Battery Energy Storage Study for the 2017 IRP

PacifiCorp

Customer Reference: Battery Energy Storage Study for IRP 2016 SOW
Document No.: 128197#-P-01-A
Date of this Issue: 8/22/2016
Date of last Issue: 7/27/2016
Legal Entity: KEMA, Inc.

Customer Details

Customer Name:	Pacificorp
Customer Address:	1407 West North Temple Salt Lake City, UT 84106 Tel: +1 801 220 2017
Customer Reference:	Battery Energy Storage Study for IRP 2016 SOW
Contact Person:	Ian Hoag

DNV GL Company Details

DNV GL Legal Entity:	KEMA, Inc.
DNV GL Organization Unit:	Advisory Americas
DNV GL Address:	4377 County Line Road, Chalfont, PA 18914
DNV GL Telephone. No.:	215-997-4500
DNV GL doc. No.:	128197

About this document

Report Title:	Energy Storage Technology Review
Date of this issue:	2016-08-22
Date of last revision:	2016-07-27
Validity of Report:	30 days from date of issue
Document Classification (see key below):	Customer's Discretion

KEY TO DOCUMENT CLASSIFICATION

Strictly Confidential:	For disclosure only to named individuals within the Customer's organization.
Private and Confidential:	For disclosure only to individuals directly concerned with the subject matter of the document within the Customer's organization.
Commercial in Confidence:	Not to be disclosed outside the Customer's organization.
DNV GL only:	Not to be disclosed to non-DNV GL staff
Customer's Discretion:	Distribution for information only at the discretion of the Customer (subject to the above Important Notice and Disclaimer and the terms of DNV GL's written agreement with the Customer).
Published:	Available for information only to the general public (subject to the above Important Notice and Disclaimer).

Important Notice and Disclaimer

This Report was prepared and issued for the sole use of the Customer. Neither this Report, nor any discussions, correspondence or other activities in connection with this Report shall form a contract or relationship of responsibility of any kind or nature regarding its subject matter without the Customer (or any third party approved in writing by DNV GL) entering into a written agreement with DNV GL in accordance with DNV GL’s standard terms and conditions, which may be contained or referenced in this Report or provided by DNV GL upon request.

This Report has been created and produced using information available as of the date of this Report and, where applicable, information relating to dates and periods referred to in this Report. There are no rights or licenses of any kind granted, and no warranties or guarantees of any kind provided with this Report or the material contained herein. Information contained in this Report may be subject to change at the sole discretion of DNV GL and the provision of this Report does not assure or imply otherwise.

Confidentiality and Copyright Protection

Copyright © 2016 DNV GL. This Report and the information contained herein, is the exclusive, confidential and proprietary property of DNV GL and is protected under the trade secret and copyright laws of the U.S. and other international laws, treaties and conventions. No part of this Report may be disclosed to any third party or used, reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying and recording, or by any information storage or retrieval system, without first receiving the express written permission of DNV GL. Except as otherwise noted, all trademarks appearing herein are proprietary to DNV GL.

For KEMA, Inc.

Prepared by:
Michael Kleinberg
Senior Consultant

Approved by:
John David Erickson
Head of Section, Distributed Energy Resources

Table of contents

List of tables

List of figures

1 INTRODUCTION

1.1 Objective and Scope of Work

At the behest of PacifiCorp, DNV GL has provided a status report and assessment of future potential applications for battery energy storage. DNV GL understands that PacifiCorp's objective is to compile and maintain a catalog of engineering estimates of costs and performance metrics for utility scale battery energy storage technology, both demonstrated for currently commercially available technology as well as forecasted for emerging technology. The 2017 PacifiCorp Integrated Resource Plan (IRP) will include a portfolio of generating resources and energy storage options for evaluation. The provided estimates and information is intended for PacifiCorp's use when preparing their upcoming and future IRPs and assessing energy storage applications for traditional utility transmission and distribution planning issues.

The scope of work is divided between cataloging technology updates and cost trends. The technology updates are broken down by current stage of commercialization, utility applications with associated value streams, and a detailed list of technology performance metrics. The cost analysis includes current system costs for the battery, PCS, controls, installation and O&M, as well as 10-year cost trends for each listed technology. PacifiCorp has specifically requested the scope to include NCM, $LiFePO_4$, and LTO Lithium-Ion (Li-Ion) batteries, Sodium Sulfur (NaS) batteries, Vanadium Redox (VRB) and Zinc Redox (ZnBr) flow batteries, as well as Zinc Hybrid Cathode (also known as Zinc-air) batteries. The report scope does not include application modeling or costs related to a specific vendor, but instead aims to cover the broader energy storage industry as it applies to applications being pursued by PacifiCorp.

The final report provides PacifiCorp with a catalog of commercially available and emerging battery energy storage technologies with forecasts and estimates for both performance and costs. DNV GL has compiled this catalog through the proposed scope of work. To further support PacifiCorp's bi-annual IRP, DNV GL has produced probabilistic cost graphs for each of the proposed technologies, broken out by technology, energy conversion system, controls, and the remaining balance of system.

1.2 Background and Materials

In 2013, PacifiCorp hired HDR Engineering to prepare an energy storage screening study, examining utility-scale storage potential, which was updated by HDR for PacifiCorp's 2015 IRP. This study covered operating and cost data for various energy storage technologies, with a section dedicated to batteries, including details on system size and lifecycle, comparing them to other storage options. The HDR study considers specific manufacturer's products and reference cases under standard operating conditions. PacifiCorp utilized the information from the HDR research to contribute to the modeling of future energy consumption, and how various technologies impact load profiles, costs, and CO2 emissions. This and other previous energy storage studies performed for PacifiCorp are available at www.pacificorp.com/es/irp.html. Energy storage continues to be of interest to stakeholders – and options for advanced large batteries (one megawatt or larger) are detailed in the IRP as quoted from the HDR study, including the battery types DNV GL has been requested to explore. To the extent possible, DNV GL has built upon and utilized existing studies and reports, to expand and update a battery catalog to include a deeper dive into battery technologies, costs, and applications for PacifiCorp's use in their 2017 IRP.

As a global advisory, classification, certification, and technical assurance company, DNV GL has served the energy sector as well as maritime and oil & gas industries for over 150 years. DNV GL is a leading authority on consulting, implementation, research, testing, and certification of solutions for the energy sector. Recognized as a global leader in the area of energy storage, DNV GL provides strategic advisory services, innovative modeling tools, and independent testing and certification of energy storage products to clients across various sectors. DNV GL operates as an independent entity without ties to any vendor, with no investments, affiliations, or financial interest with any equipment or service providers.

Most notably related to this effort, DNV GL has been actively involved in supporting multiple energy storage procurement efforts in the US. Our models for energy storage cost-effectiveness have been employed by state energy commissions, system operators, electric utilities, and project developers to assess the application value of energy operating the grid for a variety of current and future applications. DNV GL has performed independent bid evaluation for utility wholesale and distribution connected energy storage RFOs. This work involved processing energy storage offers from project developers and providing a ranking and bid evaluation on the capital and O&M costs as well as an assessment of the proposed warranty and performance guarantees. Finally, DNV GL is the industry leader in providing independent engineering analysis and technical due diligence to support third-party financing of energy storage deployments. As part of this work, DNV GL has gained significant insight into the costs, technical characteristics, and life-time performance guarantees of energy storage projects being developed in the US. For this report, DNV GL leveraged their experience with battery technology and the broader energy industry to develop reasonable average values for technology parameters, as well as how these parameters affect the cost and feasibility of a particular technology for an application.

Additionally, this study draws on a recommended practice (RP) document called GRIDSTOR (DNVGL-RP-0043), which was developed by DNV GL in partnership with members of the energy storage industry, including technology vendors, grid service providers, energy consultants, and universities. The GRIDSTOR RP provides a breadth of actionable information for deploying safe and reliable grid-connected energy storage systems, offering a blueprint for an independent quality guarantee of the safe implementation and operation of energy storage systems. This guideline draws on DNV GL experience, credible industry insight, and globally accepted regulations and best practices (such as IEC, ISO, and IEE standards), and was utilized as a reference for this report. GRIDSTOR is publicly available for free download at www.dnvgl.com/energy/brochures/download/gridstor.html.

Finally, under the scope of this effort, DNV GL also conducted current market research. This research included a review of published reports from consulting and energy-related clearinghouses, such as Navigant and IRENA, publicly available specification sheets and pricing for reviewed systems, and university and government sponsored research.

2 STAGE OF COMMERCIAL DEVELOPMENT

In this chapter, DNV GL provides an overview of the commercial development of each battery technology requested by PacifiCorp. DNV GL understands the importance of assessing the commercial viability of technologies which are intended to be procured as 10 to 20 year critical assets. With this consideration, DNV GL has provided definitions and basic information surrounding each considered technology and the associated system, followed by a sample of technology providers and sample products available on the market. This is followed by a summary of data available on current industry installation rates, including additional insight into some of the drivers behind the recent trends on installations.

2.1 Lithium-Ion Batteries

Lithium-Ion (Li-Ion) batteries utilize the exchange of Lithium ions between electrodes to charge and discharge the battery. Li-ion is a highly attractive material for batteries because it has high reduction potential, i.e., a tendency to acquire electrons (-3.04 Volt versus a standard hydrogen electrode), and it is lightweight. Li-Ion batteries are typically characterized as power devices capable of short durations (approximately 15 minutes to 1 hour) or stacked to form longer durations (but increasing costs). Rechargeable Li-ion batteries are commonly found in consumer electronic products, such as cell phones and laptops, and are the standard battery found in electric vehicles. In recent years this technology has developed and expanded its portfolio of applications considerably into utility-scale applications. Today, Li-Ion batteries have been implemented for applications relating to ancillary services in grid connected storage. Because of its characteristics, Li-Ion technology is well suited for fast-response applications like frequency regulation, frequency response, and short-term (30-minutes or less) spinning reserve applications.

Li-Ion batteries do carry some safety and environmental risk. Toxic or reactive gases may be released both during creation of the battery cells, as well as in case of thermal runaway within an operating system. However, this risk is being managed across the industry. During cell manufacture, effluent gases can be scrubbed and captured, to be disposed of safely.

Once fully constructed, Li-Ion battery systems come with various methods of cooling, not only to help prevent thermal runaway but also to provide the most beneficial operating temperatures for the battery cells. This risk is being managed from a broader perspective, too; local authorities are preparing to appropriately address any fire concerns. The New York Fire Department (FDNY) and their stakeholders in the National Fire Protection Association (NFPA) have worked with DNV GL to develop ventilation, extinguishing, and cooling requirements for battery fires. Similar types of precautions have been taken industry-wide, in coordination with local communities.

Figure 1 provides a schematic showing what is entailed in a general Li-Ion battery system. This includes monitoring, control, and management systems, power converter/inverter, and the batteries themselves.

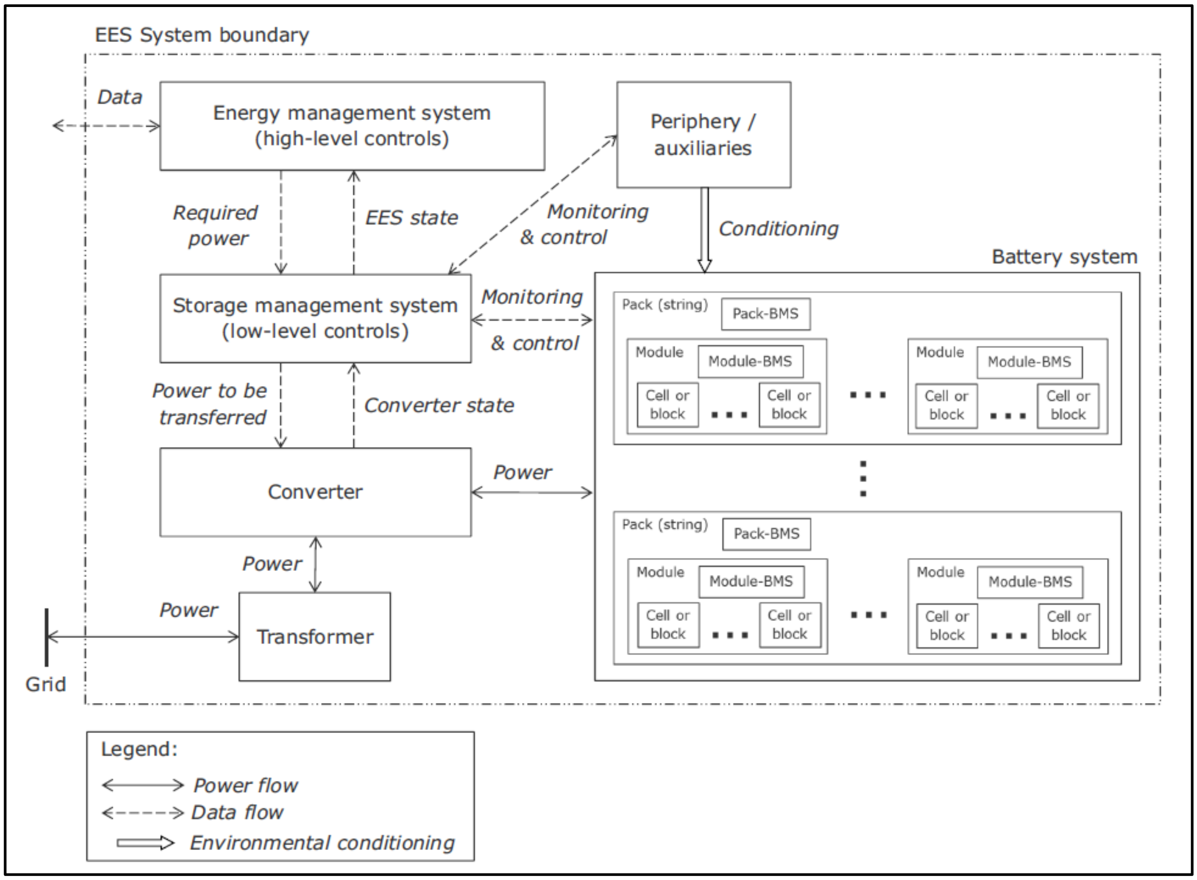

Figure 1 General Schematic and Components of a Cell-Based Battery Energy Storage System

Li-ion technology varies between chemistries. This report will focus on three of the most prominent and promising chemistries, Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$ or NCM), Lithium Iron Phosphate ($LiFePO_4$), and Lithium Titanate (Li_4Ti5O_{12} or LTO), and compare and contrast their attributes.

NCM is one of the most commonly used chemistries in grid-scale energy systems. This technology demonstrates balanced performance characteristics in terms of energy, power, cycle life, and cost. NCM chemistry is very common due to these features – it provides an engineering compromise.

$LiFePO_4$, on the other hand, can be purchased at a low cost for a high power density, and its chemistry is considered one of the safest available within Li-Ion batteries. Further, due to its very constant discharge voltage, the cell can deliver essentially full power to 100% DOD. However, LiFePO4 batteries are typically applicable to a more limited set of applications due to its low energy capacity and elevated self-discharge levels.

Finally, LTO offers a stable Li-Ion chemistry, one of the highest cycle lifetimes reported, and a high power density. Further, it is the fastest charging Li-Ion chemistry of those reviewed here. However, in balance, it has a much lower energy density and much higher average cost.

These systems are manufactured widely, but there is relatively high turn-over in manufacturers. Some of the more prominent or market-tested systems are included below, in Table 1.

Table 1 Li-Ion Battery Manufacturers

Technology	Manufacturer	Cell or System Product
NCM	Enerdel	CE175-360, 160-365 Moxie+
	Hitachi	
	LeClanche	Graphite/NMC
	LG Chem	JH2
	Panasonic	NCR18650A
	PBES	
	Samsung	25R
	XALT	31,40, 53, 75Ah HE; 31, 40, 63, 75Ah HP; 31, 37Ah UHP
	Electronova	
$LiFePO_4$	A123	AMP20, AHP14, ANR26650, APR18650
	BYD	
	K2 Energy	LFP123A
	Microvast	
	Saft	VL10Fe, VL25Fe
	Sony	IJ1001M
	Thundersky	WB-LYP, TS-LYP
	XO Genesis	
LTO	Altainano	nLTO
	LaClanche	LTO
	Microvast	LpTO (Gen 1)
	Toshiba	SCiB 2.9, 20, 23Ah
	XALT	60Ah LTO

2.2 Sodium Sulfur Batteries

Sodium-sulfur (NaS) batteries are a type of molten-salt battery. The systems have high energy density, fast response times, and long cycle lives. They also have some of the longest durations available on the market.

The inclusion of the term “molten” alludes to the battery operating temperature. NaS batteries store electricity through a chemical reaction which operates at 300 °C or above. At lower temperatures the chemicals become solid and reactions cannot occur. The high operating temperature makes the NaS batteries suitable for larger applications supporting the electric grid, but not personal electronic devices or vehicles. Further, due to the high temperature and natural reactivity of pure Sodium when exposed to water, the system can present a safety hazard if damaged.

Figure 1 above provides a schematic showing what is entailed in a general NaS battery system, which is parallel in its architecture to Li-Ion systems. This includes monitoring, control, and management systems, power converter/inverter, and the batteries themselves.

NaS batteries are a mature technology, and the system cost has generally leveled off. Although manufactured by more than one company, the market-share, and thus proven performance, of the company listed in Table 2 represents the majority of installations.

Table 2 NaS Battery Manufacturers

Technology	Manufacturer	Cell or System Product Description
NaS	NGK	NAS

2.3 Vanadium Redox Batteries

Vanadium Redox batteries (VRB), or Vanadium flow batteries, are based on the redox reaction between the two electrolytes in the system. “Redox” is the abbreviation for “reduction-oxidation” reaction. These reactions include all chemical processes in which atoms have their oxidation number changed. In a redox flow cell, the two electrolytes are separated by a semi-permeable membrane. This membrane permits ion flow but prevents mixing of the liquids. Electrical contact is made through inert conductors in the liquids. As the ions flow across the membrane, an electrical current is induced in the conductors to charge the battery. This process is reversed during the discharge cycle. Figure 2 below provides a schematic showing what is entailed in a general VRB system. This includes monitoring, control, and management systems, power converter/inverter, and the electrolyte tanks and stack of the batteries themselves.

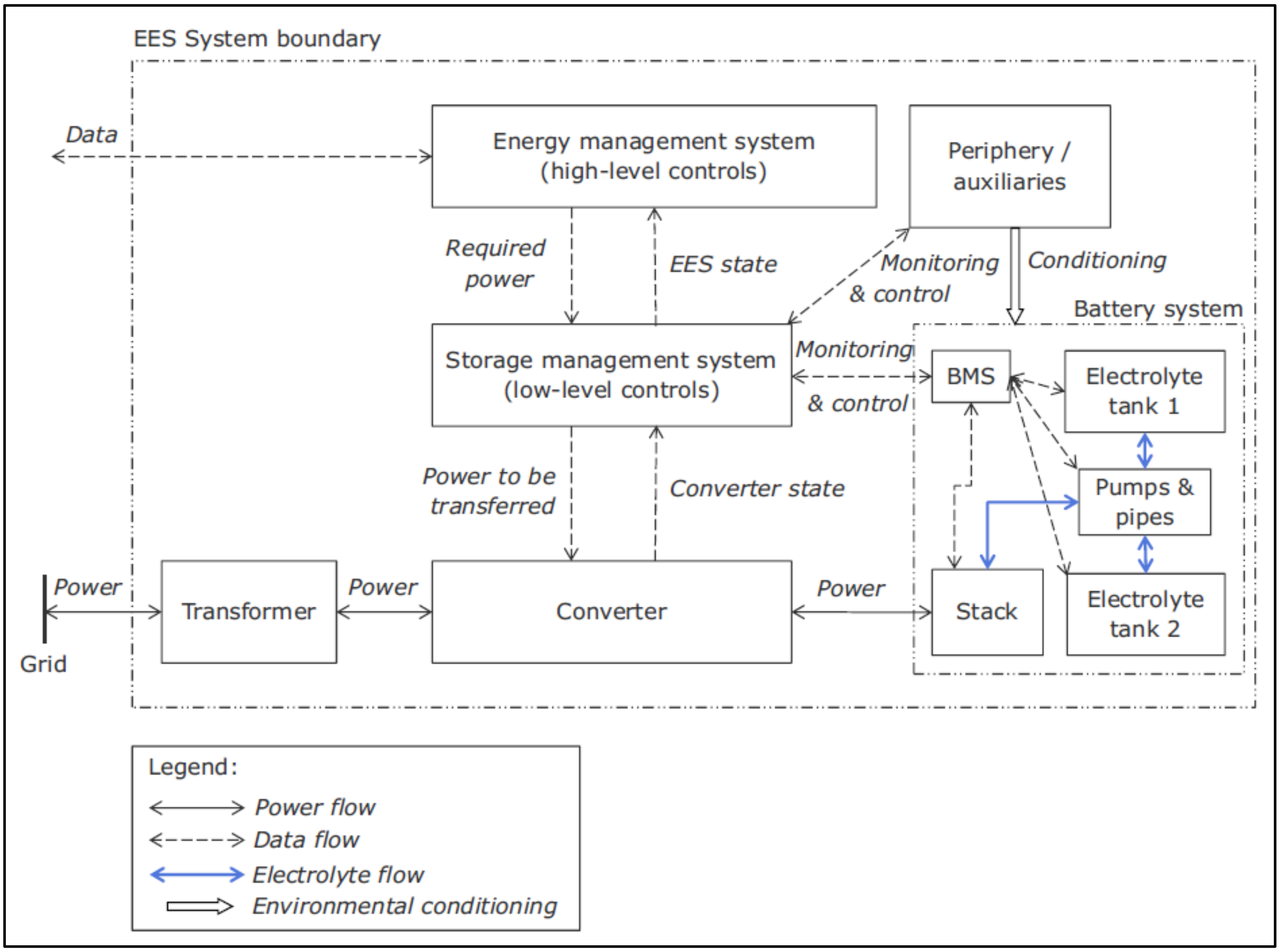

Figure 2 General Schematic and Components of a Redox Flow Battery Energy Storage System

In VRBs, the liquid electrolyte used for charge-discharge reactions is stored externally and pumped through the cell. This allows the energy capacity of the battery to be increased at a low cost. Energy and power are decoupled since energy content depends on the amount of electrolyte stored. VRB systems are unique in that they use one common electrolyte, which provides opportunities for increased cycle life. These large, liquid solution containers do however limit the VRB to stationary storage applications.

An important advantage of VRB technology is that it can be “stopped” without any concern about maintaining a minimum operating temperature or state of charge. This is a key point to most flow batteries in that the batteries can actually be “turned off.” This technology can be left uncharged essentially indefinitely without significant capacity degradation.

These systems are relatively new to the battery industry but are solidifying their place in the market. Some of the more prominent or market-tested systems are included below, in Table 3.

Table 3 VRB Manufacturers

Technology	Manufacturer	Cell or System Product Description
VRB	American Vanadium Imergy UET/UniEnergy Vionx	CellCube ESP5, 50, 250 UniSystem, ReFlex

2.4 Zinc Redox Batteries

The Zinc Bromine (ZnBr) battery utilizes similar flow battery technology as the previously discussed VRB. Due to this, it shares many of the same advantages: little to no claimed degradation over time (both in use and in the fully-discharged state), high energy density, 100% DOD, and easily scalable. The ZnBr consists of a zinc-negative electrode and a bromine-positive electrode, separated by a micro-porous separation. Solutions of zinc and a bromine complex compound are circulated through the two compartments. In a ZnBr the electrodes (Zn- and Br+) serve as substrates for the reaction. During charging, the Zinc is electroplated at the anode and bromine is evolved at the cathode. When not cycled, there is a potential for the Zinc to form dendrites that can degrade capacity or damage the battery components. To prevent this, the battery must be regularly and fully discharged.

Figure 2 above provides a schematic showing what is entailed in a general ZnBr system, which is of similar physical structure to VRB, though differing completely in chemistry at the core of energy storage. This includes monitoring, control, and management systems, power converter/inverter, and the electrolyte tanks and stack of the batteries themselves.

The response time for this technology is thought to be inadequate for fast-response applications; this should be verified on a case by case basis as new system designs may be able to improve on this limitation. ZnBr is a promising technology for balancing low-frequency power generation and consumption. However, cycle life tends to be less than that of VRBs.

These systems are in the early stages of commercialization but are being produced by multiple manufacturers. Some of the more prominent or market-tested systems are included below, in Table 4.

Table 4 ZnBr Battery Manufacturers

Technology	Manufacturer	Cell or System Product Description
ZnBr	Enphase (Previously ZBB) Primus Power Flow RedFlow	Enerstor, Agile EnergyCell ZBM2, ZBM3

2.5 Zinc Hybrid Cathode Batteries

Zinc hybrid cathode (Zinc-air) batteries are a type of metal-air battery which uses an electropositive metal in an electrochemical couple with oxygen from the air to generate electricity. Zinc-air batteries take oxygen from the surrounding air to generate current. The oxygen serves as an electrode while the battery construction includes an electrolyte and a zinc electrode that channels air inside the battery.

Zinc-air batteries have power densities similar to Li-ion batteries, but lower energy density. On the other hand, Zinc-air batteries in comparison to flow batteries can have both higher power and energy densities. Unlike Li-Ion, however, Zinc-air batteries are generally claimed to be benign, though their electrolytes – like those of other battery technologies – contain acidic or alkaline compounds and could produce SO2 if burned. The main Zinc-air battery material, zinc-oxide, is theoretically fully recyclable, though this has yet to be demonstrated at scale. In addition, the metals used or proposed in most metal-air designs are low cost.

Zinc-air systems appear attractive for utility applications if their ability to charge and recharge can be improved. The challenge for researchers has been to devise a method where the air electrolyte is not deactivated in the recharging cycle to the point where the oxidation reaction is slowed or stopped. The cessation of the oxidation reaction reduces the number of times that a Zinc-air battery can be recharged. Some of the newest emerging technology, as created by Eos, claims to have addressed these issues by implementing a near-neutral, non-dendritic, and self-healing electrolyte solutions. This, Eos claims, prevents air electrode clogging, rupture of the membrane due to dendrites, and the drying out of the electrolyte, along with other innovations that have prepared the system for commercial launch.

Potential applications include integrating renewable assets, peak shifting and load balancing, and frequency regulation. Consolidated Edison (ConEd) is currently pursuing one of the first utility-scale systems for demonstration with Eos technology.

These systems are in the early stages of commercialization and, as such, manufacturing is limited. Although being researched by more than one company, the earliest product being actively used in demonstration projects is produced by the manufacturer listed in Table 5.

Table 5 Zinc-Hybrid Cathode Battery Manufacturer

Technology	Manufacturer	Product name (if available)
Zinc-air	Eos	Znyth cell in Aurora 1000, 4000

2.6 Commercialization Data

Commercialization and installation data are based on DNV GL's research and publicly available information. This data excludes projects that have been decommissioned for any reason, or construction has not yet started.

Table 6 Installation and Commercialization Data

System Attributes	Li-Ion NCM	Li-Ion $LiFePO_4$	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air[1]
Typical project size (kW)[2]	6,500	5,000	2,000	6,000	4,000	1,000	3,500
Typical project size (kWh)	15,000	3,100	1,300	40,000	14,000	2,000	13,000
Largest project size installed (kW)[3]	30,000	31,500	40,000	50,000	15,000	1,000	250
Largest project size installed (kWh)	60,000	12,000	40,000	300,000	60,000	2,000	1,000
Current total power capacity installed (MW)[4]	77	142	31	186	66	5	0.25
Current total energy capacity installed (MWh)	30	220	19	1,254	226	25	1

---

[1] Zinc-air is an emerging technology. Due to this, the majority of the projects DNV GL cited are publicly announced but not yet installed and operational. This clarification is provided to give context to the typical system size being larger than the largest installed system size.

[2] Typical project size, both kW and kWh, are based on averages of publicly known projects that are operational, under construction, contracted, and announced. Decommissioned projects have been excluded from these counts.

[3] Largest project size, both kW and kWh, is based on projects that are currently operational, under construction, or contracted. Announced and decommissioned projects have been excluded from these counts.

[4] Current total power and energy capacity installed are based on publicly known projects that are operational, under construction, or contracted. Announced and decommissioned projects have been excluded from these counts.

3 PERFORMANCE CHARACTERISTICS

This chapter of the report provides a summary of technical parameters for each of the proposed storage technologies in a number of requested fields identified by PacifiCorp as useful for consideration within their 2017 IRP. The specific technology parameters of interest, as identified by PacifiCorp, are as follows:

1. Power Capacity
2. Energy Capacity
3. Recharge Rates
4. Roundtrip Efficiency
5. Availability
6. Degradation
7. Expected Life
8. Environmental Impact upon disposal

Each of the specified parameters are first defined and discussed below followed by a summary of values for each technology. Further, these characteristics are utilized later in this report, in Chapter 5, in determining the appropriateness of a technology for a particular application.

3.1 Power Capability

In composing this analysis, a variety of values were available given DNV GL's experience in the field, depending on operating conditions as well as marketing versus as-built specs. In all cases, all technologies in the study were available down to at least the 1 MW power capacity level, with many having wide use at smaller sizes, for commercial and industrial, residential or non-stationary storage applications. The maximum values were based on the largest installed or proposed and contracted systems to date.

The minimum size of 1 MW was based on feedback from PacifiCorp based on their IRP planning needs. DNV GL notes that all of these technologies are available in sizes smaller than 1 MW and can be installed as customer-sited, behind-the-meter resources. Storage is emerging as a technology being considered to provide utility services from aggregated behind-the-meter resources. Most notably, in 2014 Southern California Edison awarded two (2) capacity contracts to aggregated behind-the-meter energy storage.

3.2 Energy Capacity

The energy capacity DNV GL has compiled is what has been quoted by manufacturing specs as the optimal charge pattern of the entire capacity of the battery as designed. However, in many cases, these units are sold and marketed at a capacity reduced from the system's true total capacity. As such, useable or nameplate system capacity values are provided specified so that the system operates at a usable 0-100% SOC range.

3.3 Recharge Rates

All batteries have certain tolerances with regard to the rate at which they are charged or discharged. The current rating determines the C-rate for the battery, i.e., the rate at which a battery is discharged relative to its maximum energy capacity. Some batteries are more tolerant than others to high discharge rates. On the manufacturer specification sheets that accompany batteries, C-rates that are less than 1 are typically conservative, and may be recommended by the manufacturer to attain longer cycle lifetimes. Typically, discharge rates are higher than charge rates.

3.4 Round Trip Efficiency

Efficiency data provided in this report is the full energy storage system round trip efficiency (RTE). Full system RTE includes the losses from the power conversion system, HVAC equipment loads, control system losses, and self-consumption. Often a manufacturer will provide battery efficiency rather than RTE when promoting their technology. However, there can be a 5-10% difference between these efficiency ratings, when conversion equipment, air conditioning, and other “parasitic” balance of plant devices from the full system are taken into consideration. Auxiliary losses like air conditioning or heating vary considerably according to the technology and the specific application it must perform. For example, the heating requirement for a NaS battery is about 3 percent of its rating but heating is not needed if the battery is discharged daily because heat released during discharge will keep it warm. In this case, typically RTE values are reported based on the system performed a minimum amount of cycling per day.

3.5 Availability

The availability that DNV GL notes is based on guarantees being offered by manufacturers and distributors. Aside from these availability guarantees, annual planned maintenance carve-outs are typically included which do not contribute to these availability figures. Data here is provided based on currently observed guarantees being offered along with utility-scale energy storage systems, however, it should be noted that longer term operation experience will be required before these values are fully verified in practice.

3.6 Degradation

Storage is a unique technology in that its performance characteristics are significantly influenced by degradation. Degradation is highly dependent on system operation. System operation is in turn affected by location, power and energy capacity, applications, and how frequently those applications are utilized. Typically, manufacturer packaging, control and management systems, and environmental considerations are in place to ensure these parameters stay within safe and non-destructive ranges. However, outside influences and one-time events resulting from environmental control failure, BMS failures, or dispatch control error can lead to significant degradation of the device.

The degradation ranges that DNV GL has provided are given at year 10 after installation, based upon the average system operation, segmented by application type. The most common energy applications include electric time shift, electric supply capacity, spinning and non-spinning reserves, and T&D congestion relief. The Power applications include regulations, voltage support, load following and ramping support, and frequency response.

As noted previously, battery performance deteriorates as a result of various degradation mechanisms. The complexity and interactions of these mechanisms are given in detail below.

- **Temperature**: All batteries have an ideal temperature operating range; most batteries control their operation to 30ºC or less. High temperatures (generally above 30-40ºC) tend to degrade capacity severely. Many battery chemistries will indicate operational temperature ranges between 0-60ºC, however operation at or near these limits can severely impact efficiency of the cell as well as lifetime.
- **Charge and Discharge Rates:** For many batteries, high charge/discharge rates lead to higher temperature, compounding the degradation effect.
- **High or Low Average State of Charge:** If a battery spends a significant amount of time at a high state of charge, it will degrade faster than if it is left and maintained at a mid-level state of charge. Some batteries are more sensitive to this than others, but generally it is known that the higher the average state of charge (SOC) over the battery life, the faster it will degrade. Similarly, if a battery is kept at very low average SOC, it will also degrade quickly. This phenomenon has been studied extensively and it has been shown that battery capacity and average SOC are inversely proportional.
- **Depth of Discharge:** Generally, the greater the average depth of discharge (DOD), the faster the battery capacity will fade. In most cases, battery spec sheets will list the lifetime of the battery as number of cycles until 80% of capacity is reached at 100% DOD at 25 C. These conditions are considered nominal and if cycle life of the battery is mentioned without these additional specifications, it is important to verify the DOD, final capacity, and temperature of the tests. Unfortunately, these conditions are often unlike what the battery may experience in an actual application. It is often not noted whether long rest times between charge and discharge were implemented (allowing the battery to cool). Longer rest times can inflate the total cycle life.
- **Calendar Life:** The calendar life of the battery can affect its capacity as much or more than the cycling effects, but it is largely dependent on temperature. Assessing the time the battery is left at rest as a function of temperature is relevant to assessing its state of health. For this reason, most state of health predictions includes both calendar and cycling components.
- **Maintenance:** It is assumed that batteries will not operate completely autonomously. This Maintenance ensures unit operate optimally, given product specific operating constraints. Some manufacturers will further offer capacity maintenance agreements wherein systems are provided with maintenance, supplemental units integrated into the system, or refreshed electrolyte solutions in order to ensure capacity does not degrade past agreed to trigger points.
- **Compounding and Consequential Effects:** It is not possible to list the degradation factors from greatest to least without caveat considerations for specific chemistries, environment and duty cycle, but within the conservative limits established on a battery specification sheet, it may generally be assumed that abuse factors from least to greatest are: Temperature > Depth of Discharge > C-Rates . All of these factors are linked, however, and therefore have compounding effects depending on the battery duty cycle.

3.7 Expected Life

Most systems have not been available at a commercially mature stage for long enough to provide meaningful field data on lifetime performance, so the expected life is currently based on vendor projections, accelerated life-testing (ALT) on cells or modules and limited field results. Cell life tests are typically a good representation of the maximum possible lifetime under ideal conditions, and validation of these results is recommended on a case-by-case basis. With these caveats in mind, the expected life based on standardized cycling and disregarding extenuating circumstances is at least 10 years in all cases. Many manufacturers claim longer calendar lives; these claims assume periodic maintenance, including integrating new modules or adding new electrolyte. The number of cycles that these claims cover varies from technology to technology, based on the applications expected for use. As with calendar life claims, vendors typically claim cycle life in excess of 3,000 cycles. These claims are tied to the same periodic maintenance as previously mentioned. Further, all of the mechanisms discussed above that cause degradation are related to expected life and the system's ability to continue to meet the needs of the customer.

3.8 Environmental Effect Upon Disposal

While batteries claim advantages over traditional energy sources, including the ability to provide energy and power essentially instantaneously and without emission, the components will eventually require disposal. Disposal or recycling, however, comes with consequences. The United States Environmental Protection Agency states that no rechargeable electrochemical cells may lawfully be disposed of to be taken to a landfill. Li-ion and nickel-based electrochemical cells are classified as toxic due to the presence of lead, as well as cobalt, copper, nickel, chromium, thorium, and silver.

The majority of energy storage technologies covered in this report have yet to see adoption rates, much less decommissioning rates, high enough that significant research has been conducted on opportunities and limitations to recycling. While the US Department of Energy has pursued research on the subject, even producing functional Li-Ion cells from recycled materials, the process is so far limited to small pilot operations. For this reason, when decommissioning, disposing of, or pursuing potential recycling of batteries, the manufacturer of the energy storage system should be consulted for guidance. As energy storage systems are deployed in greater numbers, decommissioning and recycling are rising as important facets to financing agreements, contributing to the total cost of ownership.

Lead-acid battery repurposing and recycling activities are a well-established and extremely successful system. The policy has not addressed lithium and nickel-based battery recycling the same way it has lead-acid, and this is due to a number of challenges. The construction materials used in these systems are similar to the advanced technologies covered in this report (alloy and mild steel, aluminum alloys, copper, titanium, HPDE, etc.) and thus the majority of the challenge faced has to do with disassembly, destruction, sorting and any potential contamination. These batteries are mechanically varied between manufacturers and technologies, and packs are very sophisticated relative to lead-acid. In addition, there is a much larger range of materials in each battery, as well as a wide range of chemistries between batteries. Mined Lithium itself is low cost so although recycling is feasible, at present it is not economical. Instead, the primary components of interest are nickel and cobalt (and copper), and not all Li-ion batteries contain them in sufficient quantities. In many cases, the metals involved may just be sent to slag, to be burned for process heat (with the appropriate emission scrubbing). Materials can be recovered from this slag, but they must be in high enough quantity, quality, and demand to merit the additional effort. NCM batteries, for instance, contain a high enough percentage of valuable constituents (nickel and cobalt) to be recyclable.

Beyond the potential for emissions from burning slag, the chemicals have additional properties that affect disposal options. A universal issue for Li-Ion battery recycling is Lithium's high reactivity, creating a risk of fire if handled incorrectly. Otherwise, DNV GL's own research indicates that the materials within Li-Ion batteries are individually not exotic – for instance, Iron Phosphate is used as a non-toxic pesticide – but their destruction or combustion can create flammable gases such as ethylene, methane, and carbon monoxide. Toxic gases are also created, such as hydrogen fluoride, hydrogen chloride, and hydrogen cyanide. It should be noted that all of these gases are also created during the burning of plastics. To provide perspective as to Li-Ion battery toxicity, on a mass and volume equivalence, plastics are equally or more toxic than the by-products of Li-ion battery combustion.

As to redox flow batteries, electrolytes such as Zinc bromide and Vanadium solutions can typically be reused, sometimes for the life of the battery. However, contaminants or impurities may occur, requiring monitoring and removal. Additionally, upon decommissioning, the Vanadium and Zinc from these batteries may be recycled. It should be noted, however, that several materials commonly found in redox flow batteries are environmentally hazardous and regulated and thus should be disposed of according to regional government requirements. VRB electrolytes can dry or evaporate to form V_2O_5 dust as well as sulfate salts, while ZnBr electrolytes can evolve bromine at temperatures above 50^{o}C.

Finally, Zinc-air batteries, upon decommissioning, have similar overall construction materials that can be recycled via standard processes. Further, the aqueous electrolyte is non-flammable and non-hazardous (both non-toxic to humans and the environment). This electrolyte solution contains salts that are mildly corrosive but are not uniquely different or more hazardous than competing chemistries. The main component of Zinc-air batteries is Zinc-oxide, which is theoretically fully recyclable, although this has not yet been demonstrated on a large scale.

Properties of potential byproducts of battery decomposition are shown in Table 7.

Table 7 Combustion Byproducts of Commercially Available Batteries

		Concentration (ppm unless otherwise noted)								
	Chemical Formula	**LEL (Lower Explosion Limit)**	**IDLH (Immediately Dangerous to Life and Health)**	**Solubility in Water (mg/L)**	**Autoignition Temp (degC)**	**Thermal Instability Threshold (deg C)**	**NFPA Flammability**	**NFPA Health**	**NFPA Reactivity**	**Ref.**
Methane	CH4	50,000	5,000	22.7	537	-	4	1	0	NJ DOH
Carbon Monoxide	CO	12,500	1,500	27.6	609	-	4	2	0	CDC.gov
Ethylene	C2H4	27,000	-	2.9	490	-	4	2	2	Matheson MSDS
H2S	H2S	4,000	300	4,000.0	260	-	4	4	0	CDC.gov
Hydrogen Fluoride	HF	-	30	miscible	-		0	4	0	CDC.gov
Hydrogen Chloride	HCl	-	100	720.0	-	1500	0	3	1	CDC.gov
Hydrogen Cyanide	HCN	-	50	miscible	-		4	4	2	CDC.gov
V2O5 Dust	V2O5	-	35 mg/m^3	0.8	-		0	3	0	CDC.gov
Pb Vapor, salts, dust	Pb	-	700 mg/m^3	10^-5 to 4400	-		0	2	0	CDC.gov
SO2	SO2	-	100	94,000.0	-		0	3	0	CDC.gov

3.9 Technical Parameters Data

System parameters and characteristics are based on DNV GL's industry experience, internal research, and publicly available data. They are subject to the assumptions detailed in the previous sections.

Table 8 Technical Parameters and Performance Characteristics Data, from Both Cell and Project-Scale Perspectives

Parameter/ Technology		Li-Ion NCM	Li-Ion LiFePO$_4$	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air
Power capability	**Available down to 1 MW[1]**	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Maximum[2] (MW)	35	35	40	50	20	20	15
Energy capacity[3]	**SOC upper limit**	90%	85%	98%	90%	95%	98%	98%
	SOC lower limit	10%	15%	10%	10%	5%	5%	10%
Recharge rates		1C	2C-1C	3C-1C	1C-0.5C	1C-0.25C	1C-0.25C	2C-1C
Round trip efficiency		77 - 85%	78 - 83%	77 - 85%	77 - 83%	65 - 78%	65 - 80%	72 - 75%
Availability	**Up-time**	97%	97%	96%	95%	95%	95%	96%
	Carve Outs	72 hr/yr	72 hr/yr	72 hr/yr	72 hr/yr	1 wk/yr	1 wk/yr	72 hr/yr
Energy Capacity Degradation[4]	**Energy Applications**	30-40%	20-40%	15-25%	15-30%	5-10%	5-10%	15-25%
	Power Applications	10-20%	15-25%	5-15%	5-15%	5-10%	5-10%	5-15%
Expected life[5]	**Years**	10	10	10	15	10	10	10
	Cycles	3,500	2,000	15,000	4,500	5,000	3,000	5,000
Environmental effect upon disposal?[6]		Yes	Yes	Yes	Yes	Yes	Yes	Yes

---

[1] The minimum size of 1 MW was based on feedback from PacifiCorp based on their IRP planning needs. DNV GL notes that all of these technologies are available in sizes smaller than 1 MW and can be installed as customer-sited, behind-the-meter resources.

[2] Maximum power capability based on largest publicly proposed project.

[3] For usable energy capacity, manufacturers will commonly advertise their battery as allowing 100% DOD based on nameplate capacity. SOC limits given here reflect limits with respect to actual installed energy capacity.

[4] Degradation value based on percent of installed nameplate capacity lost after 10 years of operation. These values assume maintenance is performed as a part of normal operation. Flow battery degradation (VRB and ZnBr) can be mitigated to an extant through normal maintenance and chemistry refresh.

[5] Expected life in calendar years is given for the energy storage component of an ESS and is based on operation at 100% DOD, 25°C, 1C for the number of cycles shown. These values assume maintenance is performed as a part of normal operation. Full system life, including PCS and balance of plant equipment have been observed in range of 15-25 years, implying full replacement of energy storage system components.

[6] Discussion of the severity and risk of these effects are discussed in detail in section 3.8.

4 COST ESTIMATES AND TRENDS

In addition to the commercial and technical review, PacifiCorp requested DNV GL utilize industry experience, in-house data, and market research to the prepare capital and O&M cost estimates for each technology, expressed in mid-2016 dollars. Costs estimates are broken down as follow:

1. Energy Storage Equipment
2. Power Conversion Equipment
3. Power Control System
4. Balance of System
5. Installation
6. Fixed Operation and Maintenance

Each of these costs components are provided as a range covering currently observed industry estimates. In addition to current cost estimates, cost trends over 10 years will be provided as graphs demonstrating a breakdown of system costs in the requested components.

The capital cost for an installed energy storage system is calculated for a system by adding the costs of the energy storage equipment, power conversion equipment, power control system, balance of system, and the installation costs. Each of these categories is accounted for separately because they provide different functions or cost components and are priced based on different system ratings. System component costs based on the power capacity ratings are priced in $/kW, while component costs based on the energy capacity ratings, such as the DC energy storage system, are priced in $/kWh. A description of the system and project development elements included in each cost component is provided below, followed by a summary table of all system costs and graphs depicting 10-year cost trends of relevant components.

4.1 Energy Storage Equipment Costs

Energy storage equipment costs are inclusive of the DC battery system which includes the costs of the energy storage medium, such as Li-Ion battery cells or flow battery electrolyte, along with associated costs of assembling these components into a DC battery system. For Li-Ion systems, battery cells are arranged and connected into strings, modules, and packs which are then packaged into a DC system meeting the required power and energy specifications of the project. The DC system will include internal wiring, temperature and voltage monitoring equipment, and an associated battery management system responsible for managing low-level safety and performance of the DC battery system. For flow batteries, the DC system costs include electrolyte storage tanks, membrane power stacks and container costs for the system along with associated cycling pumps and battery management controls. Energy storage equipment costs are provided on a $/kWh basis which is most appropriate for quantifying the cost of an energy capacity constrained resource. The DC system cost trends are shown in Figure 3.

4.2 Power Conversion System Equipment Costs

Power conversion system (PCS) costs are inclusive of the cost of the inverter, packaging, container, and controls. Inverters employed in energy storage systems are more expensive than the grid-tied inverters widely deployed for solar PV generation, and differentiated by their bi-directional, 4-quadrant operational capabilities. The cost of the power conversion equipment is proportional to the power rating of the system and provided in $/kW. The PCS cost trends are shown in Figure 4.

4.3 Power Control System Costs

Unique to energy storage systems are the required high-level controllers being deployed to dispatch and operate the systems. With dispatch becoming an ever more important part of storage system design, controllers have to combine multiple functions – from forecasting the load, to understanding the tariff structure and factoring in the type of charge management required for a specific application and technology. The energy industry is currently seeing a number of software companies emerging which are focused solely on control and management of energy storage systems. This includes companies such as Geli, Greensmith, 1Energy Systems, and Intelligent Generation. System integrators and battery storage vendors themselves are also producing controls to operate their systems. These companies include storage and renewable energy companies such as Stem, Advanced Microgrid Systems, RES Americas and SolarCity, as well as established utility energy industry players such as General Electric, Schneider Electric, and ABB. For systems owned or operated by a utility, these controllers must additionally be integrated with utility monitoring and control systems such as Supervisory Control and Data Acquisition Systems (SCADA), Energy Management Systems (EMS), and Distribution Management Systems (DMS), among others. As more advanced applications are considered, such as the energy storage Virtual Power Plants (VPP) currently being considered at Duke Energy and Consolidated Edison, these control layers will become increasingly critical to the success of a given project. At present, the costs for the power control systems have been observed to vary widely and are provided here based on the power capacity of a plant as $/kW. The trend graphs show conservative reduction in costs over ten years; as controls grow more prevalent and efficiencies are found, the control requirements and designs will likely increase in intricacy. The controls cost trends are shown in Figure 5.

4.4 Balance of System

The equipment cost of the storage system will further depend on ancillary equipment necessary for the full storage system interconnection. The balance of system cost here includes wiring, interconnecting transformer, and additional ancillary equipment. For some technologies, this may include the cost of centralized HVAC systems which is required for maintaining acceptable environmental equipment. The balance of system cost is proportional to the power rating of the system and provided in $/kW. The balance of system cost trends are shown in Figure 6.

4.5 Installation

Installation cost accounts for associated Engineer-Procure-Construct (EPC) costs inclusive of installation parts and labor, permitting, site design, and procurement and transportation of all equipment.

4.6 Fixed O&M

Yearly operation and maintenance costs is currently a debated issue for storage projects employing the technologies discussed in this report, as the industry does not yet have longer term operating experience with the technologies. O&M requirements for Li-Ion systems are generally assumed to be light and include maintenance of HVAC system, tightening of mechanical and electrical connections, cabinet touch up painting and cleaning, and landscaping maintenance. Further, the majority of projects being developed for utilities applications include some type of capacity maintenance agreement. This capacity maintenance agreement guarantees some fixed level of available energy capacity in the system over the term of the project. The cost of the capacity maintenance agreement can be accounted for in the Fixed O&M or as part of the upfront capital costs of the system. For flow battery systems, maintenance services include power stack and pump replacements, tightening of plumbing fixtures, tightening of mechanical and electrical connections, as well as semi-annual chemistry refresh and full discharge cycles to refresh capacity. Further, while many technologies are developing third party training and qualification programs for O&M services, at present many of vendors technology companies themselves are providing O&M services.

Variable O&M costs, while typical to conventional generation sources, are generally assumed negligible for most energy storage systems. It is noted that systems operators can use a variable O&M cost as one means of including the capacity degradation within an energy storage dispatch model. However, there is not currently a uniform or industry acceptable methodology for quantifying variable O&M in this manner. For the purposes of this report, energy storage variable O&M is considered to be negligible.

4.7 Total System Cost Estimates

System costs are based on DNV GL's industry experience, internal research, and publicly available data. These costs are provided in 2016 dollars. This information is given in further context in Section 4.9, which provides calculations for an example installation.

Table 9 Energy storage system cost estimates[1]

Cost Parameter/ Technology	Li-Ion NCM	Li-Ion $LiFePO_4$	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air
Energy storage equipment cost ($/kWh)[2]	$325-$450	$350-$525	$500-$850	$800-$1000	$500-$700	$525-$725	$200-$400
Power conversion system equipment cost ($/kW)[3]	$350-$500	$350-$500	$350-$500	$500-$750	$500-$750	$500-$750	$350-$500
Power control system cost ($/kW)[4]	$80-$120	$80-$120	$80-$120	$80-$120	$100-$140	$100-$140	$100-$140
Balance of system ($/kW)[5]	$80-$100	$80-$100	$80-$100	$100-$125	$100-$125	$100-$125	$80-$100
Installation ($/kWh)[6]	$120-$180	$120-$180	$120-$180	$140-$200	$140-$200	$140-$200	$120-$180
Fixed O&M cost ($/kW yr)[7]	$6-$11	$6-$11	$6-$11	$7-$12	$7-$12	$7-$12	$6 - $12

---

[1] All cost estimates provided in mid-2016 dollars

[2] Energy storage equipment includes the full DC battery system which includes the costs of the energy storage medium, such as Li-Ion battery cells or flow battery electrolyte, internal wiring and connections, packaging and containers, and battery management system (BMS).

[3] PCS equipment includes the inverter, packaging, container and inverter controls.

[4] Control system includes supervisory control software, along with the controller and communications hardware required to dispatch and operate energy storage systems.

[5] Balance of system includes site wiring, interconnecting transformer, and additional ancillary equipment.

[6] Installation includes Engineer-Procure-Construct (EPC) costs inclusive of installation parts and labor, permitting, site design, procurement and transportation of equipment.

[7] Fixed O&M costs are provided as real levelized dollars with assumed 20 year project life.

4.8 Example Installed Cost Calculation

Table 10 below shows an example calculation to estimate the installed cost of 10 MW, 20 MWh NCM Li-Ion energy storage system using the cost estimates provided in Table 9. The provided cost estimates result in a low side estimate of $14,000,000 and a high side estimate of $19,800,000 for the system, with component sub-total costs based on the power or energy rating of the system.

Table 10 Example Installed Capital Cost Calculation for 10 MW, 20 MWh NCM Li-Ion Energy Storage System

Cost Parameter	ESS Size	Component Unit Cost Low	Component Unit Cost High	Component Sub-Total Low	Component Sub-Total High
Energy storage equipment cost ($/kWh)	20,000 kWh	$325/kWh	$450/kWh	$6,500,000	$9,000,000
Power conversion equipment cost ($/kW)	10,000 kW	$350/kW	$500/kW	$3,500,000	$5,000,000
Power control system cost ($/kW)	10,000 kW	$80/kW	$120/kW	$800,000	$1,200,000
Balance of system ($/kW)	10,000 kW	$80/kW	$100/kW	$800,000	$1,000,000
Installation ($/kWh)	20,000 kWh	$120/kWh	$180/kWh	$2,400,000	$3,600,000
				Low Total	**High Total**
				$14,000,000	$19,800,000
				Average $16,900,000	

4.9 System 10-Year Cost Trends

As referenced in sections 4.1 to 4.4, graphs depicting 10-year future cost trends are shown below. Cost trends are based on currently available industry projections, as well as DNV GL's interaction with industry partners, and basic cost reduction assumptions, as well as the information discussed in the relevant section, 4.1 through 4.4. These trends are provided for the period from 2016 to 2026.

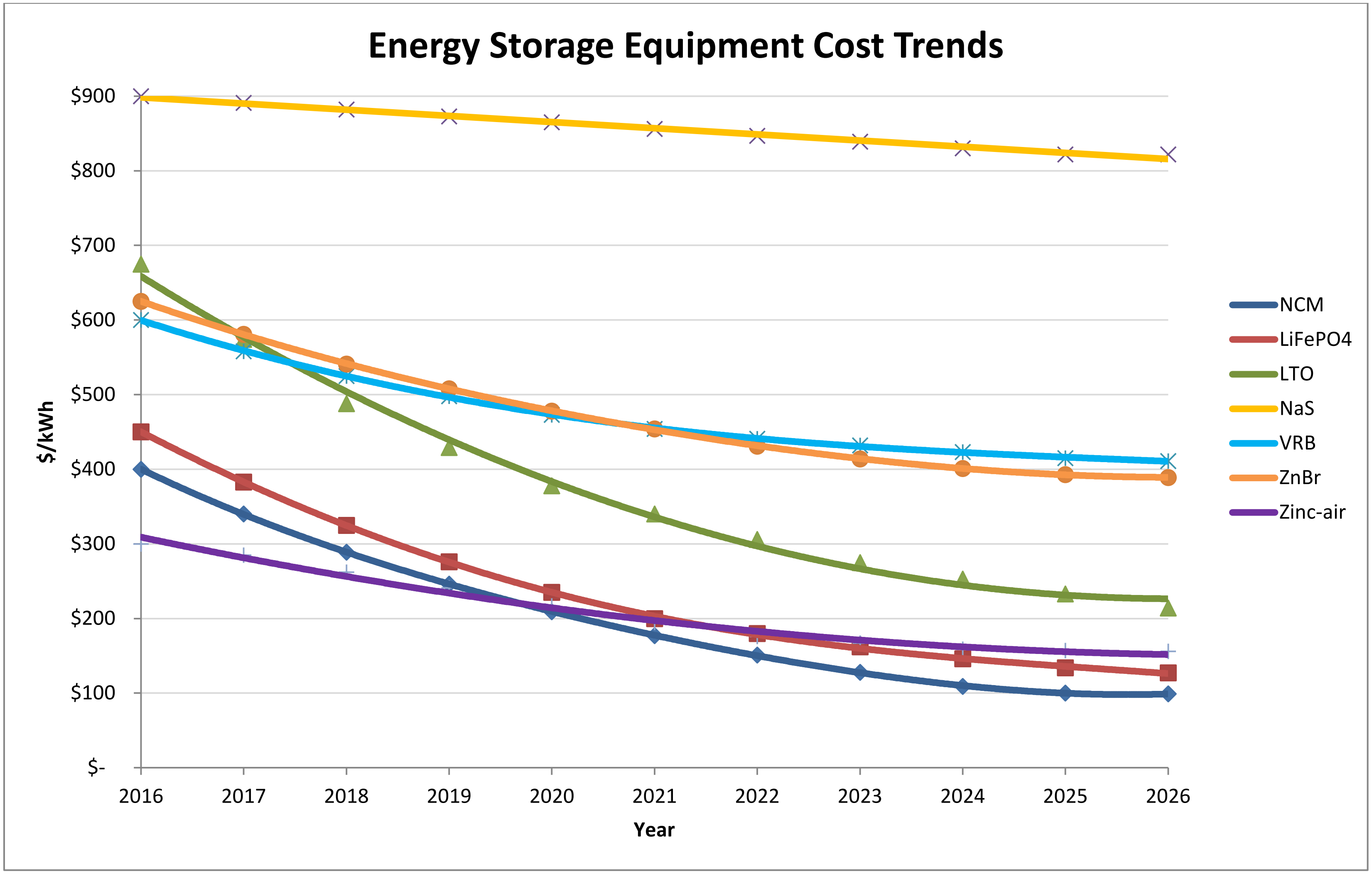

Figure 3 Projected Energy Storage Equipment Cost Trends for Various Technologies, From 2016 to 2026

PCS cost trends are shown in Figure 4. The PCS cost trends mirror each other across two technology groupings. The PCS costs for all Li-ion and Zinc-air technologies are expected to follow similar trends as they are pulling from the same manufacturers utilizing more mature PCS architectures. PCS costs for flow batteries, while currently offered at a higher price point, are expected to converge to similar costs as the Li-ion over time as these technologies mature and gain additional commercial adoption. While NAS is a more mature technology, current PCS costs are above those of Li-ion technologies with future cost reductions expected to benefit from increased adoption of flow battery PCS architectures.

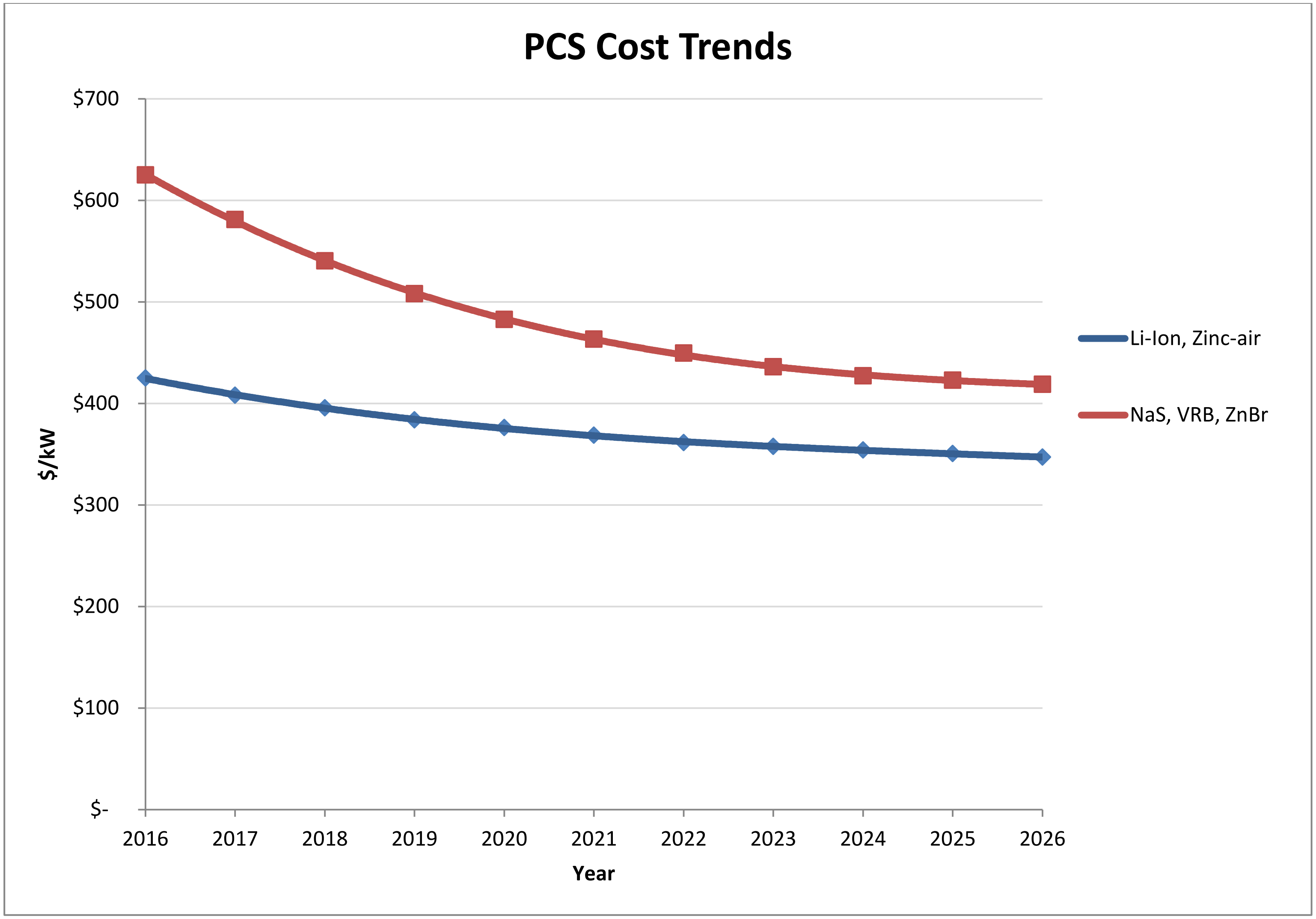

Figure 4 Projected PCS Cost Trends for Various Technologies, From 2016 to 2026

Controls cost reductions, shown in Figure 5, are expected to be relatively uniform across all technologies. While competition in the space is expected to continue, the need for increasingly sophisticated controllers which interact with both utility and distributed behind-the-meter storage assets are expected to result in modest cost reductions over time, converging to a relatively uniform price across technologies.

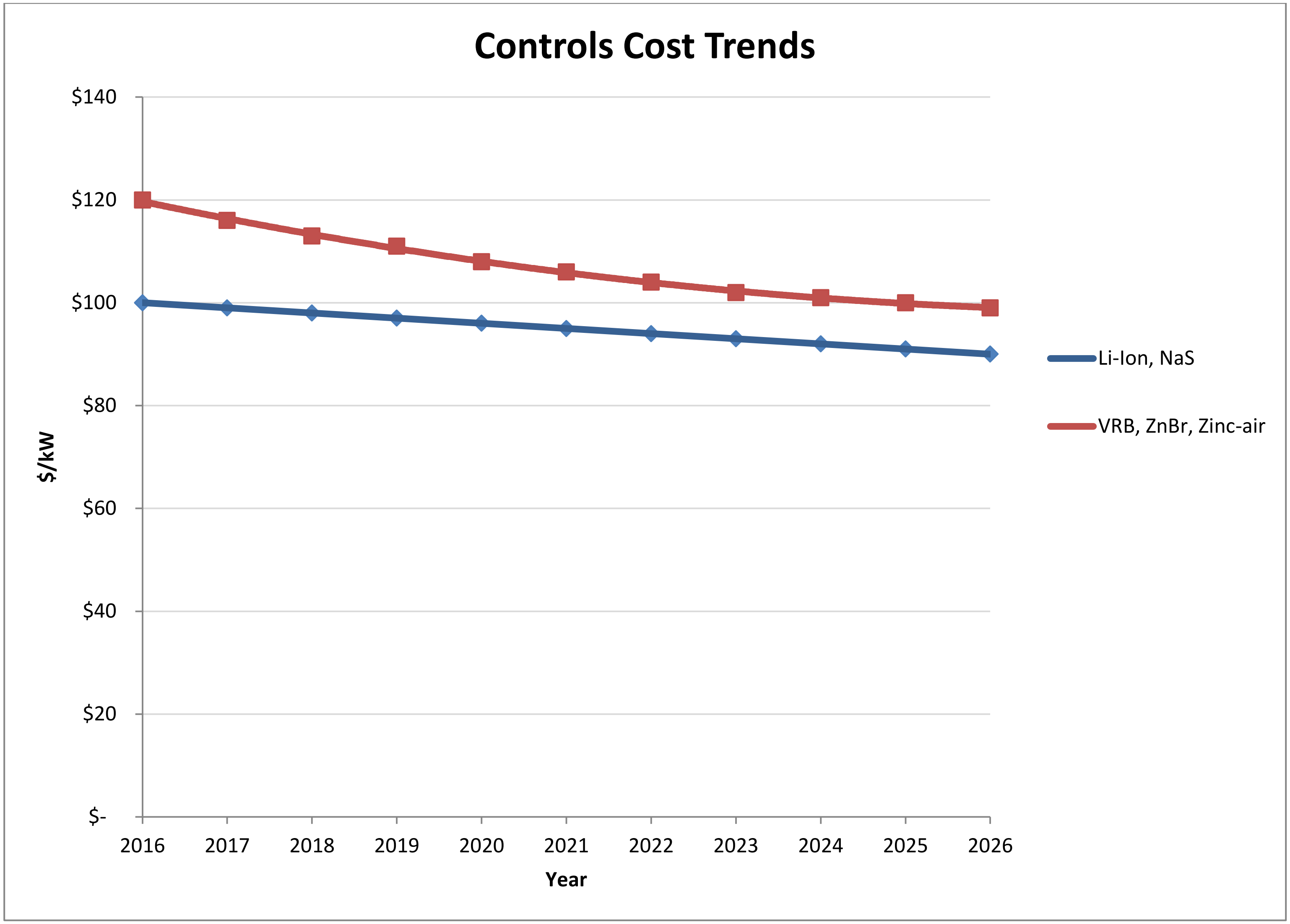

Figure 5 Projected Controls Cost Trends for Various Technologies, From 2016 to 2026

Balance of system costs, shown in Figure 6, is expected to fall dramatically over the next 5 years with continued modest gains through 2026. Cost reductions are expected as project developers gain experience deploying these technologies and system interconnection requirements become more uniform for storage technologies. Li-ion technologies and Zinc-air follow similar trends due to similarities in construction and balance of plant requirements, while reductions for flow batteries and NaS systems are expected to follow similar patterns.

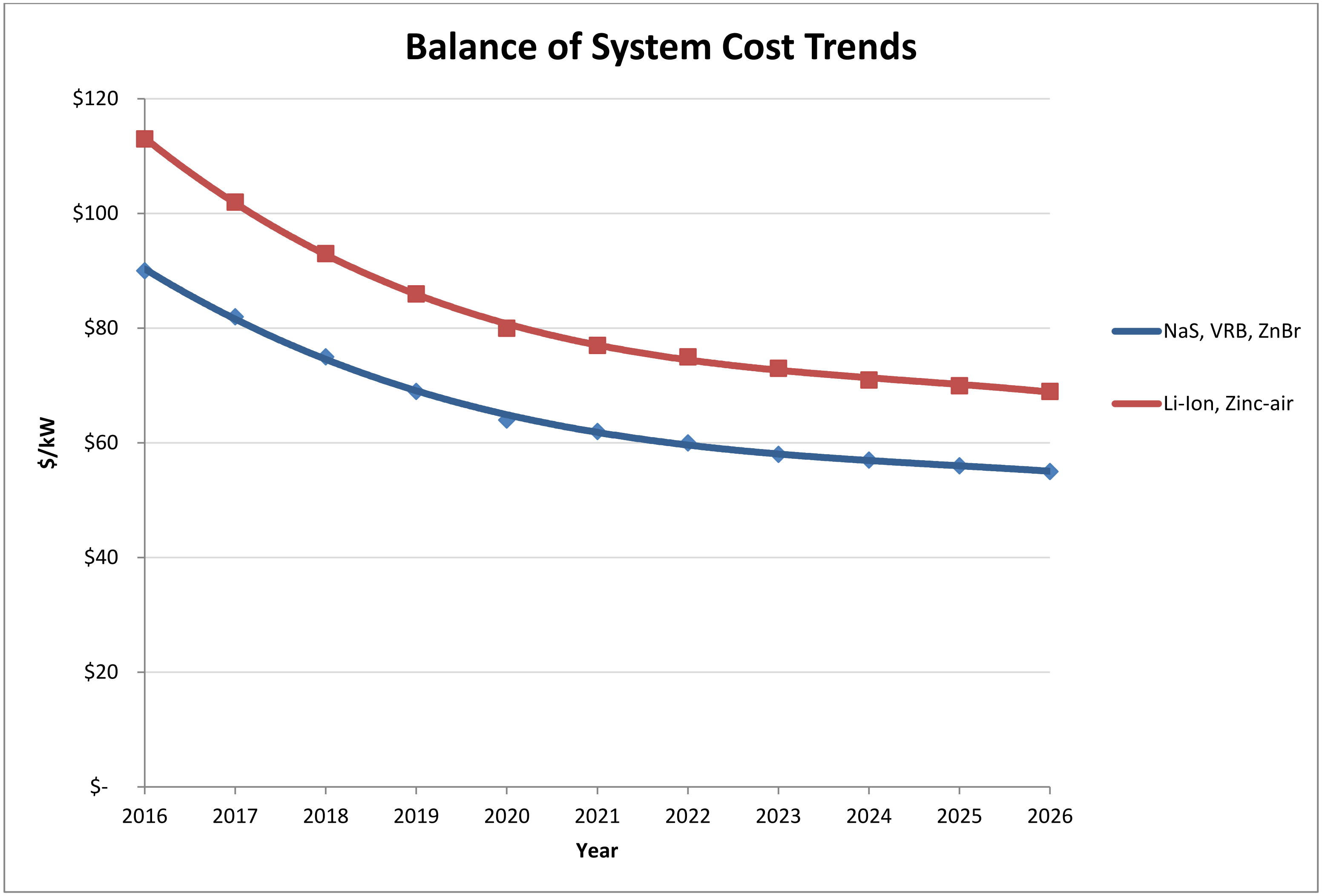

Figure 6 Projected Balance of System Cost Trends for Various Technologies, From 2016 to 2026

5 UTILITY APPLICATIONS AND VALUE STREAM

In this chapter, an application-technology ranking is provided which is intended to indicate the applicability of each technology and their relative potential for generating economic value for at least one of eight (8) benefit cases within PacifiCorp's service territory over the next 20 years. This assessment considers both the likelihood that a particular storage application is relevant to the current PacifiCorp market, as well as the appropriateness of a specific technology to serve the needs of that application. The eight applications identified by PacifiCorp for considerations are as follows:

1. Electric Energy Time Shift
2. Electric Supply Capacity
3. Regulation
4. Spinning, Non-Spinning, and Supplemental Reserves
5. Voltage Support
6. Load Following/Ramping Support for Renewables
7. Frequency Response
8. T&D Congestion Relief

In this chapter, definitions of each application will be provided, followed by an overview of regulatory concerns specific to PacifiCorp territory providing an assessment of both planned regulatory initiatives and local network and market conditions in the PacifiCorp region. These will be reviewed specifically as they relate to energy storage potential. Finally, results of the assessment are provided indicating the applicability of each technology and the relative potential for generating economic value for at least one of the benefit cases within PacifiCorp's service territory over the next 20 years. These rankings are provided on a 1 to 10 scale.

At PacifiCorp's request, this report additionally includes an assessment on applicability of each technology and the relative potential for generating economic value under an alternative market scenario with PacifiCorp operating under market rules similar to those implemented in California ISO (CAISO).

5.1 Considered Applications

DNV GL reviewed applications for energy storage systems based on the regulations and standards in place in PacifiCorp territories, including the availability of financial resources to support energy storage development, as well as the general expansion of demand. Descriptions of these applications are provided below, based on the Department of Energy's Energy Storage Handbook and DNV GL's recommended practice guide, GRIDSTOR.

- **Electric energy time shift –** Energy storage systems operating within an electrical energy time-shift application are charged with inexpensive electrical energy and discharged when prices for electricity are high. On a shorter timescale, energy storage systems can provide a similar time-shift duty by storing excess energy production from, for example, renewable energy sources with a variable energy production, as this might otherwise be curtailed. If the difference in energy prices is the main driver and energy is stored to compensate for (for example) diurnal energy consumption patterns, this application is often referred to as arbitrage.

Storing energy (i.e. in charge mode) at moments of peak power to prevent curtailment or overload is a form of peak shaving. Peak shaving can be applied for peak generation and also – in discharge mode – for peak demand (e.g. in cases of imminent overload). Peak shaving implicates that the energy charged or discharged is discharged or recharged, respectively, at a later stage. Therefore, peak shaving is a form of the energy time-shift application.

An energy storage system used for energy time-shift could be located at or near the energy generation site or in other parts of the grid, including at or near loads. When the energy storage system used for time-shift is located at or near loads, the low-value charging power is transmitted during off-peak times.

Important for an energy storage system operating in this application are the variable operating costs (non-energy related), the storage round-trip efficiency and the storage performance decline as it is being used (i.e. ageing effects).

- **Electric Supply Capacity -** An energy storage system could be used to defer or reduce the need to buy new central station generation capacity and/or purchase capacity in the wholesale electricity market. In this application, the energy storage system supplies part of the peak capacity when the demand is high, thus relieving the generator by limiting the required capacity peak. Following a (partial) discharge, the energy storage system is recharged when the demand is lower. The power supply capacity application is a form of generation peak shaving, therefore a form of electrical energy time-shift. An energy storage system participating in the electrical capacity market may be subject to restrictions/requirements of this market, for example required availability during some periods.
- **Regulation** - Regulation is used to reconcile momentary differences between demand and generation inside a control area or momentary deviations in interchange flows between control areas, caused by fluctuations in generation and loads. In other words, this is a power balancing application. Conventional power plants are often less suited for this application, where rapid changes in power output could incur significant wear and tear. Energy storage systems with a rapid-response characteristic are suitable for operation in a regulation application.

  Energy storage used in regulation applications should have access to and be able to respond to the area control error (ACE) signal (where applicable), which may require a response time of fewer than five seconds. Furthermore, energy storage used in regulation applications should be reliable with a high quality, stable (power) output characteristics.
- **Spinning, Non-spinning, and supplemental reserves** - A certain reserve capacity is usually available when operating an electrical power system. This reserve capacity can be called upon in case some generation capacity becomes unavailable unexpectedly, thus ensuring system operation and availability. A subdivision can be made based on how quickly a reserve capacity is available:
  - Spinning reserve is reserve capacity connected and synchronized with the grid and can respond to compensate for generation or transmission outages. In remote grids spinning reserve is mainly present to cover for volatile consumption. In case a reserve is used to maintain system frequency, the reserve should be able to respond quickly. Spinning reserves are the first type of backup that is used when a power shortage occurs.

  - Non-spinning reserve is connected but not synchronized with the grid and usually available within 10 minutes. Examples are offline generation capacity or a block of interruptible loads.
  - Supplemental reserve is available within one hour and is usually a backup for spinning and non-spinning reserves. Supplemental reserves are used after all spinning reserves are online.

  Stored energy reserves are usually charged energy backups that have to be available for discharge when required to ensure grid stability. An example of a spinning reserve is an uninterruptible power supply (UPS) system, which can provide nearly instantaneous power in the event of a power interruption or a protection from a sudden power surge. Large UPS systems can sometimes maintain a whole local grid in case of a power outage; this application is called island operation.

- **Voltage support** - Grid operators are required to maintain the grid voltage within specified limits. This usually requires management of reactive power (but also active power, e.g. in the LV grid), therefore also referred to as Volt/VAr support. Voltage support is especially valuable during peak load hours when distribution lines and transformers are the most stressed. An application of an energy storage system could be to serve as a source or sink of the reactive power. These energy storage systems could be placed strategically at central or distributed locations.

  Voltage support typically is a local issue at low voltage (LV), medium voltage (MV) or high voltage (HV) level. The distributed placement of energy storage systems allows for voltage support near large loads within the grid. Voltage support can also be provided by operation of generators, loads, and other devices. A possible advantage of energy storage systems over these other systems is that energy storage systems are available to the grid even when not generating or demanding power.

  Note that no (or low) real power is required from an energy storage system operating within a voltage/VAr support application, so cycles per year are not applicable for this application and storage system size is indicated in MVAr rather than MW. The converter needs to be capable of operating at a non-unity power factor in order to source or sink reactive power. The nominal duration needed for voltage support is estimated to be 30 minutes, which allows the grid time to stabilize and/or begin orderly load shedding.

- **Load following / ramping support for renewables** - Load following is one of the ancillary services required to operate a stable electricity grid. Energy storage systems used in load following applications are used to supply (discharge) or absorb (charge) power to compensate for load variations. Therefore, this is a power balancing application. In general, the load variations should stay within certain limits for the rate of change, or ramp rate. Therefore, this application is a form of ramp rate control. The same holds for generation variations, which is very applicable to renewable energy sources. Due to the intermittency of renewables production, having a storage device with several hour durations can provide a large advantage to renewable efficiencies, easing of grid impacts, and renewable production. Conventional power generation can also operate with a load following (or RES compensating) application. Within these applications, the benefits of energy storage systems over conventional power generation are that:
  - most systems can operate at partial load with relatively modest performance penalties
  - most systems can respond quickly with respect to a varying load

  - systems are suitable for both load following down (as the load decreases) and load following up (as the load increases) by either charging or discharging.

  Note that an energy storage system operating with a load-following or ramp rate control application within a market area needs to purchase (when charging) or sell (when discharging) energy at the going wholesale price. As such the energy storage efficiency is important when determining the value of the load following application.

- **Frequency response -** Synthetic inertia behavior is the increase or decrease in power output proportional to the change of grid frequency; physical inertia is provided by conventional power generators, i.e. synchronous generators. If the total amount of physical inertia decreases in a power system, the amount of synthetic inertia should be increased to maintain a certain minimum amount of total inertia. Many grid-connected renewable energy sources do not provide additional synthetic inertia. Therefore, larger grid frequency deviations may occur as the total inertia in the power system decreases. Keeping track of the total system inertia could be a future task of ISOs.

  Some energy storage systems add synthetic inertia to the system and can thereby be used to compensate for fluctuations in the grid frequency. Causes of fluctuations could be the loss of a generation unit or a transmission line (causing a sudden power imbalance). Various generator response actions are needed to counteract a sudden frequency deviation, often within seconds.

  Energy storage within a frequency response application could support the grid operator and thereby assure a smoother transition from an upset period to normal operation. For a frequency response type of application, the energy storage is required to provide support within milliseconds. Storage helps to maintain the grid frequency and to comply with Control Performance Standards (CPSs) 1 and 2 of the North American Reliability Council (NERC). Aside from this quick response, the frequency response application is similar to load following and regulation, as described previously.

- **Transmission and distribution congestion relief** – During moments of peak demand, it may occur that the available transmission lines do not provide enough capacity to deliver the least-cost energy to some or all of the connected loads. This transmission congestion may increase the energy cost.

  Energy storage systems at strategic positions within the electricity grid help to avoid congestion-related costs and charges. The energy storage system can be charged when there is no congestion and discharged when congestion occurs. Energy storage can, in this way, additionally delay and sometimes avoid the need to upgrade a transmission or distribution system.

5.2 PacifiCorp Territory Regulatory Concerns and Application Drivers

Currently, the largest drivers of energy storage deployment nationally have been a direct result of state and federal level regulatory actions encouraging or mandating procurement and installation of energy storage technologies. Much of the regulatory action has come as follow-up initiatives to more aggressive renewable portfolio standards (RPS) with storage seen as an enabling technology which can mitigate issues associated with higher level of renewable penetration. To a lesser extent, regulatory action around energy security has additionally spurred some development opportunities for energy storage as a reliability resource.

Additionally, a small set of cost-effective applications in select markets, such as frequency regulation, supply capacity, and transmission and distribution deferral have been driving installations. Where market operators have permitted energy storage systems to obtain capacity credits, larger-scale energy storage systems have been justified financially based on the capacity payments over 10-20 year contracts. These structures have additionally supported storage applications for transmission and distribution (T&D) congestion relief. Finally, markets which have developed mechanisms to compensate fast regulation or pay-for-performance market products, have allowed for an opportunity for battery energy storage systems which can obtain high-performance scores in these markets.

Of note, the growth of commercial and industrial behind-the-meter storage installations has been driven in select markets where customers are exposed to high retail rates, and more importantly, high monthly peak demand charges. At the residential level, in select markets where net-metering rules are unfavorable to customers installing solar generation, and high retail energy rates exist, residential self-supply is also seen as a cost-effective energy storage application.

Based on these current trends, storage applications related to capacity such as supply capacity and T&D congestion relief, as well as applications supporting renewable integration, such as renewable time shifting, regulation, and load following, and to a lesser extent, frequency response and voltage support, are likely to be the more likely application for storage over the next 20 years. The relative ranking of these applications is more nuanced and requires a look at the policies in-place or planned for PacifiCorp's service territory.

The PacifiCorp territory is comprised of regions throughout California, Oregon, and Washington (under PacificPower), and Idaho, Utah, and Wyoming (under Rocky Mountain Power). Each state observes a variety of regulations relating to energy security, distribution, and storage. Further, the federal government provides additional regulation that must be observed. At both the state and federal level, incentives are additionally provided in some cases.

The PacificPower region, in particular, has a well-developed set of regulations and incentives already in place. Oregon, Washington, and California all have Renewable Portfolio Standards (RPS) as well as other legislation that encourages utility pursuit of clean energy and potentially energy storage systems.

Oregon's most influential energy storage-specific legislation that passed in 2015, HB 2193, directs the state's electric utility companies to procure one or more energy storage systems capable of storing a specified energy capacity by 2020, allowing them to recover all costs through electrical rates. Additionally, SB 1547 passed in 2016, requiring, among other things, an RPS which would amount to 50% renewables for PacifiCorp by 2040, and the elimination of coal-generated energy utilization by 2030. This legislation will put additional pressure for energy storage to support the growing renewables portfolio.

In the state of Washington, several bills have been passed that create a supportive infrastructure for energy storage. For example, HB 1897 established a program in support of R&D to develop next generation clean energy technology sustainably; HB 1296 legislated that an IRP is required to include energy storage; SB 5025 amended laws to support the meeting of renewable energy targets by utilities and minimum standards for energy efficient buildings; and HB 1895, a bill currently pending a hearing, if passed would promote the deployment of clean distributed energy, and prioritizes deployment of smart grids and microgrids. Further, the Energy Independence Act, or I-937, specifically requires a 15% RPS by 2020. The pursuit of these standards has recently been supported by HB 1115. This legislation sets aside $44 million in grants that are to be directed towards renewables advancement and technology, specifically including energy storage.

California has for many years been a leading state in the pursuit of clean energy. Many pieces of legislation support renewable technology infrastructure, especially focused on the causes of reducing emissions and improving energy resiliency. For instance, SB 1358 specifies emission performance standards and SB 350 requires an increase in the amount of electricity generated and sold from renewable energy resources in order to strengthen the diversity and resilience of the electrical system. California further passed SB 83, requiring public utilities to enact net metering tariffs to enhance diversification and reliability of the state's energy resources. Recently, AB 1530 states that clean distributed energy must be deployed by utilities, and prioritizes deployment of smart grids and microgrids. Specifically, California utilities must meet an RPS of 50% by 2030, with intermediate goals, as initiated by AB 327 and SB 350, noted previously.

In contrast, the Rocky Mountain Power region does not have as many or as specific regulation or support. While Utah provides a renewable energy target of 20% by 2025, but not an RPS, neither Idaho nor Wyoming has any RPS or voluntary renewable goals. There are, however, several pieces of legislation that support, directly or indirectly, energy storage, chiefly as a method to support reliability and resiliency.

Utah leads the way with SB 0115, called the Sustainable Transportation and Energy Plan (STEP) Act. This bill allows for the Public Service Commission to authorize the implementation of tariffs by utilities in order to establish electric efficiency technology programs, allows the utility to provide incentives for air quality improvement technology and electric vehicle infrastructure development, and provides support for clean energy programs implemented by utilities. PacifiCorp has already reacted to this legislation with their STEP initiative. This includes the STEP Pilot programs, 5-year programs providing funding to, among other projects, battery storage development. Additionally, PacifiCorp has applied to the Public Service Commission to offer large customers the option to participate in a Renewable Energy Tariff, paying directly to get part or all of their electricity from a specific renewable project. Further, Utah has passed SB 280, which promotes the development of diverse energy resources, including nonrenewable and renewable resources, nuclear, and alternative transportation fuels. This distributed generation policy's focus is to promote resiliency and reliability of the grid, and will likely naturally lead to an investigation of energy storage procurement and integration.

Idaho passed HB 189, which removed all property taxes on renewable generation sites, in favor of a 3-3.5% tax on generation. Otherwise, although Idaho has neither net metering law nor RPS, it does offer tax credits for renewable energy.

Wyoming, meanwhile, has no net metering law and provides no credits or exemptions for clean distributed energy resources. Further, Wyoming taxes wind generation and is currently considering further raising those taxes. As noted previously, Wyoming has no RPS.

Finally, the Federal Government has put in place regulations to encourage renewables and energy storage. Widely known and utilized is the Investment Tax Credit provided by the Federal government. This 30% direct tax credit was extended until 2019, reduced stepwise annually after that, to 26% in 2020, 22% in 2021, and 10% in 2022, before ending. As to standards, the Clean Power Plan, as regulated by the EPA, assigns each state an emissions reduction target by 2030, contributing to a 32% reduction nationwide. Specific to PacifiCorp, Wyoming, Utah, and Washington have aggressive reduction targets, above 31%, while California, Oregon, and Idaho have reduction targets below 20%, in comparison with 2012 levels. These targets are based on, among other things, generation activity, as well as actions already taken to reduce emissions. States are required to submit a plan for compliance by September 2016, or be subject to a federally developed plan, both likely to directly affect utilities. Although there is some Congressional action to block these requirements, none has currently passed.

5.3 Application Ranking Methodology and Results

DNV GL developed a ranking system for the various applications that battery energy storage systems may be utilized for within PacifiCorp territory. Within this ranking system, information about each technology is used to ascertain its appropriateness for a particular application. The battery type's typical size, technology maturity level, market penetration, as well as technical parameters and various costs influenced these rankings.

First, each application was defined by its requirements for power, energy, cycling, and response time. These Application Requirements were scored on a comparative scale. For instance, in the case of the application of Electric Energy Time Shift, the energy capacity of the system is paramount and thus ranked highly. Alternatively, in the case of the application for Frequency Response, the energy capacity of the system is of lesser importance while response time and power capability are the prioritized requirements. Each technology was then defined by its capabilities to meet these requirements for power, energy, cycling, and response time. These technology capabilities were similarly scored on a comparative scale. For instance, Li-ion technology provides nearly instantaneous response time and was thus ranked highest in that parameter. Flow batteries, on the other hand, scored highest for cycling as they are capable of fully discharging daily with less impact on lifetime and degradation. A Technology Maturity score was then also assigned to technology each based on its current stage of commercialization and scale of field deployments.

The Application Requirements and Technology Capability scores were then compared, defining how well-matched a specific technology was for a given application. For instance, if an application required fast response time, the technologies that provide a fast response time would score highest. Scores across each property were then averaged to provide a Technology Application score for each technology providing each application.

A PacifiCorp Application Need score was then assigned to each application based on the high-level cost-effectiveness and regulatory analysis of the PacifiCorp territory. Based on current PacifiCorp market scenario, storage applications with high value that are not dependent on market-related rule changes, such as T&D congestion relief, are expected to be the most likely candidates for PacifiCorp to deploy energy storage. Additionally, as noted in the review, renewable portfolio standards across the PacifiCorp region will drive some renewable integration applications such as renewable time shifting, regulation, and load following. Faster regulation applications such frequency response and voltage support are likely to be lower value applications. A second set of Scores for PacifiCorp Application Need scores were provided for the alternative market scenario with PacifiCorp operating under market rules similar to those implemented in California ISO (CAISO). For this scenario, CAISO market rules which directly allow storage to qualify for supply capacity credit increased this application score. Also, further developed fast regulation and emerging ramping market products increased the PacifiCorp Application Need score for frequency regulation and applications tied to renewable integration.

Finally, PacifiCorp application rankings were computed for each application and technology under each market rules scenarios. The final rankings were computed by taking the average score over the Technology Application score, the Technology Maturity Score, and the PacifiCorp Need score. This methodology resulted in Table 11 and Table 12.

Table 11 Application Rankings in Current Market Rules Scenario

Application	Current Market Scenario						
	Li-Ion NCM	Li-Ion LiFePO4	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air
Electric Energy Time Shift	9	8	8	9	8	8	7
Electric Supply Capacity	9	9	9	9	8	8	7
Regulation	9	9	9	9	8	8	7
Spinning, Non-spin, Supplemental reserves	8	8	9	8	8	8	7
Voltage support	7	8	8	7	6	6	6
Load following / ramping support for renewables	8	8	9	8	8	8	7
Frequency response	7	7	8	7	6	6	5
Transmission and distribution congestion relief	9	9	9	9	9	9	8

Table 12 Application Rankings for CAISO Market Rules Scenario

Application	CAISO Market Scenario						
	Li-Ion NCM	Li-Ion LiFePO4	Li-Ion LTO	NaS	VRB	ZnBr	Zinc-air
Electric Energy Time Shift	9	9	9	9	9	9	7
Electric Supply Capacity	9	9	9	9	9	9	8
Regulation	9	9	9	9	8	8	7
Spinning, Non-spin, Supplemental reserves	9	9	9	9	8	8	7
Voltage support	7	8	8	7	6	6	6
Load following / ramping support for renewables	9	9	9	9	8	8	7
Frequency response	7	7	8	7	6	6	5
Transmission and distribution congestion relief	9	9	9	9	9	9	8

6 CONCLUSION

The data from this study is intended to support PacifiCorp in making decisions regarding energy storage procurement and grid integration to support their 2017 IRP, giving confidence in the current state of the industry while providing insight into what trends and regulations which will prevail in the future. Further, this study is intended to provide general guidance on the appropriateness of each presented technology for specific applications, as needs and requirements vary across each PacifiCorp region. The inclusion of battery energy storage, particularly when paired with other distributed energy resources, will allow PacifiCorp to comply with emerging energy regulations while also providing greater flexibility, resiliency, and efficiency in the allocation of resources.

ABOUT DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter, and greener.