An Alaska case study: Energy storage technologies

Jeremy VanderMeer, Marc Mueller-Stoffels, and Erin Whitney
Alaska Center for Energy and Power, University of Alaska Fairbanks, P.O. Box 755910, Fairbanks, Alaska 99775-5910, USA

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In the analysis of energy storage systems (ESSs) in Alaska, the most significant trend in the data considered is the increased variance in costs with time. Thus, more options are now available for ESS with "low cost per kW/high cost per kW h" and vice versa, indicating a greater variety of specialized ESS for targeted applications. The data analyzed do not show any difference in the cost of energy storage in Alaska compared to such costs in the rest of the nation or world. Alaska has had relatively few energy storage technology failures, and most that occurred were caused by improper operation. It is often difficult to justify energy storage economically based on fuel savings alone. Significant work remains to quantify other possible cost savings afforded by energy storage, such as reduced fuel consumption and stress on a diesel generator by smoothing out the load. The lack of standardization and quantification of costs and benefits is the main barrier to determining the economic potential for implementation of energy storage in Alaska. In addition, communities in Alaska often wish to avoid ESS that uses hazardous materials since each community will eventually have to deal with disposal issues. *Published by AIP Publishing.* https://doi.org/10.1063/1.4986580

INTRODUCTION

Since the discovery of electricity, humans have sought effective methods to store that energy for use on demand. Energy storage systems (ESSs) provide a technological approach to managing power supply to create a more resilient energy infrastructure. In this paper, ESS refers to systems that store electrical energy (either chemical, mechanical, or electrical) and later return it to the grid. There are 514 grid-connected ESS installations in the United States, totaling over 24 GW of power capacity. According to the U.S. Department of Energy (U.S. DOE, 2017), 159 new ESS projects have been announced or contracted, which will increase grid-connected energy storage by 7.2 GW.

Remote microgrids are not connected to a larger electrical grid. This means that they must generate all electricity that is consumed within the grid. In Alaska, remote microgrids are small, which means there are relatively few electrical loads in a system and thus a high level of stochasticity in the total microgrid electrical load. Adding high penetrations of stochastic renewable energy makes it increasingly difficult to match generation with demand. Energy storage systems offer an attractive solution to this challenge. Alaska currently has eight grid-connected ESS installations totaling 61 MW, with one project totaling 0.32 MW currently contracted (U.S. DOE, 2017).

Energy storage systems can be divided into the energy storage unit and the power conditioning system, as shown in Fig. 1. The energy storage unit determines the amount of energy that can be stored, or the energy capacity, in kilowatt-hours. The power conditioning system is the interface between the grid and the energy storage unit and controls charging and discharging. Thus, the power conditioning system is largely responsible for the power in kilowatts of ESS.

This review of ESS in Alaska is a result of Alaska Senate Bill (SB) 138. In this bill, the Alaska State Legislature created an uncodified section of law entitled "Plan and Recommendations to the Legislature on Infrastructure Needed to Deliver Affordable Energy of the State to Areas That Do Not Have Direct Access to a [proposed] North Slope Natural Gas Pipeline." To support the Alaska Energy Authority (AEA) in its development of an affordable energy strategy for Alaska, the Alaska Center for Energy and Power (ACEP) contracted with AEA to document technology development needs specific to the state with regard to renewable

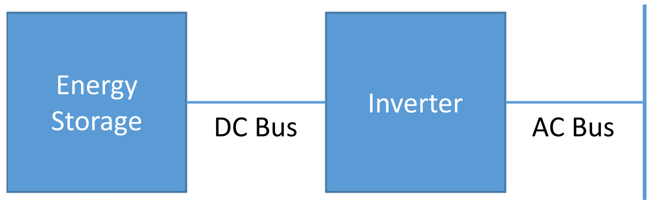

FIG. 1. A basic energy storage system contains an energy storage unit and a power conditioning system; in this case, the energy storage unit operates with a DC voltage and an inverter is used to convert the DC power into AC on the distribution or transmission grid. The inverter will also need to be able to act as a rectifier and convert AC power into DC to charge the energy storage unit.

and sustainable energy technologies. The intention was to determine what targeted, energy technology development solutions could be implemented in Alaska to make energy more affordable in the Alaska Affordable Energy Study area. While the focus was on technology research solutions, other factors such as logistics, labor, and training were also addressed. Drafts of technology reviews were vetted by expert roundtables in late February and early March 2016.

These reviews are not meant to be exhaustive discussions of energy technologies in Alaska or proper designs for each technology, and they should not be used as guides for the choice and installation of specific systems. As such, not all possible issues with power production and each technology are addressed. Data for each technology were collected from surveys and publically available databases. Only completed projects, or projects with clearly reported data, were included in each technology analysis. These distinctions and descriptions of data sources are included in each technology review.

METHODS

Deployment of ESS is still nascent in Alaska, with a few exceptions. Thus, the dataset developed from AEA Renewable Energy Fund (REF) applications has been supplemented with data from the U.S. DOE Global Energy Storage Database. The U.S. DOE database captures installation data worldwide from Sandia National Laboratory's energy storage reports (several editions) and data collected by ACEP through personal communication with energy storage developers and utilities. Data sources are detailed in Appendix A.

Lead-acid, advanced lead-acid (Xtreme Power), lithium-ion, flow (vanadium redox and zinc-bromine), nickel-based (nickel cadmium) batteries, flywheels, compressed air, and closed-loop pumped hydro and open-loop pumped hydro energy storage are the technologies represented by the available data. Demonstration projects were removed from this paper since many of them had inexplicably high costs.

Note that none of the flow battery projects reported here are currently operational, including the vanadium redox flow battery that Kotzebue had received a quote on from VRB before the company went out of business, the zinc-bromine flow battery purchased by Kotzebue from Premium Power, which was decommissioned and two other batteries that are contracted/under construction. We are not certain, therefore, that the prices presented accurately reflect the cost of functioning systems. All costs have been converted to 2015 dollars based on the Consumer Price Index (CPI) (U.S. Bureau of Labor Statistics, 2016).

DISCUSSION

Capital costs by power and energy capacity

Energy storage systems generally consist of the actual storage device (e.g., a battery or flywheel), which defines the energy capacity and theoretical maximum power available, and power conversion systems, which determine the actual maximum power available for both charging and discharging. As the two systems—storage device and power conversion system—are separate units selected depending on a particular application, it makes sense to examine the capital cost of systems in relation to both energy storage capacity and power capacity, referred to herein as the Capacity and Power of an ESS. In the rest of this review, capital costs will be

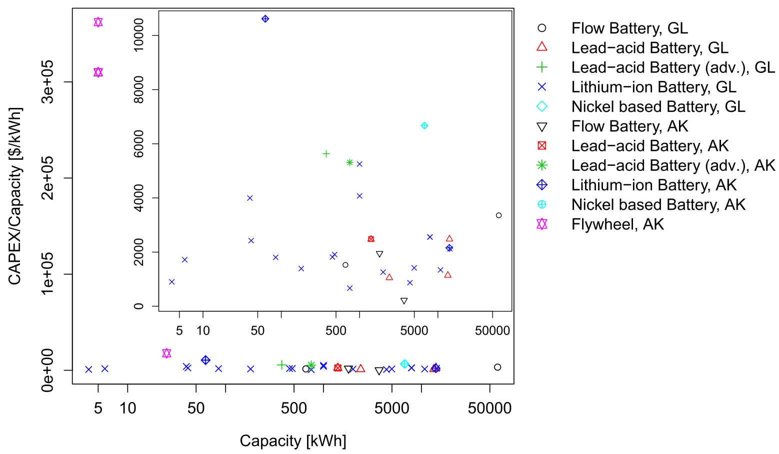

FIG. 2. The plot of CAPEX/capacity versus capacity for non-hydro energy storage. The inset shows a scaled view of the *y*-axis for easier viewing of lower CAPEX/capacity values. Data are shown for both global and Alaska installations. Flywheels tend to be more expensive per capacity (kW h) than other forms of energy storage; they tend to be cheaper per rated power (see Fig. 3).

referred to as CAPEX, which denotes the capital expenditures required to acquire the energy storage system, as opposed to later operating expenses (OPEX).

Figures 2 and 3 show the cost per capacity ($/kW h) and rated power ($/kW) plotted against capacity and rated power for global and Alaska projects. The variation in CAPEX/capacity and CAPEX/power is wide, and no trends are obvious, both overall and within particular technologies.

The wide variation in CAPEX/capacity and CAPEX/power can be partly explained by differences in the infrastructure included in CAPEX. For example, one project simply involved replacing the batteries in an existing installation, while other projects required various infrastructures such as a building and interconnection. Cost breakdowns were not given for most of the data, and it was not always clear what was included in CAPEX. All costs from REF applications for projects in Alaska (labeled AK on the plots) include transport, hardware, and installation.

The variation can also be partly explained by the ratio of capacity to rated power (or the duration in hours). CAPEX/power tends to be higher for ESS with a longer duration, while CAPEX/capacity tends to be lower. The plots of CAPEX/capacity and CAPEX/power versus duration can be seen in Figs. 6 to 9 in Appendix A.

The costs presented in Figs. 2 and 3 are best understood in the context of what each data point represents. A short description of the different projects presented in these figures is given in Appendix B and helps to explain the variation seen in costs. Note that the cost data on flow batteries are for installations that are not currently operational.

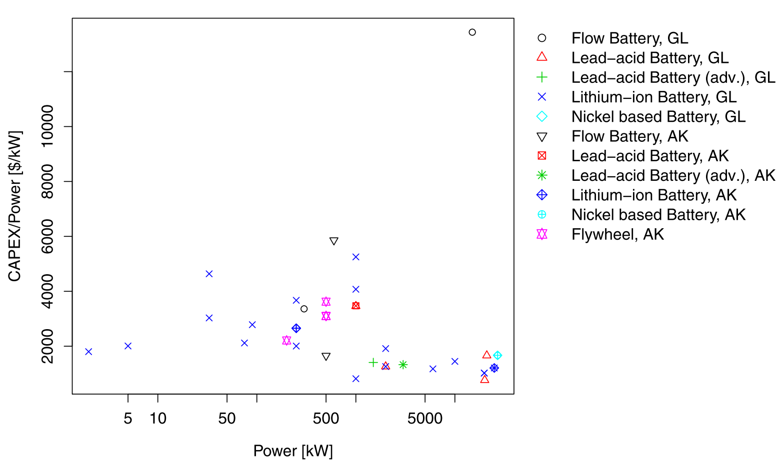

FIG. 3. The plot of CAPEX/power versus power for non-hydro energy storage. Data are shown for both global and Alaska installations.

TABLE I. Mean CAPEX/power and CAPEX/capacity for global and Alaska data.

	Global		Alaska	
Technology	Mean CAPEX/power ($/kW)	Mean CAPEX/capacity ($/kW h)	Mean CAPEX/power ($/kW)	Mean CAPEX/capacity ($/kW h)
Flow battery	8401	2444	3758	1089
Lead-acid battery	1785	1785	3472	2480
Lead-acid battery (advanced)	1408	5634	1328	5311
Lithium-ion battery	2292	2115	2172	7797
Nickel-based battery	1668	6674	979	2650
Closed-loop pumped hydro	1438	141		
Open-loop pumped hydro	995	77		
Compressed air energy storage	1120	80		
Flywheel			3026	261 978

Table I shows mean values of CAPEX/power and CAPEX/capacity for global and Alaska data. Similar to Figs. 2 and 3, these values are best understood in the context of the projects they represent. See Appendix B for an overview of the different projects.

Operation and maintenance ($/kW)

Data for global and Alaska operation and maintenance (O&M) costs were minimal. A report by Sandia (Schoenung and Hassanzahl, 2003) gives the estimates shown in Table II. The O&M values given for flow batteries are low, based on the experience and knowledge of the authors.

Expected life and efficiency

The energy efficiency and expected number of cycles before replacement/overhaul, from a 2011 Sandia report (Schoenung, 2011), are shown in Table III. Electro-mechanical systems, like pumped hydro and flywheels, typically can be overhauled at minimal cost, while electro-chemical systems typically need to be replaced. The replacement period in years is used for levelized cost of energy (LCOE) and levelized cost per cycle power (LCCP) calculations and corresponds to the end of the cycle life. The performance metrics listed for flow batteries are much higher than what the authors have experienced or are aware of in actual installations.

The expected efficiency of an ESS is highly technology and use dependent. Table III shows average values for the round trip efficiency of different ESS technologies. For a given ESS, the

TABLE II. O&M costs for different energy storage technologies, from Sandia's 2003 report (Schoenung and Hassanzahl, 2003); O&M is reported in $/kW yr. Note: Costs have been increased by 30% to update them to 2015 dollars based on the CPI. The costs for power generation are not as straightforward as the costs for energy storage, as O&M is influenced by more variables.

Name	O&M [$/(kW yr)]
Lead-acid battery (flooded cell)	19.5
Lead-acid battery (advanced)	6.5
Lithium-ion battery	32.5
Nickel cadmium battery	32.5
Zinc bromine flow battery	26
Vanadium redox flow battery	26
Flywheels (high speed)	6.5
Compressed air energy storage (surface)	13
Pumped hydro	3.25

TABLE III. Performance characteristics of ESS technologies (Schoenung, 2011; Schoenung and Hassanzahl, 2003; Divya and Ostergaard, 2009; Butler *et al.*, 2000; Viswanathan *et al.*, 2013).

Technology	Round trip efficiency (%)	Depth of discharge (%)	Cycle life	Replacement period (yr)
Lead-acid battery (flooded cell)	75	50	2000	6
Lead-acid battery (advanced)	80	50	2000	6
Lithium-ion battery	85	80	4000	10
Nickel cadmium battery	65	100	3000	10
Zinc bromine flow battery	70	100	3000	8
Vanadium redox flow battery	65	100	5000	10
Flywheels (high speed)	95	100	25 000	20
Compressed air energy storage (surface)	70	100	25 000	30
Pumped hydro	85	100	25 000	30

round trip efficiency will vary depending on how it is operated. For example, a fly wheel's efficiency will vary depending on its rotational speed (amount of stored energy) and its power output or input. The length of time between charge and discharge will also affect round trip efficiency due to the rotational losses (friction) in the flywheel. Thus, the method of operation will have a significant impact on the round trip efficiency of a flywheel. This is also true to varying degrees for other ESS technologies. See the section on Conditions for the Greatest Efficiency for a discussion of the different types of energy losses in an ESS.

Capacity factor

The capacity factor for energy storage technology is not applicable.

Diesel offset

General uses for ESS are peak shifting (charging during low load/high generation events and discharging during high load/low generation events), power quality support (balancing high ramp rates in the load or renewable generation), and supplying spinning reserve capacity (SRC: the ability to meet suddenly rising demand or replace suddenly dropping generation; this allows smaller generators or no diesel generators to run online). Peak shifting generally saves diesel by increasing the utilization of renewable energy. Providing power quality support reduces

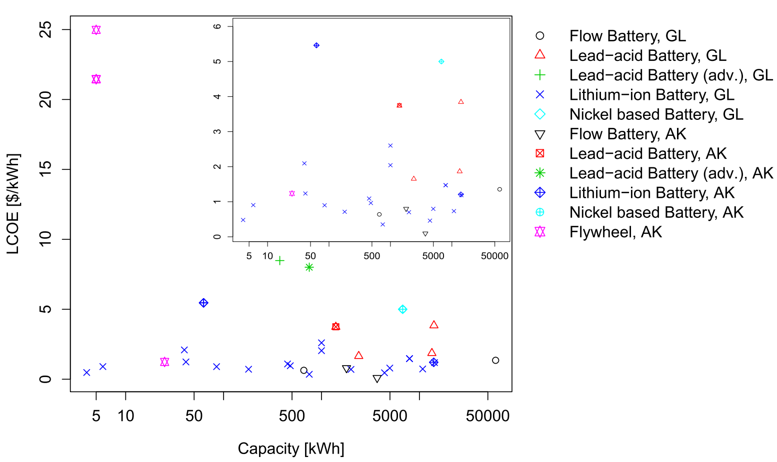

FIG. 4. LCOE for energy storage applications. The inset shows a scaled view of the y-axis for easier viewing of lower LCOE values. LCOE values for energy storage only show the energy throughput of the storage device and not the increase in energy production from cheaper sources, such as renewable energy, that it enables. The LCOE and LCCP of energy storage must be understood in terms of how they affect the cost of energy in the entire system.

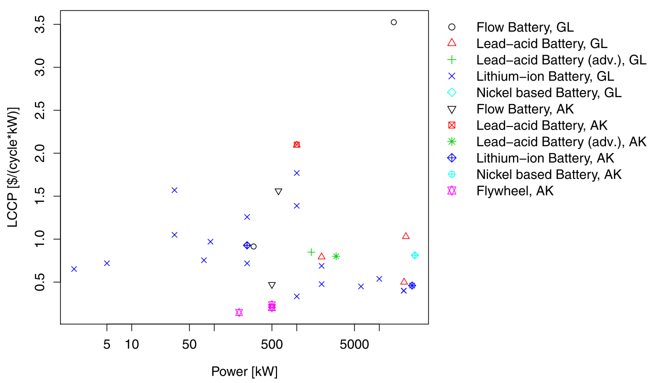

FIG. 5. LCCP for energy storage applications.

stress on diesel generators, which increases their lifespan and efficiency. Providing SRC saves diesel by allowing a smaller or no diesel generator to run online, enabling a much higher use of renewable energy.

Schaede *et al.* (2015) provided an example of possible diesel savings with energy storage. They modelled Nome's grid with 959 kW/58 kW h flywheel energy storage supplying SRC. Nome's grid has an average load of 4 MW and an installed wind power capacity of 2.7 MW. The flywheels supplied SRC (as well as load leveling), which allowed smaller diesels to run online and let wind power supply a higher fraction of the load when wind power was available, reducing diesel consumption. The energy storage reduced diesel consumption by 850 gal/week during periods with high levels of wind power and by 450 gal/week during periods with low levels of wind power.

Cost per kW h

For energy storage, the levelized cost of energy (LCOE) is defined as the levelized cost of storing energy ($/kW h stored). However, this metric does not give the whole picture since it does not take into account the power at which energy storage is able to charge and discharge. A second metric called levelized cost per cycle power (LCCP) is used for this. The LCCP, which provides levelized cost per cycle per kW [$/(cycle kW)], does not take into account the duration of the discharge (charge) and is more relevant for applications, such as power quality, that need high power and not necessarily long duration.

The equations for LCOE and LCCP are given in Appendix C. Both LCOE and LCCP were calculated assuming an inflation rate of 2%, an interest rate of 5%, and the typical depth of

TABLE IV. Mean LCOE and LCCP for global and Alaska data. Note that all data used in this paper for flow batteries are from systems that are not currently operational.

	Global		Alaska	
Technology	Mean LCOE ($/kW h)	Mean LCCP [$/(cycle kW)]	Mean LCOE ($/kW h)	Mean LCCP [$/(cycle kW)]
Flow battery	1.0	2.2	0.45	1.0
Lead-acid battery	2.8	1.1	3.8	2.1
Lead-acid battery (advanced)	8.5	0.85	8.0	0.80
Lithium-ion battery	1.1	0.81	4.0	0.77
Nickel-based battery	5.0	0.81	5.0	0.81
Closed-loop pumped hydro	0.013	0.12		
Open-loop pumped hydro	0.0075	0.081		
Compressed air energy storage	0.010	0.10		
Flywheel			18	0.20

TABLE V. Comparison of Sandia cost estimates with costs from global and Alaska data (2015 dollars) shows, on average, significantly higher costs for Alaska.

	Sandia		Global and Alaska	Calculated from Sandia		Global		Alaska	
Tech1	Power conditioning cost ($/kW)	Energy storage cost ($/kW h)	Mean duration (h)	Mean CAPEX/power ($/kW)	Mean CAPEX/capacity ($/kW h)	CAPEX/power difference ($/kW)	CAPEX/capacity difference ($/kW h)	CAPEX/power difference ($/kW)	CAPEX/capacity difference ($/kW h)
Flow battery	420	525	4.2	2625	625	5776	1819	1133	464
Lead-acid battery	420	346.5	1	766.5	766.5	1018.5	1018.5	2705.5	1713.5
Lead-acid battery (advanced)	420	346.5	0.25	506.625	2026.5	901.375	3607.5	821.375	3284.5
Lithium-ion battery	420	630	1.2	1176	980	1116	1135	996	6817
Nickel-based battery	292.5	780	0.31	534.3	1723.548	1133.7	4950.452	444.7	926.4516
Closed-loop pumped hydro storage	1260	78.75	10	2047.5	204.75	−609.5	−63.75		
Open-loop pumped hydro storage	1260	78.75	13	2283.75	175.6731	−1288.75	−98.6731		
Compressed air storage	735	5.25	18	829.5	46.08333	290.5	33.91667		
Flywheel	630	1680	0.033	685.44	20 770.91			2340.56	24 1207.1

discharge (DOD), cycle life, year life, and efficiency shown in Table III. These values can vary widely depending on the system and how it is operated. Different energy storage technologies have different replacement costs, which affect LCOE and LCCP, but are not considered here. Figures 4 and 5 show a more detailed analysis on the cost of different ESS technologies and show the LCOE and LCCP for global and Alaska energy storage system installations. The mean values of LCOE and LCCP for global and Alaska data are shown in Table IV. Certain technologies have a lower LCOE, while others have a lower LCCP, indicating their feasibility for high energy or high power applications. Again, these values are best understood in the context of the projects they represent, described in Appendix B. Note that the values for flow batteries have been calculated using cost data from non-operational projects and performance data from the literature that seem to be high based on the authors' experience. Thus, these values may offer overly optimistic figures.

Conditions for the greatest efficiency

The efficiencies of ESS are largely influenced by the technology type (see the section on Expected Life and Efficiency) and usage. The three main forms of energy loss are charge/discharge (losses in energy storage medium and power electronics), storage (self-discharge), and parasitic due to balance of plant (e.g., cooling systems). An inefficiency is always associated with converting electrical energy into chemical or mechanical energy. Between technologies, levels of self-discharge vary, which results in losses during storage, with the more the losses, the longer the storage. Other factors such as temperature can play a significant role as well. Thus, the conditions for the greatest efficiency are technology and use dependent.

Cost curve over time

The U.S. DOE, together with industry, has developed the near-term (present–2018) goals of under $250 per kW h of installed capacity for storage technologies and under $1750 per kW of rated power for power conditioning technologies. The long-term (2018–2023) goals are under $150/kW h for storage systems and under $1250/kW for power conditioning technologies (U.S. DOE, 2013). These numbers need to be converted into CAPEX for the entire energy storage system and divided by capacity and power for comparison with the costs of the ESS presented in this paper. The total energy storage system costs (CAPEX) presented in this paper are an average of \$591/kW, \$6.6/kW h higher than the short-term goal (2018) and an average of \$1213/kW and \$860/kW h higher than the long-term goal (2023).

Installed costs by major components

Sandia's reports include energy storage system costs by technology (Schoenung and Hassanzahl, 2003; Schoenung, 2011). The authors split the costs between the power conditioning system, listed in \$/kW, and the energy storage system, listed in \$/kW h. The costs, updated to 2015 dollars, are shown in Table V. Sandia's cost estimates have been converted to total CAPEX/capacity and CAPEX/power using the average duration of the different technologies. These costs have then been compared with the global and Alaska data. The difference between Sandia's calculated costs and costs from the data is also shown in Table V. The data show, on average, significantly higher costs except for pumped hydro storage, which is cheaper than Sandia's costs.

Transportation

Only one data entry had an estimate for transportation costs: Kotzebue budgeted \$40 000 for the transport of a vanadium redox flow battery from VRB (the project did not go through). Transportation costs are highly dependent on the weight, size, and shipping restrictions of the energy storage unit as well as the distance and available means of transportation to the end destination.

Technology trends

Recent material advances, especially in nanotechnology, have been significant in the development of ESS: low-cost, long-life electrodes and membranes for flow batteries, flywheel design, increased surface area supercapacitors, and superconducting materials. New chemistries are the focus of research: different redox equations and electrolyte solutions for lower cost, higher performance, higher safety, and longer life of batteries and flow batteries. Inverters and converters have been improving in performance and decreasing in price with advanced power electronics and new topologies. System design is a major part of bringing a technology out of the lab and into a product that is easy to use and maintain in the field. The electric vehicle (EV) market is a major driver of ESS development, resulting in home and grid-connected batteries.

Tech-specific storage systems

Tech-specific storage systems (i.e., ultra-capacitors with wind) are not applicable to energy storage technology.

Refurbishment/upgrade market

For electro-mechanical ESS such as pumped hydro and flywheels, refurbishment is often a cost-effective way to extend the life of the system. An example of a growing refurbishment market is old electric vehicle (EV) batteries. After the battery drops to 70%–80% of its initial capacity, it becomes insufficient for automotive use. However, the battery is still useful for stationary energy storage. Nissan is the first EV manufacturer to launch a startup—Green Charge Networks—which resells old Nissan Leaf batteries as part of stationary storage systems (Neubauer and Pesaran, 2010; St. John, 2015).

Realized cost savings

Cost savings from integrating renewable power are difficult to gauge due to technical and incentive impacts at the entire power system level. At the technical level, for example, effects of diminished losses of secondary services such as recovered waste heat and reductions in fuel efficiency are hard to gauge, as they depend not only on average reductions in load but also on specific operating schemes, such as minimum allowable loads on diesels and the spinning reserve kept.

CONCLUSIONS

Deployment of ESS is nascent in Alaska, with a few exceptions. Thus, the dataset developed from AEA REF applications has been supplemented by data from the U.S. DOE Global Energy Storage Database, which captures installation data worldwide from Sandia National Laboratory's energy storage reports (several editions) and data collected by ACEP through personal communication with energy storage developers and utilities.

Energy storage is hard to quantify in terms of performance, cost, and economic value. Costs and performance in the overall energy storage market have been evolving sporadically, and it is not easy to discern any clear trend. The most significant trend in the data considered here is the increased variance in costs with time. Thus, more options for ESS with "low cost per kW/high costs per kW h" and vice versa are now available, indicating a greater variety of specialized ESS for targeted applications.

It is often difficult to justify energy storage economically based on fuel savings alone. Significant work remains to quantify other possible cost savings afforded by energy storage, such as reduced fuel consumption and stress on a diesel generator by smoothing out the load.

The data analyzed for this paper do not show any difference in the cost of energy storage in Alaska compared to the rest of the nation or world. Alaska has had relatively few energy storage technology failures, and most that occurred were caused by improper operation.

Recent material advances, especially in nanotechnology, have been significant in the development of ESS: low-cost, long-life electrodes and membranes for flow batteries, flywheel designs, and increased surface area supercapacitors and superconducting materials. New chemistries are a focus of research with regard to different oxidation-reduction reactions and electrolyte solutions for lower costs, higher performance, higher safety, and longer life of batteries and flow batteries. Inverters and converters have been improving in performance and decreasing in price, with advanced power electronics and new topologies. The electric vehicle market is a major driver of energy storage system development, resulting in home and grid-connected battery development.

The lack of standardization and quantification of costs and benefits is the main barrier to determining the economic potential for implementation of energy storage in Alaska. In addition, communities in Alaska often wish to avoid ESS that uses hazardous materials since each community will eventually have to deal with disposal issues.

Energy efficiency grants could be leveraged for ESS. The development of standardized use scenarios for the operation of such systems would maximize the economic benefits in Alaska. These scenarios would ideally include quantification of economic savings, performance specifications for ESS manufacturers, and calculations of comparison metrics based on performance specifications. Guidance documents for determining needs, required specifications, and selection procedures for ESS would be extremely helpful. These documents should include information on how to protect an investment from technical failures by agreeing on performance and lifetime guarantees as well as responsibility for failure.

ACKNOWLEDGMENTS

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APPENDIX A: ADDITIONAL ANALYSIS AND PLOTS

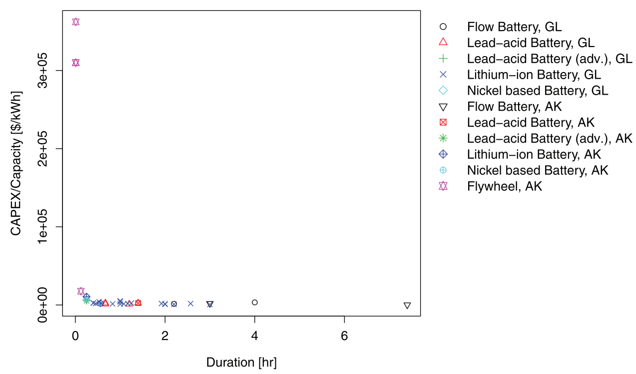

FIG. 6. Plot of CAPEX/capacity versus duration. The high cost per capacity of flywheels and high duration of flow batteries make this plot hard to read.

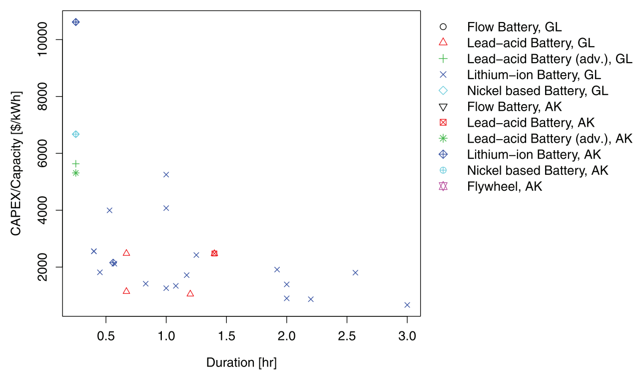

FIG. 7. Plot of CAPEX/capacity versus duration with flywheels and flow batteries removed.

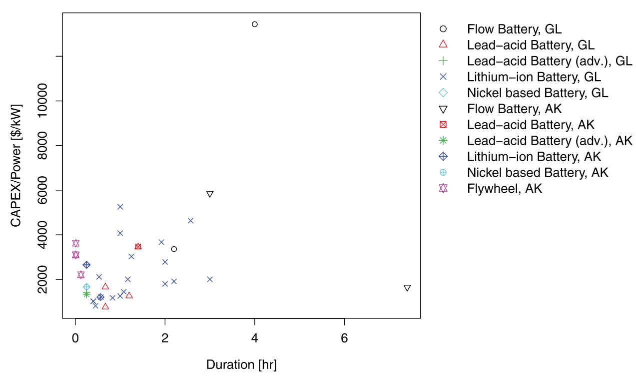

FIG. 8. Plot of CAPEX/power versus duration. The high duration of flow batteries makes this plot hard to read.

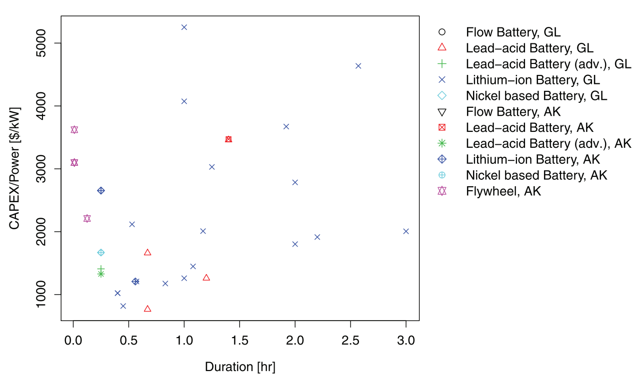

FIG. 9. Plot of CAPEX/power versus duration with flow batteries removed.

APPENDIX B: REFERENCED ENERGY STORAGE PROJECTS AND SOURCES

Tables VI–X list the energy storage projects studied in this paper and where they are sourced. *REF* refers to the Renewable Energy Fund, *DOE* refers to the DOE global energy storage database, *EETF* refers to the emerging energy technology fund, *ACEP* refers to the Alaska Center for Energy and Power, and *ARTEC* refers to Alaska Railbelt Cooperative Transmission & Electrical Company.

TABLE VI. Lithium-ion battery.

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/power ($/kW)	CAPEX/capacity ($/kW h)	Notes
NICE GRID project in Carros (Southern France): Primary Substation Battery (PSB)	DOE	7/31/2013	Provence-Alpes-Côte dAzur	France	1000	450	817.62	1816.93	There are 3 "NICE GRID" data points, consistent CAPEX/capacity with varying CAPEX/Power.
Jake Energy Storage Center: RES Americas	DOE	2/25/2015	Illinois	United States	19 800	7920	1022.66	2556.66	Relatively low CAPEX/power and high CAPEX/capacity.
Elwood Energy Storage Center: RES Americas	DOE	2/25/2015	Illinois	United States	19 800	7920	1022.66	2556.66	Relatively low CAPEX/power and high CAPEX/capacity.
KIUC Anahola Solar Array and Battery	DOE	12/29/2014	Hawaii	United States	6000	4980	1175.69	1416.49	
Anchorage Area Battery Energy Storage System	DOE and ARTEC	1/1/2016	Alaska	United States	25 000	14 250	1208.00	2119.30	Data are from ARCTEC "2013 Railbelt Energy Priorities."
Stafford Hill Solar Farm and Microgrid: Lithium Ion	DOE	12/18/2014	Vermont	United States	2000	2000	1259.67	1259.67	
10 MW/10 MW h—Feldheim Regional Regulating Power Station (RRKW)	DOE	2/14/2015	Brandenburg	Germany	10 000	10 800	1447.78	1340.54	
5kW h LiFePO4 DIY ESS	DOE	11/3/2012	Ile de France	France	2	4	1802.30	901.15	

TABLE VI. (*Continued.*)

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/power ($/kW)	CAPEX/capacity ($/kW h)	Notes
2 MW/4.4 MW h Puget Sound Energy—Glacier WA	DOE	12/17/2014	Washing-ton	United States	2000	4400	1914.69	870.31	
Oncor Battery Storage	DOE	6/23/2014	Texas	United States	250	750	2006.43	668.81	
JuiceBox Residential solar energy storage SES—AC-coupled peak-shifting and backup	DOE	5/10/2015	California	United States	5	5.85	2009.11	1717.19	
Landing Mall DR	DOE	5/21/2011	Washing-ton	United States	75	39.75	2117.78	3995.80	Remotely controlled by utility for demand response.
Tuntutuliak	REF	1/1/2011	Alaska	United States	250	62.5	2654.00	10 617	Tuntutuliak and Kwigillingok are identical REF applications. Both were declined funding due to control and integration issues. Kwigillingok installed Chevy-volt batteries with an ABB PCS-100 inverter, the same specs and price. The very high CAPEX/capacity is likely partly due to the very low duration.
Kwigillingok	REF	1/1/2011	Alaska	United States	250	62.5	2654.00	10 617	
90 kW/180 kW h Santa Cruz County Building GCN	DOE	9/28/2015	California	United States	90	180	2784.15	1392.08	
ZECO Energy	DOE	#N/A	Victoria	Australia	33	41.25	3030.30	2424.24	This installation is off-grid, which is likely the cause for the relatively high cost.
NICE GRID project in Carros (Southern France): Secondary	DOE	8/24/2013	Provence-Alpes-Côte dAzur	France	250	480	3672.46	1912.74	There are 3 “NICE GRID” data points, consistent CAPEX/capacity with

TABLE VI. (*Continued.*)

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/power ($/kW)	CAPEX/capacity ($/kW h)	Notes
Substation Battery (SSB)									varying CAPEX/Power.
Fort Hunter Liggett Battery Storage Project	DOE	10/1/2013	California	United States	1000	1000	4074.23	4074.23	This installation is on a military base. Perhaps higher building standards result in high cost.
NICE GRID project in Carros (Southern France): Low Voltage Grid Batteries (LVGB)	DOE	8/23/2013	Provence-Alpes-Côte dAzur	France	33	84.81	4636.94	1804.26	There are 3 "NICE GRID" data points, consistent CAPEX/capacity with varying CAPEX/Power.
UBC Electrochemical Energy Storage Project	DOE	11/6/2012	British Columbia	Canada	1000	1000	5252.40	5252.40	This was installed on a university campus and intended for research as well as grid support, which possibly led to high costs.

TABLE VII. Lead-acid battery.

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/power ($/kW)	CAPEX/capacity ($/kW h)	Notes
PREPA BESS 2	DOE	4/21/2002	Puerto Rico	United States	20 000	13 400	763.6019	1139.704	This is the cost of replacing the existing installation "PREPA BESS 1." Having existing infrastructure results in the lowest CAPEX/Power.
Stafford Hill Solar Farm and Microgrid: Lead Acid	DOE	12/18/2014	Vermont	United States	2000	2400	1259.665	1049.721	
Kodiak-Pillar Mountain	REF	1/1/2012	Alaska	United States	3000	750	1327.818	5311.273	This is an "advanced" lead acid battery, which results in a higher CAPEX/capacity.
KIUC Koloa—Xtreme Power DPR	DOE	7/15/2011	Hawaii	United States	1500	375	1408.405	5633.622	This is an "advanced" lead acid battery, which results in a higher CAPEX/capacity.
PREPA BESS 1	DOE	2/10/1992	Puerto Rico	United States	21 000	14 070	1660.707	2478.667	The higher cost is likely due to the early installation date.
Metlakatla BESS	DOE	2/3/1997	Alaska	United States	1000	1400	3459.063	2470.759	The higher cost is likely due to the early installation date as well as being installed in a remote microgrid.

TABLE VIII. Flow battery.

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/($/kW)	CAPEX/Capacity ($/kW h)	Notes
Kotzebue Premium Power	REF	1/1/2010	Alaska	Unite States of America	500	3700	1655.345	223.6953	The cost of purchasing, transporting, and installing a Zinc-Bromine Flow Battery from Premium Power. It did not perform to required specs, was decommissioned.
RedFlow 300 kW Adelaide	DOE	4/17/2015	South Australia	Australia	300	660	3363.406	1528.821	The cost of purchasing and transporting a Zinc-Bromine Flow Battery from RedFlow. Under construction.
Kotzebue VRB	REF	1/1/2008	Alaska	Unite States of America	600	1800	5860.927	1953.642	The price quoted to Kotzebue for a Vanadium Redox Flow Battery before VRB went out of business.
Minami Hayakita Substation Vanadium Redox Flow Battery	DOE	4/17/2014	Hokkaido	Japan	15 000	60 000	13 438.93	3359.733	Project cost of installing Vanadium Redox Flow Batteries. These costs are much higher possibly due to higher infrastructure costs. Contracted/under construction.

TABLE IX. Flywheel.

Project name	Source	Date	State	Country	Power (kW)	Capacity (kW h)	CAPEX/power ($/kW)	CAPEX/capacity ($/kW h)	Notes
Chugach FESS	EETF	5/26/2015	Alaska	United States of America	200	25	2210	17 680	The installed cost of Flywheel energy storage for Chugach's announced project.
Kwigillingok FESS	REF	1/1/2010	Alaska	United States of America	500	5	3100	31 0010	Kwigillingok, Tuntutuliak, and Kongiganak submitted identical REF applications which were not funded. Kipnuk also was not granted funding through REF. Kwigillingok installed Lithium-ion Batteries instead. The high CAPEX/Capacity is due to the low Capacity.
Tuntutuliak FESS	REF	1/1/2010	Alaska	United States of America	500	5	3100	31 0010	
Kongiganak FESS	REF	1/1/2010	Alaska	United States of America	500	5	3100	31 0010	
Kipnuk high penetration	REF	1/1/2010	Alaska	United States of America	500	5	3622	36 2183	

TABLE X. Pumped storage and compressed air energy storage.

Project name	Source	Date	State	Country	Power (MW)	Capacity (MW h)	CAPEX/ power ($/kW)	CAPEX/ capacity ($/kW h)	Notes
Yards Creek Pumped Storage	DOE	#N/A	New Jersey	United States	400	2400	38	6	Open-loop pumped hydro
Blenheim-Gilboa Pumped Storage Power Project	DOE	7/1/1973	New York	United States	1160	17 400	659	44	Open-loop pumped hydro
Northfield Mountain Pumped Storage Hydroelectricity Facility	DOE	12/31/1969	Massachusetts	United States	1119	8482	790	104	Open-loop pumped hydro
Raccoon Mountain Pumped Storage Plant	DOE	1/1/1974	Tennessee	United States	1652	36 344	934	42	Open-loop pumped hydro
Silver Creek Pumped Storage Project	DOE	5/15/2012	Pennsylvania	United States	300	2400	1041	130	Closed-loop pumped hydro
McIntosh Compressed Air Energy Storage Plant	DOE	1/1/1991	Alabama	United States	110	2860	1048	40	Compressed air energy storage
Pacific Gas and Electric Company Advanced Underground Compressed Air Energy Storage	DOE	1/1/2015	California	United States	300	3000	1192	119	Compressed air energy storage
Bath County Pumped Storage Station	DOE	1/12/1985	Virginia	United States	3003	30 930.9	1200	117	Open-loop pumped hydro
Lake Elsinore Advanced Pumped Storage	DOE	8/6/2007	California	United States	500	6000	1835	153	Closed-loop pumped hydro
Ingula Pumped Storage Scheme	DOE	11/1/2007	Kwa-Zulu Natal	South Africa	1332	21 312	2350	147	Open-loop pumped hydro open-loop pumped hydro

APPENDIX C: EQUATIONS FOR LCOE AND LCCP

Equations for LCOE:

$$LCOE = \frac{NPV_c \cdot CRF}{Annual\,Energy\,Stored},$$
$$NPV_c = CAPEX + \sum_{j=1}^{N}\left(\frac{1+i}{1+r}\right)^j \cdot OM,$$
$$CRF = \frac{r}{1-(1+r)^{-N}},$$
$$Annual\,Energy\,Stored = \frac{Cap \cdot DOD \cdot \eta \cdot Cycles}{Years},$$

where *NPVc* is the net present value of the annual cost of the system, *CRF* is the capitol recovery factor (the ratio of a constant annual cost to the present value of that cost), *CAPEX* is the capital expenditure, i is the inflation rate, r is the interest rate, N is the system lifetime in years, Cap is the capacity of the installation, DOD is the depth of discharge, η is the efficiency, $Cycles$ is the number of cycles the system is rated for, and $Years$ is the number of years the system is rated for.

Equations for LCCP:

$$LCCP = \frac{NPV_c \cdot CRF}{Cycles \cdot Power/Years},$$

where $Power$ is the rated power of the energy storage system.

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