Pumping and Storage as a Distributed Energy Resource (DER): Lessons in Costs from Oahu

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ABSTRACT

Distributed energy resources (DERs) are often narrowly defined as generation and storage technologies that can supply power into a transmission and distribution system or a microgrid. However, energy efficiency and demand response have also begun to be conceived as DERs. Responsive end-use loads, energy recovery devices, and load shifting strategies associated with water and wastewater treatment and distribution systems can join the class of technologies that offer grid benefits including economic returns, grid resilience, low-carbon energy, and deferred investment.

This paper shares lessons from a recently completed study of load increase response from pump systems at one of Hawaiian Electric Company's (HECO) largest customers. HECO is interested in automated load increase because it can potentially provide a mechanism for using excess electricity during times when generation levels exceed demand. In this study, we assessed customer-side costs and efficiency impacts associated with automated load increase by water pumping systems. Although changes to water flow rates induced by load increase signals can cause pumps to operate outside of optimal efficiency, we found that pumps might be unique relative to other DERs in their ability to exhibit higher device efficiency when subject to higher flow, depending on the location of a pump's normal operating point. In addition to providing grid benefits, bidirectional load response by water pumping systems may in fact offer very low incremental pumping costs per volume of water pumped during response events. We will contrast these incremental costs and efficiency trade-offs with conventional DERs that offer comparable benefits.

Background and Introduction

To alleviate the dependence on imported oil and coal, the State of Hawaii has a mandate to achieve 40% renewable energy generation by 2030. This mandate and other initiatives have resulted in a large growth of renewable energy system installations. For example, the amount of photovoltaic (PV) energy generation from systems installed on residential and commercial properties increased from 56 GWh in 2010 to 378 GWh in 2013 (Hawaii State Energy Office 2014). However, renewable resources are intermittent and not always available at the same time as customers' demand for electricity and vice versa, and this causes an imbalance of supply and demand on the electricity grid.

The Hawaiian Electric Company (HECO) is interested in using automated, bidirectional load response at customers' facilities as an option for balancing increasingly variable generation with demand on the grid. Automated demand response (including bidirectional response) would provide a mechanism for using excess electricity during times when generation levels exceed demand. HECO has an automated demand response program that is designed to help keep the grid stable and prevent unplanned outages when demand exceeds generation capacity. Although the plan is to include demand response that increases load, as of the end of 2014, program participants only provided load decreases.

In July 2014, the Hawaiian Electric Companies consisting of Hawaiian Electric Company, Maui Electric Company, and Hawaii Electric Light Company submitted their Integrated Demand Response Portfolio Plan (IDRPP) to the Hawaii Public Utilities Commission (Hawaiian Electric Companies 2014). The Hawaiian Electric Companies proposed to implement a portfolio of demand response programs that provide residential and commercial customers with more options to reduce the cost of electricity while at the same time enable higher levels of renewable energy integration and service reliability. One of the grid service requirements outlined in the IDRPP is accelerated energy delivery, which entails shifting the demand for energy from high demand periods to lower demand periods of the day. Furthermore, one of the categories of demand response programs proposed in the IDRPP is Commercial and Industrial Pumping.

Given this background, HECO conducted a study to investigate the potential for implementing automated load increase that specifically targets the water treatment and distribution processes located at one of their largest customers on Oahu. The study was conducted during April to September 2014, and the study team was composed of HECO and three contractors: Applied Energy Group, Aqua Engineers, and EnerNOC (collectively referred to as the “study team” hereafter). This study aspired to provide real-world investigation and demonstration of load increase performance and customer-side costs associated with water pumping within a demand response framework with automated, responsive loads.

Facility Information

The study was performed at a water treatment plant that treats groundwater from a source located underground (known as the “deep well”). The water mainly serves residential users, as well as the office and administrative facilities, while some water is also used for irrigation purposes. Electric loads at the water treatment plant consist mainly of pump loads that amount to 2,580 horsepower, but there are some significantly smaller loads due to aeration blowers and the plant’s offices. Three water pumping stations located downstream from the plant serve to distribute the treated water to a network of storage tanks and reservoirs.

All pumps located at the water treatment plant as well as the three pump stations are controlled by a central SCADA system located within the plant’s office building. All of the pumps in the entire system have soft-start controls, but none of the pumps have variable frequency drive (VFD) controls.

HECO and Aqua Engineers had previously collaborated to enable the water treatment plant to provide automated load decrease and participate in HECO’s automated demand response program. To facilitate communications between the plant’s SCADA and HECO’s demand response automation system (DRAS), a GRIDlink gateway device manufactured by IC Systems was installed in 2013. Aqua Engineers had estimated that the water treatment plant could provide a maximum of 938 kW of load reduction.

Upon examination of the electricity load profile of the water treatment plant, the study team found a high degree of variability in electricity usage by time of day. There appeared to be no discernible usage pattern in the electric loads at the water treatment plant on both weekdays and weekends. As such, it was concluded that the water treatment plant does not follow a fixed schedule of operation, but instead the operation of the plant varies from one day to the next. The maximum demand recorded on a weekday was approximately 1,350 kW, and approximately 1,000 kW on a weekend.

Methodology

Automated Load Increase Strategy

The study team visited the water treatment plant and pump stations in April 2014 to identify potential automated load increase strategies. The strategy that was identified and implemented involves issuing a command at the central SCADA system to fill all reservoirs and tanks. This command initiates pumping at the plant as well as at the three pump stations downstream of the plant. The enablement of the automated load increase strategy was completed during May 2014, and built upon the facility's existing communication infrastructure that was enabled for automated load decrease participation in HECO's automated demand response program.

Test Procedures

After the automated load increase was enabled, a total of 14 one-hour tests were conducted from June to July 2014 to collect data on load increase performance. The testing schedule was designed to (1) focus on increasing loads during the 10AM to 4PM timeframe to coincide with the time of day when the solar energy resource peaks, (2) cover every day of the week, and (3) avoid excessive disruption of the water treatment plant's operations by limiting tests to no more than 2 per day and no more than 3 days per week. The following steps describe the test procedure during each automated load increase test:

1. HECO scheduled a load increase event in their demand response automation system (DRAS).
2. At the pre-determined time, the DRAS provided a load increase signal to the GRIDlink gateway at the water treatment plant.
3. The GRIDlink gateway responded to the signal from the DRAS by triggering the appropriate relay.
4. The water treatment plant's SCADA system responded to the relay closure by issuing a universal command to fill all water storage reservoirs and tanks in the system. At this point, all necessary pumps at the water treatment plant and the three pump stations downstream from the plant operated in response to the SCADA system's universal command.
5. Using the DRAS, HECO scheduled the load increase event to end after one hour has elapsed since the beginning of the test. The DRAS turned off the load increase signal, and the GRIDlink gateway responded by opening the appropriate relay. The SCADA system in turn responded by issuing a universal command to stop filling the reservoirs and tanks.

For each day of the test, the study team collected 5-minute interval demand data for the water treatment plant and the entire facility where the plant is located. The SCADA log of ON/OFF status of all pumps and flow rates at the deep well pumps were also collected.

Baseline Methodology

The study team selected a "Meter Before/Meter After" baseline methodology, consistent with North American Energy Standard Board's performance evaluation methodologies (NAESB 2008). This baseline methodology entails using the 1-hour period immediately before a load increase test as the baseline. Using this baseline methodology was appropriate for this study because (1) the increase in pumping loads are easily observable in the meter data and distinguishable from the period immediately before the increase, (2) the operation of the water treatment plant is highly variable and akin to industrial processes where loads do not follow a fixed schedule, and (3) this methodology carries minimal danger of customers taking advantage of the baseline methodology or "gaming" the system (Holmberg, Hardin, and Koch 2012).

Study Results and Findings

Load Impacts

Load increase magnitude. The average load increase across all test events measured at the HECO meters for the entire facility and pump stations are 671 kW and 42 kW, respectively. The sum of these two figures yields an average load increase of 713 kW at the HECO meters. However, this average load increase figure is misleading because the HECO meter includes loads for the entire facility. The "true" average load increase due only to the controlled loads in the water treatment and distribution system is the sum of the average load increase measured at the submeter for the water treatment plant (526 kW) and the HECO meter for the pump stations (42 kW), which is 568 kW. The following table shows summary statistics for load increase tests.

Table 1. Load increase summary statistics

	Total load increase using HECO meters	Total load increase using submeter for the water treatment plant
Average load increase	713 kW	568 kW
Standard deviation	± 227 kW	± 245 kW
Max. load increase	1,217 kW	1,198 kW
Min. load increase	212 kW	167 kW

Response time and ramp rates. The average load increase response times measured at the HECO meters for the main facility and pump station are both less than or equal to 11 minutes. The average load increase response time for the water treatment plant is less than or equal to 17 minutes.

The load increase ramp rate for each event was calculated by dividing the load increase magnitudes by the corresponding response times. The ramp rates are *minimum* values because the response times are *maximum* values. In other words, the actual load increase ramp rate for each event is expected to be greater than or equal to the values shown in the following table.

Table 2. Ramp rate summary statistics

	Entire facility using HECO meters (kW per minute)	Water treatment plant using submeter (kW per minute)
Average ramp rate	≥ 74	≥ 37
Standard deviation	± 55	± 33
Max. ramp rate	≥ 226	≥ 115
Min. ramp rate	≥ 8	≥ 6

Efficiency Impacts

The load increase tests often triggered additional pumps to operate at each location in the water treatment and distribution system to operate at the same time, compared to normal operating conditions where the pumps more frequently operate individually. When more pumps operate at the same time, water flow rates increase but friction losses in the pipe increase as well. Ultimately, pumping efficiency decreases during the load increase tests due to the increase in friction losses.

Using the flow rate data for the deep well pumps, the study team determined that the total average flow for three pumps running simultaneously was 5.60 kgal/min, which equates to 1.87 kgal/min per pump. In comparison, the average flow for each pump when operating alone was 1.93 kgal/min. Therefore, operating three pumps at once results in a reduction in flow of 0.06 kgal/min per pump or a difference of 3.3%, compared to when the pumps run individually.

The water treatment plant personnel provided the study team with manufacturer pump test data (including pump curves) for the deep well pumps. The manufacturer data was used to develop a regression analysis that describes the relationship between flow and pump efficiency for the deep well pumps. Using this regression analysis, the study team found that a reduction in flow of 0.06 kgal/min would result in a loss in pump efficiency of only 0.3%.

Cost Impacts

The cost of automated load increase enablement at the water treatment plant and the three pump stations totaled $76,304. This entire cost was paid by HECO, and the facility did not incur any direct costs due to load increase enablement. The “true” average load increase (obtained from submetering) that only includes loads at the water treatment plant and the pump stations results in the enablement cost per kW of load increase of $134 per kW.

The total increase in energy due to the load increase test events conducted in this study is estimated to be 8,311 kWh for the facility and 366 kWh for the pump stations (total of 8,677 kWh). This translates into a total increase in energy cost of $2,145 for all 14 test events, or $153 per test event, using HECO’s Rate Schedule DS. However, most of the additional energy consumed during the load increase events is actually stored as head pressure in the water reservoirs and tanks. That energy is recovered when water flows out of the reservoirs and tanks, and therefore the additional energy consumption due to the load increase events is small. The small portion of energy that is not recoverable is attributable to increased system pressure and friction losses that lower the pumping efficiency when multiple pumps run at the same time. This non-recoverable increase in pumping energy was estimated to be only 0.3% for the deep well pumps.

The study team also found that the load increase tests resulted in an increase in billing demand during the months of June and July when the tests were conducted. HECO provided the facility with demand charge protection and removed the demand increase amounts from the electric bill. Without the demand charge protection provided by HECO, there would have been an additional demand charge of $768.60 on the June bill and $8,043 on the July bill due to high peak demand caused by the load increase tests.

Grid Benefits and Costs of Distributed Energy Resources (DERs)

As the definition of DERs has expanded to encompass generation, energy storage, and responsive end-use technologies in grid-connected or microgrid applications, so too has the suite of grid-related benefits and approaches for their valuation. One framework for valuation is perspective-based—utility/grid benefits and costs; customer benefits and costs; and societal benefits and costs.

For responsive end-uses and demand response in particular, the suite of grid benefits has evolved toward ancillary services and related products,[1] including scheduling, system control and dispatch; reactive supply and voltage control; regulation and frequency response; energy imbalance; operating reserves; and black start. However, due to the distinct requirements for each of these services, only end-uses and technologies with applicable physical and technical characteristics should be compared to assess costs and benefits.

Classifying Responsive End-Uses as DERs

Although only a limited number of end-uses have been tested as DERs to date and at scale, Olsen et al. (2013) as part of major national laboratory collaborative effort have developed a broad framework for assessing the value of end-uses as DERs—particularly in those with demand response and energy storage capabilities. The modernization of the grid offers the possibility for DERs to provide ancillary services that have historically been limited to supply-side and transmission and distribution (T&D) assets. The set of end-uses considered as DERs are those that (1) are responsive (i.e. controllable) and (2) offer the potential to give (use less), take (use excess), or store energy.

Table 3 below outlines a set of grid services together with the physical requirements for each, subsequently used for production cost modeling by Hummon et al. (2013). Figure 1 includes a set of end-uses across various customer segments that have capability and potential for providing the services outlined in Table 3.

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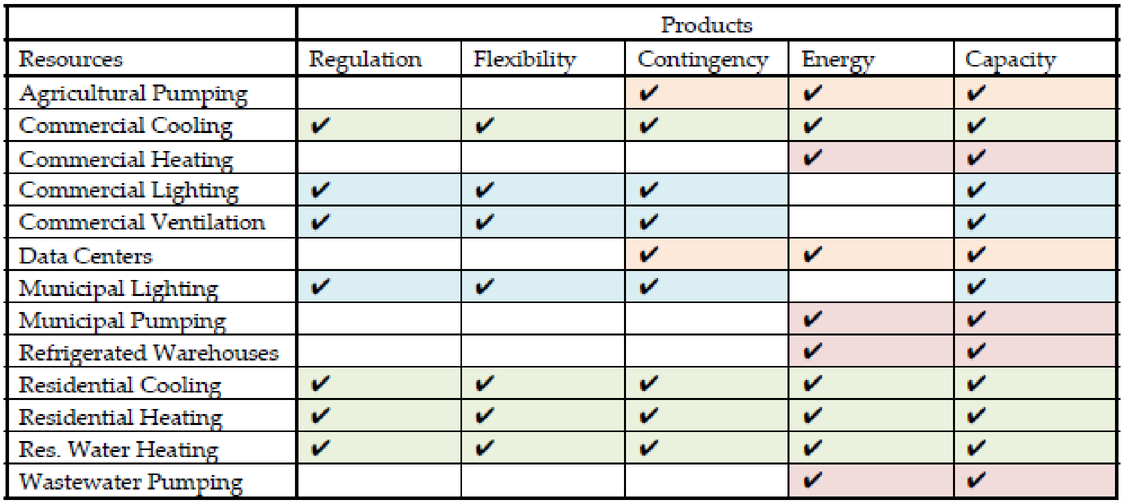
[1] Ancillary services have been defined by FERC (1995) as “those services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.” However, the set of terms and related products differ across providers, jurisdictions, and in the literature.

Table 3. Selected grid services/products and associated physical requirements

Grid service / product	Description	Response time	Time to full response	Response duration	Response frequency
Energy	Shed or shift energy use over time	5 minutes	10 minutes	≥ 1 hour	1-2 times daily, with 4-8 hour notification
Regulation	Response to random unscheduled deviations in scheduled net load (bidirectional)	30 seconds	5 minutes	15 minutes till energy neutral	Continuous during bid period
Flexibility	Additional load-following reserve for large unforecasted wind/solar ramps (bidirectional)	5 minutes	20 minutes	1 hour	Continuous during bid period
Contingency	Rapid and immediate response to a loss in supply	1 minute	≤ 10 minutes	≤ 30 minutes	Less than once daily

Adapted from *Source*: Hummon et al. 2013.



	Products				
Resources	Regulation	Flexibility	Contingency	Energy	Capacity
Agricultural Pumping			✔	✔	✔
Commercial Cooling	✔	✔	✔	✔	✔
Commercial Heating				✔	✔
Commercial Lighting	✔	✔	✔		✔
Commercial Ventilation	✔	✔	✔		✔
Data Centers			✔	✔	✔
Municipal Lighting	✔	✔	✔		✔
Municipal Pumping				✔	✔
Refrigerated Warehouses				✔	✔
Residential Cooling	✔	✔	✔	✔	✔
Residential Heating	✔	✔	✔	✔	✔
Res. Water Heating	✔	✔	✔	✔	✔
Wastewater Pumping				✔	✔

Figure 1. Participation of resources in ancillary services, energy, and capacity products.[2] Color shading represents end-uses that provide comparable sets of grid services. *Source*: Olsen et al. 2013.

The data presented in Figure 1 are consistent with modeling exercises, real-world projects, and pilot programs that demonstrate the grid services capabilities indicated for each of the end-use DERs shown. The “Capacity” product is described as the “ability [for the end-use

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[2] Industrial manufacturing end-uses have been classified similarly in a separate report (Starke et al. 2013). Other end-uses that were not considered due to inadequate data or perceived low load magnitude/capability include residential appliances, commercial water heating, electric vehicles, and miscellaneous plug loads (Olsen et al. 2013).

resource] to serve as an alternative to generation" for the top-20 hours coincident with system peak (Olsen et al. 2013). The water pumping end-use resources tested in our load increase study are most similar to municipal pumping, which can provide energy and capacity grid services. Municipal pumping is comparable to wastewater pumping, refrigerated warehouses, and commercial space heating for providing energy and capacity grid services.[3]

Efficiency Comparisons

Comparing device and system efficiencies across various end-uses and technologies can be challenging due to the variety of performance ratings for each end-use technology. One commonly used approach for performance rating is estimating the ratio of input energy (or power) to useful output (mechanical work, stored energy, transformed energy, useful service, etc.) or vice versa. For instance, refrigeration systems are commonly rated using the ratio of input electric power (kW) to rate of cooling supplied (tons), whereas pump systems are characterized by a dimensionless pump efficiency that is the ratio of hydraulic (or fluid) power delivered to input electric power. Rather than direct performance comparisons across the foregoing end-uses, we discuss performance *changes* during typical operations for each end-use and comment on system behavior and possible points of comparison.

Water pumping systems. Figure 2 below illustrates the possible change in operating efficiency for a pump system due to changes in pump speed (and flow).

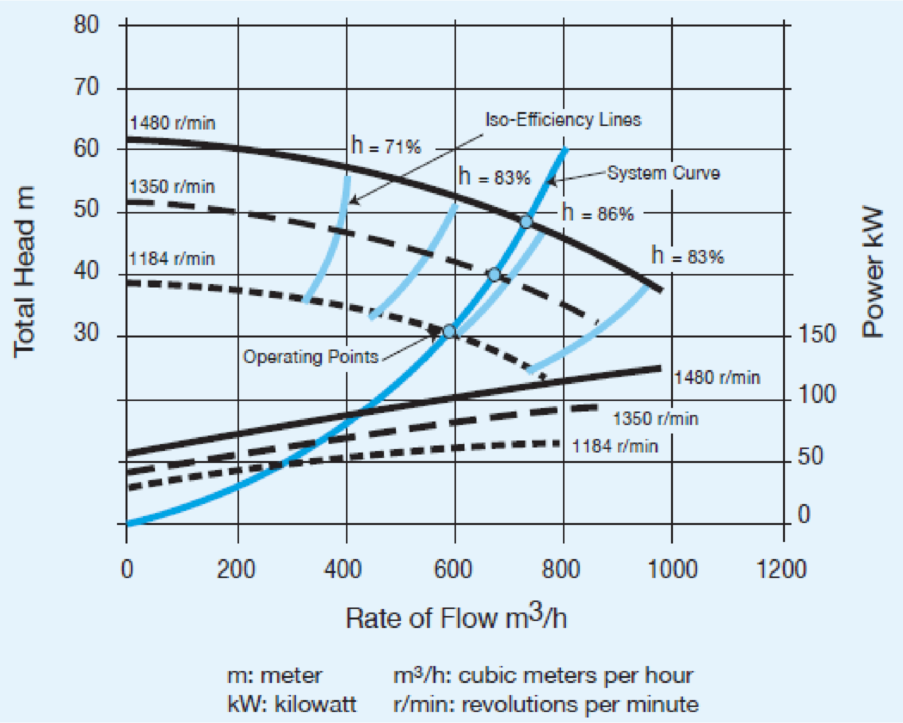

Figure 2. Effect of pump speed change in systems with only friction loss. *Source*: Hydraulic Institute 2004.

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[3] Technologies are emerging that add controllability and storage capabilities to each of these end-uses that may allow each to provide ancillary services such as regulation or flexibility—e.g. variable frequency drives (VFDs), phase change materials (PCMs), and thermal storage systems for pumping, refrigerated warehouses, and commercial space heating respectively.

When properly designed, pump systems normally operate at or near their best efficiency point (BEP). However, increases or decreases in pump flow can result in deviations from BEP and normal operating efficiency. Depending on the characteristics of the system head curve, increases or decreases in pump flow could correspond to increases in pump system efficiency. Typical design efficiencies (i.e. BEP) for centrifugal pumps are 65-90% (Pumps & Systems 2015), while designers tend to specify operating points that are within 10-20% of the BEP. The normal operating point for one of the deep well pumps in our study was 3% less than the BEP of 83%.

Refrigeration systems. Refrigeration system performance depends primarily on compressor performance, which in turn depends on compressor type and size and the condenser type. Typical performance ranges are 0.8-1.2 kW/ton (air-cooled systems) and 0.3-0.7 kW/ton (water-cooled systems) (Progress Energy 2015; E Source 2015).

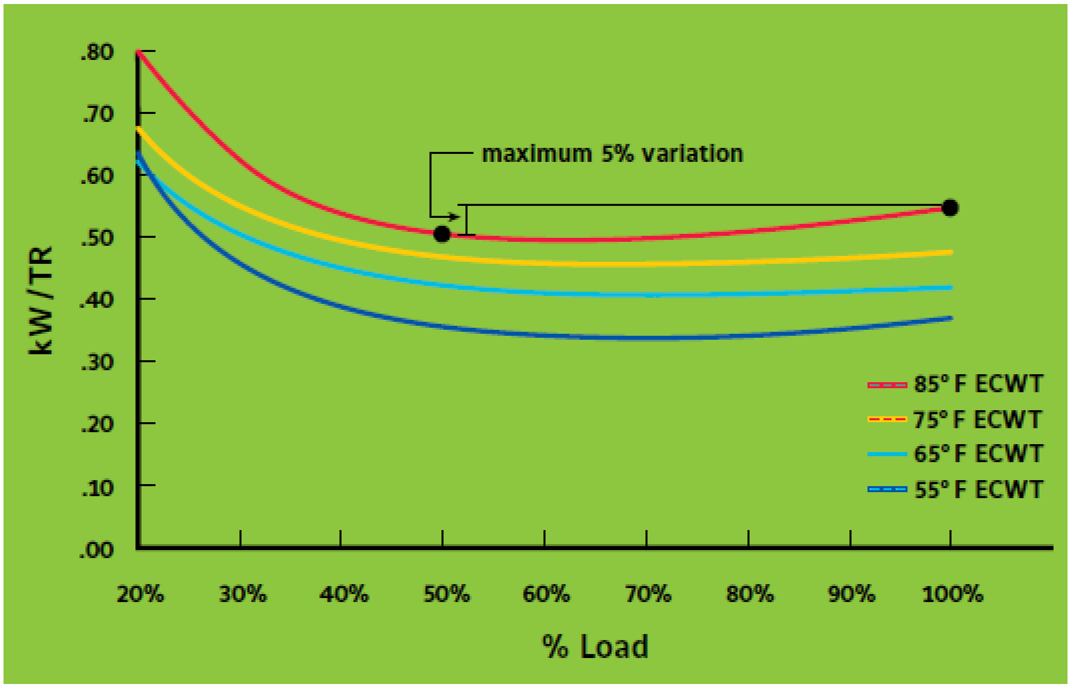

Figure 3. Chiller performance changes with variable load at different condensing conditions for "average" water-cooled centrifugal chiller. *Source*: Johnson Controls 2009.

Similar to centrifugal pumps, under certain conditions, some types of chillers can exhibit increased system efficiency due to increases or decreases in load. As shown in Figure 3 above, this level of variation can be up to 5%.

Commercial space heating systems. These systems vary in type from forced air furnaces to hydronic systems with boilers. The annual fuel utilization efficiency (AFUE) is used to characterize the performance of space heating systems and represents the conversion efficiency of various fuels into heat, whilst accounting for cyclic changes in operation due to changes in heat load throughout the year. Therefore, AFUE is a fixed rating for a given furnace or boiler. For all-electric furnaces and boilers, typical AFUE is 95-100% (U.S. DOE 2015).

Conventional DERs. These resources include energy storage technologies of comparable scale to the end-use DERs above, including conventional batteries. Efficiencies for electrochemical batteries range from 60-94% (Ecofys 2014), depending on type.

Cost Comparisons

The determination of true costs associated with DERs' provision of ancillary services is still the subject of much research, market, and policy debate. Several major collaborative efforts have been completed and are ongoing to address these questions (Hummon et al. 2013; Watson et al. 2012).

Deployment and enablement costs.[4] The average enablement cost obtained in our study was \$134/kW, which compares favorably with historical automated demand response enablement costs ~\$276/kW (Wikler et al. 2009) and even more so with capital costs for electrochemical batteries, ~\$1,031-\$5,320/kW (Carnegie et al. 2013).

Conclusions and Recommendations

We have shown that water pumping with storage capability can provide load increase in the context of bidirectional, automated demand response testing and do so at competitive costs for deployment at prevailing energy rates, while minimizing demand charges. We found that municipal and agricultural pumping together with some refrigeration end-uses are somewhat unique in their ability to exhibit increased system efficiency at increased loads. However, to provide ancillary services such as regulation, both water pumping and refrigerated warehouse end-uses require sufficient storage capability to ensure that normal operations are not compromised.

We also established that the addition of suitable telemetry and metering, in conjunction with variable frequency drives could improve response times and ramp rates and potentially sustain continuous, near-real-time operation during response periods. In addition to conventional DERs such as electrochemical batteries, controllable end-uses with both active and passive storage capability such as water pumping/storage could also be cost-effective resources for energy services, capacity services, and maintaining grid reliability as the penetration of variable renewable generation increases.

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[4] Study costs are reported in 2014 dollars. Other costs converted to 2014 dollars for comparison.

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