Conservation Voltage Reduction – On the Other Side of the Meter: An Evaluation Case Study

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ABSTRACT

Conservation voltage reduction (CVR) is a type of distribution efficiency, also known as conservation voltage regulation or voltage optimization. CVR is the long-term practice of controlling distribution voltage levels in the lower range of acceptable levels, as defined by the American National Standards Institute, to reduce demand and energy consumption. CVR can provide both energy and peak load savings. Savings from CVR require a distribution infrastructure investment, but at a relatively low-cost.

Avista Utilities' CVR program includes two Integrated Volt/VAR Control (IVVC) projects. The IVVC module issues commands to the station or midline regulators to maintain the minimum voltage setpoint within a specified voltage dead-band. Avista based the business case for IVVC on the avoided cost of energy resulting from the reduction of load by lowering the distribution line voltage, supported by energy efficiency requirements in its Washington service territory.

Washington investor-owned utilities are required to report on progress in the preceding year in meeting regulatory targets. The Washington Utilities and Transportation Commission (UTC) issued an order requiring Avista to provide third-party verification of distribution efficiency savings evaluated using the Regional Technical Forum's (RTF's) Automated CVR Protocol No. 1, but allowed Avista to develop additional methodology.

Avista and the Northwest Energy Efficiency Alliance (NEEA) sponsored an evaluation of the program. The evaluation used the RTF Automated CVR Protocol No. 1 and also used an alternative approach that produced similar results to the RTF Automated CVR Protocol No. 1 and is somewhat less burdensome to implement. The estimates of savings were approximately 42 gigawatt-hours (GWh) per year, which is 0.4% of native load.

Introduction

Avista Utilities (Avista) is an energy company involved in the production, transmission, and distribution of energy to customers in eastern Washington, northern Idaho, and parts of southern and eastern Oregon. Avista implemented a conservation voltage reduction (CVR) program in 2013 as part of larger Smart Grid projects. This paper presents an evaluation of the impact of that program by Navigant, Inc. (Navigant).

Description of the Program

CVR is a type of distribution efficiency, also known as conservation voltage regulation or voltage optimization. CVR is the long-term practice of controlling distribution voltages in the lower range of acceptable levels, as defined by the American National Standards Institute (ANSI; ANSI 1995), to reduce demand and energy consumption.

The Northwest Energy Efficiency Alliance (NEEA) conducted a major study on the effects of CVR, known as the NEEA Distribution Efficiency Initiative (Leidos 2007). The objective of this initiative was to establish the viability of CVR as a conservation measure through pilot projects and demonstrations starting in 2003 and extending through 2007. The results of the study conclusively showed that operating a utility distribution system in the lower half of the acceptable voltage range (120V–114V) saves energy, reduces demand, and reduces reactive power requirements without negatively affecting the customer.

Avista's CVR program is a part of its two Smart Grid 2.0 projects, implemented in 2013. In Spokane, the utility's Smart Circuits project involved upgrading 14 substations and 58 distribution feeders (Avista 2009). In Pullman, Avista's Smart Grid Demonstration project encompasses updating and automating the distribution system, installing an advanced metering infrastructure, implementing a Web portal where customers can monitor their energy use, and a demand response pilot project. Three substations and 13 feeders (Avista 2010) were included in the upgrades.

Both projects incorporate Integrated Volt/VAR Control (IVVC), an automated system. The IVVC predictive application leverages existing power flow models, loading information, and network topology to calculate the minimum voltage allowed on the feeder. The IVVC module issues commands to the station or midline regulators to maintain the minimum voltage setpoint within a specified voltage dead-band. Avista based its business case for IVVC on the avoided cost of energy resulting from the reduction of load by lowering the distribution line voltage (Avista 2010).

Commissioning of IVVC in Spokane and Pullman began in September 2013 and concluded on December 31, 2013.

Regulatory Requirements

The Washington State Energy Independence Act, enacted by voters in 2006 as Initiative 937, imposes targets for energy conservation and the use of eligible renewable resources on all electric utilities that serve more than 25,000 customers in the state. Each year, beginning in June 2012, Washington's public utilities are required to report to the State Department of Commerce on the utilities' progress in the preceding biennium in meeting the targets. To comply with this requirement, the state's Utilities and Transportation Commission (UTC) issued an order (UTC Docket UE-111882) requiring that Avista provide third-party verification of distribution efficiency savings:

> *For savings claimed from distribution efficiency, Avista Corporation must provide third-party verified values calculated using applicable parts of the RTF's Automated CVR Protocol No. 1, Voltage Optimization Protocol, or any other protocol recognized by the RTF following the date of this order.* (UTC 2012)

Overview of the Impact Evaluation

As noted above, the UTC required that Avista have distribution efficiency savings evaluated using the Regional Technical Forum's (RTF's) Automated CVR Protocol No. 1, but also allowed Avista to develop additional methodologies. The following sections discuss the RTF Automated CVR Protocol No. 1 and an alternative direct regression methodology.

RTF Automated CVR Protocol No. 1. The protocol specifies an approach for measurement and verification of energy savings on electric power distribution circuits and substations on which a utility has implemented CVR. It is flexible with respect to the type of load, and the utility can apply the approach to circuits serving any combination of residential, commercial, and industrial customers. The main requirements include the ability to measure and record voltage levels and energy usage at uniform time

intervals[1] and the ability to vary circuit target voltage levels on each controlled circuit at the same time every day for periods of up to one year.[2] The protocol consists of an experimental design prescribing the procedures to follow for generating experimental data and a recommended method for statistically estimating the conserved energy from the experimental data (RTF 2004).

Experimental Design. The protocol calls for an initial verification period lasting for one year, beginning with three months of alternating, on successive days, among full voltage reduction (CVR-on), voltage set at the legacy level (CVR-off), and voltage set at the nominal midpoint between CVR-on and CVR-off. During the next nine months, the protocol specifies that all test circuits are to be on full CVR reduction continuously except for three months, selected based on season and other factors, when the utility alternates the voltage between full voltage reduction and the controlled nominal midpoint on successive days.

During the verification period, the utility measures and records end-of-line voltages and low-side circuit loads at each time interval. The only additional information required to measure energy savings is local ambient temperature, at uniform intervals of no more than one hour. The protocol recommends collecting the temperatures at each substation connected to experimental circuits as well as at the feeder end-of-line locations in order to reduce the possibility of confounding due to localized microclimates.[3]

Recently, Utilidata, Inc., the principal author of the RTF Automated CVR Protocol No. 1, proposed altering the experimental design of the protocol to eliminate the third setpoint at the nominal voltage midpoint so that all cycling of voltage settings occurs between full voltage reduction (CVR-on) and CVR-off on alternate days. Utilidata proposed this change because it now considers the third setpoint unnecessary.[4]

Data Preparation. The protocol recommends grouping the experimental voltage and load observations into twenty-four-hour periods, aggregating them up to hourly intervals, matching them to their corresponding hourly weather series, and separating the resulting twenty-four-hour ensembles into CVR and non-CVR categories.

Statistical Estimation Procedure. The protocol recommends using robust time-series econometric techniques to identify "integrated demand profiles" for CVR-on and CVR-off periods separately for each combination of season (summer, winter, and shoulder) and day-type (weekday and weekend/holiday). The twenty-four-hour sums of the differences between the CVR-on and CVR-off demand profiles constitute the daily energy savings due to CVR for each season and day-type. To estimate the CVR factor (CVRf), the percent difference in energy usage per unit reduction in voltage, this difference is expressed as a percentage reduction relative to the non-CVR usage and divided by the average percentage reduction in measured end-of-line voltage for the circuit over the same time interval.

No control group was required because with on-off and variable voltage setpoint capability, the application group can act as its own control group during testing periods. Essentially, the protocol requires conducting an experiment with voltage control.

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[1] Preferred interval length is anywhere between 5 seconds and 15 minutes (Donohue July 25, 2013).

[2] The need for systematic changes in voltage settings to take place at the same time every day over long periods makes this approach most suitable for automated CVR systems; hence, the title of the protocol document.

[3] However, hourly National Weather Service data from the closest available weather station is also acceptable (Donohue, July 25, 2013).

[4] The third setpoint called for in the 2004 protocol at the nominal midpoint between the on and off CVR settings was originally included out of concern for the possibility that there may be significant nonlinearities in the relationship between voltage and load that would not be captured if the only experimental data corresponded to the extremes of full voltage reduction and removing CVR control altogether. However, with the benefit of experience, it has become clear that this is unnecessary, because CVR programs generally reduce nominal voltage settings by relatively small amounts, typically 1-3 percent. Over such short intervals, the third setpoint is extraneous (Donohue, July 25, 2013; Utilidata 2011).

Implementation of the Experiment. Avista began daily cycling between CVR and non-CVR setpoints on a representative sample of test circuits on January 1, 2014 and concluded on April 8, 2014. Given the constraints of implementation and report timing, it was not possible to conduct a full year of cycling. Navigant worked with Avista personnel to conduct as thorough and defensible an evaluation as possible using the RTF Automated CVR Protocol No. 1 given the existing time constraints.

Direct Regression Modeling. Navigant developed parallel savings estimation methodologies to evaluate alternative calculations in comparison to RTF Automated CVR Protocol No. 1. Navigant used the same data set as that specified in RTF Automated CVR Protocol No. 1, but relied instead on direct regression modeling to estimate energy savings. Navigant formulated several alternative model specifications and relied on empirical testing methods to select the one(s) with the most desirable properties. More details are provided in the methodology section below.

Description of Data

The primary data Navigant used to evaluate Avista's CVR program savings consists of automated distribution line measurements recorded at 15-minute intervals on the quarter-hours by Avista's IVVC system on a sample of 25 distribution feeder circuits that was representative of the population of controlled circuits. The measurements include phase-specific kilovolts (kV), amperes (Amps), kilowatts (kW), and kilovolt-amperes-reactive (kVAR). Because the evaluation's primary purpose was estimating the total energy savings from the CVR program, Navigant focused mainly on aggregate kW and kV. Navigant evaluated measurements at several distinct points along each feeder: at the circuit breaker immediately downstream of the substation transformer, at up to three "smart" reclosers, and at a voltage regulator. Navigant also evaluated limited information at up to three capacitor banks. In addition to these quantitative measurements, qualitative information pertaining to status of the IVVC system and its components was also provided at 15-minute intervals, including the date-time stamp, the feeder identifier, the measurement location on the feeder, CVR on or off status, capacitor banks on or off status, and whether the IVVC reporting and communication system was functioning. The system automatically delivered files containing each day's data to Navigant via the Internet.

In addition to the interval data covering all of the sample feeders continuously from the point at which daily voltage cycling began on January 1, 2014, Avista provided Navigant with limited additional data from the commissioning phase of the IVVC program (i.e., September through December 2013). Avista recorded these observations while installing and testing the system on each feeder participating in the program and, as such, the observations are intermittent and sparse, covering only some of the sample on any given day and for only limited periods. Nevertheless, Navigant welcomed the opportunity to include this data, as it allowed Navigant to extend its analysis period back into the fall 2013 season.[5]

Navigant designed the sample of feeders studied for this evaluation in conjunction with Avista staff. Navigant used information provided by Avista on the distribution of loads by customer class on each of the 71 feeder circuits in Spokane and Pullman on which Avista commissioned IVVC to draw a representative sample of 25 feeders. The sample drawn targeted a maximum program-level relative precision of 10 percent with a one-tailed 90 percent confidence interval over five customer strata.[6]

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[5] Navigant statistically tested whether inclusion of this data altered the results before including the data and found no evidence that it did so. Navigant's main purpose in including commissioning period data was to increase the reliability of the statistical results by increasing the sample size and to strengthen the ability to identify "shoulder season" (i.e., spring and fall) CVR effects.

[6] Avista provided Navigant with a table of kilovolt-ampere (kVA) loadings attributable to each of several customer classes by feeder. Navigant used this information to sort the 71 IVVC feeder circuits into five broad strata: residential (at least 85 percent residential load); rural/agricultural (20-30 percent agricultural loads or with significant rural stretches); industrial (at

Navigant included in the sample all available circuits in the industrial and rural/agricultural categories and randomly sampled from the residential and commercial-mixed strata in proportion to their relative shares in the number of IVVC feeders. Navigant also selected two Pullman feeders dedicated to delivering power to the Washington State University (WSU) grid. Table 1 shows the list of sample feeders, along with their locations and characteristics.

Table 1. Feeder Circuit Sample

No.	City	Substation	Feeder	Category
1	Spokane	GLN	GLN12F1	Predominantly residential (7 of 26)
2		L&S	L&S12F2	
3		SE	SE12F5	
4		9CE	9CE12F4	
5	Pullman	SPU	SPU123	
6		TUR	TUR113	
7			TUR117	
8	Spokane	3HT	3HT12F1	Commercial/mixed (9 of 32)
9			3HT12F7	
10		F&C	F&C12F4	
11			F&C12F5	
12			F&C12F6	
13		L&S	L&S12F1	
14		ROS	ROS12F6	
15		SE	SE12F4	
16		SUN	SUN12F1	
17	Spokane	GLN	GLN12F2	Significant rural/ agricultural (census)
18		NE	NE12F3	
19	Spokane	3HT	3HT12F5	Predominantly industrial (census)
20		BEA	BEA12F3	
21			BEA12F4	
22			BEA12F5	
23		NE	NE12F5	
24	Pullman	TVW	TVW131	Express feeder (13.2 kV)
25		SPU	SPU125	Express feeder (13.2 kV to 4 kV)

Notes: Data from LoadingByFeederAndZone.xlsx (Avista) and Navigant analysis.

A representative example of the daily voltage cycling that was performed on the 25 sample feeders is shown in Figure 1, which is a time plot of the 15-minute interval kV measurements on one sample feeder (3HT12F1) for the month of January 2014.

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least 50 percent industrial load); commercial/mixed (either predominantly commercial or mixed commercial-residential); and dedicated lines providing power to WSU.
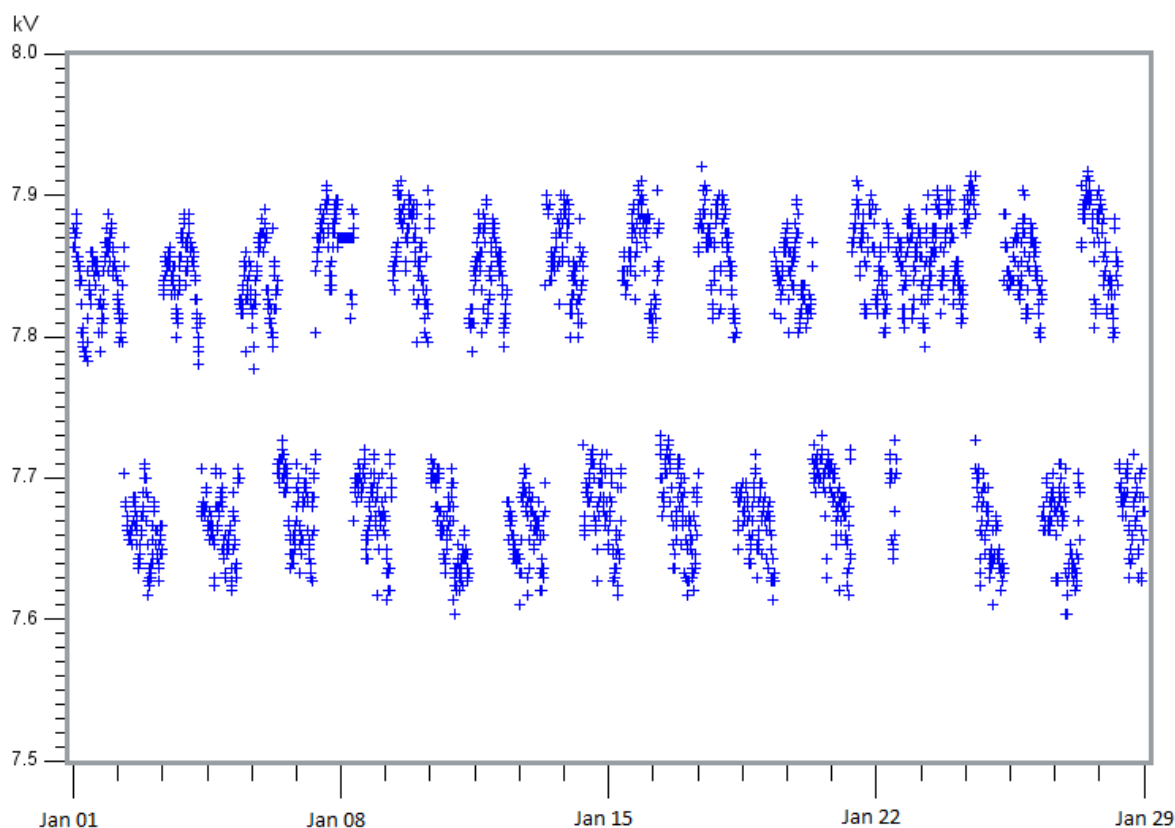
Figure 1. Plot of Voltage Cycling on Feeder 3HT12F1, January 2014

Figure 1 illustrates how CVR works: a target reduction of approximately 2 percent is set. During each IVVC state (on and off) voltage continues to fluctuate about the setpoint, but the separation between the setpoints during the on and off states is clear.

Figure 2 shows the time plot of the corresponding kW series for the same feeder and period (3HT12F1, January 2014). What is notable here is the strong daily cyclical pattern of aggregate load, with a characteristic humped or sawtooth shape with load rising to a peak during the day and falling back at night, superimposed on a clear weekly pattern with five similar weekday load shapes followed by notches on the weekends when the daily peaks are much less pronounced. The pattern observed in the kW series in Figure 2 underscores the need to develop a statistical model for explaining load fluctuations that accommodates these intra-day, daily, and weekly patterns. Failure to do so runs the risk of attributing load fluctuations to CVR that are actually due to these secular patterns.
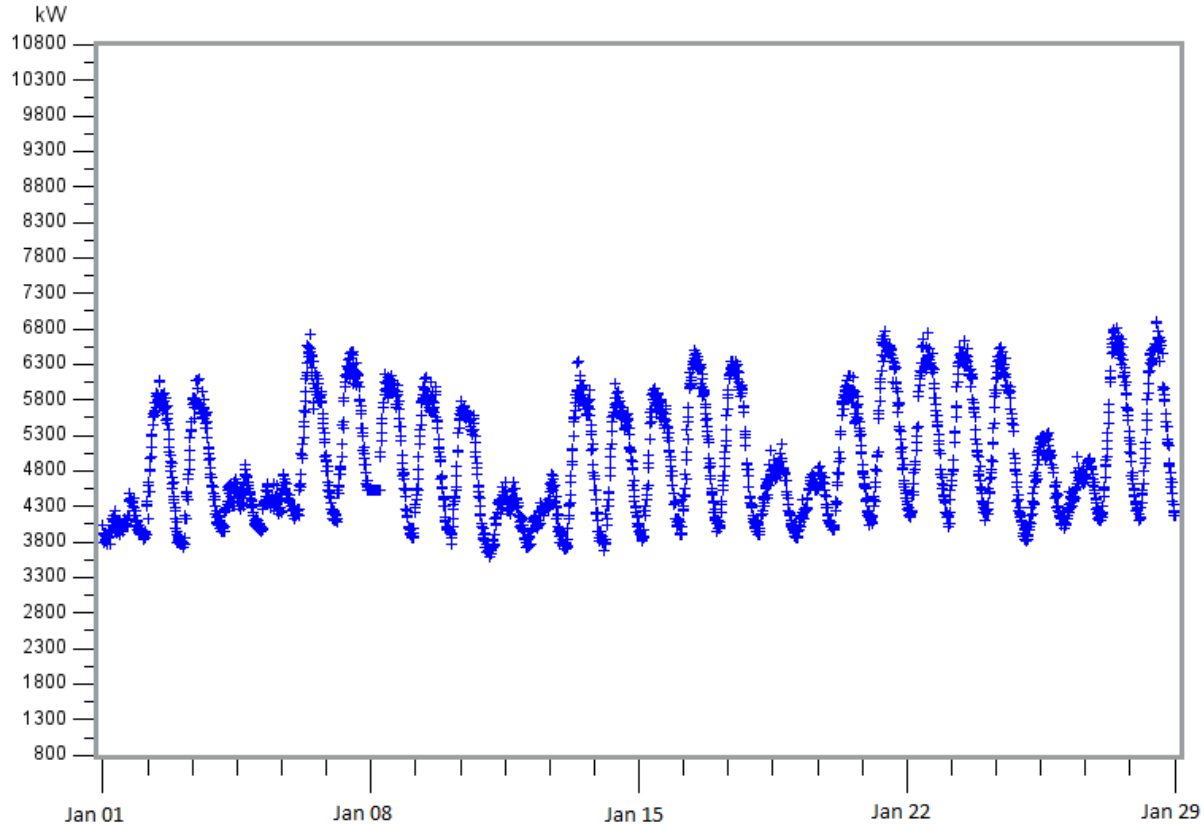
kW by Feeder Jan-Apr 2014

Figure 2. Plot of kW on Feeder 3HT12F1, January 2014

Additional data used by Navigant to evaluate Avista's CVR program savings consisted of weather data from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). Navigant obtained hourly temperature and humidity series from the NCDC's Quality Controlled Local Climatological Data site (NOAA 2014) for Spokane International Airport and Pullman/Moscow Regional Airport. After aligning the series to the nearest whole hour, Navigant used cubic spline interpolation to generate 15-minute series for each weather station, which were then merged with the IVVC interval data (i.e., 15-minute observations on the quarter-hour).

RTF Automated CVR Protocol No. 1

RTF Automated CVR Protocol No. 1 establishes a method for measuring and verifying energy savings from CVR voltage reductions using experimental data produced by alternating the voltage setpoints on a set of distribution circuits on successive days. The protocol uses data collected during an extended period of voltage cycling to estimate energy savings using time-series analysis and robust statistical methods.

To implement the protocol, Navigant worked with Avista staff to develop a sampling methodology that resulted in a representative sample selection of 25 distribution feeder circuits, as described above. Avista began daily cycling of the voltage setpoints on these circuits between full CVR voltage control (IVVC on) and no CVR control (IVVC off) on January 1, 2014, a process that continued through April 8, 2014.

Avista provided Navigant with 15-minute interval data from the 25 sample feeders collected over the 98-day period, as described above. Navigant grouped the data for each feeder into 24-hour ensembles identified by day-type (weekday or weekend/holiday), season (winter or shoulder), and IVVC system state (IVVC on, IVVC off, or IVVC system not operational). Navigant aggregated phase-specific data to feeder level by summing the phase-specific loads (kW), taking the arithmetic means of the phase-specific voltages (kV). Navigant also cleaned the data, dropping observations where the IVVC system was reported to be offline, kW was reported as zero, or repeating identical kV values were encountered (indicating a nonfunctioning volt meter).

Navigant produced integrated demand profiles for each feeder by day-type, season, and IVVC state using robust time-series methods to isolate the effects of voltage reduction from the effects of other factors, such as weather, load characteristics, and customer behavior.[7] This resulted in two demand profiles per sample feeder for each combination of day-type and season: one when IVVC is off, and the other when IVVC is on. Figure 3 shows plots of the demand profiles for one of the feeder circuits in the sample, BEA12F3, for winter weekdays.
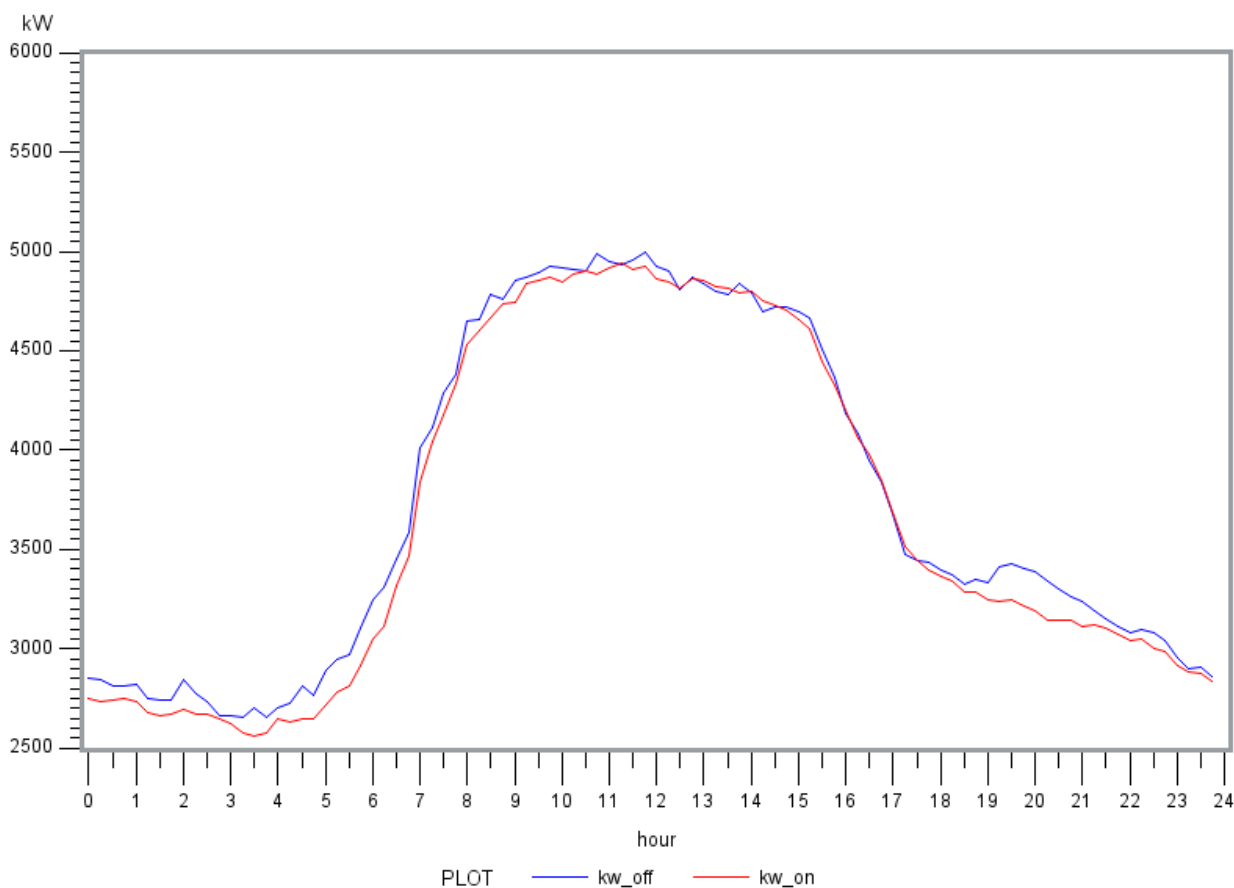

Figure 3. Integrated Demand Profiles, Feeder BEA12F3, Winter Weekdays

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[7] Weather effects were explicitly modeled using data on ambient temperature and season. Load characteristics and customer behavior with respect to loads generally occur behind the customer meter and are thus not directly observed. However, the effects of time-invariant load characteristic differences across feeders are reflected in the load profiles estimated separately for each feeder. Time-varying effects due to shifting customer loads (intra-day, inter-day, inter-week) are accommodated through the use of high-frequency (15-minute) interval data; time-varying effects over longer intervals are accommodated by estimating separate load profiles by season.

Summing the vertical differences between the two demand profiles for each feeder over the 24-hour period estimates the CVR energy savings for each day-type/season combination. To estimate the CVRf[8] for a given feeder, season, and day-type, this sum is expressed as a percentage reduction relative to the corresponding baseline energy usage for the same feeder, day-type, and season, and is divided by the corresponding mean percentage reduction in voltage on the circuit.

The resulting CVR factors range from 0.705 on weekends/holidays in the winter and 0.942 in the shoulder period on weekdays. Corresponding energy savings range from 1.440 to 1.919 percent. Table 2 summarizes these results.

Table 2. Summary of Findings from RTF Automated CVR Protocol No. 1

Day-Type	Measurement	Season	
		Winter	Shoulder
Weekday	%ΔVolts	2.020%	2.016%
	%ΔkWh	1.694%	1.919%
	CVRf	0.833	0.942
Weekend/Holiday	%ΔVolts	1.984%	1.810%
	%ΔkWh	1.440%	1.520%
	CVRf	0.705	0.834

To estimate the annual energy savings attributable to Avista's CVR program, Navigant calculated an average annual CVRf value of 0.881 as the weighted average of the four season/day-type specific factors by their relative shares of the year and applied them to the post-implementation estimated annual energy usage for the 71 IVVC-controlled distribution circuits. Total estimated annual usage is 2,442,217 MWh. Multiplying the estimated annual energy usage by the weighted average 2 percent voltage reduction and 0.881 CVRf yields an estimated annual energy savings of 42,292 MWh.[9]

The basis for these savings does not include summer data values; Navigant has extrapolated the results of winter and spring periods for the year. A recent study of CVR savings in Pennsylvania (Navigant 2011) found CVR factors and savings were significantly higher in summer periods than in the rest of the year. Therefore, the savings resulting from a year-round experimental design may be higher than what is shown here.

Regression Methodology

In addition to the measurement and verification methodology specified in RTF Automated CVR Protocol No. 1, Navigant pursued a parallel statistical analysis to produce an alternate estimate of CVR savings using the same dataset described above. The approach, which applies regression analysis to the data using a flexible, semi-parametric functional form, employs robust time-series econometric techniques similar to those used in the RTF approach. It has the advantage of producing CVRf estimates directly, rather than having to calculate them in a separate post-hoc analysis, which can save time and resources. It also permits direct estimation of standard program evaluation metrics, including statistical confidence and precision.

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[8] The CVR factor (CVRf) is defined as the ratio of the mean percentage energy saved to the mean percentage voltage reduction: $CVRf = \%\Delta E/\%\Delta V$.

[9] Navigant calculated a relative precision of 6.36 percent for the annual energy savings estimate. The corresponding one-sided 90 percent confidence interval is annual energy savings > 39,607 MWh.

To estimate the net effect of CVR voltage reductions on energy usage, Navigant performed regression analyses, modeling the average load in each 15-minute interval as a function of interval average voltage, interval heating degree-hours (HDH), and a set of time-of-day and day-type (i.e., weekday/weekend) indicators. To allow the model to reflect differences in the characteristics of the loads served by each test feeder, which are largely unobserved, Navigant ran separate regressions for each feeder, as well as for each season.[10] The model is as follows:

$$f(kW_{it}) = \beta_{i1}g(kV_{it}) + \beta_{i2}HDH_t + \beta_{i3}HDH_t \cdot g(kV_{it}) + \sum_{t=1}^{96}\sum_{j=Weekday}^{Weekend} \beta_{itj}^{DTYPE}TOD_t \cdot DayType_j + \varepsilon_{it}$$

where:
- $i, t, and\ j$ are index feeder circuits, time intervals, and day-types, respectively;
- kW_{it} and kV_{it} are the instantaneous power demand and voltage, measured at the circuit breaker and voltage regulator, respectively, on feeder i at time interval t;
- TOD_t and $DayType_j$ are sets of 96 time-of-day and 2 day-type indicators, respectively; and
- $f(\cdot)$ and $g(\cdot)$ are functions of the variable contained in the parentheses.[11]

Navigant used robust regression methods to estimate the parameters of the above model for each combination of feeder and season, and calculated the system average CVRf as the weighted average of the individual feeder estimates using the annual feeder MWh as weights.

To obtain estimates of the annual energy savings attributable to Avista's CVR program, Navigant applied the weighted average CVRf value above to the estimated annual energy usage for the 71 IVVC-controlled distribution circuits in calendar 2014, as was done for the RTF Automated CVR Protocol No. 1 calculation. Multiplying the estimated annual energy usage by the weighted average 2 percent voltage reduction and 0.883 CVRf yields an estimated energy savings of 42,374 MWh, very similar to that produced by the RTF Protocol No. 1.[12]

As with the RTF Automated CVR Protocol No. 1 results, the basis for these savings does not include summer data values. As noted previously, an analysis that includes summer data could well result in higher savings.

The Washington Public Counsel described the evaluation as "…an excellent example of promising evaluation results that may have significant benefit not only for Avista, but the region."

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[10] This is a common method used in applied statistics when confronting panel data (i.e., multiple observations over time on a set of individual sample units) reflecting the influence of multiple unobserved factors that vary systematically across individual units – in this case, customer load characteristics. This technique allows the model results to reflect not only different mean load levels, but also differential effects of voltage, weather, time of day, day-type, and season on the loads served by different circuits (Wooldridge 2010).

[11] Navigant tested several functional forms and selected the double-logarithmic form based on statistical testing.

[12] Navigant calculated a relative precision of 6.39 percent for the annual energy savings estimate. The corresponding one-sided 90 percent confidence interval is annual energy savings > 39,591 MWh.

Summary

Navigant completed an impact evaluation of Avista's CVR program. Navigant used two methods:
1. RTF Automated CVR Protocol No. 1
2. Navigant Regression Methodology

The RTF and Navigant approaches yielded savings estimates as shown in Table 3.

Table 3. Summary of Savings Estimates

Approach	CVRf	Savings Estimates (MWh)
RTF Automated CVR Protocol No. 1	0.881	42,292
Navigant	0.883	42,374

The two estimates are statistically identical, giving confidence that the RTF estimate is reasonable. Navigant expects that inclusion of summer data would not substantially change the savings estimate and might well increase it.[13]

Navigant also recommends that the RTF consider adopting Navigant's alternative econometric approach to evaluation, measurement, and verification of savings for automated CVR programs. It produces similar results to the RTF Automated CVR Protocol No. 1 and is somewhat less burdensome to implement.[14]

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[13] The difference between the two savings estimates is not statistically significant at the 5 percent level using a t test. Looked at another way, the lower bounds of their respective one-sided 90 percent confidence intervals are separated by just 16 MWh.
[14] For example, the regression approach produces an estimate of the CVR factor directly as a coefficient of the model.

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