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Smart End-use Energy Storage and Integration of Renewable Energy

A Pilot Project Overview

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Bonneville Power Administration, Technology Innovation Program

Project Partners

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Date

October 16, 2012

Acknowledgements

This report is a reflection of the collaborative nature of the project and includes important contributions from many talented individuals. The Authors wish to extend our gratitude to the Bonneville Power Administration's Technology Innovation Program and Energy Efficiency / Demand Response Program. Both of these groups provided not only generous funding for the work described herein, but also rich and substantial cooperation and support throughout the project timeframe.

Executive Summary

Ecofys has led an investigation into the viability of smart end-use energy storage technologies in the Pacific Northwest region of the United States. These resources can help meet important needs of the region's primary producer of electric power, the Bonneville Power Administration (BPA), as well as its customer utilities. The main driver for this project is the need to identify new cost-effective, low carbon resources to help integrate renewable energy into electricity grids, particularly wind.

As a practical matter, the levels of generation and load must equal on a moment-to-moment basis to maintain grid stability and power quality. The theory behind the project is that in principle, the control actions traditionally taken by generating units to ensure this balance have an equivalent countermeasure that can be achieved by loads. The recent advances in, and the relative ubiquity of, modern information technology is beginning to allow power system operators to tap into a potential demand-side resource for services historically provided by generation.

For this project, Ecofys and its partners have identified and applied responsive thermal end-use technologies that can provide conventional demand-side management, such as peak reduction and load shaping, as well as novel balancing services that will assist with the integration of variable renewable energy sources, such as wind. These technologies span the residential, commercial, and industrial end-use sectors and includes:

1. Electric water heaters
2. Electric furnaces
3. Cold storage facilities
4. Commercial HVAC systems

The scope of all demonstrations together is a portfolio of more than 1 MW of controllable load distributed throughout seven regional utility districts.

Different load control strategies aimed at different operational objectives have been implemented. Of particular interest to the project stakeholders is the ability to control the demand-side resources to provide both a decrease and increase in load. This requirement is mainly due to the need for bi-directional balancing services, which result from over and under generation forecasts of both variable supply and demand. This further allows consumer utilities to charge thermal mass during off-peak periods, in order to reduce future demand peaks.

Implementation of this type of control strategy involves installing communication infrastructure either directly on existing devices or during retrofit stages. The resultant network is connected to the system operator, who utilizes online operational data to manage the available portfolio accordingly. A major project component has been to define management strategies in a manner that seamlessly integrates these new resources within conventional power system management.

The results of the project are encouraging. The cold storage facilities and HVAC systems have shown great potential to shift large amounts of load; the water heaters have displayed the ability to provide enough flexibility to take advantage of multiple value streams (balancing, peak reduction, and load-shaping). In all cases, end-use functionality of participating units is maintained at levels commensurate with consumer satisfaction.

Detailed analysis of the project results has allowed Ecofys to develop an integrated business case model. The tool can potentially be used to develop future build-out plans for increasing the penetration of responsive end-use devices.

In general, the outcomes of this project will prove vital for BPA and other participating regional utility districts in moving forward with the development of a smart end-use energy resource. Furthermore, this project provides real experience that has great potential to be applied within a variety of different power systems here in North America and abroad.

1 Introduction

The Bonneville Power Administration (BPA) is the primary producer of electricity in the Pacific Northwest region of the United States. BPA provides power to approximately 2.5 million customers (87% residential, 12% commercial, and 1% industrial). The area is blessed with access to low carbon energy. Beyond the 22 GW of seasonal hydro capacity, BPA currently has more than 5 GW of wind resources connected within its management area. Significant expansion of wind power is further predicted over the next decade (Figure 1).

Wind power production is inherently variable and difficult to accurately predict. In order to ensure supply and demand balance, power system operators must have a coordinated set of reserves. BPA studies suggest that the extensive Columbia River hydro system that it oversees may not be able to provide the balancing reserves future regional wind capacity will require.

Constructing flexible natural gas combustion turbines as an alternative balancing resource is an option. However, these systems are expensive to operate. Furthermore, this configuration will result in wind power intrinsically relying on fossil fuel—the very thing that is to be displaced by wind integration.

A further issue is that of over-supply. During the spring run-off, significant hydro capacity is available in the region. When combined with instances in which wind power production is also high, there are in fact times when too much clean energy is available. Fish & wildlife regulations prevent BPA from reducing hydro output; instead, wind energy has been curtailed. Having a place to store this excess energy would avoid low carbon resource waste. However, conventional energy storage systems are very expensive and can be inefficient. For this reason, current energy storage technology is not considered a viable option at this time.

Over the period from September 2010 to September 2012, Ecofys has led an investigation into alternative approaches and technologies that can help BPA meet balancing and storage necessities moving forward. The primary driver for the project is the need to identify cost-effective, low carbon resources that can help integrate large amounts of wind power into electricity grids.

The operational issues identified above are not unique to BPA. Other system operators experiencing rapid expansion of variable renewable energy resources, such as in Hawaii, Germany, and Ireland, are facing similar problems. The outcomes of this project therefore have broad implications that can potentially be applied globally.

The primary driver for the project is the need to identify cost-effective, low carbon resources that can help integrate large amounts of wind power into electricity grids.

1.1 Smart Demand-side Resources

Fundamentally, any actions taken by generating units to ensure that supply and demand balance have an equivalent countermeasure that can be achieved by loads. The recent advances in, and the relative ubiquity of, information technology is beginning to allow grid operators to tap into demand-side resources for services historically provided by generation. Referred to as demand response (DR), these programs exist in many power systems for peak demand reduction. However, DR has yet to be a proven resource for balancing reserves or over-supply mitigation.

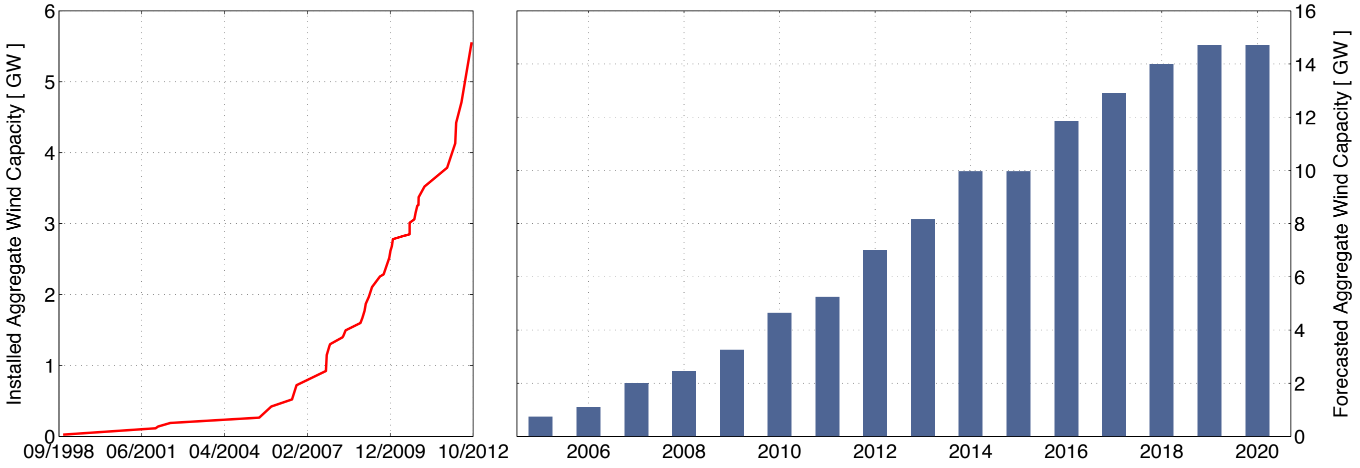

Figure 1: Current (left) and forecasted (right) wind power capacity in the BPA management area

Current DR products only have the capacity to reduce demand. Wind generation and demand forecast error can be positive or negative, meaning that balancing would require the capability to control the demand-side resources to provide both a decrease *and* increase in load. Over-supply mitigation would further require demand to increase, in order to absorb excess energy.

For the demonstration project, Ecofys and its partners have identified and applied responsive end-use technologies that can provide conventional DR, as well as novel products that will assist with variable renewable generation integration, traditional unresponsive load variability, and over-supply. The goal is to obtain a *smarter* DR resource; one that is valuable to multiple stakeholders. This smart DR resource will help overcome forecasted balancing and over-supply constraints, as well as reduce peak demand. The latter delays generation expansion and grid infrastructure upgrades, which will reduce the cost of electricity for BPA customer utilities.

The goal is to obtain a smarter DR resource; one that is valuable to multiple stakeholders.

1.2 Smart End-use Technologies

Many end-uses are inherently flexible. Specifically, thermal loads that are designed to operate over a range of conditions have inherent energy storage in the form of thermal mass. Thermal loads can charge thermal mass and then coast through intervals inactive by relying on thermal energy stored in the system. Grid operators could defer operation to more cost-effective times, such as when an excess of wind power is available, without reducing functionality. Thermal loads could therefore act as a source of energy storage distributed throughout the grid.

Thermal loads are prevalent, representing more than half of the residential and commercial sector electric power demand in the Pacific Northwest. This includes heating and cooling systems in buildings, as well as water heaters. The demonstration project concentrated on an array of these thermal end-uses including:

1. Electric water heaters
2. Electric furnaces
3. Cold storage facilities
4. Commercial HVAC systems

The tested electric furnaces and water heaters are special in the sense that they have been manufactured specifically for increased energy storage capabilities. The water heaters have a mixing valve that allows above average hot water temperatures; the furnaces have dense ceramic bricks that can store heat for later use in building temperature control. Either technology can extract more energy from the grid than conventional designs, and wait longer between charging events.

Thermal loads that are designed to operate over a range of conditions have inherent energy storage in the form of thermal mass.

Buildings themselves contain significant thermal mass that can also be charged with energy from the grid. Whether it be for cooling or heating, if there is flexibility in temperature, building HVAC loads can be increased or decreased over brief periods without impacting occupant comfort. This applies for cold storage as well, which must cool thermal mass using large refrigeration equipment.

In order to make these loads smart, devices are equipped with two-way communication technology. Many of these devices are then connected via a network. Real-time data is monitored, and sent to the network operator, who utilizes it to manage the portfolio according to the current needs of the grid.

A major project component has been to define network control strategies that seamlessly integrate within conventional power system management. One option is to control loads using dynamic electricity prices. This framework relies on the consumer, or device-level automation technology, reacting to changes in price. The Pacific Northwest lacks a sub-hourly power market, meaning that price changes could not be used to achieve sub-hourly responses. This timeframe is of particular importance to balancing, and therefore the demonstration project focused on a different route. Namely, directly controlling the responsive end-use technologies in real-time based on the needs of the consumer and the grid.

1.3 Pilot Project Sites

Figure 2 depicts the geographic distribution of the pilot project sites and associated technologies tested therein. BPA does not serve end-use consumers directly, but instead supplies power to approximately 150 utility customers. A large number of these customer utilities are publicly owned, while others are owned by investors. Supply contracts and sector demand breakdown also differs between utilities. In order to capture the varying needs of regional stakeholders, the project pursued demonstrations in multiple utility districts. In total, seven utilities distributed across 3 states participated in the project.

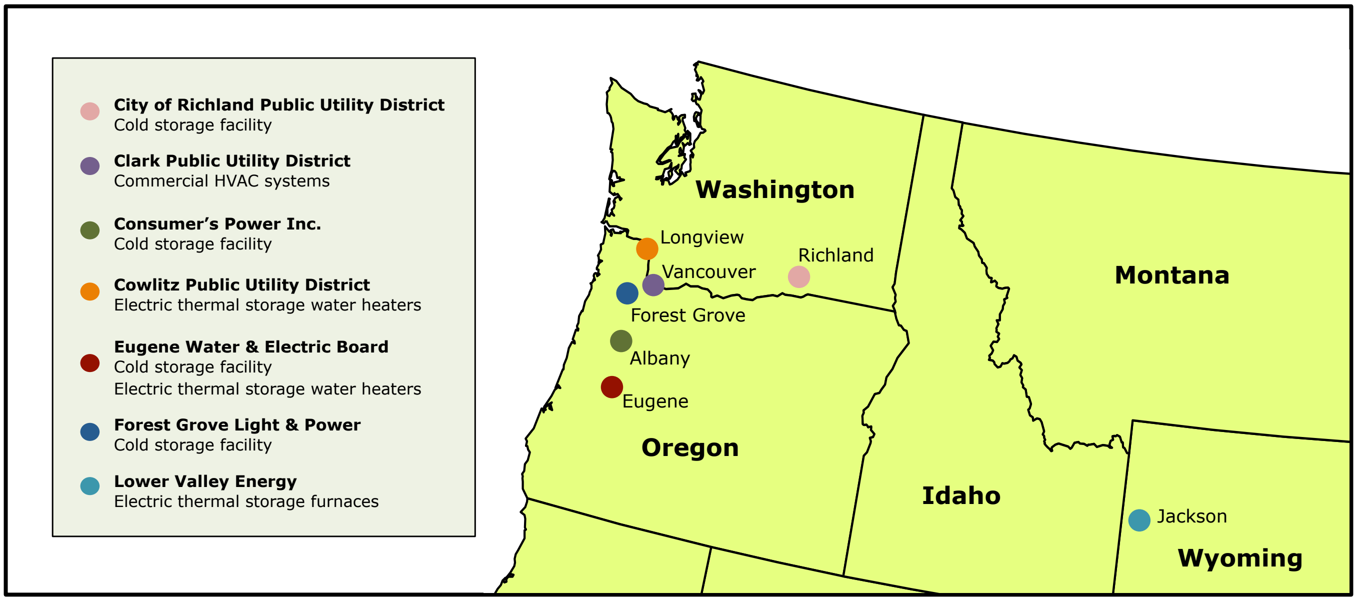

Figure 2: Project type, host utility, and geographic distribution of the pilot projects

2 Cold Storage and HVAC Pilot Projects

2.1 Configuration

The cold storage and commercial HVAC systems are connected to network operation centers through a wireless internet connection (Figure 3). There were three separate vendors that provided the technology and operational support to enable the connection and operate the network servers. This included EnerNOC (four sites), Cypress Envirosystems (two sites), and UISOL (one site).

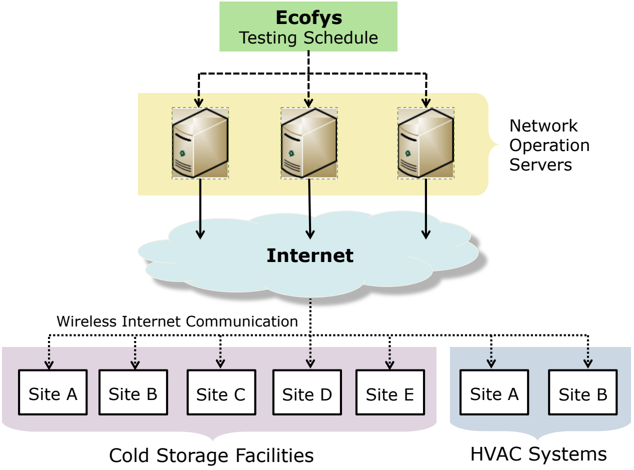

Figure 3: Testing configuration for the cold storage facilities and commercial HVAC systems

Test events were planned at least a day in advance and consisted of a request from the site for either an increase or decrease in demand. Site operators and customer utilities were first consulted to identify periods in which DR control would be disabled. This included times for site maintenance, utility peak demand periods, and when operation of the targeted equipment was deemed critical.

A central issue identified during this process was that smart DR control (increases in load) can conflict with current utility pricing strategies. Many commercial pricing contracts set the monthly price based on the monthly demand peak. Demand increase tests have the potential to cause new demand peaks, which would result in higher site-wide electricity prices. In order to overcome this problem, Ecofys negotiated with utilities to provide sites with pricing amnesty during testing events.

The vendor that enabled the HVAC sites offered an interactive web-based DR event scheduling portal. Test events consisted of temperature set-point changes. Increasing the temperature set-point results in an increase in heating demand or HVAC load. Conversely, decreasing the set-point reduces demand. The internet communication system connected to building-distributed wireless pneumatic thermostats, which updated controlled zonal set-points on a 15 minute timeframe.

For the cold storage sites, Table 1 summarizes the targeted equipment and responses. The average demand at the sites is also provided for comparison with the requested response. The average demand varies due to seasonal cooling requirements.

Site	Controlled Equipment	Average Demand	Target Increase	Target Decrease
A	Compressors	400 – 700 kW	200 kW	200 kW
B	Compressors, Evaporators	400 – 700 kW	100 kW	200 kW
C	Compressors, Evaporators	100 - 450 kW	50 kW	200 kW
D	Compressors, Evaporators	700 – 1100 kW	100 kW	200 kW
E	Compressors, Evaporators	700 – 900 kW	200 kW	200 kW
Total	-	**2300 - 3850 kW**	**650 kW**	**1000 kW**

Table 1: Characteristics of the cold storage demand response pilot sites

Upon receipt of a DR request, the refrigeration control system responds by implementing the appropriate load curtailment or increase strategy. The system architecture required for establishing this communication over the internet consisted of two major elements: a server for dispatching the event signal, and a client located at each facility to monitor the signal and interface with the refrigeration control system.

2.2 Cold Storage Results

Up to 20 increase and 20 decrease events occurred over the testing period. In order to mimic the response of a portfolio, the requests were synchronized across all sites. Nonetheless, operational constraints often resulted in certain sites only participating in some events.

The main outcomes of the testing phase are summarized in Figure 4. A boxplot of the response error distributions is depicted. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually. The outliers are data points that fall outside a 99% confidence interval.

Figure 4 shows that substantial variability in the response error occurred. In some instances, a demand increase or decrease request was followed by the opposite reaction. In other cases, significantly more or less response was seen as compared to that requested. Overall, demand decrease events were followed more accurately than demand increase events. Also, when the total response is considered, variability and error is reduced. It is further noteworthy that some sites performed markedly better than others. For instance, Site E in comparison to Site C.

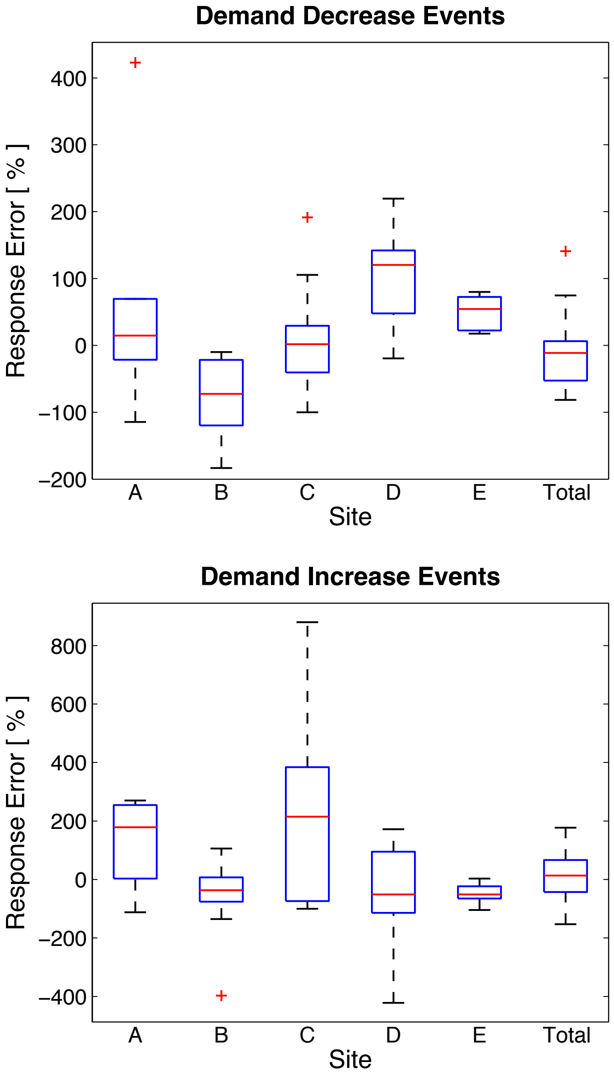

Figure 4: Variability observed in cold storage demand response pilots

2.3 Commercial HVAC Results

Testing of Commercial HVAC system DR consisted of several pre-planned events. Positive and negative set-point changes were implemented in order to increase or decrease the load. A major objective of the testing phase was to demonstrate the capability of the smart DR technology to pre-heat building thermal mass in order to shift HVAC load away from the morning peak.

The HVAC systems responded sluggishly to the set-point changes. This was partially the result of the HVAC temperature control system, which relies on integral gain within the control loop. Further compounding the problem was the slow thermostat update times, which often resulted in responses taking greater than 30 minutes.

3 Water Heater and Furnace Pilot Projects

3.1 Configuration

The water heater and furnace installations are connected to a server over the internet. Steffes Corp. provided the technology and support to enable the connection and operate the network server. At the device-level, a laptop controls and monitors important state variables in real-time (Figure 5). Tank temperature is measured at several locations throughout the tank. Electric power consumption is controlled via a power processing unit.

Conventional water heaters charge at a single demand-level and reach a maximum temperature of about 125 °F. The water heaters used in the project are equipped with a mixing valve that allows water temperatures to reach a maximum of 170 °F, and further support variable charging rates. These added features enable the water heater greater response granularity and energy storage capabilities as compared to classical designs.

Control strategies were initially focused at the individual water heater level, and later transitioned to managing the loads as a fleet. BPA balancing reserve dispatch requests were sent directly to the devices, where it was processed into a local objective. The hydro system is well-equipped to follow small amplitude balancing requests, so water heater response was only triggered when the dispatch level went above a certain threshold. The aim was to charge the units when the balancing request was negative (a generation surplus) and remain idle when the balancing request was positive (a generation deficit). Simultaneously, the local controllers guarantee that water temperature remains sufficient to meet consumer demand.

Figure 5: Installed 105 gallon water heater with Steffes™ mixing valve and interactive controls

Similar to the commercial cold storage and HVAC pilots, the host utilities were asked to provide time intervals over which zero water heater demand would be beneficial. This corresponded to the utility's peak load hour.

The furnace systems are operated similarly to the hot water heaters. Testing is only now commencing and will continue through the end of the year.

3.2 Results

Control strategies have been tested almost continuously since device installation, which has resulted in a plethora of operational data. Figure 6 depicts an example of the water heater performance, where the aggregate response of two units is given over a 24-hour period. The dispatched balancing reserves trajectory is also depicted. It has been inverted (multiplied by -1) for comparison purposes, as it conventionally represents the need for generation, and not the need for demand.

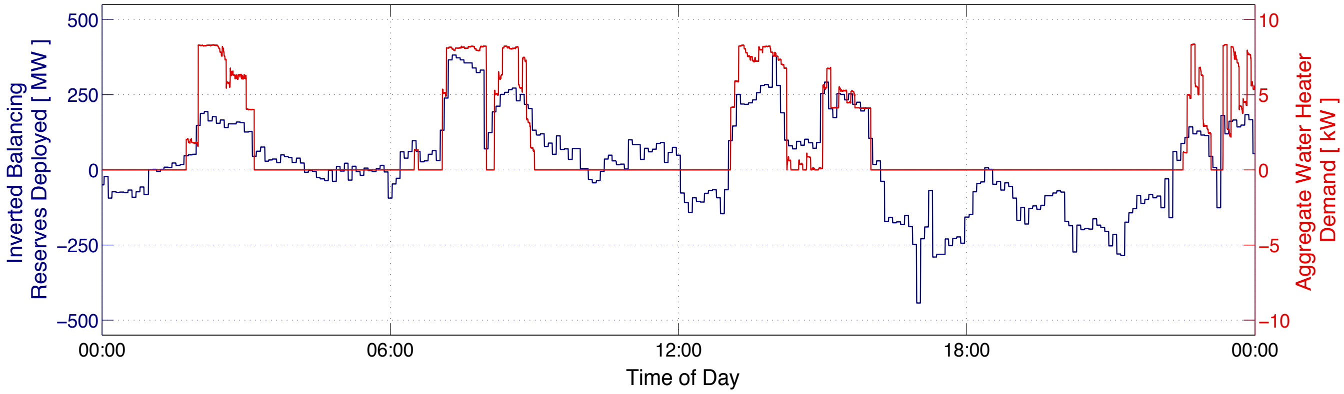

Figure 6: Balancing reserves deployed (inverted) and aggregate response from two Steffes™ thermal storage water heaters over a one day period

The water heaters respond quickly and accurately to the large amplitude balancing requirements. The units are also able to coast through generation deficit intervals and the utility peak demand hours inactive.

During all tests, water temperature is strictly maintained at a level ensuring consumer satisfaction. In order to gage actual end-user experience, a customer feedback survey was distributed to participants. All respondents indicated that the water heater matched and often outperformed their previous unit's quality of service.

4 Business Case Model

4.1 Description

Although the verified pilot project results are encouraging and have provided invaluable firsthand experience, the full potential of a smart DR program is to be observed when there exists a high-penetration of the technology. Such a build-out will be costly, which begets the need for planning models capable of accurately assessing investments and payback periods. For this purpose, Ecofys developed an integrated business case model, designed to provide a description of the salient economic impacts expected under different penetrations of smart DR resources.

Figure 7 depicts the input-output structure of the business case model. The user inputs their electricity pricing strategy and selects which DR technologies they would like to investigate. The current version allows for different water heating and furnace technologies to be analyzed, with expansion to other devices planned in the future. The user is also able to input and toggle important DR revenue assumptions, such as those from DR resources providing balancing, and reducing peak demand. The user inputs are then implemented within a model to compute important parameters. This includes program build-out strategy, capital costs, operating costs, and revenue streams. The model is calibrated based on actual technical and economic data obtained from the pilot project results.

4.2 Example

An example of the business case model is provided in Figure 8. Four technologies have been selected for the analysis. In total, the build-out consists of 480 responsive end-use technologies. The model considers DR revenue from multiple streams including balancing, peak reduction, and load-shaping. Costs include capital and program operating expenditures. After nine years the DR project is estimated to have a net present value of almost $70k.

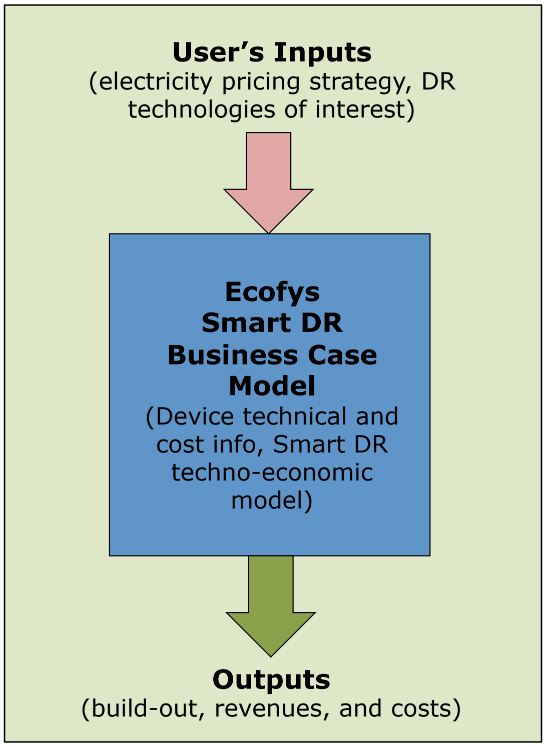

Figure 7: Input-output structure of the smart DR business case model

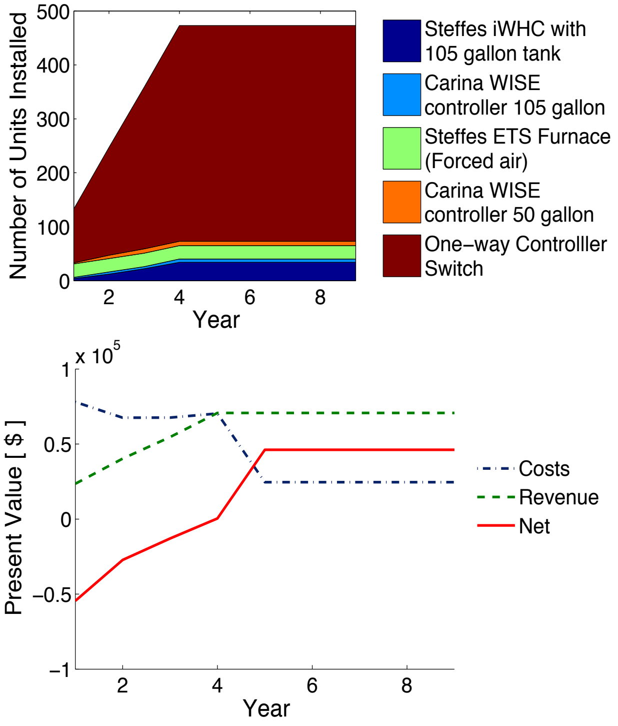

Figure 8: Example results of the business case model

Conclusions

Ecofys has led an investigation into the viability of smart end-use energy storage technologies in the Pacific Northwest region of the United States. Various thermal end-uses were enabled with advanced DR capabilities, allowing for demand to be increased and decreased by network operators. This included cold storage facilities, commercial HVAC systems, electric water heaters, and electric furnaces. The complete portfolio represented more than 1 MW of controllable load distributed throughout seven regional utility districts. Testing was pursued over a one year period, resulting in a surplus of operational data and modern DR program development experiences.

In the case of cold storage, program aspects such as inflexible demand charges affected sites' ability to add load as much or more than the historical demand capability. Furthermore, technology vendors were thus far only experienced in providing load shedding DR services. The learning curve resulted in load increase response accuracy significantly improving over the course of the project. Certain sites performed far better than others, emphasizing the need to fully assess operational differences when recruiting potential sites. When considered across the entire portfolio, variability and response error was meaningfully reduced; an outcome that underlines the importance of a portfolio approach.

The water heating systems displayed the ability to provide enough flexibility to take advantage of multiple DR value streams. These devices responded accurately and quickly to balancing requests. Overall, this technology displayed the greatest potential to become a source of balancing reserve and over-supply mitigation. Detailed analysis of these project results allowed Ecofys to develop an in-house business case model. The software can potentially be used to develop future build-out plans for increasing the penetration of responsive end-use devices.

Future project work will focus on completing and extending the portfolio of operating technology demonstrations, and continuing to develop the controls for the technologies. Ecofys has also been selected by BPA to pursue another demonstration project, which will investigate the potential for data centers to act as a DR resource.

In general, the outcomes of this project will prove vital for BPA and other regional utility districts in moving forward with the development of a smart end-use energy resource. Furthermore, this project provides real experience that has great potential to be applied within a variety of different power systems here in North America and abroad.

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