JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **9**, 061709 (2017)

An Alaska case study: Cost estimates for integrating renewable technologies

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(Received 6 June 2017; accepted 2 September 2017; published online 21 December 2017)

Adding renewable energy to a grid, especially high penetration in a remote microgrid, requires grid integration to maintain stability and maximize the economic benefit of the new energy source. This analysis of integration technologies in Alaska shows a statistically significant increase of around $27/kW in the total integration cost per percent increase in wind energy penetration. This is an initial estimate based on twenty-four pre-project cost estimates and designs submitted to the State of Alaska Renewable Energy Fund grant program between 2008 and 2015. For integration systems incorporating thermal or electrical storage, the average control integration cost is around 66% of the total cost and storage is 34%. Trends that are being used to integrate higher penetrations of renewable energy in grids include demand-side management, excess generation to heat, energy storage with grid-forming inverters, and advanced control systems. *Published by AIP Publishing.* https://doi.org/10.1063/1.4986581

INTRODUCTION

Adding renewable energy to a grid, especially high penetration in a remote microgrid, requires grid integration to maintain stability and maximize the economic benefit of the new energy source. According to Greening, the Grid (http://greeningthegrid.org/integration-in-depth) in a larger grid can be achieved by

- importing and exporting power between areas that have an excess or lack of power,
- using demand response or energy storage to consume extra power,
- using flexible generation such as gas turbines that can turn on and off quickly, support high-power ramp rates, and offer ancillary services to maintain grid stability, and
- load and renewable energy forecasting.

In a remote microgrid, there is no larger grid to export or import power. Thus, all generation and consumption must be balanced within the microgrid. Diesel generators are common and supply flexible generation that can support the integration of renewables up to a certain point. With high enough penetration of renewables, diesel generators need the ability to turn off or run at lower capacity. This ability requires other grid components such as energy storage, grid-forming inverters, and demand response (Schaede *et al.*, 2015). In Alaska, load and renewable energy forecasting is not as accurate as in the rest of the United States, partly due to the lack of meteorological data, the high stochasticity of microgrid loads, and small renewable energy installations.

For the purposes of this analysis, *integration* refers to the modifications and additions made to a microgrid in order to incorporate a new energy source, not including transmission/distribution. This analysis looks specifically at the costs of integrating wind power since most available data are for wind, but this analysis is relevant to other energy sources as well. A qualitative description and comparison of the integration requirements of different energy sources are given in Table I.

TABLE I. General power integration requirements depending on the capability of the energy source.

	Dispatchable power generation	Synchronous front end
Definition	Real power output can be controlled and generated according to a schedule or demand	The power factor (ratio of real to apparent power), used to supply loads that consume reactive power, can be controlled. Frequency and voltage references are provided to all other sources of generation and those sinks that require it
Energy sources that commonly have this capability	Hydroelectricity, biomass, geothermal, and diesel	Hydroelectricity and diesel
Integration needs for energy sources that do not have this capability	There must be sufficient spinning reserve capacity (SRC) to cover possible short-term inadequate generation	The voltage and frequency of the grid need to be maintained.
	There must be standby generation/stored energy to cover long-term inadequate generation	The grid power factor needs to be maintained
	If the source can overgenerate (generate more power than demanded) "negative-SRC" in form if diversion loads may also be necessary	
Available integration hardware	Dispatchable and synchronous generators such as diesel and hydroelectric power are able to supply SRC when sufficient capacity is running online. They can supply standby generation when online and offline[a]	Dispatchable and synchronous generators such as diesel and hydro are able to maintain voltage, frequency, and power factor when sufficient capacity is online
	Electrical energy storage and inverters can supply SRC and/or stored energy	Capacitor banks and synchronous condensers can be used to correct the grid power factor. Synchronous condensers can be used to maintain voltage and frequency
	Demand response or secondary loads can be used together with excess generation from the energy source to supply some of the SRC. This depends on the variability of the energy source and the size and granularity (available load steps) of the secondary load	A grid-forming inverter (also known as a voltage source inverter), placed between the energy source and the grid, can maintain voltage, frequency, and power factor but may not be able to follow demand Electric energy storage with a grid-forming inverter can maintain voltage, frequency, and power factor
Integration options to increase the energy harvested from high penetrations of energy sources that do not have this capability	Diversion loads Secondary loads Demand response Energy storage	Synchronous condensers Energy storage with a grid-forming inverter

[a]Different diesel generators require different durations of time to be brought online. Some can be brought online as quickly as within 30 s, while others require over 30 min. The duration of time largely depends on the size of the generator (the larger it is, the longer it takes) and standby practices. Cold engines require more time than engines kept in "hot" standby.

The goal of integration is to maintain a stable grid while maximizing economic benefits. Table I provides an overview of the integration requirements for energy sources, depending on their capabilities. Energy sources can be categorized by whether they are dispatchable (can generate power according to a schedule and follow demands within the operating range of the energy source) and whether they have a synchronous front end (able to control real and reactive power flow, either with a synchronous generator or a grid-forming inverter, a voltage source that can operate in four quadrants, meaning that it can output and absorb real and reactive power).

Energy sources that are both dispatchable and have a synchronous front end do not need any special integration beyond dispatch control, which is fairly straightforward and part of any modern powerhouse. Energy sources that do not have a synchronous front end require other components in the grid to supply reactive power to maintain an acceptable power factor and provide voltage and frequency reference. Energy sources that are not dispatchable require available spinning reserve capacity (SRC) and standby generation for times when the energy source can no longer meet the load. Spinning reserve capacity can supply instantaneous power, while standby generation is brought online.

Diesel generators and usually hydroelectric sources are dispatchable and have a synchronous front end. Biomass and geothermal power generation systems are dispatchable but often do not have a synchronous front end. Wind and solar photovoltaic (PV) power are not dispatchable and generally do not have a synchronous front end.

Integration costs for nondispatchable variable energy sources such as wind and solar PV power also depend on the nature of their variability. Solar PV can be more variable than wind, with higher ramp rates, which may result in higher integration costs per installed capacity ($/kW) compared to modern wind turbines.

This review of electrical integration technologies 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 Alaska Affordable Energy Strategy, the Alaska Center for Energy and Power (ACEP) contracted with AEA to document technology development needs specific to Alaska with regard to renewable 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

The following analysis largely relies on data extracted from twenty-four applications to the State of Alaska Renewable Energy Fund (REF) grant program, Rounds 1–8, and thus may not always represent actual as-built costs. Integration is broken down into the categories of SCADA (supervisory control and data acquisition) and hardware, integration and testing, thermal storage (converting electrical energy into thermal energy, which is later used to supply thermal loads), and electrical storage (electrical energy being converted and stored (usually as mechanical or chemical energy), which is later reconverted to electrical energy to supply electrical loads) (Table II).

Controllable loads are another integration category, but they were not included in the REF applications used for this paper. There is some overlap between the definition of controllable loads and energy storage. Electrical and thermal energy storage could be considered a controllable load since it can be charged with excess generation. Electrical storage could also be considered a generating source when discharging. Energy storage is a subset of controllable loads, and many controllable loads do not have a significant storage component. Distributed masonry heaters in homes were considered thermal energy storage since they include a thermal storage component. However, they have also been classified as controllable loads.

In the data, SCADA and hardware costs included "low load diesel modifications," "power factor correction," "upgraded transfer trip scheme," "SCADA/communications," and "power plant improvements." Thermal storage included large centralized boilers in power stations and community centers and distributed masonry heaters in residences. Electrical energy storage included a flow battery and an advanced lead-acid battery. Integration projects usually only include a subset of the above integration categories. For example, many projects do not include electrical or thermal storage.

DISCUSSION

Capital costs

In Fig. 1, the capital costs (capital expenditure or CAPEX) of wind integration per kilowatt of installed wind capacity can be seen plotted against grid wind energy penetration. Wind energy penetration was calculated as the total predicted wind generation in 1 year (existing capacity and additional capacity from the project) divided by the grid electrical consumption for 1 year. A dashed line connects the individual integration costs with the total cost for projects with more than one type of integration.

The data in Fig. 1 show a statistically significant increase of around $27/kW in the total integration cost per percent increase in wind energy penetration. Note that these are predicted values from applications, not as-built costs. With increasing penetration of a variable energy resource, integration becomes increasingly complex. Thus, it is expected that costs will increase as seen in Fig. 1. Higher integration costs can be offset by lower CAPEX per kilowatt installed for larger renewable energy systems. See the wind power review for average wind CAPEX for different-sized systems.

Operation and maintenance $/kW

Operation and maintenance (O&M) cost data are only available for electrical energy storage. Other O&M costs are needed for SCADA and hardware and thermal storage. See the review on energy storage for electrical storage O&M costs.

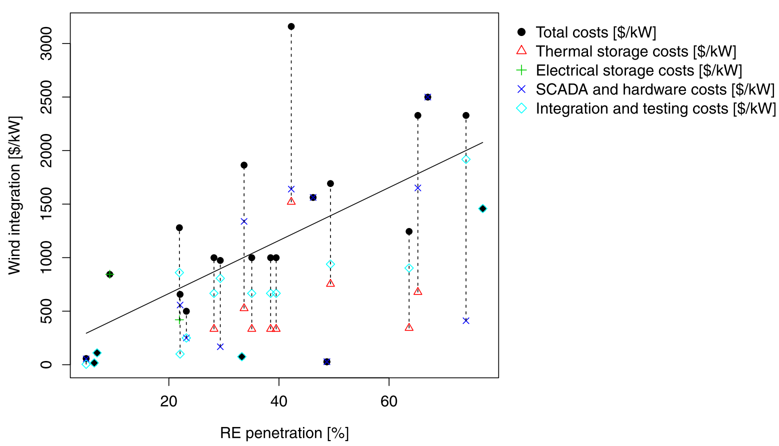

FIG. 1. Capital costs per kW of installed wind capacity plotted against wind energy penetration. The inset shows low values that are difficult to see in the main plot. Wind energy penetration was calculated as the total predicted wind generation in 1 year (existing capacity and additional capacity from the project) divided by the grid electrical consumption for 1 year. A dashed line connects the individual integration costs with the total cost for projects with more than one type of integration.

Expected life

Expected life data are only available for electrical energy storage. The expected life of SCADA and hardware and thermal storage is also relevant. See the review on energy storage for electrical storage expected life.

Capacity factor

Capacity factors are not applicable.

Diesel offset

Proper integration of a variable energy resource into a grid is important for grid stability and power quality. For low energy penetrations ($\lesssim$8% for wind), all the energy from the resource can be used and the diesel generators can account for its fluctuations. At higher penetrations, excess generation begins and cannot be directly fed into firm demands while maintaining grid stability. Different integration schemes allow the use of excess generation to supply electrical or thermal storage or controllable loads.

Upgrades to diesel generators (such as low-load diesels), controllable loads, and electrical energy storage can allow more energy into the grid to supply electric loads (Schaede *et al.*, 2015; Sortomme and El-Sharkawi, 2009). Electrical energy storage accomplishes this by providing SRC or by storing energy during excess generation and releasing it during low generation. See the energy storage review for more information. Controllable loads can be turned on when excess generation is available.

Thermal loads can be supplied with excess generation. In the applications included in this analysis, this process was done by converting electrical energy into thermal energy and storing it in thermal storage, including centralized boilers and distributed masonry heaters.

Using excess generation to supply electric loads displaces more diesel than supplying thermal loads because diesel is much more efficient at supplying thermal loads than electric loads. For example, if a diesel generator generates 13 kWh and a boiler generates 30 kWh of heat with 1 gallon of diesel, then it will take around 13 kWh and 30 kWh of renewable energy to displace 1 gallon of diesel while supplying electric and thermal loads, respectively. However, the integration costs to supply thermal loads with excess generation are often less than the integration costs to supply electric loads.

Cost per kW

Cost per kW or levelized cost of energy (LCOE) data are only available for electrical energy storage. The LCOE for SCADA and hardware and thermal storage is also needed. See the review on energy storage for electrical storage LCOE and levelized cost of cycle power (LCCP).

Conditions for the greatest efficiency

Integration is not a form of energy generation, and thus, integration does not necessarily have its own energy efficiency. Integration does help to increase the energy efficiency of a grid by increasing the utilization of renewable energy generation and reducing diesel consumption. See the *Diesel Offset* section for more information.

Different components used in integration have their own energy efficiency or consumption. A significant example is energy storage, which has losses while charging and discharging and during storage (see the energy storage review for more information). Other components such as switchgear and inverters represent smaller energy losses, with losses in the 5 and 1% range, respectively. A well-designed integration scheme will result in much higher energy savings than losses.

Cost curve over time

The cost curve over time is not only available for electrical energy storage but also needed for SCADA and hardware and thermal storage. For electrical energy storage, see the review for the cost curve over time.

Installed costs by major components

Figure 2 shows the maximum, upper quartile, median, lower quartile, minimum, and outliers for the breakdown of total costs for control integration equipment relative to storage for integration systems incorporating thermal or electrical storage. Control integration equipment includes SCADA, hardware, integration, and testing costs. For both electrical and thermal energy storage, the average control integration cost is around 66% of the total cost and storage is 34%.

Transportation

Transportation costs depend on the weight, size, and shipping restrictions of the integration hardware as well as the distance and available means of transportation to the end destination. Energy storage units can be quite large and can fill several sea containers, depending on the containers' capacity and on the technology. Integration hardware such as switchgear generally can be broken down and transported in small planes, if necessary. An entire electrical cabinet is more difficult to transport. Some forms of energy storage have hazardous materials that need to be disposed off at the end of their life, which often involves transporting them somewhere for safe disposal.

Technology trends

Trends that are being used to integrate higher penetrations of renewable energy in grids include demand-side management (Sortomme and El-Sharkawi, 2009), excess generation to heat (Thomsen *et al.*, 2014), energy storage with grid-forming inverters (Ortjohann *et al.*, 2006), and advanced control systems. Demand-side management allows electrical loads to be turned on and off, depending on the presence of excess electrical generation. Excess generation can be stored in thermal and electrical energy storage. Electrical energy storage and grid-

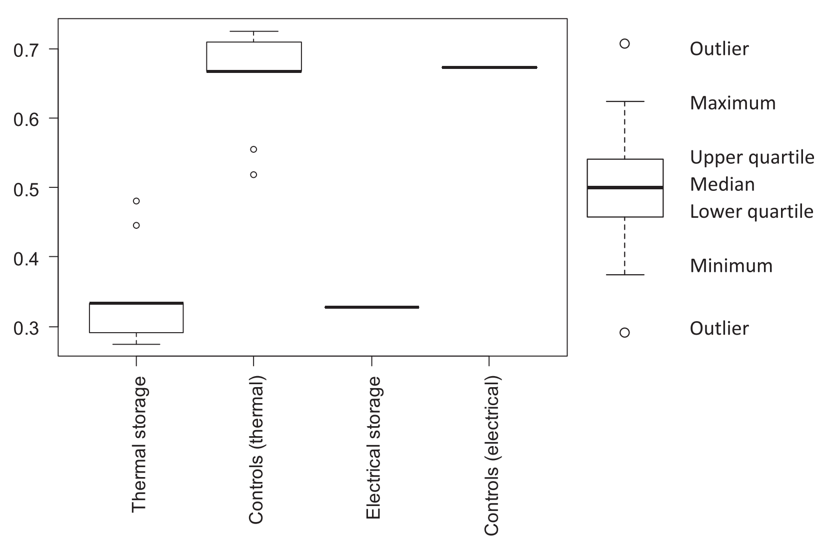

FIG. 2. Ratio of individual to total cost for integration systems including thermal and electrical storage. Controls (thermal) represent the SCADA and hardware and the integration and testing cost ratio for systems including energy storage, and controls (electrical) represent the same for systems including electrical storage.

forming inverters can be used to maintain grid stability and allow diesel generators to be turned off with sufficiently high penetration of renewable energy. Advanced control systems are being developed for microgrids; however, they are often designed for grid-connected microgrids, and it is uncertain how well they will work for remote microgrids.

Tech-specific storage systems

Various electrical or thermal storage systems can be part of integrating an energy source into a grid, as discussed previously.

Refurbishment/upgrade market

Refurbishment/upgrade market data are only available for electrical energy storage. These data are also relevant to SCADA and hardware and thermal storage. For the electrical energy storage refurbishment/upgrade market, see the respective review.

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, the 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 loads but also on specific operating schemes regarding minimum allowable loads on diesels and on available spinning reserve.

CONCLUSIONS

This analysis largely relies on data extracted from twenty-four applications to the State of Alaska Renewable Energy Fund grant program, Rounds 1–8 (2008–2015), and thus may not always represent actual as-built costs. However, the data provide an initial estimate of integration costs. Analysis shows a statistically significant increase of around $27/kW in the total integration cost per percent increase in wind energy penetration. Higher integration costs can be offset by lower CAPEX per kilowatt installed for larger renewable energy systems.

For integration systems incorporating thermal or electrical storage, the average control integration cost is around 66% of the total cost and storage is 34%. Control integration equipment includes SCADA, hardware, integration, and testing costs. Trends that are being used to integrate higher penetrations of renewable energy in grids include demand-side management, excess generation to heat, energy storage with grid-forming inverters, and advanced control systems.

ACKNOWLEDGMENTS

The authors wish to thank the Alaska Energy Authority for its funding to support this project.

Many people have contributed information and insight to this report. For their review and comments, we wish to thank John Cameron from Marsh Creek, LLC; Martin Miller from Coffman Engineers; Ingemar Mathiasson, Energy Manager of the Northwest Arctic Borough; David Burlingame of Electric Power Systems; Jason Custer of Alaska Power and Telephone; Cal Kerr and Dave Weiss of Northern Economics; Dave Messier, Rural Energy Coordinator at the Tanana Chiefs Conference; and Josh Craft, Neil McMahon, and Dan Hertrich of the Alaska Energy Authority.

APPENDIX: INDIVIDUAL PROJECT COSTS FOR INTEGRATING RENEWABLE ENERGY TECHNOLOGIES

TABLE II. Individual project costs. "Wind Power" refers to the wind capacity installed with the current project. "Existing wind power" refers to the wind capacity already existing in the grid before the current project.

Names	Year	Wind power (kW)	Existing wind power (kW)	Average load (kW)	SCADA and communications ($/kW)	Integration hardware ($/kW)	Integration and testing ($/kW)	Electrical energy storage ($/kW)	Thermal storage ($/kW)	Total ($/kW)
Nome phases 3 and 4	2012	900	900	4200	0	0	17	0	0	17
Nikiski wind farm construction	2008	18 000	0	10 976	0	28	0	0	0	28
Kenai winds	2009	18 000	0	10 976	0	28	0	0	0	28
Eva creek wind farm construction	2008	24 000	0	157 000	54	0	4	0	0	58
St. Mary's/Pitkas point	2011	400	0	356	0	0	75	0	0	75
Bethel	2011	1000	0	5000	0	0	111	0	0	111
St. Mary's	2012	300	0	414	0	250	250	0	0	500
Teller	2010	300	0	217	0	558	100	0	0	658
Kongiganak wind farm construction	2008	450	90	210	0	1651	0	0	678	2329
Pillar Mountain	2012	4500	4500	17 000	0	0	0	844	0	844
Nome/newton peak wind farm construction	2008	3000	0	3487	168	0	807	0	0	974
Kaktovik	2011	300	0	420	0	0	667	0	333	1000
Point hope	2011	300	0	620	0	0	667	0	333	1000
Point lay	2011	300	0	310	0	0	667	0	333	1000
Wainwright	2011	300	0	525	0	0	667	0	333	1000
Sand point wind	2009	1000	0	461	0	0	903	0	342	1245
Kotzebue	2010	1800	0	2500	0	0	860	420	0	1280
St. Mary's/Pitkas	2013	900	0	368	0	0	1458	0	0	1458
Emmonak/Alakanuk wind and trans	2009	800	0	489	0	1563	0	0	0	1563
Unalakleet wind farm construction	2008	1200	800	458	411	0	1918	0	0	2329
St. Mary's/Pitkas	2015	380	0	367	0	1338	0	0	526	1865
Tuntutuliak high-penetration wind diesel	2009	475	0	150	0	0	939	0	754	1693
Shaktoolik wind	2009	200	0	92	0	2500	0	0	0	2500
Pilot point	2010	100	0	60	0	1640	0	0	1520	3160

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