SAN DIEGO GAS AND ELECTRIC COMPANY
EMERGING TECHNOLOGIES PROGRAM
PROJECT ID ET12SDGE0003

MULTI-VENDOR RTU RETROFIT CONTROLLER FIELD STUDY FINAL REPORT

PREPARED FOR

KATE ZENG, NATHAN TAYLOR
SAN DIEGO GAS AND ELECTRIC COMPANY
8306 CENTURY PARK COURT
SAN DIEGO, CA 92123

PREPARED BY

BO WHITE, MARC ESSER
NEGAWATT CONSULTING, INC.
WWW.NEGAWATTCONSULT.COM

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Project Team

SDG&E- Kate Zeng, Emerging Technologies Program Manager; Nate Taylor, Project Manager
Host Site Staff- Tony Williams, Joel Oropesa, & Mando Zapanta: Facility Management
NegaWatt Consulting- Bo White, Project Engineer; Marc Esser, Principal

Disclaimer

Executive Summary

Four different retrofit RTU controllers were tested on four 7.5 ton heat pumps serving office space at one building in San Diego. The operation of those units was alternated on a weekly basis from baseline to retrofit mode. Proper operation of the each controller was verified and the features of the controllers were compared to each other. Total heat pump electric power was measured at 1 minute intervals. The data was then resampled at hourly and daily intervals and was compared to various independent variables. Linear regression models were created to normalize for those independent variables and energy savings was calculated. The energy savings results and modeling statistics are shown in Figure 1.

One of the four controllers was omitted because of unforeseen circumstances. The other three controllers performed as expected when compared to the vendor's claims and the existing research.

The market opportunity, applicable codes and standards, cost-influencing factors, customer feedback, applicable incentive programs, error analysis, benefits, and risks were also studied. A major finding was that substantial re-commissioning of the existing equipment and control system might be necessary to ensure proper controller operation. These controllers add energy saving features to less efficient constant speed equipment but they do not inherently fix all existing problems.

Unit #, Baseline/Retrofit, Heat/Cool	Independent Variable(s)	R^2	CVRMSE	# of Observations	Date Filtering	RTU Energy Savings
HP-17, Baseline, Cooling	Daily outside dry bulb temperature	0.78	0.27	77	Business days after 9/2/2012	
HP-17, Retrofit, Cooling		0.81	0.37	89		24%
HP-17, Baseline, Heating		0.78	0.40	62		
HP-17, Retrofit, Heating		0.72	0.47	54		26%
HP-17, Annual Total						26%
HP-26, Baseline, Cooling	Daily outside dry bulb temperature	0.82	0.14	40	Business days after 1/11/2013	
HP-26, Retrofit, Cooling		0.85	0.13	50		18%
HP-26, Baseline, Heating		0.82	0.25	30		
HP-26, Retrofit, Heating		0.72	0.20	27		3%
HP-26, Annual Total						13%
HP-27, Baseline, Cooling	Daily outside dry bulb temperature	0.83	0.15	41	Business days after 2/15/2013	
HP-27, Retrofit, Cooling		0.81	0.24	63		27%[1]
HP-27, Baseline, Heating		N/A	N/A	N/A		
HP-27, Retrofit, Heating		N/A	N/A	N/A		N/A[2]
HP-27, Annual Total						N/A[2]

Figure 1: Statistics & Savings Calculations

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[1] Please note that the economizer appeared to be malfunctioning and was not corrected for.

[2] Insufficient heating data

Table of Contents

Document Change Tracking

Document Date	List of Changes
07/25/2013	Initial version
11/01/2013	Peer review edits
11/12/2013	Edited per technical discussion with a vendor and added Appendices

List of Figures

Introduction

As stated in Appendix A: Project Plan,

> Packaged air conditioning units (i.e. RTUs) accounted for 46% of main commercial cooling equipment as of 2003 according to the Department of Energy Buildings Energy Data Book (Department of Energy, 2012a). The average EER efficiency of RTUs in service in 2010 was 11.2 even though the best-available on the market was 13.9 (Department of Energy, 2012b). The EER values at the pilot site range from 8.7 to 13.2 as per the nameplates. Many installed RTUs, including those at the pilot site, have constant volume fans and compressors which are inefficient when compared to variable speed equipment. Ventilation levels are often excessive and compressors often deliver too much cooling and/or short cycle.
>
> The median lifetime of commercial RTUs is 15 years (Department of Energy, 2012c) which may help to explain the poor efficiencies of in-service RTUs and why retrofit energy-saving controllers have market potential.

There are various retrofit controller products on the market. One product each from four vendors is evaluated in this study. Their different features, energy saving methods, and cost will be compared.

Project Objective

[Updated copy of a similar section in Appendix A: Project Plan]

The primary goal of this study is to confirm plausibility and actual energy savings of each technology. Savings will be assessed based on measurements and calculations for energy, demand, and cost. The functionality of each technology will also be reviewed and confirmed.

Overall, we can summarize the goals of this assessment project as follows:

1. Describe system setup, operations, and functionality
2. Quantify energy savings, cost and simple payback time
3. Analyze factors that may cause variations in energy savings, cost and payback times under different circumstances such as different base RTUs or different climate zones.
4. Review utility programs with respect to their present applicability to this technology and provide recommendations as to how utilities could further support this technology
5. Research the potential market size and possible barriers to adoption, given enough information
6. Gather and present customer feedback
7. Suggest possible improvements to the technology, if applicable
8. Assess risks introduced by this technology, if any

Four different vendors' products were evaluated. One product per vendor for a total of 4 products was evaluated. Given the dissimilarities, these four products were compared and contrasted qualitatively. While the savings calculations are tabulated for brevity, the reader shall be wary of making quantitative comparisons of the products given the sample size of one each and the fact that each product affects a different heating, ventilation, and air conditioning (HVAC) zone of the building.

The savings in one case was calculated over the (filtered) measurement period only per (ASHRAE, 2002) instead of over a typical meteorological year. Here, the filtered data set was too small to yield acceptable regression models over both the baseline and retrofit periods.

Project Methodology

[Full details can be found in Appendix A: Project Plan and *Appendix B: Measurement & Verification Plan*]

The Project Plan contains detailed information on the following:

- Technology description
- Description of incumbent technology
- Project Goals
- Technology Application
- Project Milestones

The M&V Plan contains detailed information on the following:

- Test Site Description
- Measurement & Verification Options
- Data Collection / Analysis Procedures
- Calculations of Energy Savings
- Cost savings calculations

Technology Overview

[Updated copy of a similar section in Appendix A: Project Plan]

All four technologies studied here are controllers which are designed to be retrofitted onto existing, packaged RTUs preferably 5 tons or larger. All technologies involve innovative control of either the fans, compressors, or both. Figure 2 provides a table of the features and attributes of each technology, labeled per the heat pump number on which they are installed for the sake of anonymity. Statements from each vendor concerning the operating life of their products were not given but warranty lengths as far as they are known are included.

Technology feature	HP-17	HP-20	HP-26	HP-27
Compressor cycling		X	X	X
Compressor speed control				X
Compressor short cycling awareness		X	X	X
Supply fan speed control	X			X
Economizer control	X			
Demand control ventilation (DCV) option	X			
FDD option	X			
Applicable to packaged units	X	X	X	X
Applicable to split systems	X	X	X	
Reduces energy	X	X	X	X
Reduces demand	X			X

Figure 2: Technology comparison chart

Host Site Overview

[Updated copy of a similar section in *Appendix B: Measurement & Verification Plan*]

EMD Millipore is a two story commercial building located at 10394 Pacific Center Court, San Diego, CA 92121 in California Climate Zone 7. General building features are listed in Figure 3.

Building Feature	Building Attribute
Building Name	EMD Millipore
Year built	1993
Size	60,000 ft^2
Location	Sorrento Valley, San Diego, CA 92121
California Climate Zone	7
Occupancy type	Office/Laboratory
Occupancy schedule	Monday – Friday, 06:00 – 19:00
Building Management System	Siemens
Mechanical System Summary	Constant Volume Packaged, Single Zone Heat Pumps

Figure 3: Building Features

Four heat pumps were utilized in this study. All have cooling capacities of 7.5 tons, all are packaged rooftop units, and all serve office spaces. They each have economizers, constant volume fans, and two constant speed compressors each. They are all manufactured by Carrier, have EER values that range from about 8.7 to 11.2, and are anywhere from 4 to 20 years old (as of 2013). All operate on weekly time schedules. For a full equipment schedule, see Figure 4.

Unit			Compressor								Fans						Area Served			
Unit #	Make	Model #, Tonnage, Serial #	Qty	Type	Refri-gerant	Volt.	Ph.	Hz	RLA	LRA	Qty	Type	Volt.	Ph.	Hz	FLA	Area Function	Area (sqft)	EER, IPLV	Quality Control Inspection Results
HP-17	Carrier	50TCQD08A2A6A0A0A0, 7.5 Tons, 4309G30655	1	scroll	R-410A	460	3	60	6.1	41	2	Outdoor	460	1	60	0.8	Offices, Cubicles	1600	11.2, 12.4	2009, good, charge, replace caps
			1	scroll	R-410A	460	3	60	6.1	41	1	Indoor	460	3	60	3.4				
HP-20	Carrier	50QJ0----0, 7.5 tons, 0593G10652	1	hermetic	R-22	460	3	60	7.9	49.5	1	Outdoor	460	3	60	1.5	Corridor, Offices	1875	8.7, ---	1993, poor, brittle coils, many repairs
			1	hermetic	R-22	460	3	60	7.0	49.5	1	Indoor	460	3	60	2.6				
HP-26	Carrier	50HJQ008---621--, 7.5 Tons, 1207G50873	1	scroll	R-22	460	3	60	6.4	44	2	Outdoor	460	1	60	0.7	Offices	1100	10.3, 10.5	2007, fair, clean corrosion, charge
			1	scroll	R-22	460	3	60	6.4	44	1	Indoor	460	3	60	3.4				
HP-27	Carrier	50LJQ008610, 7.5 Tons, 0393G04434	1	scroll	R-22	460	3	60	7.9	49.5	1	Outdoor	460	3	60	1.5	Cubicles	1900	9.1, 10.3	1993, poor, brittle coil, charge, replace caps
			1	scroll	R-22	460	3	60	7.0	49.5	1	Indoor	460	3	60	2.6				

Figure 4: Heat pump equipment schedule

The BMS computer is on-site, does not have remote login capability, and the author was not granted access beyond a few cursory viewings. It includes fan status, compressor status, zone temperature, and zone temperature set point. The occupied and unoccupied heating and cooling set points on 05/03/2013 were 65/70/74/82°F for HP-17 and 65/72/73.5/82°F for HP-26. None of these points are trended to the author's knowledge. HP-27 has a vendor installed thermostat with occupied set points of 70/74°F and, accidentally, the supply fan is forced into ventilation mode overnight. The HP-20 set points are not provided because an energy savings calculation will not be provided for that unit. See Figure 5 for a BMS screenshot of a typical heat pump.

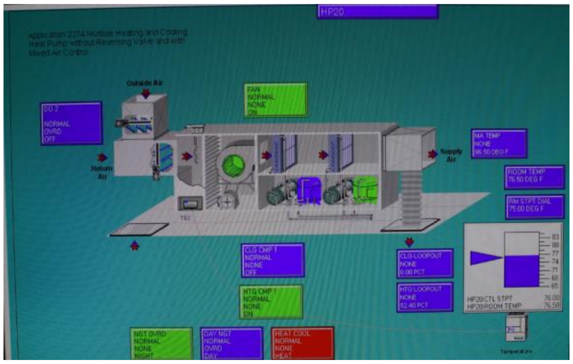

Figure 5: BMS screenshot of a typical heat pump (HP-20 shown)

Measurement & Verification Plan Overview

[Full details can be found in *Appendix B: Measurement & Verification Plan*]

System setup and operation, roles and responsibilities, cost and cost influencing factors, system functionality, impact to host site staff, customer feedback, energy reduction, and applicability of existing SDG&E programs are all evaluated. Emphasis is placed on the following aspects:

Verification of system operation and design

- Do the controllers work as stated?
- Do the controllers work automatically?
- Is the zone temperature set point satisfied?
- Do the RTU components react as expected and such that no components are excessively worn?

Potential energy and cost savings

Energy savings and simple payback periods were calculated to the extent possible and without incentives or rebates. Consequently, the payback calculation is only a rough estimate. One year of recent utility bills for the host site were studied to determine the cost of electricity. Parts and installation costs per technology were those from this particular project with any revisions noted.

Customer feedback

- Does the customer like the system? Would they purchase it independent from this project?
- What would he or she improve to make the system more attractive?
- Did the system require further training for the host site staff?

Applicability of SDG&E incentive and rebate programs

We review relevant SDG&E programs with respect to this technology, and provide recommendations for where we believe program support may apply.

Conclusions

- Benefits of each technology
- Improvement opportunities for each technology
- Applicability of this study to other load types and sectors
- Considerations for large-scale market implementation
- Potential future study

Market Overview

Opportunity

According to (W. Wang, 2012), packaged RTUs are predominantly used in stand-alone retail and medium office building types. Average savings of multi-speed fan control and DCV are about 40% of building HVAC energy use (assuming a baseline of constant speed fans and no DCV). The California Commercial End-Use Survey (Itron, Inc., 2006) indicates that the combined annual HVAC electric usage of small office (< 30,000 ft^2) and retail building types in the SDG&E region is 514 GWh (see Figure 6). As an arbitrary example, let’s assume the products were installed at 10% of all available California sites each year (this is for illustration purposes only and not meant to suggest that 10% market penetration can or will be accomplished). Energy savings in the SDG&E region would then be about 20 GWh.

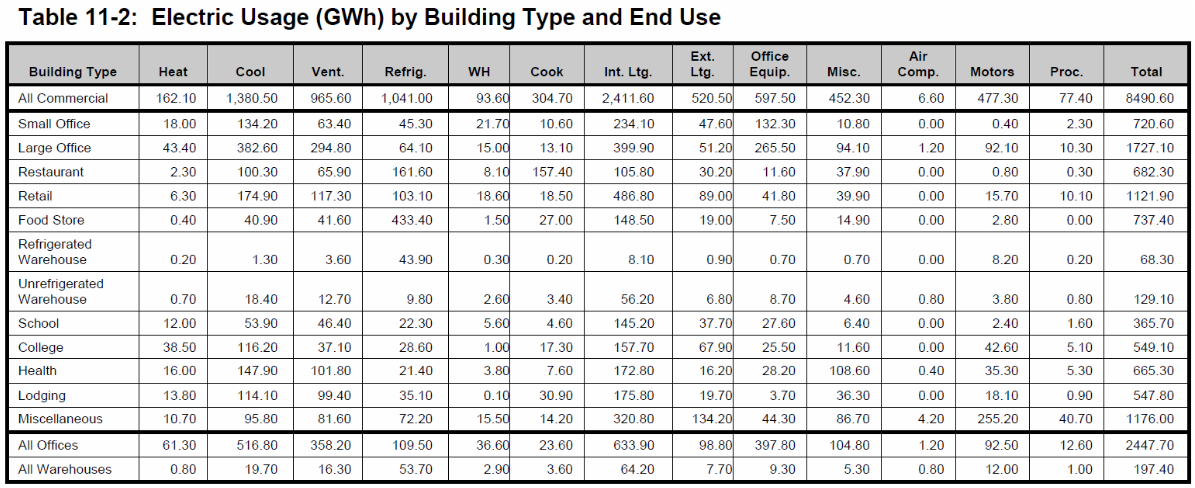

Table 11-2: Electric Usage (GWh) by Building Type and End Use

Building Type	Heat	Cool	Vent.	Refrig.	WH	Cook	Int. Ltg.	Ext. Ltg.	Office Equip.	Misc.	Air Comp.	Motors	Proc.	Total
All Commercial	162.10	1,380.50	965.60	1,041.00	93.60	304.70	2,411.60	520.50	597.50	452.30	6.60	477.30	77.40	8490.60
Small Office	18.00	134.20	63.40	45.30	21.70	10.60	234.10	47.60	132.30	10.80	0.00	0.40	2.30	720.60
Large Office	43.40	382.60	294.80	64.10	15.00	13.10	399.90	51.20	265.50	94.10	1.20	92.10	10.30	1727.10
Restaurant	2.30	100.30	65.90	161.60	8.10	157.40	105.80	30.20	11.60	37.90	0.00	0.80	0.30	682.30
Retail	6.30	174.90	117.30	103.10	18.60	18.50	486.80	89.00	41.80	39.90	0.00	15.70	10.10	1121.90
Food Store	0.40	40.90	41.60	433.40	1.50	27.00	148.50	19.00	7.50	14.90	0.00	2.80	0.00	737.40
Refrigerated Warehouse	0.20	1.30	3.60	43.90	0.30	0.20	8.10	0.90	0.70	0.70	0.00	8.20	0.20	68.30
Unrefrigerated Warehouse	0.70	18.40	12.70	9.80	2.60	3.40	56.20	6.80	8.70	4.60	0.80	3.80	0.80	129.10
School	12.00	53.90	46.40	22.30	5.60	4.60	145.20	37.70	27.60	6.40	0.00	2.40	1.60	365.70
College	38.50	116.20	37.10	28.60	1.00	17.30	157.70	67.90	25.50	11.60	0.00	42.60	5.10	549.10
Health	16.00	147.90	101.80	21.40	3.80	7.60	172.80	16.20	28.20	108.60	0.40	35.30	5.30	665.30
Lodging	13.80	114.10	99.40	35.10	0.10	30.90	175.80	19.70	3.70	36.30	0.00	18.10	0.90	547.80
Miscellaneous	10.70	95.80	81.60	72.20	15.50	14.20	320.80	134.20	44.30	86.70	4.20	255.20	40.70	1176.00
All Offices	61.30	516.80	358.20	109.50	36.60	23.60	633.90	98.80	397.80	104.80	1.20	92.50	12.60	2447.70
All Warehouses	0.80	19.70	16.30	53.70	2.90	3.60	64.20	7.70	9.30	5.30	0.80	12.00	1.00	197.40

Figure 6: Electric Usage in SDG&E region (Itron, Inc., 2006)

Products and Systems

A list of vendors and products competing in this market sector is provided below in alphabetical order. Some of these products may be a better representation of the products in this study than others.[3]

- All Original Equipment Manufacturers implement similar features in their higher end products
- Catalyst by Transformative Wave Technologies (Transformative Wave Technologies, 2013)
- Digi-RTU by Bes-Tech (Bes-Tech, 2013)
- Enerfit by Enerfit (Enerfit, 2013)
- Energy WorkSite by NorthWrite (NorthWrite, 2013)
- IntelliCon-CAC by Intellidyne (Intellidyne, LLC, 2013)
- Optimum Energy (Optimum Energy, 2013)
- PACE2 by PaceControls (PaceControls, 2013)
- Swarm Energy Management by REGEN Energy (REGEN Energy, 2013)
- UtilityPRO thermostats by Honeywell (Honeywell, 2013)
- VPower by Viridity Energy (Viridity Energy, 2013)

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[3] The list is in alphabetical order, provided as is, not exhaustive, and the selection is arbitrary. The authors of this report do not endorse or guarantee, and disclaim any responsibility for: the content, products or services offered, their performance or suitability, and any consequences or damages, incidental or otherwise, that may result from their consideration or use.

Applicable codes and standards

The current 2008 Building Energy Efficiency Standards (California Energy Commission, 2010) state in Section 121 that mechanically ventilated spaces must be continually ventilated during occupied hours. Furthermore, the outside air flow rate must meet certain tabulated values based on room area, room type of use, and occupant quantity. While there are some exceptions that allow for reduced airflow, the regulations disallow "fan cycling" control in which fans are turned off when the zone temperature is within the dead-band between the heating and cooling set points. This is pertinent to this study of retrofit RTU controllers given that many existing RTUs have been found to be in violation (Architectural Energy Corporation, 2003). When this condition is fixed as can happen in the scope of a retrofit project, RTU energy use increases and reduces the payback period of a retrofit controller.

In addition, the 2008 Building Energy Efficiency Standards state in Section 144 (l) that single zone systems with a cooling capacity greater than or equal to 110,000 *Btu/hr* must have at least two speed supply fan motors. Furthermore, the upcoming 2013 Standards that go into effect January 1, 2014 will include the following RTU-related change according to (California Energy Commission, 2013):

1. Added requirements for Fan Control and Integrated Economizers. Packaged units down to 6 tons must be VAV with the ability to modulate cooling capacity to 20% of maximum. Economizers must also be able to modulate cooling capacity to match VAV units. (Section 140.4(c) & (e))

According to Table 140.4-D in (California Energy Commission, 2013), the VAV requirement for 6 ton units will go into effect on 1/1/2016 while the same requirement for 7.5 ton units will go into effect on 1/1/2014.

The 2013 Standards (Section 120.2(i)) also make fault detection and diagnostics (FDD) a mandatory measure for all air-cooled unitary direct-expansion units with cooling capacities greater than or equal to 54,000 *Btu/hr*.

These new regulations reinforce the idea that retrofit RTU controllers must be cost competitive with new RTUs. The least expensive 7.5 ton unit purchased after 1/1/2014 will have at least a two speed supply fan motor, an integrated economizer, and FDD. So, it will also reap much of the same energy reduction of some of the technologies evaluated here.

Project Results and Discussion

Detailed Host System Description

Expounding upon section *Technology Overview*, here are more details of each of the four technologies using the heat pump numbers as proxy names to preserve anonymity. Photos are also omitted to preserve anonymity.

HP-17

The main product is a microprocessor-embedded VFD which is installed within the fan section of the RTU cabinet and in series with the thermostat wiring. The following sensors are also added and communicate with the VFD: outside air temperature, return air temperature, discharge air temperature, and return air CO_2. During calls for ventilation, heating, or cooling, the product analyzes the temperature data and calculates optimal fan speed, making the supply fan variable instead of constant speed.

The microprocessor also assumes control of the economizer. It makes the economizer an integrated economizer meaning that it allows the damper to be fully open during compressor operation when helpful. It controls the damper by differential dry bulb temperature. It closes the damper during occupied hours. Finally, it adds demand control ventilation, reducing ventilation during periods of low CO_2.

Optionally, additional hardware can be mounted in a waterproof box on the exterior of the RTU to provide additional features. This hardware can communicate with the local utility to participate in demand response programs. Web-based monitoring, FDD, alarming, and BMS capabilities can also be added.

The vendor claims to save 25 to 40% of HVAC energy. They include a 5 year hardware warranty. Compressor operation is not affected.

HP-20

This product saves energy by taking over control of and allegedly improving the cycling of the compressors. The vendor claims to reduce electrical consumption by 10 to 20%. The product is cube shaped, is small enough to hold in one hand, and is installed inside the RTU cabinet near the OEM controls and in series with the thermostat wiring. One device is required per compressor. The required power input is 24/115/220 VAC at 5 Watts. The product includes an algorithm which studies the existing cycle pattern and then intelligently reduces compressor runtime while still maintaining the thermostat set points. It is especially effective when the existing RTU is oversized and the OEM compressor cycling sequence of operations is not optimized for the actual thermal load of the zone. The product includes a 15 year replacement warranty for manufacturing defects.

HP-26

This product is similar to HP-20. It cycles the compressors more frequently (but not too frequently) and with overall reduced runtime. The vendor claims that each compressor “runs less but on average more-efficiently”. They claim to reduce demand, too. One device is required to control heating and another to control cooling (the next generation model will only require one piece of hardware). An outside air sensor is also installed.

HP-27

This product consists of one VFD which simultaneously controls the supply fan and both compressors and requires that the existing thermostat be replaced with a vendor provided thermostat (unless the facility staff gives the vendor full and real time access to the BMS). The product leaves the existing economizer and outdoor fan control intact.

The VFD includes a proprietary algorithm which decides when to stage on each compressor and what speed to run whatever components are enabled to run. The thermostat is a programmable type with time scheduling capabilities.

System Deployment and Operations-Related Roles and Responsibilities

Facility staff operation & maintenance duties are not intended to be increased as a result of the installation of any of these retrofit products. However, HVAC maintenance providers should understand the basic operation of the products so that they may troubleshoot any possible failures.

The vendor is responsible to provide operation and maintenance documentation and/or training to the facility staff. They should also give the facility staff contact information for customer support.

List of Controlled Points

The BMS points which are controlled by the various technologies are listed in Figure 7.

Controlled Point	HP-17	HP-20	HP-26	HP-27
Compressor 1 start/stop		X	X	X
Compressor 2 start/stop		X	X	X
Compressor 1 speed				X
Compressor 2 speed				X
Supply fan speed	X			X
Economizer damper position	X			

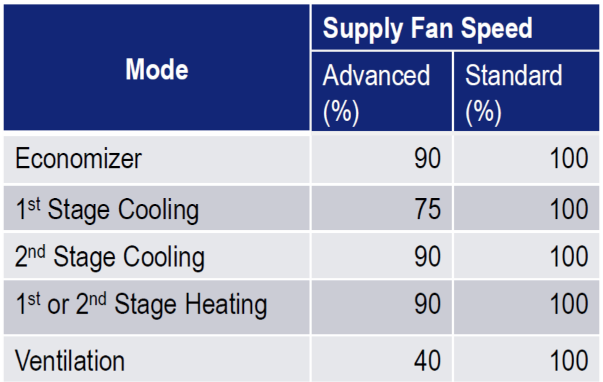
Figure 7: List of Controlled Points per Technology

Sequence of Operations

Basic outlines of the sequence of operations are provided below per technology. Please note that the vendors withheld precise details for proprietary reasons. For generic heat pump sequence of operations, please refer to (W. Wang, 2012).

HP-17

No specific sequence of operations was provided, likely for proprietary reasons. However, a recent PNNL presentation (PNNL, 2013) gives some values of typical supply fan speeds at the various modes of RTU operation (see Figure 8). The vendor did verify the 40% setting for ventilation mode.



Mode	Supply Fan Speed	
	Advanced (%)	Standard (%)
Economizer	90	100
1st Stage Cooling	75	100
2nd Stage Cooling	90	100
1st or 2nd Stage Heating	90	100
Ventilation	40	100

Figure 8: Typical supply fan speeds for VAV RTUs (PNNL, 2013)

HP-20

The product intercepts thermostat cooling and heating calls, saves energy by occasionally preventing them, and never adds such calls. After it analyzes the existing cycle pattern, it calculates an optimal "hold off" time during which it prevents the compressors from running starting at the point in time of a compressor call from the thermostat. The product also includes an anti-short-cycle timer which prevents the compressor from restarting for a certain span of time after stopping to prevent excessive compressor wear (default is 2 minutes).

HP-26

This product only affects compressor cycling, like HP-20, but the sequence of operation is different. Each hardware component has dip switches which the installing contractor sets to match certain characteristics of each compressor. Based on the dip switch positions and the measured outside air temperature, an algorithm on the device calculates the optimal compressor runtime during a cooling call from the thermostat. Without the device, the compressor(s) would remain on during the entire duration of a cooling call. With the device, the compressors instead cycle on and off.

HP-27

This product takes control of all RTU operation except the economizer and the condenser fan, which retain their OEM sequences. To the best of our knowledge, the economizer is non-integrated and controlled with outside air dry bulb temperature. The condenser fan is interlocked with the first stage compressor. The vendor's product sends start/stop signals to both compressors and to the supply fan. One signal from one VFD is delivered to all of the enabled components. An embedded algorithm is used to calculate which components to enable and to calculate the optimal VFD output frequency based on the current zone and outside air temperatures. During a ventilation only period, the supply fan speed is always set to run at 30% speed. No other sequence of operations details were shared with us by the vendor.

System Cost and Cost-Influencing Factors

[Updated copy of a similar section in Appendix A: Project Plan]

RTU retrofit controllers may be installed in any building that has existing RTUs. However, the controllers are most cost effective when the existing RTUs meet all or most of the following conditions:

- Fans and compressors are constant volume and speed
- RTU has no economizer or non-integrated economizer
- Zone has highly variable occupancy but RTU does not have DCV
- Manufacturer nameplate rated EER is low and/or part load efficiency is poor
- Tonnage is at least 5 tons but preferably higher (because of fixed cost per RTU)
- RTU annual runtime is high
- RTU is in decent condition (if in poor condition, it is difficult to commission the new controllers)
- RTU is less than about 10 years old (if the RTU will be replaced soon, a retrofit isn't worthwhile)
- RTU is continually delivering ventilation during occupied hours per Title 24
- BMS is in good operating condition (or no BMS but a well-functioning thermostat instead)
- High level of facility staff engagement in maintaining, monitoring, and optimizing their RTUs

The item about ventilation is noted because according to Small HVAC System Design Guide (Architectural Energy Corporation, 2003), the indoor fans in about 38% of the existing RTUs in California are cycled improperly. The fans are off during occupied periods when there is call for cooling or heating. This isn't code compliant. If this condition is found on-site and if facility staff corrects it, energy savings will be substantially negated when compared to non-code-compliant operation.

The items about the BMS and facility staff engagement are important because most of the controllers studied do not replace the thermostat or disconnect the BMS. The algorithms assume that these devices are working properly, that they are no improper BMS operator overrides, and that all set points are code compliant and reasonable.

Verification of System Operation and Design

HP-17

At the RTU, we visually verified that the fan was running at reduced speed during ventilation only mode. In the zone, we verified that airflow was emitting from the diffusers. While collecting data on a weekly basis, we verified that the power signature of the RTU was reasonable. A typical day of retrofit operation is shown in Figure 9. As expected for June in San Diego, it was mildly cold in the morning and mildly warm in the afternoon. The RTU was off during the night, went into heating mode around 6 AM, then ventilation mode, then two stages of cooling cycled on/off during midday. During the unoccupied period, the compressors cycled from cooling mode to completely off indicating that perhaps the unoccupied temperature set points were in operator override. The unoccupied period also indicates that the parasitic power of the VFD and all other control components is about 120 Watts. The occupied period indicates that the RTU power during ventilation mode is about 180 Watts, during heating mode (likely one stage) the power is about 9 kW, during two stages of cooling is about 5.6 kW, and during one stage is about 3.5 kW.

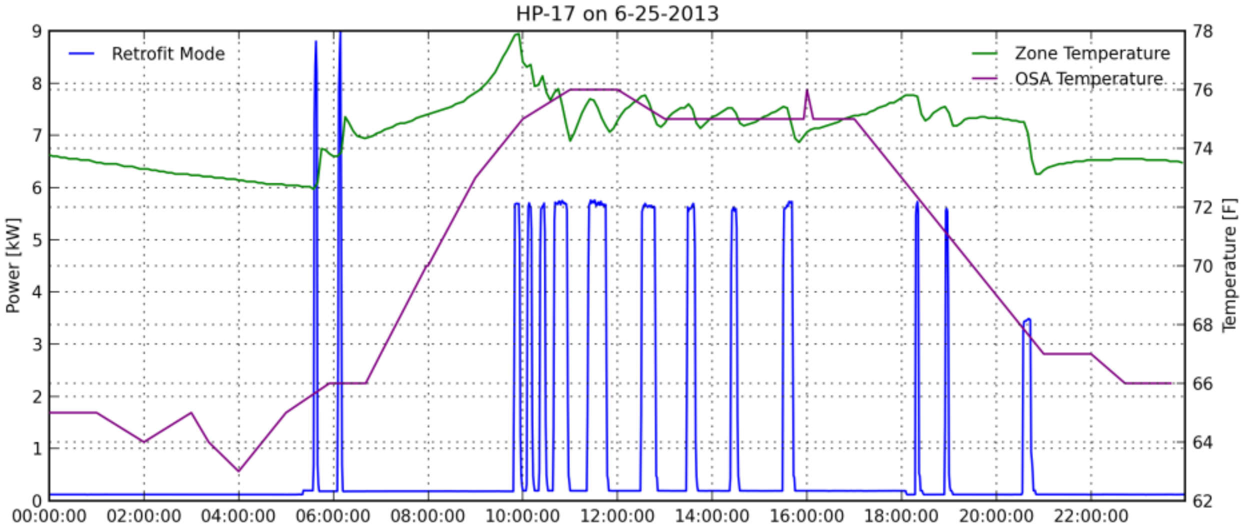


Figure 9: Typical day of HP-17 operation in retrofit mode

Figure 10 shows similar results. It is a plot of the maximum 1-minute interval power measurements per hour for both the baseline and retrofit data sets during business days after September 2, 2012. The data near 0 represent periods when the RTU was off or was in retrofit ventilation mode. The data near 1 kW represent periods of baseline ventilation mode or retrofit economizer mode. The data near 3.5 kW represents one stage of cooling and the cloud above that represents two stages of cooling. The largest savings are during ventilation mode and some savings occur during cooling mode as indicated by the blue clouds being slightly lower than the red clouds. The clouds above 6 kW indicate one and two stages of heat pump heating. The energy use is significantly higher here and it appears that the heat pump uses the second stage more often during the retrofit mode. This may be due to the erratic behavior of the RTU during unoccupied periods. If the RTU comes on during the weekend before a week of baseline operation, heating energy will be reduced unfairly as compared to normal weekend operation prior to a retrofit period.

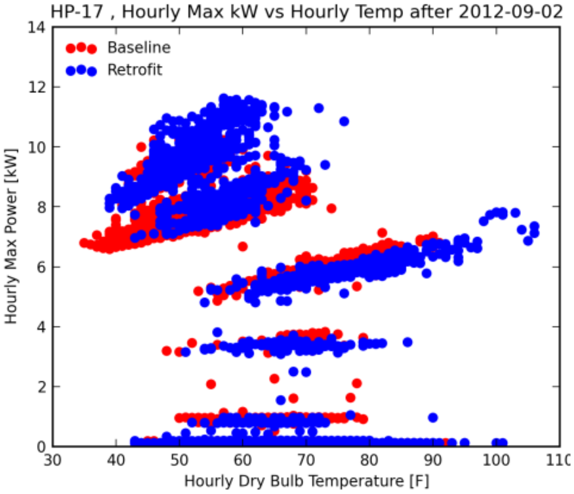


Figure 10: HP-17 Modes of operation

HP-20

This particular installation of this product ultimately failed for some undetermined reason. During our study, the outdoor coil iced over and we determined that the two products (one per compressor) were wired backwards. The second stage compressor was being used as the first stage and therefore the outdoor fan was not turning on.

After this was fixed, we discovered that the RTU was stuck in ventilation mode for weeks on end. We first concluded that the parasitic power of the products was too large for the aged existing transformer. As the contractor was about to replace it, the compressors started operating again so they did not install it. Later, the compressors failed again. The owner then called off further repairs and instructed us to uninstall the products.

HP-26

Figure 11 shows a typical day of HP-26 retrofit operation. The unit comes on at 6 AM, maintains ventilation during occupied hours, enables two stages of compressors regularly to maintain zone temperature, and enables one stage of cooling during the unoccupied night hours to presumably satisfy an unusually low cooling setup temperature set point. Please note that multiple thermostats in multiple rooms in the zone are averaged to yield the “zone temperature”. The zone temperature data in the plot is for one room only.

Figure 12 shows the modes of operation. Starting from the bottom, the horizontal cloud near 1 kW is supply fan only operation, the next cloud up is one stage of cooling, then two stages of cooling, then one stage of heating. The second stage of heating is never used.

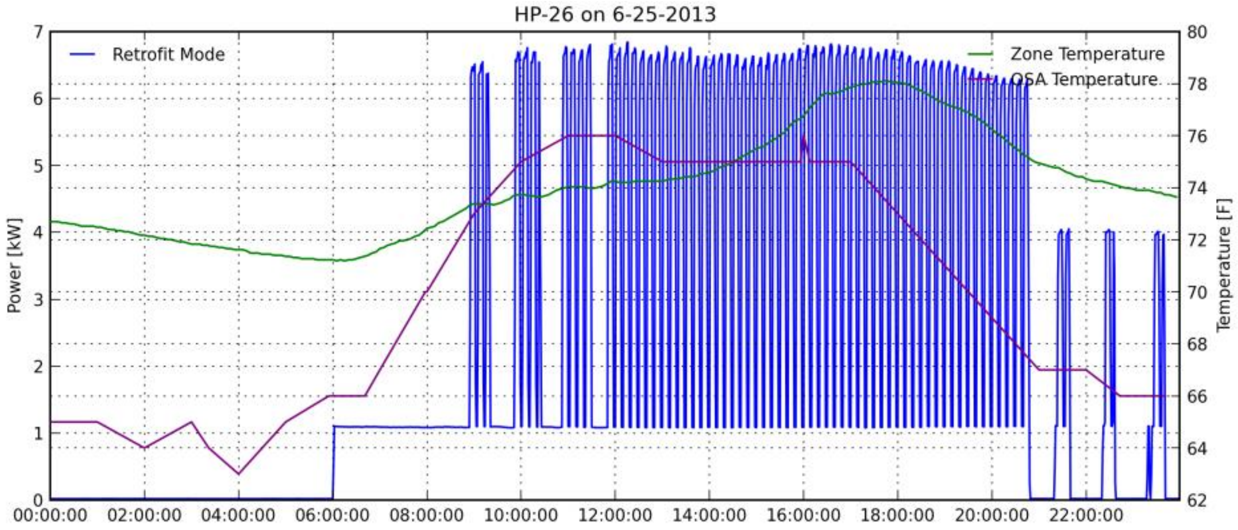


Figure 11: Typical day of HP-26 operation in retrofit mode

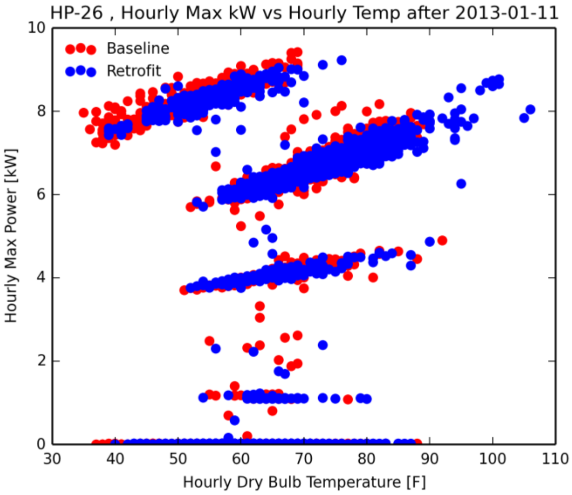


Figure 12: HP-26 Modes of operation

HP-27

Figure 13 shows a typical day of HP-27 retrofit operation. Ventilation is maintained during occupied hours (at a low wattage given the reduced speed of the VFD) and the compressors cycle on to maintain cooling. Please note that the supply fan continues to provide ventilation during unoccupied hours.

Figure 14 shows the modes of operation. No heating ever occurs which is reasonable given that this heat pump is one of two heat pumps serving an interior zone of open office space. There are multiple clouds (or lines of data) near the bottom of the plot given the multiple speeds delivered to the supply fan and compressors.

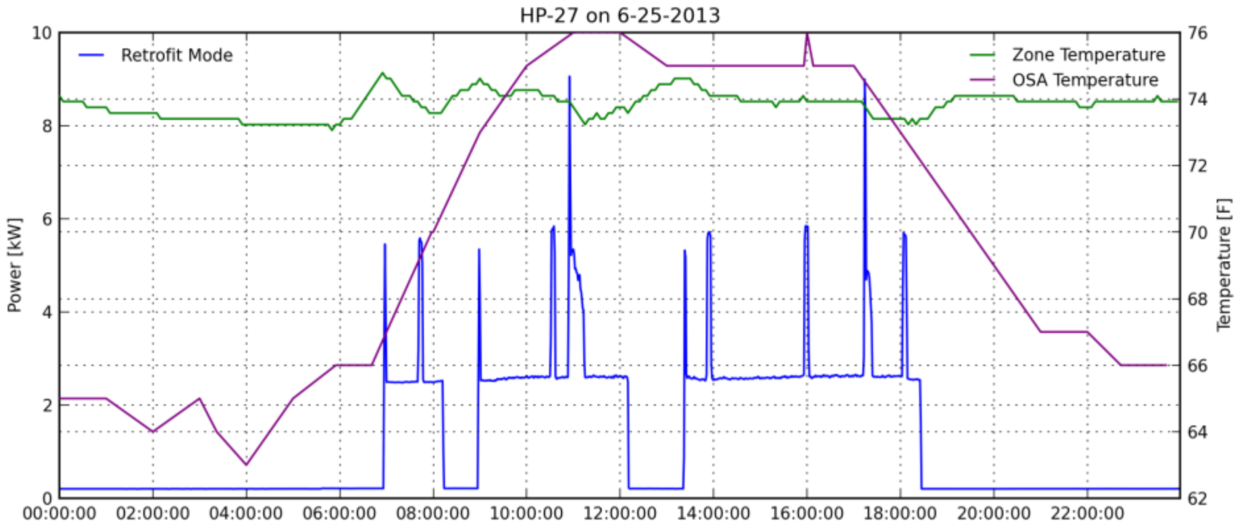


Figure 13: Typical day of HP-27 operation in retrofit mode

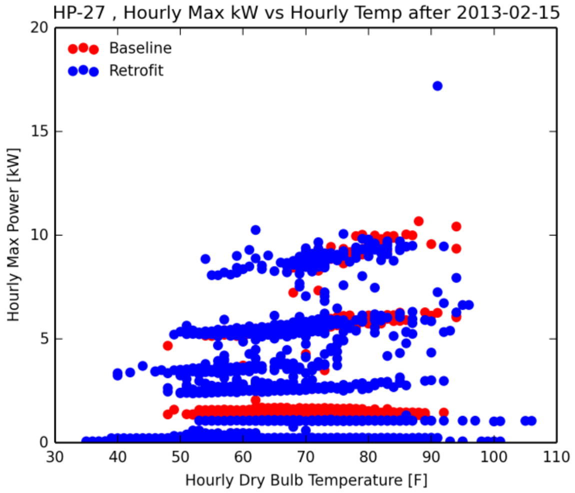


Figure 14: HP-27 Modes of operation

Above and beyond our analysis of the data, the HP-27 vendor answered our questions concerning their implementation of variable speed operation to compressors which were originally designed to be constant speed. They provided us with a bulletin about the same subject written by the parent company of Copeland, a major compressor manufacturer (Emerson Climate Technologies, 2011). After reviewing it, we engaged in the following question and answer session with the vendor:

> Author: Have you checked that these particular Copeland compressors at EMD are part of the model families that they discuss in the [Copeland] bulletin? If they are not listed one could imply that they are not approved for this type of operation. Either way minimum frequency would be 45Hz, did you dial that in?
>
> Vendor: *The low limit is determined based on oil return. We have come up [with] a technique, which allows much lower than stated low limit. If oil return is not ensured, the compressor can be burned in matter of minutes…The Copeland compressor for air conditioning is the same type. The minimum frequency is 45HZ based on Copeland recommendation. We have come up a technique, which allows much lower frequency. The major reason for the low frequency limitation is due to lubrication. Our technique has solved this issue.*
>
> Author: Regarding soft start [and according to the Copeland bulletin], "The VFD must be able to deliver sufficient power at the lower frequencies to ensure that the compressor accelerates to nominal speed in approximately 3 seconds or less....Longer ramp up times could result in inadequate lubrication". I imagine this is part of your control strategy as well?
>
> Vendor: *We use a special VFD, which delivers more torque at low speed and ensures proper lubrication at start up as well…*
>
> Author: Lastly, I am learning from the bulletin that attaching VFDs to some compressors that have "conventional capacity control methods" is not a good idea…Do we know whether there may be a conflict in this respect at EMD?

> Vendor: *Yes. For some of the compressors from Copeland, VFDs can't be implemented directly without other treatment. For example, VFD should not be implemented for lubricant injected compressor.*

We have not verified the above claims. However, in the course of our testing we did witness a related event. It was initially found that the first compressor would not turn on during a cold start. The vendor subsequently reprogrammed their controller to deliver more current in these cases and the issue was resolved. The HP-27 vendor has also stated that, since this test was conducted, their control strategy has been updated to provide further savings. We have not verified this claim either.

Evaluation of Impact to Host Site Staff

The host site staff was most concerned about occupant comfort and HVAC maintenance. When a product prevented an RTU from satisfying the zone temperature set point or when troubleshooting was required, the staff was understandably disappointed. However, when that product was quickly repaired and when the M&V data showed that energy was being saved, the staff was happy to keep the product installed.

Customer Feedback

Aside from the persistent failure of HP-20, there was minimal impact to the occupants. The only other zone in which the occupants noticed a difference was the HP-17 zone. They noticed that the supply diffusers were much less drafty and much quieter when the heat pump was in retrofit mode.

Energy & Cost Savings

There were a few circumstances which complicated our energy and cost savings calculations. First, we only installed one product each for the four vendors so the sampling error was substantial. PECI's *Premium Ventilation Package Testing* (PECI, 2008) report takes the same stance when discussing the various methods of calculating RTU related energy savings:

> Field-based monitoring approach – there have been some attempts to collect field data for HVAC systems pre- and post-retrofit and use that data to generate savings. So far, this method has been elusive, and the sample sizes or time of data collection have been too small to generate data that can be used to generate savings with a high degree of confidence.

Another complication is that the BMS occasionally had errant operator overrides or behaved erratically for some unknown reason. Also, the vendors tuned their algorithms a few times during the M&V period. In addition, creating weather normalized regressions is difficult with heat pumps given that both heating and cooling can occur each day and both use electricity.

Data collection began on 08/24/2012 and ended on 08/02/2013. For HP-17, data prior to 09/02/2012 was ignored because some of the timestamps were invalid and separately because the logger was replaced with a newer model. For HP-26, data prior to 01/11/2013 was ignored for a few reasons. First, the heating data was marred by a miscommunication in which the heating mode remained in retrofit mode during weeks which were intended to be baseline periods. Also, the outdoor fan failed and was offline for a short period. A few subsequent weeks during which the compressors failed due to some existing flaw in the existing equipment or controls were also ignored. For HP-27, data prior to 02/15/2013 was ignored for a few reasons. First, the second stage compressor was failing during that period. Second, the vendor was continually improving their algorithms during that period and consequently their product was not ready to be tested.

In all cases, weekends were ignored since the HVAC schedule commanded the equipment off during those days. Holidays were ignored since the building was mostly empty and had very little HVAC load in the office space. Virtually all Fridays were ignored since the equipment was switched over between retrofit and baseline mode on those days.

Consequently, the numbers of daily observations shown in Figure 1 are lower than they otherwise would have been.

Our calculations varied slightly per heat pump. In all cases, 1-minute interval RTU power data and hourly outside air NOAA dry bulb temperature data was used to determine the modes of operation, to determine the best method to separate heating from cooling, and to identify anomalous data to remove. Then, daily RTU cooling energy use and daily heating energy use were compared to various independent variables and the best regression models were chosen.[4] The independent variables tested included average NOAA dry bulb temperature, wet bulb temperature, dew point temperature, and measured average daily zone temperature. The daily NOAA data was from the GSOD dataset for San Diego Miramar NAS and the hourly NOAA data was from the QCLCD dataset for San Diego Montgomery Field (the hourly Miramar data was missing days of data). In all cases, the best correlations were found using the single independent variable of daily NOAA dry bulb temperature.[5]

Four regressions (baseline cool, retrofit cool, baseline heat, retrofit heat) were attempted so that all could be used against TMY3 data (for Miramar NAS and aggregated to daily values) to calculate annual savings. If only the cooling models yielded acceptable correlation, then only annualized cooling savings were calculated. The scripting language Python was used for all calculations and plotting.

For HP-17, Figure 10 was used to separate the heating from the cooling hours. Then, those respective hours were summed per day. Then, daily cooling sums below 1 kWh were removed since those days essentially have no significant amount of cooling. For heating, daily temperatures above 69 F were ignored because above that temperature there was only a small amount of heating. Daily heating sums above 60 kWh were also ignored because they only occurred at very low temperatures and seemed to be correlated with erratic RTU behavior at night or on the weekend. The heating and cooling scatter plots are shown in Figure 15 and the savings and modeling statistics are tabulated in Figure 1. Similar methods of filtering were used for HP-26 and the results are also shown in those same figures.

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[4] Please note that the author also up-sampled to weekly intervals to see if that would yield better regression statistics than daily intervals. It did not and consequently those results are omitted.

[5] The author considered not normalizing for weather given the long data collection duration and the regular (weekly) switchovers from baseline to retrofit modes. However, this was abandoned because the correlation between RTU energy and dry bulb temperature was fairly high.

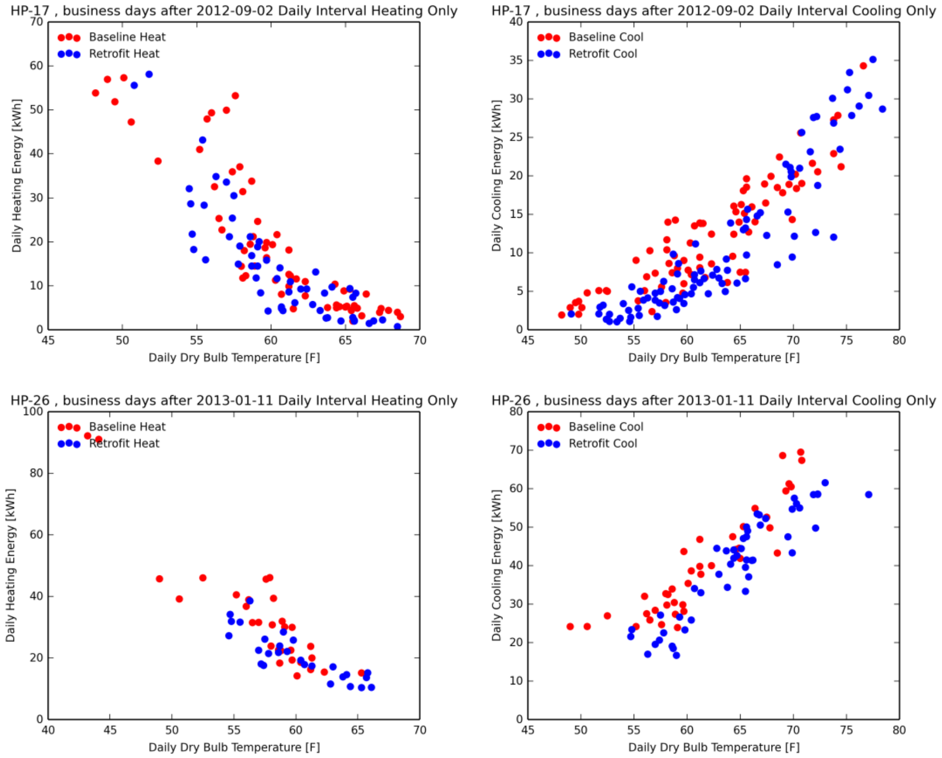


Figure 15: Daily Cooling and Heating Energy Consumption for HP-17 and HP-26

HP-27 was treated differently given that the hourly plot indicated that no heating occurred during the chosen M&V period. So, only cooling savings were calculated. See Figure 1 for the calculation results and Figure 16 for a scatter plot of the daily cooling data. Please note that energy use before 4 AM and after 9 PM was ignored since the RTU was intended to be off but was incorrectly forced by the thermostat into ventilation mode at night. This was also done with HP-26 to remove erratic nighttime operation.

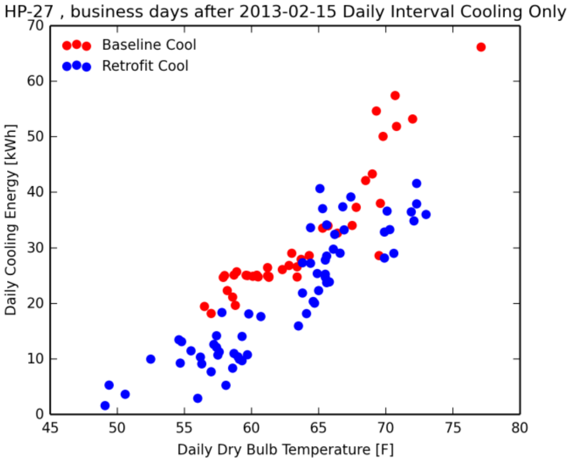


Figure 16: Daily Cooling Energy Consumption for HP-27

Concerning payback period, the aforementioned report by W. Wang at Pacific Northwest National Laboratory (W. Wang, 2012) includes a calculation of acceptable RTU retrofit controller cost. They assume a 3 year payback period, savings of about 40% of annual HVAC energy use, and they run their calculations for two different building types. The report states, “The controller cost can range between $4,180 and $8,390 for the retail building and between $1,560 and $2,990 for the office building.” The PNNL calculations could most closely be applied to the technologies installed on HP-17 and HP-27 since those controllers vary the supply fan speed (among other things). HP-20 and HP-26 only affect compressor cycling and are not expected to reap that level of savings.

In our study, HP-17 installed controller cost was $3800, HP-26 was $950, and HP-27 was $8500. Assuming a blended electricity consumption rate of $0.08/kWh and annual savings of about 2700 kWh for HP-17, the simple payback period for HP-17 without incentives is 17.5 years. Using our calculated annual savings of about 2860 kWh, the simple payback period for HP-26 without incentives is 4.2 years.

Applicability of existing rebate and incentive programs

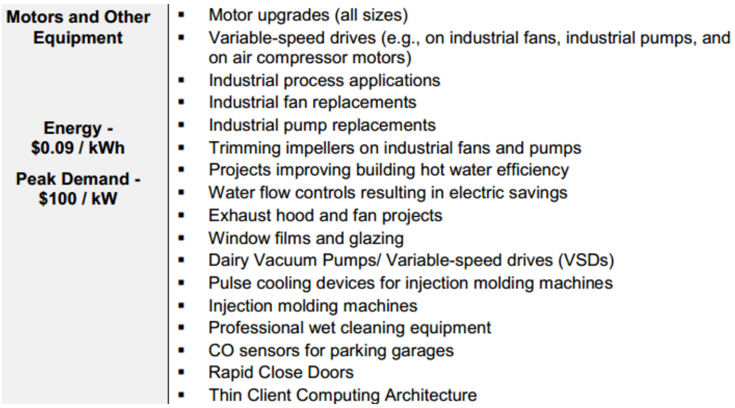
There are various energy use reduction and demand reduction programs and tariffs available throughout SDG&E. Some provide ongoing or event-based operative incentives, while others provide one-time incentives geared towards reducing the customer’s initial investment. It is important to note that participants cannot receive incentives from more than one program for the same project, unless stated otherwise in the program materials. A summary of all the programs in SDG&E territory is shown in Figure 17 and a detailed discussion of some of the relevant programs follows.

Program Name	Applies as is	Applies w/ changes	Discussion summary	More on Page…
Energy Efficiency Business Rebates	Yes		VFDs qualify for $80 rebate per unit	
Energy Efficiency Business Incentives	Yes		Directly applicable due to use of variable speed drives and/or motor upgrades	26
On Bill Financing	Yes		Can be applied to any incentive program	26
Education Partnership Program	Yes		Useful if a college has numerous RTUs	27
Base Interruptible Program (BIP)	No	Yes	This demand response program could work with the one web enabled product we tested (HP-17)	
Capacity Bidding Program (CBP)	No	No	This demand response program is designed for specific aggregators.	
Critical Peak Pricing (CPP-D and CPP-E)	No	Yes	This is a tariff change which benefits customers who shift demand. If enough VFD-type controllers were installed, it could make financial sense.	
Summer Saver	No	No	SDG&E uses their own third party wireless boxes to enable participation here	
TA/TI	No	Yes	This automated demand response program could work with the web enabled product we tested (HP-17)	
Savings By Design	No	No	This program is for new construction only	

Figure 17: Summary of SDG&E incentive programs

Energy Efficiency Business Incentive

SDG&E offers an Energy Efficiency Business Incentive (EEBI) to customers involved in the installation of new high-efficiency equipment or systems (SDG&E, 2012). The projects that fall within EEBI generally consist of the retrofit of existing equipment/systems. Eligibility consists of any commercial, industrial or agricultural customer who pays the public goods charge regardless of size or project scope.



Motors and Other Equipment **Energy - $0.09 / kWh** **Peak Demand - $100 / kW**	▪ Motor upgrades (all sizes) ▪ Variable-speed drives (e.g., on industrial fans, industrial pumps, and on air compressor motors) ▪ Industrial process applications ▪ Industrial fan replacements ▪ Industrial pump replacements ▪ Trimming impellers on industrial fans and pumps ▪ Projects improving building hot water efficiency ▪ Water flow controls resulting in electric savings ▪ Exhaust hood and fan projects ▪ Window films and glazing ▪ Dairy Vacuum Pumps/ Variable-speed drives (VSDs) ▪ Pulse cooling devices for injection molding machines ▪ Injection molding machines ▪ Professional wet cleaning equipment ▪ CO sensors for parking garages ▪ Rapid Close Doors ▪ Thin Client Computing Architecture

Figure 18: Examples of eligible HVAC systems (SDG&E, 2012)

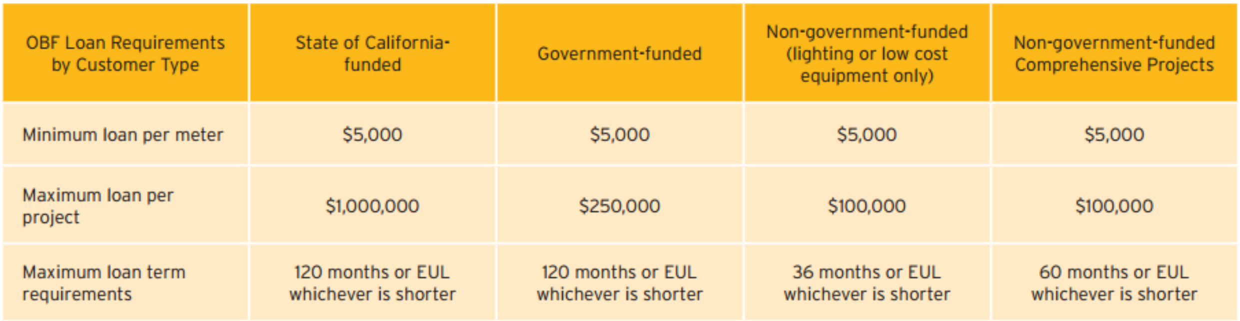
The reviewed technologies should be directly applicable to this incentive structure due to the use of variable speed drives and/or the implementation of motor upgrades (see Figure 18). The EEBI program is a statewide program and therefore the incentives paid off of verified savings should be a constant throughout California. It is important to note that the incentive is capped at “50% of your project cost” (SDG&E, 2012).

Please note that the Energy Savings Bid Program was discontinued on December 31, 2012 (SDG&E, 2012). It was consolidated into the EEBI program.

On-Bill Financing

In addition to the incentives allowed by EEBI, SDG&E also offers an On-Bill Financing (OBF) program (SDG&E, 2012). This can be applicable in conjunction with any utility incentive program. The program offers to finance, at 0% interest, energy-efficient business improvements through the SDG&E bill. This allows a commercial customer to pay for energy efficient programs with the savings acquired from energy efficient technology, with no out of pocket expenses.

When applying OBF to the technology it is very important to note the maximum loan amounts per type of SDG&E customer. SDG&E divides the energy consumers into two categories: taxpayer-funded and non-taxpayer-funded. Taxpayer funded entities are defined as a customer that uses tax revenue to pay utility bills. Taxpayer funded customers are entitled to an interest free loan maximum of $250,000 per project. Non-taxpayer-funded customers are entitled to an interest free loan maximum of $100,000 per project. Figure 19 shows these figures and additional terms.



OBF Loan Requirements by Customer Type	State of California-funded	Government-funded	Non-government-funded (lighting or low cost equipment only)	Non-government-funded Comprehensive Projects
Minimum loan per meter	$5,000	$5,000	$5,000	$5,000
Maximum loan per project	$1,000,000	$250,000	$100,000	$100,000
Maximum loan term requirements	120 months or EUL whichever is shorter	120 months or EUL whichever is shorter	36 months or EUL whichever is shorter	60 months or EUL whichever is shorter

Figure 19: On Bill Financing loan terms (SDG&E, 2012)

Education Partnership Program

The Education Partnership Program is one of SDG&E's Energy Efficiency Partnership Programs (SDG&E, 2012). The goal is to permanently reduce demand and energy use on college campuses. According to the Partnership website, "The program employs four key strategies to meet its goals: energy efficiency retrofits, monitoring based commissioning (MBCx), emerging technology demonstrations, and training and education." (UC/CSU/IOU Energy Efficiency Partnership, 2007)

This particular project falls under the energy efficiency retrofit category and SDG&E provides incentives of $0.24/kWh and $1.00/therm. It would be most useful for campuses with numerous RTUs.

Project Error Analysis

Project Plan Deviation

The primary deviation is that we did not analyze the M&V data for HP-20. That product failed for undetermined reasons and the owner was not interested in continuing that test. In addition, we did not calculate annual heating energy savings for HP-27. There was insufficient heating data after poor data was removed.

Anomalous Data and Treatment

Here is a concise list of the anomalous data and how we treated it:

1. We ignored every day when a switchover was made between baseline and retrofit control. As a result, most Fridays were thrown out.
2. Some heat pumps occasionally turned on during the nights and weekends. We completely ignored the weekends under the assumption that they were intended to be forced off by the facility staff. Then, we filtered out nighttime hours when the heat pump experienced unusually high or low daily heating energy use.
3. HP-20 had iced over outdoor coils on multiple mornings and experienced a long stretch of time during which the compressors did not turn on. We are not sure of the reason for this and attempts to correct the problem failed. So, we are withholding all judgment on its performance aside from suggesting some precautions for future installations. It was removed from the M&V study.
4. The aged compressors on HP-27 failed to turn on for weeks until we discovered that the retrofit controller was not giving enough current to the compressors during a cold start. The algorithm was updated and the poor data was ignored.

5. HP-17 fan speed was initially too low during heating and perhaps causing re-entrainment of supply air into return air registers. The algorithm was updated and unusually high or low daily heating energy use was ignored.
6. An HP-26 condenser fan blade assembly fell off of its shaft so the few days before the repair were omitted.
7. HP-26 experienced a long stretch of time during which the compressors did not turn on. After reviewing the BMS graphic and set point, it appeared that a certain point was improperly overridden. This issue was then fixed and those days of failed compressor operation were omitted.
8. The HP-26 supply fan did not turn on during some occupied hours due to the incorrect setting of the fan cycling BMS data point. This was later corrected by the facility manager and that data was ignored.
9. On HP-26, we didn't properly disable the heating controller from Sept 12 to Dec 12. That data was ignored.
10. On HP-27, the vendor's thermostat improperly forces the heat pump to provide ventilation throughout the night when the unit should be off. This anomaly was corrected for by ignoring all energy use at night.
11. On HP-27, the economizer appeared to be malfunctioning. This was not corrected for.

Technical, Statistical, and Error Analysis

Coefficient of determination (R^2) and coefficient of variation of the root mean squared error (*CV-RMSE*) were used to determine model uncertainty. Those calculations are shown in *Project Results and Discussion* section. Our first rounds of simple regressions did not yield good correlation so we made small iterations to our strategy until we arrived at acceptable correlations. For instance, we used different independent variables, inferred the building heating/cooling balance point from our scatter plots, and calculated multiple variable regressions using Python scripts.

Our measurement error was as follows:

- Power meter errors are about 1%
- NOAA weather data has assumed error of zero per (ASHRAE, 2002)

Net Determination Bias was also calculated. However, overall savings uncertainty calculations are not included.

Conclusions

Benefits

The main benefit is that energy savings can be substantial. RTU operation may also be improved, especially if the existing RTU is oversized or the supply diffusers are drafty. Better zone temperature management is possible. The RTUs could potentially last longer given less runtime and slower speeds. In most cases, the installation is relatively simple with little zone downtime and minimal occupant impact.

Possible Risks

These products add complexity to an existing RTU, add potential points of failure, and may increase required RTU maintenance. The payback period may be long unless incentives are added. It may be difficult to prove energy savings unless numerous HVAC units are retrofitted. Choosing appropriate heat pumps on which to install may be difficult. An RTU must first be in decent condition before the product is installed or it will be difficult to commission. An up-front survey of the equipment by an experienced HVAC mechanic may be required.

System and Technology Improvement Opportunities

Product cost and installation cost should be minimized to improve payback period. The product should be simplified to the extent possible to reduce its potential for failure. FDD would be a worthwhile addition given the upcoming code requirements. Finally, the sequence of operations should be tuned to the RTU on which the product is installed. This could reduce the potential for failure.

Applicability of Case Study Findings to Other Load Types and Sectors

This report most directly applies to office buildings, restaurants, and retail. These buildings on average likely all have constant volume RTUs serving non-critical spaces.

Considerations for Large-scale and Persistent Market Implementation

Vendors should be careful not to overstate the market potential of their products. Buildings with only a few rooftop units, with dilapidated rooftop units, and/or without a decent HVAC maintenance program are not good prospective customers. Payback period would lengthen if significant on-site commissioning or troubleshooting is required.

Possible future Study

M&V sampling error would be greatly reduced if multiple controllers by the same vendor were installed and tested in multiple building types in multiple climate zones. Another potential study would be to calculate savings using Energy Plus whole building models as was done in (W. Wang, 2012). However, specific sequence of operations details from each vendor would be needed.

Glossary and Acronyms

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BMS – Building Management System
CAV – Constant Air Volume
CDD – Cooling Degree Days
CEC – California Energy Commission
CEUS – California End-User Survey
CV-RMSE – Coefficient of variation of the root mean squared error
DCV – Demand control ventilation
DOE – Department of Energy
EEBI – Energy Efficiency Business Incentive
EPA – Environmental Protection Agency
FDD – Fault Detection and Diagnostics
HDD – Heating Degree Days
HVAC – Heating, Ventilation, and Air Conditioning
IPMVP – International Performance Measurement & Verification Protocol
IV – Independent Variables
MBCx – Monitoring based commissioning
M&V – Measurement and Verification
NAS – Naval Air Station
NOAA – National Oceanic and Atmospheric Administration
OBF – On-Bill Financing
OEM – Original Equipment Manufacturer
PECI – Portland Energy Conservation, Inc.
PG&E – Pacific Gas & Electric
R^2 – Coefficient of determination
RTU – Packaged Rooftop Unit
SDG&E – San Diego Gas & Electric
TMY3 – Typical Meteorological Year 3
VAV – Variable Air Volume
VFD – Variable Frequency Drive

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Appendix A: Project Plan

SAN DIEGO GAS AND ELECTRIC COMPANY
EMERGING TECHNOLOGIES PROGRAM
PROJECT ID ET12SDGE0003

MULTI-VENDOR RTU RETROFIT CONTROLLER

PROJECT PLAN

PREPARED FOR
AHMED ABDULLAH, NATHAN TAYLOR
SAN DIEGO GAS AND ELECTRIC COMPANY
8306 CENTURY PARK COURT
SAN DIEGO, CA 92123

PREPARED BY
BO WHITE, MARC ESSER
NEGAWATT CONSULTING, INC.
WWW.NEGAWATTCONSULT.COM

08/03/2012B

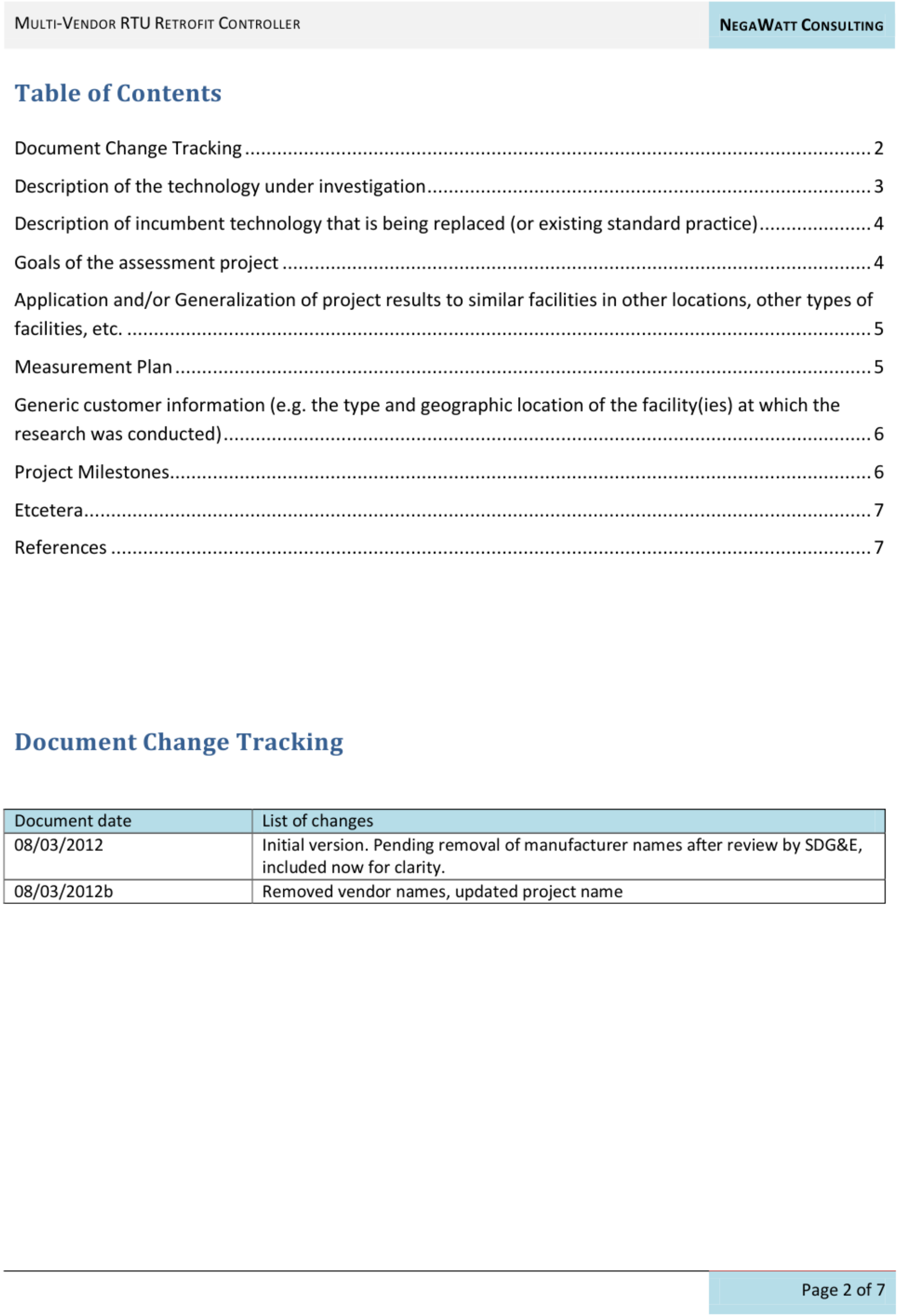
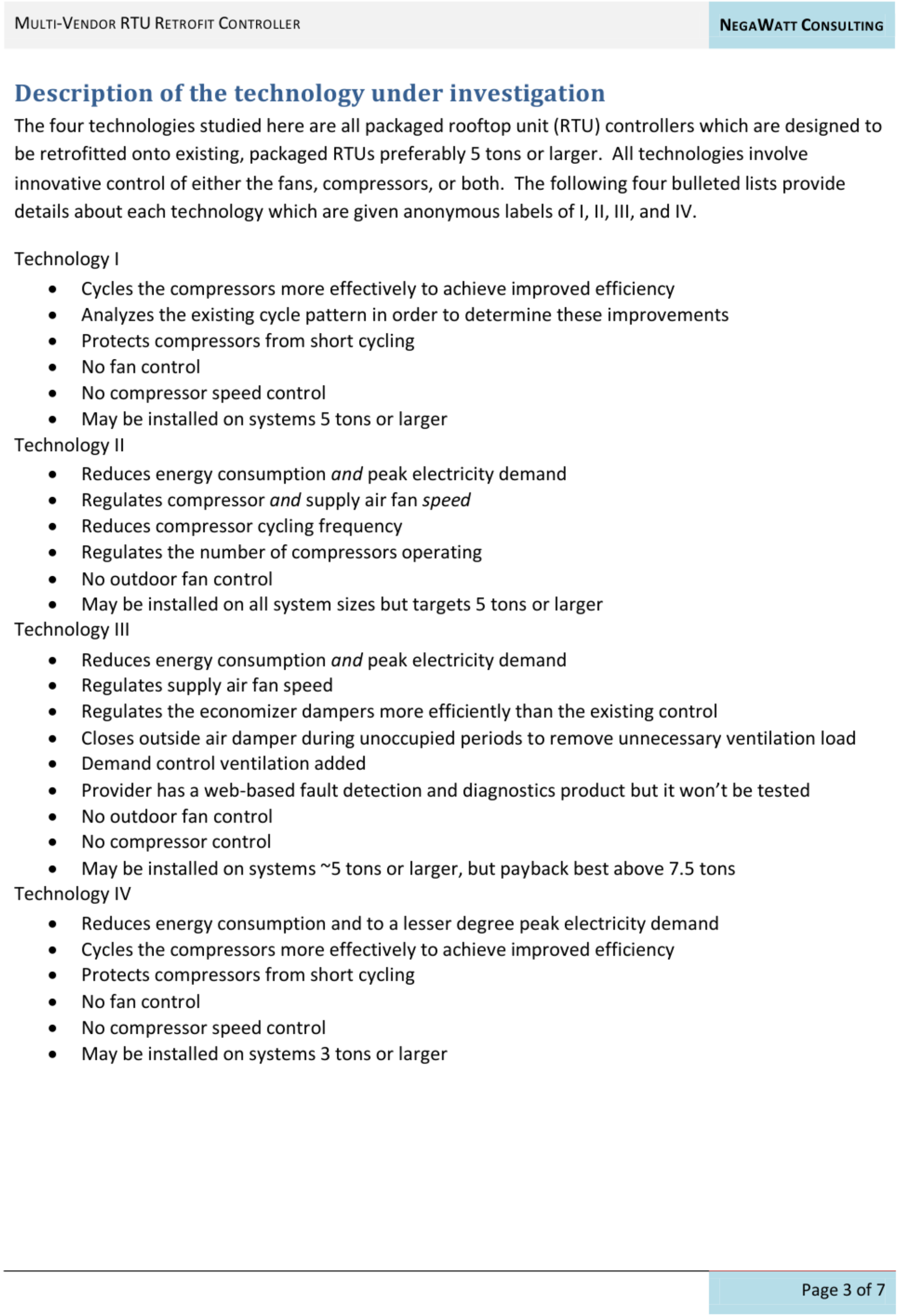


Table of Contents

Document Change Tracking

Document date	List of changes
08/03/2012	Initial version. Pending removal of manufacturer names after review by SDG&E, included now for clarity.
08/03/2012b	Removed vendor names, updated project name



Description of the technology under investigation

The four technologies studied here are all packaged rooftop unit (RTU) controllers which are designed to be retrofitted onto existing, packaged RTUs preferably 5 tons or larger. All technologies involve innovative control of either the fans, compressors, or both. The following four bulleted lists provide details about each technology which are given anonymous labels of I, II, III, and IV.

Technology I

- Cycles the compressors more effectively to achieve improved efficiency
- Analyzes the existing cycle pattern in order to determine these improvements
- Protects compressors from short cycling
- No fan control
- No compressor speed control
- May be installed on systems 5 tons or larger

Technology II

- Reduces energy consumption *and* peak electricity demand
- Regulates compressor *and* supply air fan *speed*
- Reduces compressor cycling frequency
- Regulates the number of compressors operating
- No outdoor fan control
- May be installed on all system sizes but targets 5 tons or larger

Technology III

- Reduces energy consumption *and* peak electricity demand
- Regulates supply air fan speed
- Regulates the economizer dampers more efficiently than the existing control
- Closes outside air damper during unoccupied periods to remove unnecessary ventilation load
- Demand control ventilation added
- Provider has a web-based fault detection and diagnostics product but it won't be tested
- No outdoor fan control
- No compressor control
- May be installed on systems ~5 tons or larger, but payback best above 7.5 tons

Technology IV

- Reduces energy consumption and to a lesser degree peak electricity demand
- Cycles the compressors more effectively to achieve improved efficiency
- Protects compressors from short cycling
- No fan control
- No compressor speed control
- May be installed on systems 3 tons or larger

Description of incumbent technology that is being replaced (or existing standard practice)

Packaged air conditioning units (i.e. RTUs) accounted for 46% of main commercial cooling equipment as of 2003 according to the Department of Energy Buildings Energy Data Book (Department of Energy, 2012a). The average EER efficiency of RTUs in service in 2010 was 11.2 even though the best-available on the market was 13.9 (Department of Energy, 2012b). The EER values at the pilot site range from 8.7 to 13.2 as per the nameplates. Many installed RTUs, including those at the pilot site, have constant volume fans and compressors which are inefficient when compared to variable speed equipment. Ventilation levels are often excessive and compressors often deliver too much cooling and/or short cycle.

The median lifetime of commercial RTUs is 15 years (Department of Energy, 2012c) which may help to explain the poor efficiencies of in-service RTUs and why retrofit energy-saving controllers have market potential.

Goals of the assessment project

The primary goal of this study is to confirm plausibility and actual energy savings of each technology. Savings will be assessed based on measurements and calculations for energy, demand and cost. The functionality of each technology will also be reviewed and confirmed.

Overall, we can summarize the goals of this assessment project as follows:

1. Describe system setup, operations, and functionality
2. Quantify energy savings, cost and simple payback time
3. Analyze factors that may cause variations in energy savings, cost and payback times under different circumstances such as different base RTUs or different climate zones.
4. Review utility programs with respect to their present applicability to this technology and provide recommendations as to how utilities could further support this technology
5. Research the potential market size and possible barriers to adoption, given enough information
6. Gather and present customer feedback
7. Suggest possible improvements to the technology, if applicable
8. Assess risks introduced by this technology, if any

Application and/or Generalization of project results to similar facilities in other locations, other types of facilities, etc.

RTU retrofit controllers may be installed in any building that has existing RTUs. However, the controllers are most cost effective when the existing RTUs have all or most of the following conditions:

- Fans and compressors are constant volume and speed
- Manufacturer nameplate rated EER is low and/or part load efficiency is poor
- Tonnage is at least 5 tons but preferably much higher (fixed system cost has better payback time on units that consume a lot of energy)
- RTU annual runtime is high

The controllers save energy by improving fan and compressor control over all operating conditions. The cost of each controller does not vary with system size, therefore a larger RTU tonnage for a given EER results in a shorter payback period.

Volume pricing may be available if there are multiple RTUs per site, further reducing payback time.

As part of this project, we will establish concrete recommendations on how to estimate energy savings for the purposes of incentive administration. The RTUs in this project fulfill all of the target conditions above.

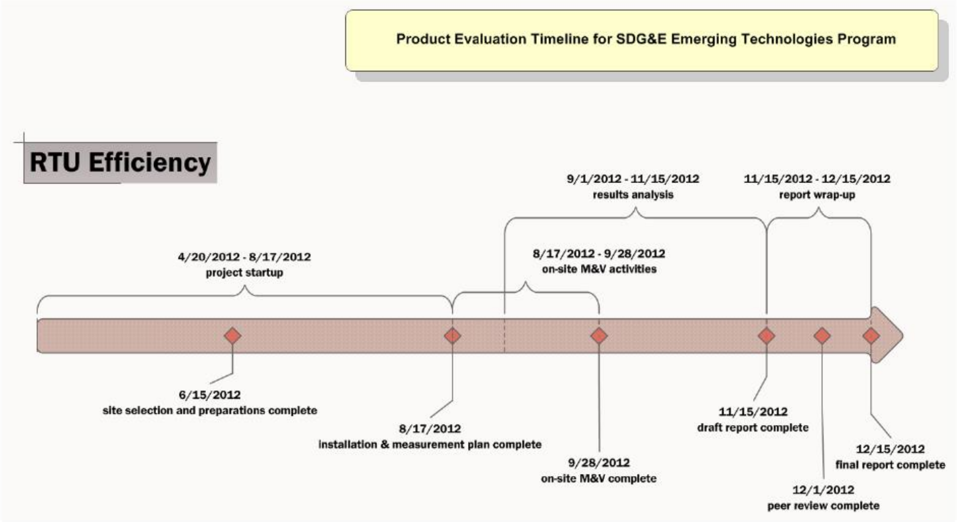
Measurement Plan

Please see (NegaWatt Consulting, 2012a).

Generic customer information (e.g. the type and geographic location of the facility(ies) at which the research was conducted)

Building Name	EMD Millipore
Year built	1993
Size	60,000 ft^2
Occupancy type	Office/Laboratory
Building Management System	Siemens
Mechanical System Summary	Constant Volume Packaged, Single Zone Heat Pumps

Project Milestones



Milestones are subject to change.

Etcetera

For a detailed statement of work and estimate please see (NegaWatt Consulting, 2012b).

This assessment follows the scientific rigor protocol described in (SDG&E, 2010).

The final report for this project will be made available as (NegaWatt Consulting, 2013) on www.etcc-ca.org. Additional references will be contained therein.

This project will be tracked in NegaWatt's online project management tool once the project plan has been approved. The document repository for this project is NegaWatt's secure file server. Please contact the authors of this project plan if you need access to these systems or to any of the referenced documents.

References

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Appendix B: Measurement & Verification Plan

San Diego Gas and Electric Company
Emerging Technologies Program
Project ID ET12SDGE0003

RTU Efficiency M&V Plan

Prepared For
Ahmed Abdullah, Nathan Taylor
San Diego Gas and Electric Company
8306 Century Park Court
San Diego, CA 92123

Prepared By
Bo White, Marc Esser
NegaWatt Consulting, Inc.
www.negawattconsult.com

09/17/2012

Table of Contents

Document Change Tracking

Document date	List of changes
08/17/2012	Initial version.
8/20/2012	Internal QA edits by NegaWatt, then released to SDG&E for approval
8/20/2012b	Fixed some grammatical errors
9/17/2012	Fixed model number and link for HOBO data logger

Introduction

This measurement plan is an integral part of the project described in (NegaWatt Consulting, 2012).

It follows the guidelines established in (SDG&E, 2010).

It has been designed to accurately assess both the baseline performance of the incumbent technology (or standard practice in the absence of an incumbent) and the performance of the technology under study.

It has been designed in compliance with one of the evaluation methods identified in the International Performance Measurement and Verification Protocol (IPMVP) except where site- or technology-specific circumstances dictated a deviation from one of these protocols. The Measurement Plan identifies selected IPMVP method to be used or the justification for any deviations from IPMVP.

All instrumentation under the control of evaluation staff shall be calibrated in accordance with guidelines established in the IPMVP as described in (SDG&E, 2010).

For field evaluations, all reasonable efforts shall be made to calibrate or replace any customer-owned instrumentation or where this is not possible, to document the calibration status of such instrumentation.

Measurement uncertainty for each monitoring device will be documented. Note that an error analysis evaluating the uncertainty associated with energy and demand savings estimates will be required for the Final Report.

All instrumentation will be commissioned prior to initiating data collection to ensure that measurement and logging systems are functioning properly, to minimize risk of unusable data sets.

Any anomalous data will be investigated and explained. Following investigation, careful consideration will be given to whether such data should be incorporated in the analysis or replaced by additional data collection.

Any events that occur at customer premises during the data collection period that are likely to compromise the validity of the assessment project and that are beyond the control of evaluation staff will be communicated to program management without delay.

Test site description

EMD Millipore is a two story commercial building located at 10394 Pacific Center Court, San Diego, CA 92121 in California Climate Zone 7. General building features are listed in Figure 1 below. Most of the heat pumps are 5 or 7.5 tons and all are roof-mounted. They each have economizers, constant volume fans, and constant speed compressors. Most are manufactured by Carrier, have EER values that range from about 8.7 to 13.2, and are anywhere from 1 to 19 years old. All of the units serving office spaces operate on a time schedule of 6AM to 7PM weekdays only.

The BMS computer is on-site and does not have a remote login capability. It includes fan status, compressor status, zone temperature, and zone temperature set point. None of these points are trended beyond about one day in length. See Figure 2 below for a BMS screenshot of a typical heat pump.

Building Name	EMD Millipore
Year built	1993
Size	60,000 ft²
Occupancy type	Office/Laboratory
Building Management System	Siemens
Mechanical System Summary	Constant Volume Packaged, Single Zone Heat Pumps

Figure 1 Building Features

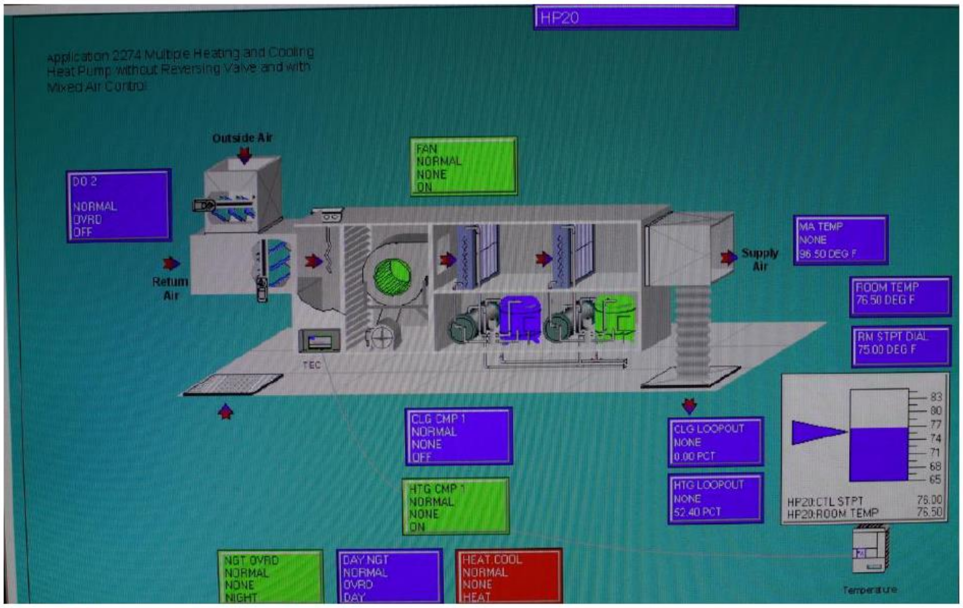


Figure 2 BMS screenshot of a typical heat pump

Data collection procedures

We will evaluate four RTU controllers from four controller vendors, each installed on a single zone 7.5 ton heat pump serving only office space. The heat pumps will be inspected and repaired as needed by a qualified mechanical contractor prior to data collection to prevent data anomalies and ensure that the results are typical and can be extrapolated to other buildings and systems. Three single zone 5 ton heat pumps serving office space may be used alternatively in case of unforeseen issues with the 7.5 ton units.

We will systematically gather data in order to establish baseline energy usage and energy usage with the RTU controllers active. The data will primarily be taken from our own loggers. See Figure 3 below for the full list of data points. Additional items of focus are:

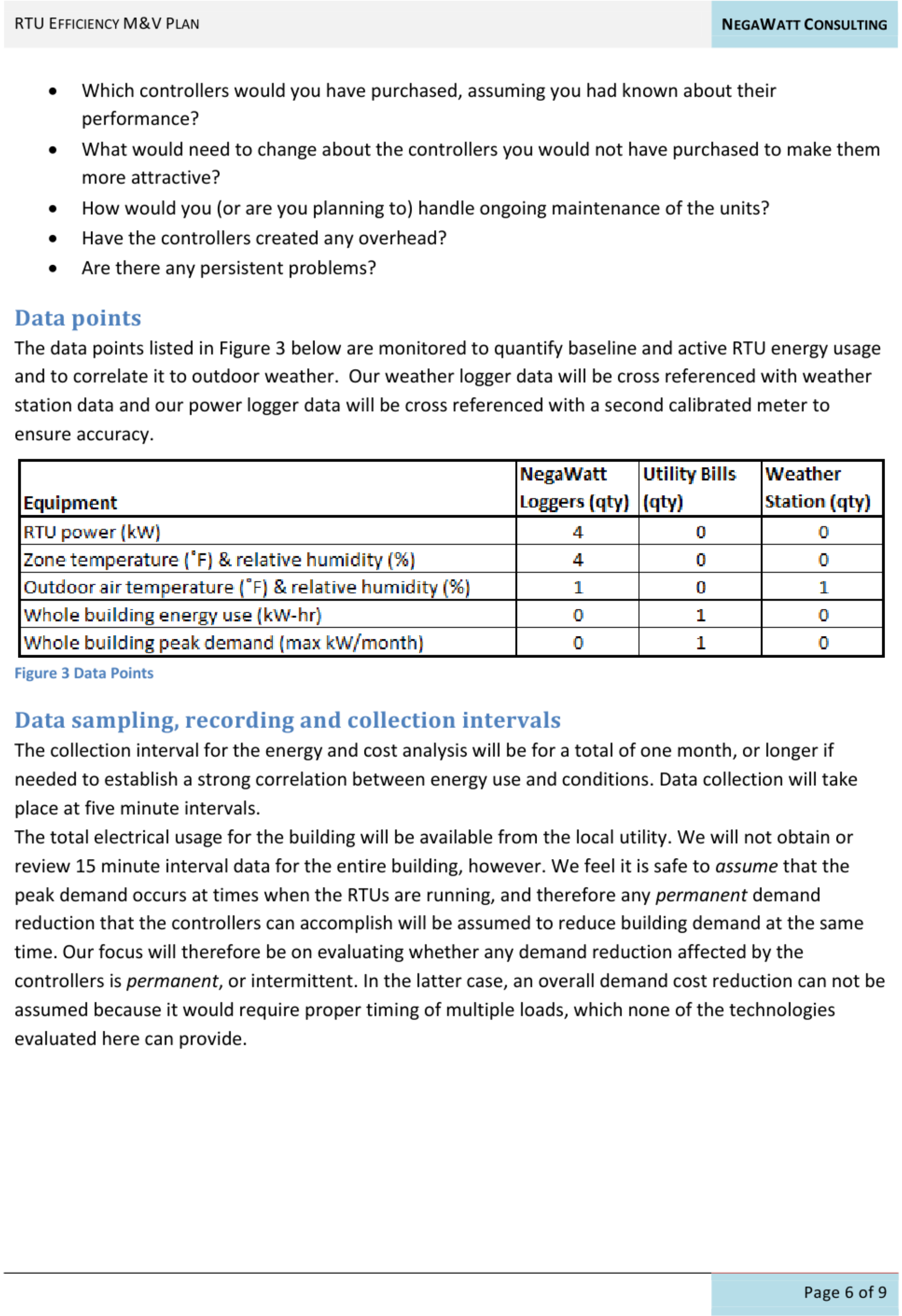
- Verify how occupant comfort is negatively affected by the controllers, if at all
- Report on impact to BMS functionality, if any

Baseline and active data collection will alternate in weekly cycles. We will collect data until we have established a strong enough correlation between energy consumption and outside conditions to allow for accurate annualizing of the results. We estimate this to take about one month, depending on weather and usage patterns. The RTU controllers will be installed but deactivated during baseline data collection. Pending facility staff approval, transition between data collection periods will take place on weekends to minimize data anomalies due to the transition or occupancy (every transition will require a site visit). We will share our data with the controller providers and address any possible concerns. We will cross check the weather data from our loggers with a nearby weather station. Whole building energy usage and peak demand will be retrieved from the local utility. This data will be used to estimate demand savings, and to evaluate the fraction of RTU energy usage of whole building energy use.

Data will be collected during summer and possibly early fall months (collection beginning in August of 2012). Our study will focus on cooling (electricity) energy savings. The summer months are excellent for data collection because of high energy use for cooling at that time. We will extrapolate annual energy savings using the "bin method", with typical weather data provided via BinMaker Pro.

Throughout the course of the project, we will perform multiple informal interviews with facilities staff and record meeting minutes. At the end of the data collection period, a written (online) survey will also be given to the facility manager to formally capture his feedback. These activities will help to elucidate the pros and cons of the controllers as well as indicate possible improvements from the end user point of view. Questions in the survey will include:

- Did you notice any benefits or drawbacks using the controllers?
- Has comfort changed?
- Have you noticed a decrease in energy cost?
- What do you think of cost vs. performance?
- Which controllers will you keep and which will you remove?



- Which controllers would you have purchased, assuming you had known about their performance?
- What would need to change about the controllers you would not have purchased to make them more attractive?
- How would you (or are you planning to) handle ongoing maintenance of the units?
- Have the controllers created any overhead?
- Are there any persistent problems?

Data points

The data points listed in Figure 3 below are monitored to quantify baseline and active RTU energy usage and to correlate it to outdoor weather. Our weather logger data will be cross referenced with weather station data and our power logger data will be cross referenced with a second calibrated meter to ensure accuracy.

Equipment	NegaWatt Loggers (qty)	Utility Bills (qty)	Weather Station (qty)
RTU power (kW)	4	0	0
Zone temperature (˚F) & relative humidity (%)	4	0	0
Outdoor air temperature (˚F) & relative humidity (%)	1	0	1
Whole building energy use (kW-hr)	0	1	0
Whole building peak demand (max kW/month)	0	1	0

Figure 3 Data Points

Data sampling, recording and collection intervals

The collection interval for the energy and cost analysis will be for a total of one month, or longer if needed to establish a strong correlation between energy use and conditions. Data collection will take place at five minute intervals.

The total electrical usage for the building will be available from the local utility. We will not obtain or review 15 minute interval data for the entire building, however. We feel it is safe to *assume* that the peak demand occurs at times when the RTUs are running, and therefore any *permanent* demand reduction that the controllers can accomplish will be assumed to reduce building demand at the same time. Our focus will therefore be on evaluating whether any demand reduction affected by the controllers is *permanent*, or intermittent. In the latter case, an overall demand cost reduction can not be assumed because it would require proper timing of multiple loads, which none of the technologies evaluated here can provide.

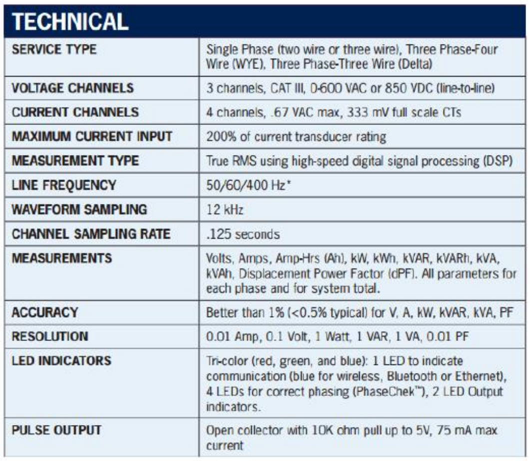
Instrumentation

All the instrumentation used in this project will be calibrated directly or indirectly (the latter by spot-checking with calibrated meters and establishing a correction method for our analysis, if applicable)

Tools and instruments that will be used in the project are:

- Fluke 1735 Three Phase Power Logger device for spot check measurements. The 1735 conducts energy consumption testing by logging most electrical power parameters and captures voltage events. Calibration of the Fluke 1735 was done on 3/30/2011. The values that will be measured are energy and power. Power measurement errors from the Fluke 1735 are calculated by adding the errors of voltage and current and including error of power factor (specified error x [1-power factor error]). For more information, see http://www.fluke.com/fluke/usen/power-quality-tools/three-phase/fluke-1735.htm?PID=56028.
    - V-RMS Wye Measurement
        - Measuring Range (V AC): 57 / 66 / 110 / 120 / 127 / 220 / 230/ 240 / 260 / 277 / 347 / 380 / 400 / 417 / 480
        - Resolution: 0.1 V
        - Intrinsic error: ± (0.2% of measured value + 5 digits)
        - Operating error: ± (0.5% of measured value + 10 digits)
    - V-RMS Delta Measurement
        - Measuring Range (V AC): 100 / 115 / 190 /208 / 220 / 380 / 400 / 415 / 450 / 480 / 600 / 660 / 690 / 720 / 830
        - Resolution: 0.1 V
        - Intrinsic error: ± (0.2% of measured value + 5 digits)
        - Operating error: ± (0.5% of measured value + 10 digits)
    - A-RMS Current Measurement
        - Range: 15 A / 150 A / 3000 A RMS (non-distorted sine wave)
        - Resolution: 0.01 A
        - Intrinsic error for ranges 150 A / 3000 A: ± (0.5 % of m. v. + 10 digit)
        - Operating error for ranges 150 A / 3000 A: ± (1 % of m. v. + 10 digit)
        - Intrinsic error for 15A range: ± (0.5 % of m. v. + 20 digit)
        - Operating error for 15A range: ± (1 % of m. v. + 20 digit)

- Dent instruments EliteProSP Recording Poly Phase Power Meter, http://www.dentinstruments.com/media/ELITEproSP_Datasheet_Brochure_Energy_Data_Logger.pdf
  new from the factory as of August 2012
  see specs on following page



TECHNICAL	
SERVICE TYPE	Single Phase (two wire or three wire), Three Phase-Four Wire (WYE), Three Phase-Three Wire (Delta)
VOLTAGE CHANNELS	3 channels, CAT III, 0-600 VAC or 850 VDC (line-to-line)
CURRENT CHANNELS	4 channels, .67 VAC max, 333 mV full scale CTs
MAXIMUM CURRENT INPUT	200% of current transducer rating
MEASUREMENT TYPE	True RMS using high-speed digital signal processing (DSP)
LINE FREQUENCY	50/60/400 Hz*
WAVEFORM SAMPLING	12 kHz
CHANNEL SAMPLING RATE	.125 seconds
MEASUREMENTS	Volts, Amps, Amp-Hrs (Ah), kW, kWh, kVAR, kVARh, kVA, kVAh, Displacement Power Factor (dPF). All parameters for each phase and for system total.
ACCURACY	Better than 1% (<0.5% typical) for V, A, kW, kVAR, kVA, PF
RESOLUTION	0.01 Amp, 0.1 Volt, 1 Watt, 1 VAR, 1 VA, 0.01 PF
LED INDICATORS	Tri-color (red, green, and blue): 1 LED to indicate communication (blue for wireless, Bluetooth or Ethernet), 4 LEDs for correct phasing (PhaseChek™), 2 LED Output indicators.
PULSE OUTPUT	Open collector with 10K ohm pull up to 5V, 75 mA max current

Figure 4 - Dent Elitepro SP specs

- DENT instruments ELITEpro Recording Poly Phase Power Meter, http://www.dentinstruments.com/media/PDF/ELITEpro_datasheet.pdf
  - Last Calibrated on January 2011
  - ELOG Windows based software package for programming, set-up, communicating, data retrieval and analysis (can export to excel or access)
  - Voltage (3 channels)
    - Range: 0-600 V (AC or DC)
    - Accuracy: < 1% of reading, exclusive of sensor (0.2% typical)
    - Resolution: Better than 0.1% FS – 12 bit A/D
  - Current (4 channels)
    - 0-6,000 A (with current sensor having 333mVac output, ordered separately)
    - Range: 0-600 V (AC or DC)
    - Accuracy: < 1% of reading, exclusive of sensor (0.2% typical)
    - Resolution: Better than 0.1% FS – 12 bit A/D
  - Single phase, three phase-four wire (WYE), three phase delta Accuracy: 1%

- HOBO U12 Temp/RH/2 External Data Logger, U12-013, by Onset Computer Corporation, http://www.onsetcomp.com/products/data-loggers/u12-013
  - Humidity Range: 5%-95% RH
  - Humidity Accuracy: ±2.5% from 10% to 90% RH (typical), Max ±3.5%
  - Humidity Resolution: 0.03% @ 25°C
  - Temperature Range: -20°C to 70°C
  - Temperature Accuracy & Resolution: ±0.35°C from 0 to 50°C; 0.03°C @ 25°C
  - Clock Accuracy: ±1 minute/month @ 25°C

- Historical weather station data from Weather Underground (http://www.wunderground.com), Weather Bug (http://www.weather.weatherbug.com), or a similarly reputable online source. Typical Meteorological Year (TMY3) data from the National Weather Service will also be used within BinMaker Pro from the Gas Technology Institute.

Data analysis procedures

As stated in the introduction, all data will be reviewed before analysis and any anomaly will be investigated and explained in the final report.

Data manipulation (aggregation, statistical analysis, etc.)

We will download RTU power, temperature, and humidity directly from our associated loggers. Whole building meter power will be received from the utility and weather station data will be retrieved from Weather Underground or a similarly reputable website.

Calculation of energy and demand savings

To estimate the yearly energy savings, we will first scatter plot our two RTU power datasets against dry bulb temperature (or enthalpy) ignoring periods where the RTU is off, fit trend equations to the plots, and calculate the correlation factors (R^2). If correlation is low and does not increase as we gather more data we will investigate and correct for outside influences (e.g. occupancy, start-up anomalies, etc) as best possible, and/or log additional data until correlation is high enough. We will ignore data when the units are off (for better correlations) and re-apply the schedule later as part of the annualizing process. Finally, we will subtract the unit-active total from the baseline to get annual energy savings.

Demand *response* capability will not be evaluated. However, we will calculate possible demand *cost* savings as outlined earlier and again below, and we will list vendor's claims w/r/t DR capabilities in the features and future study sections of the final report.

Calculation of cost savings

Utility bills will be requested from the building owner. The rates listed on the bills will be simplified to summer and winter blended on-peak, semi-peak, and off-peak energy use and demand rates, and be used to calculate annual cost accordingly. Finally, simple payback period will be calculated using the annual cost savings, the first cost of the given controller, and any recurring costs.

References

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SDG&E. (2010). *Draft ETP assessment protocol 061610.docx.*

Appendix C: Peer Review Certificate

Alternative Energy Systems Consulting, Inc.

www.aesc-inc.com

(760) 931-2641

Carlsbad, 11/14/2013

This report file, named

“Multi-Vendor RTU Retrofit Controller Final report 2013-11-12.pdf”

And titled

“Multi-Vendor RTU Retrofit Controller Field Study Final Report”

Has been peer reviewed by us, and our suggestions for improvement have been incorporated. Based on the information available, we believe that the research was conducted in a sound and rigorous manner and that the results are accurate and complete as presented.

Antonio Corradini, PE

Director of Engineering of Alternative Energy Systems Consulting Inc.