbalances in the flywheel rotor can lead to catastrophic failure events where projectiles can destroy the flywheel housing, and cause damage/injury to nearby people and property.
CAES	High	Noise from a CAES facility would be similar to an natural gas-fired power plant which require substantial setbacks from residential/commercial buildings. Compression of the underground storage formation may also produce geological impacts and vibration that must be understood.
Pumped Hydro	High	Reservoir, dam, spillway or other infrastructure failure at a pumped hydro facility would result in significant vibration from the uncontrolled release of massive amounts of water that could cause severe damage to nearby structures. Malfunctioning hydroelectric turbines could also cause excessive noise and vibration although it would be somewhat contained by generation house.

Resource Extraction

ESS Technology	Rating	Description of Impacts
LIB	High	LIBs require lithium, cobalt, manganese and a variety of other rare earth elements (such as lanthanum and neodymium) that are concentrated in only a handful of international production sites. Most of the known lithium supply is in Bolivia, Argentina, Chile, Australia and China. China controls ~95% of the global rare earth metals market.
VRFB	Moderate	Vanadium used in VRFB liquid electrolytes is a rare earth metal whose supplies are located in China, Russia, South Africa, and Brazil. China and Russia combined to produce 59,000 metric tons in 2017, about 75% of global total production of 80,000 metric tons. Increased demand has led to expanded operations in the U.S., Canada and Australia.
NaS	Low	Unlike LIB and VRFB the sodium/sulfur electrolytes used in NaS batteries are cheap and abundant raw materials.
Flywheels	Low	Flywheels are typically manufactures using steel, ceramic or carbon composite rotors mounted in steel housings and concrete encasements. They are not reliant on rare earth or precious metals.
CAES	Low	Materials used in CAES turbomachinery and other components are essentially the same as those used for natural gas-fired power plants. These products are mainly made of treated steel and are not heavily reliant on rare earth or precious metals.
Pumped Hydro	Low	Materials used in PHES hydroelectric turbines and other components are essentially the same as those used for traditional hydroelectric power plants (mainly streel and concrete). These products are mainly made of treated steel and are not heavily reliant on rare earth or precious metals.

End-of-Life (EoL) Management

ESS Technology	Rating	Description of Impacts
LIB	Moderate	Utility-scale LIBs required specialized separation activities to prepare battery modules for recycling and there are few commercial-scale recycling facilities currently operating in the U.S. Transportation at EoL may require special HAZMAT considerations to comply with DoT regulations.
VRFB	Low	Approximately 95% of the weight is recyclable and the liquid electrolyte is fully recyclable/re-usable at other VRFB sites. Containerized units should not require substantial construction work during dismantling and decommissioning activities.
NaS	Moderate	While recycling is theoretically possible, there are no commercial scale facilities to handle NaS batteries in the US. EoL NaS batteries contain solid sodium and sodium sulfides, both classified as hazardous waste, and polysulfides may be classified as hazardous based on corrosive characteristics.
Flywheels	Moderate	Decommissioning a flywheel facility may require non-trivial construction work to remove components installed below grade across a multi-acre site. Unlike BESS, flywheels do not contain hazardous materials and most of the mechanical components can be recycled.
CAES	High	Decommissioning a CAES facility would be a long and complex process, similar to retiring an natural gas-fired power plant, that would also require capping all air and wastewater injection wells. A period of post-retirement geological monitoring could also be required to ensure subsurface stability.
Pumped Hydro	High	Decommissioning a PHES facility would be a long and complex process, similar to retiring a hydroelectric power plant. Prolonged post-retirement geological monitoring could also be required to ensure the integrity of reservoir dams to protect nearby communities.

Wildlife & Habitat

ESS Technology	Rating	Description of Impacts
LIB	Low	Given the relatively small land use intensity for utility-scale LIBs, the amount of impacted habitat is typically not very large and therefore negative impacts on wildlife are also minor. Siting LIBs at existing sites minimizes ecological impacts compared to greenfield development projects.
VRFB	Low	Given the relatively small land use intensity for VRFBs, the amount of impacted habitat is typically not very large and therefore negative impacts on wildlife are also minor. Siting LIBs at existing sites minimizes ecological impacts compared to greenfield development projects.
NaS	Low	Given the relatively small land use intensity for NaS batteries, the amount of impacted habitat is typically not very large and therefore negative impacts on wildlife are also minor. Siting LIBs at existing sites minimizes ecological impacts compared to greenfield development projects.
Flywheels	Moderate	MW-scale flywheel projects require several acres of land and therefore may have greater impacts on habitat and wildlife than batteries. Some flywheels are also installed below grade resulting in earthwork that can disrupt native vegetation and habitat.
CAES	High	Large CAES facilities require 10-100's of acres of land for generation equipment and the compression wells used for air injection. These large land use requirements have the greatest impacts on habitat and wildlife among ESS technologies except PHES.
Pumped Hydro	High	Large CAES facilities require 10-100's of acres of land for generation equipment and the upper/lower water storage reservoirs. Fish and other aquatic species also face fatality risks from water intakes and hydroelectric turbines. These large land use requirements have the greatest impacts on habitat and wildlife among the ESS technologies considered in this report.

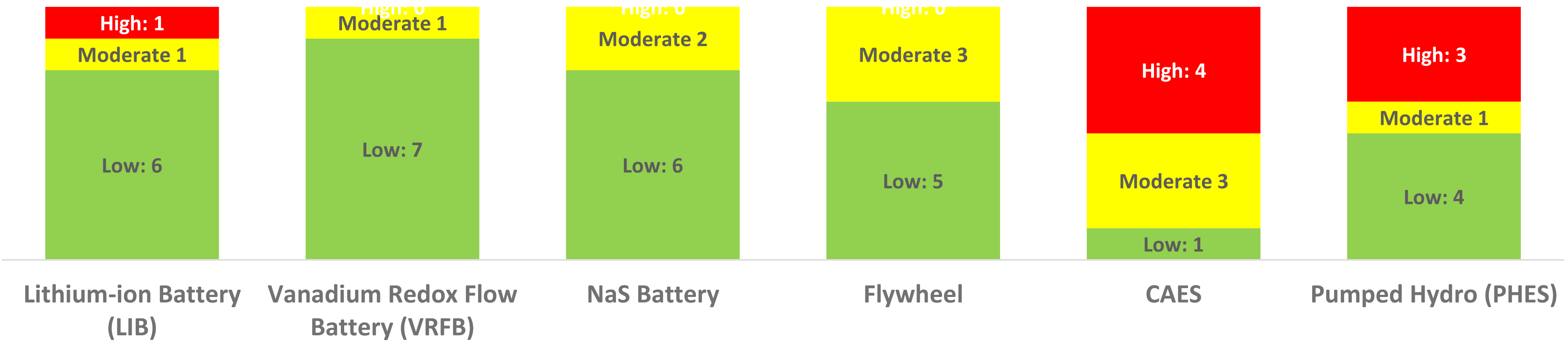
CONCLUSIONS

Key Takeaways

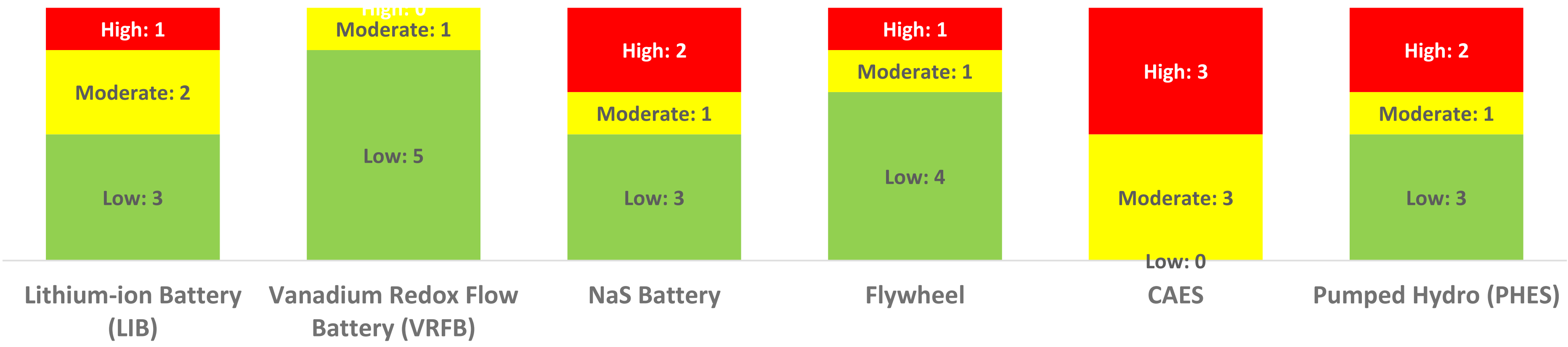
- Providing an “apples to apples” comparison of ESS technologies is challenging due to the variety of use cases, technologies, storage capacity, and physical sizes.
- CAES is the only ESS technology that produces direct emissions during normal operations but LIBs and NaS batteries have the potential to emit toxic gases during fire events.
- VRFB and flywheels have low flammability risk but VRFB electrolyte spills have the potential to contaminate soil and nearby water resources. Flywheels can cause major damage, if a catastrophic rotor failure occurs, that can be similar to an explosion.
- Electrochemical batteries (LIB, VRFB, NaS) have comparatively small land use intensity (LUI) while CAES and Pumped Hydro requires large land area and suitable geological conditions.

Key Takeaways

Summary of Low, Moderate & High Ratings by Technology: Normal Conditions
** Chart includes Resource Extraction, End-of-Life, and Wildlife/Habitat. Does NOT include Fire Effects**



Summary of Low, Moderate & High Ratings by Technology: Abnormal Conditions
** Chart does NOT include Resource Extraction, End-of-Life, or Wildlife/Habitat. Does include Fire Effects **



Conclusions & Future Research

ESS Technology	Summary of Environmental Impacts
LIB	**Pros:** Low LUI, no direct emissions or water consumption, low noise/vibration impacts **Cons:** Possible fire effects, limited end-of-life recycling options **Data Gaps:** Fire emissions data, first responder best management practices, LCA studies
VRFB	**Pros:** Low LUI, low fire risk, no direct emissions, low noise/vibration impacts, high recyclability **Cons:** Liquid electrolyte spill hazard, lower efficiency than LIBs **Data Gaps:** Spill hazard characterization and containment best management practices, LCA studies
NaS	**Pros:** Low LUI, no direct emissions, low noise/vibration impacts **Cons:** High operating temperature hazard, hazardous materials, Class D fire rating, fire emissions **Data Gaps:** End-of-life options, LCA studies, first responder best management practices
Flywheels	**Pros:** High efficiency, no toxic chemicals, low fire risk, no direct emissions **Cons:** Potential for catastrophic rotor failure **Data Gaps:** LCA studies
CAES	**Pros:** Long duration storage, no hazardous chemicals (besides natural gas) **Cons:** Geological constraints, large LUI, direct emissions/water consumption, requires wastewater injection wells **Data Gaps:** Operational data (only 2 exist), LCA studies, end-of-life options
Pumped Hydro	**Pros:** No hazardous chemicals or fire risk, well established technology **Cons:** Geological constraints, large LUI, substantial and irreversible ecological/hydrological impacts **Data Gaps:** Approaches to reduce land use and ecological impacts

Future Research:

- Metric tabulation could be developed further and used as the basis for an expert elicitation
- Conduct in-depth literature review on specific metrics of interest

Appendix: Additional Methodological Information

Introduction to Additional Methodological Information

This appendix summarizes the questions, inputs and subjective ratings used to calculate the impact ratings or each energy storage technology under both normal and abnormal conditions (note that fire effects, end-of-life, resource extraction, and wildlife and habitat impacts are not divided into these two conditions). Ultimately, the goal is to organize the information collected during the literature review in a useful way that facilitates a consistent metric-based approach to rating EHS impacts using qualitative information. In the future, quantitative environmental impact assessments could be combined with surveys and expert elicitations to update the estimated impact metrics and ratings.

Note: In most charts there are two columns for each ESS technology. The left column shows responses for normal operating conditions while the right column shows ratings for abnormal events.

Acronyms

- CAP – Criteria Air Pollutant
- CWA – Clean Water Act
- DOT HMR – Department of Transportation Hazardous Materials Regulations
- HAP – Hazardous Air Pollutant
- GHG – Greenhouse Gas
- NFPA – National Fire Protection Agency
- NPDES – National Pollutant Discharge Elimination System
- NYS DEC – New York State Department of Environmental Conservation
- PSD – Prevention of Significant Deterioration
- SWPPP – Stormwater Pollution Prevention Plan

Emissions & Air Quality

- Normal operations include direct emissions of gases regulated under the Clean Air Act, including criteria air pollutants (CAPs), toxic/hazardous air pollutants (HAPs), and greenhouse gases (GHG) from combustion or other industrial processes. Does not include the indirect impacts of grid emissions associated with electricity used during charging and discharging periods.
- Abnormal impacts are defined as direct emissions of flammable, hazardous, and/or toxic gases produced during failure modes and other emergency events (i.e., fires, chemical spills, etc.).
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, and applicable federal permitting/regulatory requirements.
- None of the six ESS technologies produce direct emissions of GHG or criteria air pollutants during normal operating conditions except for CAES. Current CAES technology utilizes turbine machinery similar to what is found in natural gas-fired power plants, which produce GHG and criteria air pollutants. Compressed air is used to offset approximately 50% of fuel use requirements for an natural gas-fired unit.
- Direct emissions of air pollutants during abnormal conditions (i.e., fire events) can be produced from LIBs, NaS batteries and CAES facilities; VRFB and PHES have very low risks due to the lack of flammable materials. LIB fires can produce a variety of toxic and hazardous gases with several fire tests finding HF, HCl, CO and other hydrocarbons in fire emissions. NaS batteries can produce SO_2, sodium polysulfides and other gases if the molten sodium and sulfur electrolytes mix during a major failure such as breach of battery cell containment systems. CAES facilities could produce uncontrolled emissions associated with natural gas combustion during fire events.

Emissions & Air Quality Normal

1) Are direct emissions of criteria air pollutants (O3, PM, CO, Pb, SO2, NOx) produced?														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 1	No		No	0	No	0	No	0	Yes	0	No		Yes	
1b) Number of CAPs (1-6)	0		0		0		0	0	2		0		6	
1c) Frequency of Emissions (% of total operating hours)	0%		0%		0%		0%	0	75%		0%		100%	
1d) Annual potential to emit (PTE) is above PSD major source threshold of 250tpy?	No		No		No		No	0	No		No		Yes	
1d) Weight (%)	40%													
2) Are direct emissions of toxic/hazardous air pollutants produced?														
Response to Question 2	No		No		No		No		Yes		No		Yes	
2b) Number of HAPs (choose 1 for 1-5 HAPs, 5 or 6-10 HAPs, and 10 for 10+ HAPs)	0		0		0		0		1		0		1	
2c) Frequency of Emissions (% of total operating hours)	0%		0%		0%		0%		75%		75%		100%	
2d) Annual potential to emit (PTE) is above PSD major source threshold of 25tpy combined HAPs or 10tpy for 1 HAP?	No		No		No		No		No		No		Yes	
2d) Weight (%)	40%													
3) Are direct emissions of GHG (CO2, CH4, N2O) produced?														
Response to Question 3	No		No		No		No		Yes		Yes		Yes	
3b) Number of GHGs (1-3)	0		0		0		0		3		2		3	
3c) Frequency of Emissions (% of tota	0%		0%		0%		0%		75%		100%		100%	
3d) Annual potential to emit (PTE) is above PSD major source threshold of 100,000 mtCO2e?	No		No		No		No		Yes		Yes		Yes	
3d) Weight (%)	15%		0											
4) Requires air quality monitoring/ventilation?														
Response to Question 4	No		No		Yes		No		Yes		No		Yes	
4b) Magnitude of monitoring and/or ventilation needs (1-10)	0		0		3		0		5		0		10	
4c) Weight	5%		0		0		0		0		0			
Low/Moderate/High	Low		Low		Low		Low		Moderate		Low		0	
Total Score	0.00		0.00		0.02		0.00		0.34		0.10		1.00	
Relative to Maximum Score	0.0%		0.0%		1.5%		0.0%		33.8%		10.0%		100%	

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Emissions & Air Quality Abnormal

1) Are direct emissions of criteria air pollutants ()3, PM, CO, Pb, SO2, NOx) produced?								
ESS Technology	LIB		VRFB	NaS	FESS	CAES	PHES	Max Score
Response to Question 1	Yes		No	Yes	Yes	Yes	No	Yes
1b) Number of CAPs (1-6)	2	0	0	3	1	3	0	6
1c) Probability of Emissions (% of emergency events)	100%		0%	100%	100%	100%	100%	100%
1d) First responders require special respiratory PPE?	Yes		No	Yes	No	Yes	No	Yes
1d) Weight (%)	40%							
2) Are direct emissions of toxic/hazardous air pollutants produced?								
Response to question 2	Yes		No	Yes	No	Yes	Yes	Yes
2b) Severity of HAPs emissions (1-10) based on the number, amount and toxicity of gases	3		0	5	0	1	0	10
2c) Frequency of Emissions (% of total operating hours)	100%		0%	100%	0%	100%	100%	100%
2d) HAPs released would require nearby residents to shelter in place?	No		No	No	No	Yes	No	Yes
2d) Weight (%)	40%							
3) Are direct emissions of GHG (CO2, CH4, N2O) produced?								
Response to Question 3	Yes		No	Yes	No	Yes	No	Yes
3b) Number of GHGs (1-3)	3		0	3	0	3	0	3
3c) Frequency of Emissions (% of total operating hours)	100%		0%	100%	0%	100%	100%	100%
3d) Annual potential to emit (PTE) is above PSD major source threshold of 100,000 mtCO2e?	No		No	No	No	No	No	Yes
3d) Weight (%)	15%							
4) Requires air quality monitoring/ventilation?								
Response to Question 4	No		No	Yes	No	No	No	Yes
4b) Magnitude of monitoring and/or ventilation needs (1-10)	0		0	1	0	0	0	10
4c) Weight	5%							
Low/Moderate/High	Moderate		Low	Moderate	Low	Moderate	Low	0
Total Score	0.27		0.00	0.38	0.03	0.32	0.00	1.00
Relative to Maximum Score	26.8%		0.0%	38.0%	3.3%	31.5%	0.0%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Water Consumption & Water Quality

- Impacts on water resources are defined as direct consumption of water during normal operations (i.e., cooling water intake, evaporation) and discharge of toxic and/or non-toxic liquid effluent during normal operations. This category also incorporates impacts on drainage, and stormwater runoff. Impacts from abnormal events are related to spills of hazardous liquids that could impact ground and surface water in the absence of primary and/or secondary containment systems.
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, and applicable federal permitting/regulatory requirements of the Clean Water Act (CWA).
- Some larger LIB systems may require water for fire suppression systems or maintenance facilities, but water is generally not required for cooling systems or other equipment required during normal operations. VRFB, NaS batteries and flywheels also do not require water consumption or produce waste effluent during normal operating conditions. During abnormal conditions, impacts on water quality are associated with the potential for contaminated fire suppression water to enter sewers or nearby water bodies. VRFBs utilize large volumes of liquid electrolytes that are typically comprised of vanadium pentoxide and diluted hydrochloric acid that is deemed corrosive. Primary and secondary containment systems are needed to ensure that electrolyte spills do not impact ground or surface water resources. It is imperative that first responders avoid using water for fire suppression on NaS batteries as sodium is highly reactive with water.
- CAES may require some water for cooling of the turbine equipment and these facilities may produce wastewater when pressurized air forces water to the surface. This produced water (similar to oil and gas extraction) may contain heavy metals and other harmful compounds that may need to be stored, injected in disposal wells, or shipped off-site for treatment. The amount of so-called produced water will depend on the characteristics of the underground storage reservoir and will most prevalent at facilities that utilize depleted oil and gas fields.
- Pumped hydro obviously requires massive quantities of water in the upper and lower reservoirs, but water is not actively consumed as it would be for cooling in thermal power plants. However, evaporation can occur. Water impacts are tied to changes in hydrology, run-off patterns and ecosystem impacts as opposed to water consumption and effluent discharge.

Water Consumption & Water Quality, Part 1

1) Are direct emissions of non-toxic water pollutants (nitrogen, heat, TDS) produced?														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 1	No	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1b) Number (1-6)	0	1	0	1	0	0	0	0	1	1	1	1	6	6
1c) Frequency of Emissions (% of total operating hours)	0%	100%	0%	100%	0%	0%	0%	0%	50%	100%	50%	50%	100%	100%
1d) Annual potential to emit (PTE) non-toxic pollutants is above CWA major source threshold?	No	No	No	No	No	No	No	No	Yes	No	Yes	No	Yes	No
1d) Weight (%)	20%	0												
2) Are direct emissions of toxic water pollutants produced?														
Response to Question 2	No	Yes	No	Yes	No	No	No	No	Yes	Yes	No	No	Yes	Yes
2b) Number (choose 1 for 1-5 \, 5 or 6-10, and 10 for 10+)	0	1	0	1	0	0	0	0	1	1	0	0	1	1
2c) Frequency of Emissions (% of total operating hours)	0%	100%	0%	100%	0%	0%	0%	0%	50%	100%	50%	0%	100%	100%
2d) Annual potential to emit (PTE) toxic water pollutants above CWA major source threshold?	No	No	No	No	No	No	No	No	No	No	No	No	Yes	Yes
2d) Weight (%)	20%													
3) Is direct consumption of water required?														
response to Question 3	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
4b) Magnitude of water consumption (1-10)	1	5	0	0	1	0	0	0	5	1	2	10	10	10
3c) Frequency of water consumption (% of total operating hours)	5%	100%	0%	0%	0%	0%	0%	0%	50%	100%	100%	100%	100%	100%
3d) Annual water use is above 100,000 gal/day (NYS DEC permitting threshold)?	No	No	No	No	No	No	No	No	No	No	No	No	Yes	Yes
3d) Weight (%)	20%													
4) Requires water quality monitoring?														
Response to Question 4	No	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
4b) Magnitude of water quality monitoring needs (1-10)	0	0	0	0	1	0	0	0	0	5	10	10	10	10
4c) Weight	5%													

Water Consumption & Water Quality, Part 2

5) Requires NPDES/SWPPP permit for construction activities (disturbs more than 1 acre of land?)														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 5	No	No	No	No	No	No	Yes	No	Yes	No	Yes	No	Yes	Yes
5b) Difficulty of NPDES permit preparation and magnitude of permit requirements (1-10)	0	0	0	0	1	0	5	0	10	0	10	0	10	10
5c) Weight	5%													
6) Requires Clean Water Act 316 and/or 402 permit for water intake(s)?														
Response to Question 6	No	No	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes
6b) Difficulty of CWA 316/402 permit preparation and magnitude of permit requirements (1-10)	0	0	0	0	1	0	0	0	0	0	5	5	10	10
6c) Weight	5%													
7) Requires primary/secondary spill containment under CWA Section 311 or other state/local regulations?														
Response to Question 7	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
7b) Magnitude of water quality monitoring needs (1-10)	0	0	3	3	3	3	0	0	5	5	3	3	10	10
7c) Weight	10%													
8) Requires wastewater injection (UIC I/W) or other wastewater treatment?														
Response to Question 8	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
8b) Magnitude/difficulty/complexity of wastewater disposal/treatment needs (1-10)	0	0	0	0	0	0	0	0	10	10	2	3	10	10
8c) Weight	15%									0				
Low/Moderate/High	Low	Low	Low	Low	Low	Low	Low	Low	Moderate	Moderate	Low	Moderate	0	0
Total Score	0.00	0.17	0.03	0.15	0.04	0.03	0.03	0.00	0.34	0.35	0.22	0.26	1.00	0.90
Relative to Maximum Score	0.1%	18.5%	3.0%	16.3%	3.5%	3.3%	2.5%	0.0%	34.2%	39.1%	22.2%	28.7%	100%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Land Use, Soil & Geology

- ESS Impacts on land, soil and geological resources are defined as direct impacts caused by project construction and operations on soil at the project site, land use intensity (LUI) based on total project footprint, and subsurface geology.
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, and applicable federal permitting/regulatory requirements.
- The three battery technologies (LIB, VRFB, and NaS) can all be deployed in containerized units with relative minor land use intensity (LUI), as well as minimal grading, excavation and other site preparation alongside existing electric utility infrastructure. A review of battery technology specification sheets found LUI factors of 20-30MW/acre and 130-200 MWh/acre for VRFB, ~100 MW/acre and 570-780 MWh/acre for NaS, and 150-350 MW/acre and 550-780 MWh/acre for LIBs. The LUI for flywheels (FESS) is larger on the order of 10-100 acres for multi-MW facilities. CAES and PHES were given the maximum impact rating due to their need for hundreds of acres, substantial grading/excavation, and irreversible changes to geological resources.

Land Use, Soil & Geology

1) Requires grading, trenching or other earthwork during construction?														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b) Magnitude of construction earthwork (1-10)	1	1	1	1	1	1	5	5	10	10	10	10	10	10
1c) Weight	25%													
2) Requires NPDES/SWPPP permit for construction activities (disturbs more than 1 acre of land?)														
Response to Question 2	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2b) Difficulty of NPDES permit preparation and magnitude of permit requirements (1-10)	0	0	0	0	0	0	5	5	10	10	10	10	10	10
2c) Weight	25%								0			0		
3) Requires primary/secondary spill containment to comply with federal, state or local regulations?														
Response to Question 3	No	No	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
3b) Magnitude/difficulty/complexity or spill prevention requirements (1-10)	0	0	3	3	1	1	0	0	10	10	10	10	10	10
3c) Weight	25%	25%												
4) Include land use intensity (LUI) in impact metric?														
Response to Question 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b) Land use intensity (1 for 0-1 acres, 3 for 1-10 acres, 5 for 10-50 acres, 10 for 50+ acres)	1	1	1	1	1	1	5	5	10	10	10	10	10	10
4c) Weight	25%													
Low/Moderate/High	Low	Low	Low	Low	Low	Low	Moderate	Moderate	High	High	High	High	0	0
Total Score	0.05	0.05	0.13	0.13	0.05	0.05	0.38	0.38	1.00	1.00	1.00	1.00	1.00	1.00
Relative to Maximum Score	5.0%	5.0%	12.5%	12.5%	5.0%	5.0%	37.5%	37.5%	100.0%	100.0%	100.0%	100.0%	100%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Fire Effects

- ESS fire effects are defined as concerns that arise during fires stemming from various failure modes. These include emissions of flammable/hazardous/toxic gases from off-gassing or combustion, the release of flammable/hazardous/toxic liquids, and special fire suppression and first responder requirements. The questions and resulting metrics do not attempt to quantify the probability of a fire event occurring, rather they are meant to provide a high-level metric for the presence of fire hazards and the impacts associated with worst-case scenarios for each ESS technology.
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, applicable federal permitting/regulatory requirements, and fire codes/standards.
- All ESS technologies are determined to have low to moderate fire risk under normal operating conditions due to safety design features.
- VRFB, FESS, and PHES do not utilize any flammable chemicals that present a fire hazard during normal or abnormal conditions (except for oils used in ubiquitous electrical components like transformers, inverters, switchgear and substations). LIBs and NaS batteries are both prone to thermal runaway if battery cell temperatures go outside safe ranges. CAES relies on natural gas combustion and therefore has an inherent fire risk associated with fuel gas leaks and uncontrolled combustion.

Fire Effects

1) Technology contains flammable materials?							
ESS Technology	LIB	VRFB	NaS	BESS	CAES	PHES	Max Score
Response to Question 1	Yes	No	Yes	No	Yes	No	Yes
1b) NFPA 704 flammability rating (1-4)	2	0	3	0	4	0	4
1c) Weight							
2) Technology is susceptible to thermal runaway?							
Response to Question 2	Yes	No	Yes	No	No	No	Yes
2b) Magnitude and severity of thermal runaway risk (1-10)	10	0	10	0	0	0	10
3) Fires can produce flammable, toxic and/or hazardous gases?							
Response to Question 3	Yes	No	Yes	No	Yes	No	Yes
3b) Magnitude/severity of fire emissions (1-10)	10	0	10	0	10	0	10
for							
4) Include NFPA Fire Class in impact metric?							
Response to Question 4	Yes	Yes	No	No	No	No	Yes
4b) NFPA fire class (1 for Class A / 2 for Class B / 3 for Class C / 4 for Class D	4	0	4	0	2	0	4
4c) Weight							
Low/Moderate/High	High	Low	High	Low	High	Low	0
Total Score	0.88	0.00	0.69	0.00	0.50	0.00	1.00
Relative to Maximum Score	87.5%	0.0%	68.8%	0.0%	50.0%	0.0%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Hazardous Materials

- ESS impacts are defined as direct EH&S concerns that arise from use of hazardous materials during normal operations, or release of hazardous materials during abnormal conditions. These impacts include the release of flammable/hazardous/ toxic gases or liquids, and special requirements for first responders. The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, applicable federal permitting/regulatory requirements, and fire codes/standards.
- It is determined that all ESS technologies have low/moderate impacts during normal operating conditions due to safety design features.
- VRFB liquid electrolytes are considered corrosive and require both primary and secondary containment systems. Sodium used in NaS batteries is highly reactive with water and considered a Class 9 hazardous material. LIBs are also classified as a hazardous material under U.S. DOT transportation regulations for both new and end-of-life batteries. Flywheels and PHES do not utilize any hazardous materials other than oils/fluids found in common electrical components (i.e., transformers, inverters, switchgear and substations).

Hazardous Materials

1) Technology contains or uses hazardous materials?														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 1	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes
1b) Cumulative NFPA 704 rating (1-12)	7	7	5	5	5	5	0	0	6	7	0	0	12	12
1c) Weight	30%													
2) Product is classified as a hazardous material under US DoT regulations (HMR; CFR 49 Part 171-180)?														
Response to Question 2	No	Yes	No	Yes	No	Yes	No	No	No	Yes	No	Yes	Yes	Yes
2b) Magnitude and severity of compliance with DoT HMR regulations (1-10)	3	3	1	1	5	5	0	0	0	3	0	3	10	10
2c) Weight	30%													
3) Do workers require special hazardous material training and/or PPE to perform routine maintenance nearby the energy storage unit?														
Response to Question 3	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes
3b) Magnitude/complexity of occupational safety requirements (1-10)	1	3	1	3	5	10	0	0	3	1	0	1	10	10
3c) Weight	20%													
4) Are special barriers and/or setbacks required to protect nearby residents from hazardous materials at the energy storage facility?														
Response to Question 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b) Magnitude/complexity of public safety requirements (1-10)	1	3	1	3	3	1	3	3	5	1	3	1	4	4
4c) Weight	20%													
Low/Moderate/High	Low	Moderate	Low	Moderate	Moderate	High	Low	Low	Moderate	Moderate	Low	Low	0	0
Total Score	0.25	0.48	0.20	0.37	0.38	0.53	0.15	0.15	0.46	0.34	0.15	0.16	1.00	1.00
Relative to Maximum Score	24.5%	47.5%	19.5%	36.5%	37.5%	52.5%	15.0%	15.0%	46.0%	33.5%	15.0%	16.0%	100%	100%
*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*														

Noise & Vibration

- ESS noise and vibration impacts are defined as concerns present during normal operations, or caused during abnormal conditions. These impacts include noise levels experienced during normal operations by on-site workers and off-site receptors and vibration impacts that may affect surrounding buildings and other infrastructure.
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, and applicable federal permitting/regulatory requirements.
- Noise levels from the three battery technologies will likely not cause concern for local ordinances. HVAC equipment for LIBs and NaS batteries along with pumps for the VRFB liquid electrolyte are the only components that would cause noise. Flywheels have a high rating for abnormal conditions because unwanted vibration can lead to catastrophic rotor failure with the potential to cause significant damage to life and property. CAES facilities utilize natural gas combustion turbines that produce excessive noise and the compression wells may also produce noise and vibration that can affect nearby residents.

Noise & Vibration

1) Technology generates noise that could exceed local standards (typically 45dBa at night and 65dBa during the day)?														
ESS Technology	LIB		VRFB		NaS		FESS		CAES		PHES		Max Score	
Response to Question 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b) Magnitude/severity of noise emissions (1-10)	1	1	1	1	1	1	1	3	5	7	3	5	10	10
1c) Weight	30%													
2) Does the technology cause vibration impacts or is it susceptible to vibration risks?														
Response to Question 2	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2b) Magnitude and severity of compliance with DoT HMR regulations (1-10)	0	0	0	0	0	0	3	10	7	10	5	10	10	10
2c) Weight	30%		0											0
3) Do workers require special training and/or PPE as a safeguard against noise/vibration impacts?														
response to Question 3	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
3b) Magnitude/complexity of occupational safety requirements (1-10)	0	0	0	0	0	0	0	0	5	5	5	5	10	10
3c) Weight	20%													
4) Are special barriers and/or setbacks required to protect nearby residents from noise/vibration impacts?														
Response to Question 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b) Magnitude/complexity of public safety requirements (1-10)	1	1	1	1	1	1	5	10	5	5	5	5	10	10
4c) Weight	20%			0										
Low/Moderate/High	Low	Low	Low	Low	Low	Low	Low	High	High	High	Moderate	High	0	0
Total Score	0.05	0.05	0.05	0.05	0.05	0.05	0.22	0.59	0.56	0.71	0.44	0.65	1.00	1.00
Relative to Maximum Score	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	22.0%	59.0%	56.0%	71.0%	44.0%	65.0%	100%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Resource Extraction

- ESS resource extraction impacts are defined as the direct EH&S risks associated with producing, refining and transporting raw materials for each ESS technology. The questions and resulting metrics do not attempt to quantify the cost of resource extraction activities or the quantities of different raw materials used in manufacturing, rather they are meant to provide a high-level metric for the impacts associated with resource extraction for each ESS technology.
- The questionnaire is informed by a literature review of environmental lifecycle assessments (LCA) for various ESS technologies and other reference materials.
- Understanding resource extraction impacts requires further study and refinement of appropriate metrics. This first attempt focused on the use of rare/precious materials (such as lithium and other rare earth minerals for LIBs) whose production can lead to environmental and social impacts. LIBs require supplies of lithium, cobalt, magnesium and other rare earth minerals whose supplies are concentrated in a few geographic areas with less stringent environmental regulations and worker safety protections. By comparison, NaS batteries rely on sodium and sulfur, which are both abundant in the U.S. and abroad. Flywheels, CAES and PHES mainly require common materials like steel concrete, and composites that do not present the same challenges as rare earth minerals. Establishing a robust recycling and resource recovery industry for LIBs would help reduce the impacts associated with raw material extraction.

Resource Extraction

1) ESS technology requires rare earth and/or precious metals?							
ESS Technology	LIB	VRFB	NaS	FESS	CAES	PHES	Max Score
1) ESS technology requires rare earth and/or precious metals?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b) Magnitude/severity/complexity of decommissioning activities (1-10)	5	3	1	1	1	1	10
1c) Weight	50%						
2) Raw material extraction and processing can cause negative health impacts on workers in the US and abroad?							
Response to Question 2	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2b) Magnitude/complexity of hazardous waste disposal requirements (1-10)	5	3	1	1	1	1	10
2c) Weight	50%						
Low/Moderate/High	High	Moderate	Low	Low	Low	Low	0
Total Score	0.50	0.30	0.10	0.10	0.10	0.10	1.00
Relative to Maximum Score	50.0%	30.0%	10.0%	10.0%	10.0%	10.0%	100%

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End-of-Life Management

- End-of-life management impacts are defined as direct EH&S concerns present during decommissioning and disposal of an ESS facility at the end of its operational life. The questions and resulting metrics do not attempt to quantify the cost of EoL activities or the quantities of different waste materials produced, rather they are meant to provide a high-level metric for the impacts associated with decommissioning a site remediation for each ESS technology.
- The questionnaire is informed by a literature review of lifecycle assessments (LCA) for various ESS technologies as well as applicable federal permitting/regulatory requirements [i.e., Resource Conservation and Recovery Act (RCRA) and hazardous waste disposal/transportation overseen by DOE Pipeline and Hazardous Materials Safety Administration (PHMSA)]. This is an emerging area of research and established metrics/methods for this type of comparison have not been well defined.
- All ESS technologies will require some site remediation following decommissioning at end-of-life (EOL). Removal of containerized battery technologies from electric utility sites will be relatively minor compared to CAES and PHES decommissioning. CAES facilities will require multiple injection wells to be capped and monitored for safety along with dismantling turbomachinery. PHES projects cause irreversible landscape-level changes that would require extensive remediation at EOL. In terms of disposal, all battery technologies can be recycled but commercial-scale operations do not currently exist for any of the three technologies. Components from flywheels, CAES, and PHES utilize common materials (i.e., concrete and steel) that can be recycled at scale.

End-of-Life Management

1) End-of-Life decommissioning requires use of heavy duty construction equipment??							
ESS Technology	LIB	VRFB	NaS	FESS	CAES	PHES	Max Score
Response to Question 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b) Magnitude/severity/complexity of decommissioning activities (1-10)	1	1	1	5	10	10	10
1c) Weight	30%						
2) End-of-Life disposal would require handling/transport of hazardous waste?							
Response to Question 2	Yes	Yes	Yes	No	Yes	Yes	Yes
2b) Magnitude/complexity of hazardous waste disposal requirements (1-10)	5	3	7	0	5	3	10
2c) Weight	30%						
3) EoL materials can be recycled using existing technology/facilities?							
Response to Question 3	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3b) Magnitude/complexity/difficulty of recycling (1-10)	5	1	7	3	3	3	10
3c) Weight	20%						
4) Are post decommissioning studies and remediation activities required?							
Response to Question 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b) Magnitude/complexity of post decommissioning monitoring and/or remediation requirements (1-10)	1	1	1	5	7	5	10
4c) Weight	20%						
Low/Moderate/High	Moderate	Low	Moderate	Moderate	High	High	0
Total Score	0.30	0.16	0.40	0.31	0.65	0.55	1.00
Relative to Maximum Score	30.0%	16.0%	40.0%	31.0%	65.0%	55.0%	100%

*** Total scores are normalized on ascale of 0-1. Low rating is 0-25% o the max score, moderate is 25-50% of the max score, and high is >50% of the max score*

Wildlife & Habitat

- ESS impacts on wildlife, habitat and ecological resources are defined as direct mortality risks associated with normal operation, and impacts resulting from land use change during/after construction of the ESS project. An analogous example for a non-storage technology would be the operation of wind turbines which presents a fatality risk to birds and bats who might collide with spinning rotor blades. Land use intensity (LUI) is used as a proxy for the magnitude/severity of habitat impacts.
- The questionnaire is informed by the California Environmental Quality Act (CEQA) checklist, CEQA significance determination thresholds, and applicable federal permitting/regulatory requirements.
- The magnitude of ecological impacts is a function of disturbed land area, meaning CAES and PHES will have the largest impact on both plant and animal species compared to relatively compact battery storage systems. PHES also requires the establishment of an upper and/or lower reservoir through flooding of pre-existing valleys that causes irreversible changes to non-aquatic habitats. PHES hydroelectric turbines also pose a mortality risk to aquatic life through entrainment of fish, eels and other species.

Wildlife & Habitat

ESS Technology	LIB	VRFB	NaS	FESS	CAES	PHES	Max Score
1) Project construction and site development requires grading, trenching or other earthwork that will change and degrade pre-existing natural habitat?							
Response to Question 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1b) Magnitude of construction impacts on pre-existing habitat (1-10)	1	1	1	5	7	10	10
1c) Weight	25%						
2) ESS components represent a direct mortality risk to ground and airborne animal species?							
Response to Question 2	No	No	No	No	Yes	No	Yes
2b) Magnitude/severity of fatality risks for terrestrial species	0	0	0	0	5	0	10
2c) Weight	25%						
3) ESS components represent a direct mortality risk to aquatic species?							
Response to Question 3	No	No	No	No	Yes	Yes	Yes
3b) Magnitude/severity of fatality risks for aquatic species	0	0	0	0	5	10	10
3c) Weight	25%						
4) Include land use intensity (LUI) in impact metric?							
Response to Question 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4b) Land use intensity (1 for 0-1 acres, 3 for 1-10 acres, 5 for 10-50 acres, 10 for 50+ acres)	1	1	1	5	10	10	10
4c) Weight	25%						
Low/Moderate/High	Low	Low	Low	Moderate	High	High	0
Total Score	0.05	0.05	0.05	0.25	0.68	0.75	1.00
Relative to Maximum Score	5.0%	5.0%	5.0%	25.0%	67.5%	75.0%	100%

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