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Emerging Technologies

ECO2 Heat Pump Water Heater Controller: Feasibility Study & Applications Testing

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ECO2 Heat Pump Water Heater Controller: Feasibility Study & Applications Testing

Prepared for

Karen Janowitz, Project Principal Investigator

Washington State University Energy Program on behalf of Bonneville Power Administration

Prepared by

Erik Turner, Evan Green, Jonathan Heller

Ecotope Inc.

The following report was funded by the Bonneville Power Administration (BPA) to assess emerging technology topics that have the potential to increase energy efficiency. BPA is committed to identify, assess, and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

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Acronyms

BMS – Building Management System

DHW – Domestic Hot Water

DR – Demand Response

EUI – Energy Use Intensity

Gen3/Gen4 – SANCO2 version of heat pump water heater

HPWH – Heat Pump Water Heater

I/O – Input or Output (physical points of connection on controller)

M&V – Measurement and Verification

Modbus – Serial communication protocol; "daisy chain"

NSF - National Sanitation Foundation

OAT – Outdoor Air Temperature

PLC - Programmable Logic Controller

SDWA – Safe Drinking Water Act

TIM – Technology Innovation Model

UL – Underwriters Laboratories

Executive Summary

Domestic water heating is the largest single use of energy in multifamily new construction in the Northwest. Heat pump hot water heater plants offer a means to reduce the energy intensity of heating hot water. Proper control and alarming is required to allow the promise of heat pump water heating to deliver consistently efficient results.

The SanCO2 HPWH product was developed for use in single family applications. While multiple units can be tied together with shared storage to serve larger commercial or multifamily applications, the standard controls are not set up to provide any staging controls for multiple heat pumps, alarming, or data collection functions that are important for larger commercial systems[1]. To address these issues, ECO2, the parent company of SANCO2, developed and manufacture a controller that can be paired with heat pump plants utilizing SANCO2 CO_2 heat pumps.

The standard controller will include capability to operate the heat pump plant and alarm upon certain failure conditions. More advanced functions such as measurement and verification and demand response can be incorporated with additional modules.

This study blends the first two steps in BPA's Technology Innovation Model (TIM) – by assessing the feasibility of the product with an analysis of certifications, system components, performance, cost, constructability, and maintenance as well as putting an actual installation through an Applications Test. We believe the SANCO2 controller is ready to move to the next stage and have all its advanced features, such as M&V and DR capabilities tested as part of a Demonstration Project.

Codes and Certifications: The standard SANCO2 controller will allow the system to alarm on temperatures in compliance with recent Seattle Energy Code requirements.

Performance: The SANCO2 controller enables heat pump plants to maximize the benefit of heat pump operation.

Cost: The standard control package only adds a modest increase in first cost.

Constructability: The controller is built from simple parts utilizing industry standard methodologies.

Maintenance: There are no maintenance items beyond factory start-up.

Background

Market Landscape

Domestic water heating is the largest single use of energy in Northwest multifamily new construction, responsible for up to 30 percent of the energy use of a typical apartment building. In new apartments, domestic water heating typically has an Energy Use Intensity of 8-10 kBtu/SF/yr.

Water heating can be divided into two distinct loads: 1) the heating of cold city water entering the system and 2)

[1] C02 Heat Pump Water Heater Multifamily Retrofit: Elizabeth James House Seattle WA

temperature maintenance of circulating water. Approximately one-third of energy is used to maintain the water temperature in the distribution piping.

HPWHs have the potential to reduce the energy used for water heating by approximately a factor of three if properly designed and operated. Figure 1 shows an energy use pie chart of a typical multifamily building and the savings that can be expected from an optimized HPWH system. Heating domestic hot water with central heat pumps can reduce the total energy usage by about 7 kBtu/SF/yr (EUI) or roughly 17 percent of the total building energy use.[i]

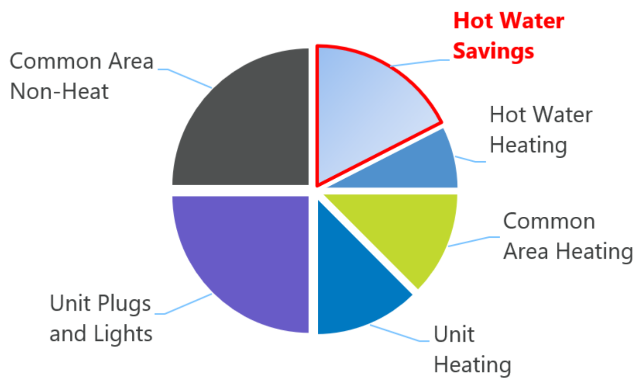

Figure 1. Multifamily energy savings with HPWH

In addition to overall energy savings, HPWH systems naturally allow for load shifting. A typical HPWH system is designed with less capacity and more storage than a traditional electric or gas water heater system and runs 12 to16 hours a day to meet the hot water demand. When sized and controlled correctly, the 12- to16-hour run period can avoid peak times and flatten overall grid load, which can lead to better controllability of grid resources and lower carbon intensities.

Domestic Hot Water HPWH Controls

Commercial-scale HPWH plants often utilize multiple heat pump units and can include supplemental electric resistance heat. Both of these features require controls to support proper system operation, as well as verification that electric resistance heating is being minimally used, since it is less efficient than heat pump operation.

Purpose

This study is the first and second step in the TIM, which is designed to take a technology through a series of stage gates representing different areas of inquiry to ensure that the product can be applied safely and cost effectively so that it can perform in the marketplace.

This report covers the Feasibility Study and Applications Testing stage gates and is meant to test the SANCO2 controller's ability to meet the controls requirements for SANCO2 heat pump hot water plants.

Key stage gates for the TIM include:

1. Feasibility Study
2. Applications Testing
3. Demonstration Project
4. M&V
5. Design Guidelines

Current Installations

The SANCO2 controller is a new product, but has been installed in a number of locations, including:

- East Colina Apartments, Seattle, WA – used to control a legacy (Gen3) SANCO2 heat pump plant
- West Colina Apartments, Seattle, WA- used to control a current generation (Gen4) SANCO2 heat pump plant

SPS has also performed factory start-up at roughly a dozen locations, and approximately 20 controllers have been shipped at the time of publication.

Codes and Certifications

This section reviews the SANCO2 controller's compliance with federal, state, and local energy codes and standards. The Energy Code addresses operational efficiencies and controls requirements, and the Electrical Code addresses the design of electrical connections.

The controller must comply with the following codes and standards to have a viable product in the Pacific Northwest and California.

Codes

FEDERAL LAW

The Safe Drinking Water Act Section 1417

ENERGY CODE

International Energy Conservation Code (Includes Idaho and Montana)

Washington State Energy Code

Oregon Energy Efficiency Specialty Code

Title 24 (in California)

MECHANICAL CODE

International Mechanical Code

PLUMBING CODE

Uniform Plumbing Code

International Plumbing Code

ELECTRICAL CODE

70 – National Electrical Code

Federal Safe Drinking Water Act

The SDWA requires all products in contact with potable water be tested through National Sanitation Foundation 372 to prove they are lead-free, meaning they contain less than 0.025% lead at wetted surfaces. The SanCO2 controller includes temperature sensors that install in dry thermowells so none of the sensors physically touch potable water. The thermowells used are industry standard for measuring temperature in pipes or tanks and are coordinated and provided by the tank manufacturer. The flow meters, which may be paired with the controller, also carry NSF 372 compliance stamps.

Energy Code

Energy code requirements have been evolving as HPWHs penetrate the market. Recent code updates in Seattle and California require automatic alarming upon equipment fault detection and sensing low temperatures, which may suggest an issue with system operation, in order to avoid inadvertently running electric resistance backup systems for long periods of time.

The standard SANCO2 controller supports these alarm requirements.

Demand based recirculation is required in some jurisdictions, such as California, and outlawed in others, such as Seattle. The standard SANCO2 controller does not address control of the recirculation pump. Where this requirement exists, stand-alone controls will need to be used.

Mechanical Code

There are no mechanical code compliance requirements for the SANCO2 controller.

Plumbing Code

There are no plumbing code compliance requirements for the SANCO2 controller.

Electrical Code

Electrical code requires that controls equipment comply with UL 508A. The SANCO2 controller, and all commonly used permutations of add-on modules will be UL 508A compliant via a component approach. Production delay and cost impacts may occur if non-standard equipment is integrated with the controller and housed within the enclosure, thus triggering a process to certify the additional components with UL prior to installation.

System Component Assessment

System Component Assessment identifies the equipment needed for a complete control system. There are three versions of the SANCO2 Controller. The standard SANCO2 controller model name is *ECO-MSCTROL-01*; we will refer to it as *standard SANCO2 controller* throughout this study.

A second model can integrate with a building management system. The BMS-capable SANCO2 controller is named *ECO-MSCTROL-BMS* and is referred to as *BMS SANCO2 controller* in this study. This version of the controller has all the capabilities of the standard SANCO2 controller, plus an ethernet connection for BMS connectivity and (2) additional points of I/O, typically used for more temperature sensors.

The BMS interface is intended to provide a communications pathway to send status or alarms, not to accept external commands. All control sequences will remain within the programmable logic controller of the controller itself.

A third model is optimized for M&V and is termed the *M&V controller*. This controller has all the functionality of the BMS-capable controller and can do the following via ModBus[2]: (2) BTU meters; (1) multi-connection single-phase power meter serving up to 12 single-phase CTs; (1) three-phase power meter. The standard M&V controller can monitor the performance of a SANCO2 heat pump water heater plant with up to (12) SANCO2 units by utilizing a CT per heat pump. The three-phase CT is typically reserved for the swing tank.

[2] Modbus is a communication protocol for transmitting information between electronic devices.

SANCO2 Controller Components

All versions of the SANCO2 controllers consist of a PLC based upon a Corel backbone. This central heart of the system communicates with temperature sensors and heat pump units. The standard SANCO2 controller can control up to 20 heat pumps: four heat pumps in each of five stages. The stages can be called on based on user-adjustable temperature set-points. The controller includes a "first on, first off" sequence and rotates stages in order to balance run-times of heat pump units.

If any of the heat pump units generate an alarm, that information will be relayed to the controller. The controller receives only a general alarm notification via contact closure in the heat pump unit, and not a specific alarm code. Maintenance staff will need to read codes off the unit itself. Ecotope recommends that enhanced communication be considered for future models of the SANCO2 heat pump units so that specific alarm codes could be provided to the controller and then sent on to maintenance staff. Information regarding the specific failure could lead to stream-lined maintenance and repair. This capability would also provide a pathway to send internal temperatures from the heat pump units to the controller, which could help diagnose root causes of heat pump unit errors.

Alarms can also be generated by low temperatures measured in the system. Low water temperature leaving the primary storage may be indicative of heat pump operation issues, which could be masked by

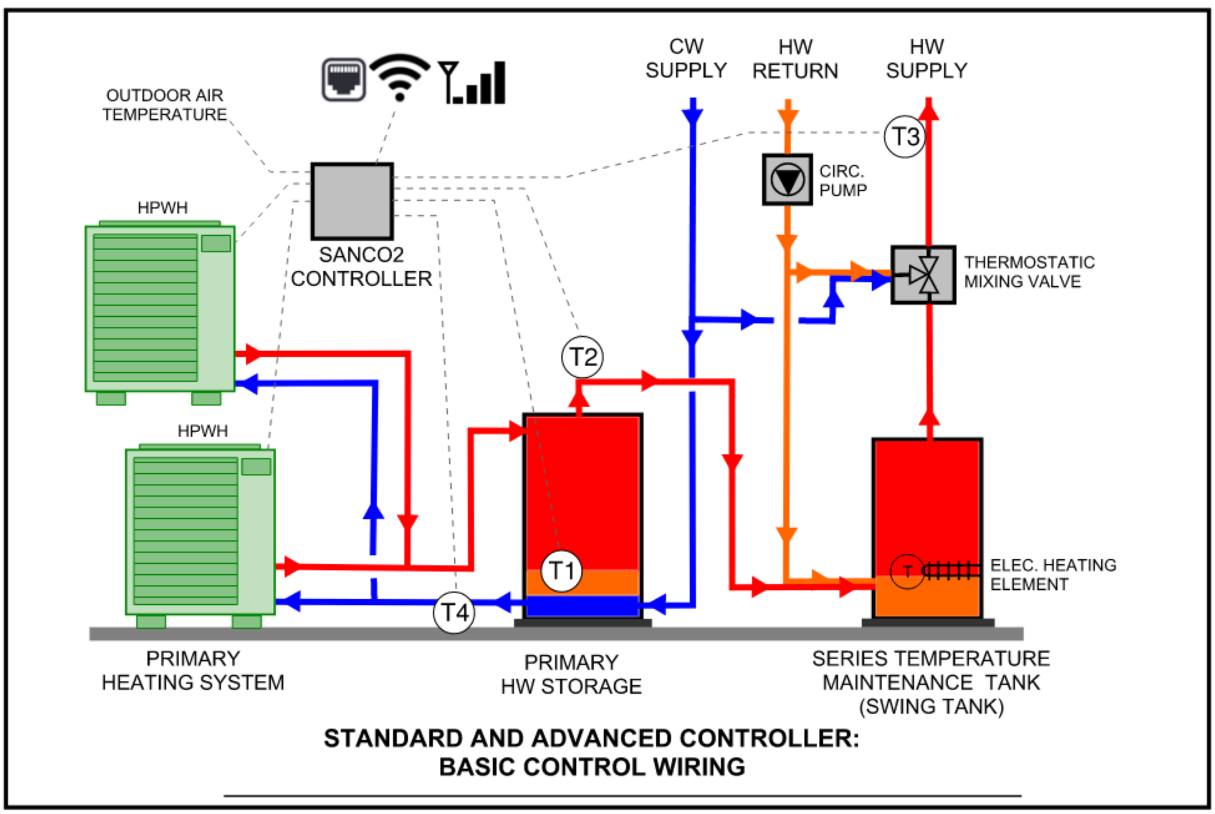

Figure 2. Basic control wiring

supplemental electric resistance heating in the swing tank. Low water temperature entering the building distribution system can also generate an alarm.

TEMPERATURE SENSORS

The SANCO2 controller comes as a package with all required temperature sensors included. There are three standard temperature sensors:

- Storage tank temperature near cold water makeup (T1)
- Pipe sensor on heat pump return (T4)
- Outdoor air temperature

Two additional temperature sensors are discussed since their inclusion and integration into the controller's sequence of operations is a code requirement in some jurisdictions within BPA service territory:

- Primary storage output temperature (T2)
- System output temperature (T3)

Twisted wire pairs will be run from the pipe or storage tank thermowells to the controller by the plumbing contractor. A factory technician will then land them on the controller prior to start-up.

COMMUNICATION LINES TO HPWH(S)

The SANCO2 controller comes as a package with wiring to the heat pump units included. Each stage of heat pumps will require two sets of wires: (1) pair to communicate alarm status; (1) pair to provide contact closure for ON/OFF control.

ALARM BROADCASTING

Alarms can broadcast via Wi-Fi, ethernet network connection, or cellular signal based upon controller configuration. At this time, the standard SANCO2 controller does not come with a communications module, leaving the designer the option to select one. Ecotope recommends that the standard SANCO2 controller include a standard communications module. As noted in the code compliance section, some jurisdictions require alarm broadcasting for code compliance.

SEQUENCE OF OPERATION

The controller will come programmed with proper sequence of operation per SANCO2 recommendations. Stages of heat pumps will be called based on storage tank temperature (T1) and turned off based on temperature in heat pump return (T4). Typical control practices, such as delaying calls to run when multiple stages are powered on and minimum on/off run-times, are provided. Stage runtimes are balanced by starting the stage with lowest run-time first.

FREEZE PROTECTION

The controller will monitor OAT and will activate freeze protection sequence when temperatures drop below 5°F (user adjustable). When freeze protection is enabled, all units will cycle on for 10 minutes, then off for 15 (times adjustable).

DIAGNOSTIC LOG

The standard SANCO2 controller saves diagnostic logs with the following fields: general alarm status, temperature sensor values, freeze protect status, HPWH stage status (ON/OFF) and HPWH stage alarm trigger are logged at 2-minute intervals.

These logs can be retrieved remotely via a web portal or USB in the field.

ADVANCED CAPABILITIES

Additional capabilities can be provided by installing additional modules:

M&V can be supported with an additional module that allows more inputs to be connected to temperature sensors, flow meters or power monitoring equipment. By utilizing these components, the overall efficiency of the plant can be calculated and tracked over time to flag any maintenance issues.

DR can be integrated into the system by adding a module featuring an EcoPORT[3], which receives signals from utility operators. This module can be added to any version of the controller. Currently SANCO2 is working with Skycentrics to integrate this module with the controller. The DR module will interface with the controller via industry standard MODBUS communication protocol. Ecotope recommends further work to establish a sequence of operations to map utility signals to operational modes without compromising hot water availability.

Performance Assessment

The Performance Assessment confirms the equipment will have adequate performance to gain acceptance from designers and users.

Architecture

Architectural concerns are likely minimal due to the typical location of the control's enclosure and all associated equipment within, or immediately adjacent to, a mechanical room.

Space requirements

The enclosure used to date is 16" wide x 16" tall x 6" deep and carries a NEMA 4 rating

Figure 3. Control enclosure

for outdoor installation. Fasteners are provided through the backwall of the enclosure. Future enclosures plan to utilize a slightly taller and narrower aspect ratio, and will provide fastening via external hardware, which will ease installation in the field. As with other electrical and controls enclosures, running piping over the top of

3 https://www.openadr.org/ecoport-info

the equipment should be minimized. These requirements should be coordinated early when space planning activities are determining the size for the DHW storage tank room.

Engineering

Engineering performance is broken into structural, mechanical, electrical, and plumbing performance.

Structural

Typical wall-mounting techniques can be used to attach the enclosure to various types of wall construction. There are no structural concerns for use of the SANCO2 controller.

Mechanical

There are no mechanical concerns for use of the SANCO2 controller.

Electrical

The SANCO2 controller will need a standard 120-volt single phase hard-wired power connection. Total panel ampacity is 1.4A at 120V/60Hz/1 phase. Incoming conductors need to be #14 AWG and provided with circuit breaker at 6A. Low-voltage control wiring will run through the mechanical room and does not need to run in conduit. Final wiring connections within the enclosure will be made by a factory representative at time of start-up.

Plumbing

Plumbing engineers are typically tasked with selecting water heating equipment. The proper operation of a HPWH plant is more complex than traditional gas or electric water heater plants. Maximizing the potential of the SANCO2 HPWH system requires that sensors are installed in the correct locations and the controls equipment is commissioned to operate the system properly. Early interaction with SANCO2 representatives can help designers develop schematics that matchSANCO2's recommended locations.

Owners – Cost, Demand Response

Owners want a product that is affordable to install, operates consistently, requires little maintenance, helps meet green building targets and reduces energy costs. When designed and maintained properly, the SANCO2 controller should be able to provide long-term quality performance.

To provide visibility to system operation, ECO2 will offer a web portal as a standard feature.

If an owner opts for the DR module, it will significantly reduce operating costs in some areas.

Ecotope recommends SANCO2 use the TIM to ensure load shifting controls operate efficiently. Current codes, standards, and cloud providers are focused on DR for unitary residential electric resistance water heaters. These systems typically only use setpoint control to "Load Up" a storage system by forcing the heat pumps to run longer during "Load Up" periods. For owners to see the most return on investment, more advanced control schemes may be required to shift as much load away from demand periods.

End Users

End Users are concerned with consistent delivery of hot water. The key to consistent delivery of hot water in a HPWH system is properly sized components, redundancy, and a fully commissioned controls system. After proper installation and factory start-up by a SANCO2 representative, the SANCO2 controller should allow for smooth operation of the HPWH system. It should be noted that End Users are highly sensitive to the temperature of delivered water. This temperature also depends on proper operation of the thermostatic mixing valve. The control and operation of this mixing valve is outside the scope of the SANCO2 controller, and optimization of this equipment should be done by the installing plumbing contractor.

Cost and Constructability Assessment

The Cost and Construction Assessment confirms challenges associated with acquiring and installing the product.

Availability

ECO2 and SPS both have stock of basic controller packages that can be paired with new heat pump system installations. If a controller requires customization or if supplier stocks are depleted, the current lead time is six to eight weeks. Needing to build a controller per order has been rare even during the supply chain interruptions of 2021. To further shield against delays, components for building new controllers are inventoried with six months of stock.

Controllers are currently being built in a UL panel shop in Washington. The current production scheme has capacity for growth regionally; if demand increases nationally, ECO2 will need to consider increased manufacturing capabilities and increased staffing or training for factory startup. Ecotope recommends that ECO2 plan for this growth in controller demand in the near term since the market for heat pump hot water heaters is likely to increase in the coming years.

Construction Schedule

There is minimal construction schedule impact when providing a SANCO2 controller.

Retrofit Feasibility

SANCO2 controllers can be utilized on existing Gen3 systems as long as additional power is available and temperature sensor type and location meet SANCO2 standards (if existing sensors do not meet the standards, new sensors will need to be installed). Even though Gen3 heat pumps were not intended to function with a central controller and did not need the T4 temperature sensor, they can be integrated with the controller by providing an additional (T4) temperature sensor and adjusting the controller programming to accommodate the sequence required to control a Gen3 unit. This approach could be used on existing Gen3 plants. SANCO2 does not recommend utilization of the controller on equipment previous to the Gen3 heat pump units.

Maintenance Assessment

Maintenance assessment is broken into two sections: customer service and maintenance. Customer service assesses the ability of the manufacturer to aid customers. Maintenance addresses upkeep requirements performed by the owner to ensure product longevity.

Customer Service

The SANCO2 controllers are sold throughout the United States via Small Planet Supply.

The two existing locations were provided with factory start-up via Small Planet Supply. Future installations on the west coast will follow the same model, but SANCO2 sales and support representatives will need training from Small Planet Supply as the demand for the controller grows beyond the west coast.

A one-year warranty is provided on the controller, its associated equipment, and the proper operation of its sequences.

Maintenance

Maintenance requirements are comparable to other control systems, which are minimal. No regular maintenance is required.

Applications Testing

Development of this controller has exceeded the pace of progression through the typical TIM process. This is due to the fact that the TIM was built around steering larger pieces of equipment through the stages, and the rapid development of the controller possible with off-the-shelf components. At the time of publication, roughly a dozen plants have been started up using the controller, and a total of 20 controllers have shipped. One controller was installed in a project with Ecotope as engineer of record, allowing Applications Testing to be performed on the unit during commissioning of the heat pump plant. The applications test procedure is outlined in appendix A.

Application Test Findings

There were two main goals for the SANCO2 basic controller Applications Test : demonstrate capability to operate a heat pump plant with multiple units and to receive and broadcast alarms. The first goal was met, as is described in detail below in Appendix A. The controller showcased the ability to stage units on and off as warm water was used in the building.

The second goal was only partially met. Alarms successfully communicated from the heat pump unit to the controller, but the controller did not have network connectivity at the time of the test, so broadcast capabilities were not tested.

Due to the nature of communications between the heat pump units and the controller, only general alarm status can be sent to the controller. Redesign of the communication between the heat pump units and the controller would need to be undertaken before specific error codes can be passed to the controller. To understand the frequency of nuisance alarms, it will need to be tracked over time. If alarms occur infrequently, and only when maintenance intervention is required, this communications limitation will not likely become an issue. But if alarms broadcast at a high enough frequency that maintenance staff begin to ignore them, this limitation could lead to less efficient plant operation. This issue should be tracked carefully through a demonstration project, and recommendations made to integrate

If an enhanced communication protocol was developed between the heat pump unit(s) and the controller, additional diagnostic information could be sent to the controller, as well. Each heat pump unit has internal sensors to ensure safe operation of the unit. Information from these sensors could be made available alongside error codes to allow remote troubleshooting of equipment failures, which could lead to less unit down-time and more efficient repair work on site. For example, if a pump failure occurs, the current controller generation would require a technician to be notified with a generic alarm via the alarm broadcast system. The technician would need to go on-site to view the error code -- and then order the pump or service. With enhanced communications, the alarm broadcast and error codes could all flow together, allowing maintenance staff to immediately have more information about system failures and increase their ability to resolve the issue faster.

Ecotope recommends that ECO2 consider improving the communications protocol between the heat pump unit(s) and the controller.

Conclusions and Recommendations

Ecotope and BPA are pleased that ECO2 has decided to invest in a controller that will more reliably control SANCO2 heat pump plants, especially those with multiple heat pump units used together, so they can be used in commercial buildings in a reliable and verifiable manner. As commercial scale HPWH systems become more common place, the need for controls to deliver on their promise of high efficiency has grown. While the SANCO2 controllers will allow for further market penetration of HPWHs into the market, Ecotope believes the following will significantly help the SANCO2 system's performance.

Recommendation 1:

ECO2 should provide a basic communications module as a base model for the controller. Alarm broadcasting is a basic function that should be present in all levels of the controller.

Recommendation 2:

ECO2 should investigate how to enhance the communication between heat pump units and the controller. Gaining the capability to send error codes, as well as diagnostic information from the heat pump to the controller would enable streamlined maintenance operation. During the water flow restriction test discussed in Appendix A, the unit was indefinitely cycling between start-up and shut-down cycles. Improved programming within the unit and/or better communication protocol between the unit and the controller are needed to generate an alarm in these situations.

Recommendation 3:

ECO2 should develop a standard sequence of operations to map DR signals to system operation. A standard kit with additional temperature sensors, if required, should be made available to ease the adoption of DR.

Recommendation 4:

ECO2 should build up support processes for a national roll-out of the controller to meet expected demand. Sales, manufacturing, and factory start-up require trained representatives be available for communication during pre-construction, and on-site during construction and hand over.

Works Cited

[i] Heller, Jonathan, K. Geraghty, and S. Oram. *Multifamily Billing Analysis: New Mid-rise Buildings in Seattle*. December 2009. Prepared by Ecotope for Seattle Department of Planning and Development

APPENDIX A – APPLICATION TEST PROCEDURE

Note: This text formatting is used to indicate notes taken during application testing.

The Applications Test for the Basic Controller (ECO-MSCTROL-001), hereafter referred to as "CTRL-1" performed by Ecotope staff in conjunction with manufacturer representative. Design is intended to provide the following:

Items in all capitals are temperature sensors shown schematically in Figure 2.

Verifying standard operation of the controller:

- Can control multiple units with single "ON" [T1] thermowell temperature sensor and single "OFF" [T4] pipe temperature sensor
- Can stage units on and off as per standard SANCO2 sequence of operations
- Verification that first "ON" unit is also first "OFF" to provide equal run-times
- Can communicate with heat pumps to flag and broadcast error status
- Verification of error status locally at controller
- Verification of error broadcast via text and/or email
- Verify how controller and associated equipment responds to the following:
    - Air flow blockages at a heat pump unit
    - Water flow blockages within the heat pump flow circuit
    - Power interruption
        - To a single, currently running heat pump unit
        - To the controller

Control Setup

Configure the system per the controller specifications, as summarized below:

- CTRL-1 shall control (T1) PRIMARY STORAGE TEMPERATURE to primary storage temperature set-point
- SANCO2 resistor used at thermowell connection
- SANCO2 heat pump model (GS4-45HPC) with dry contacts for control and error signals
- Sequence of Operations should be per the published design guidelines:

NOTE: Sequence of heat pump to turn on is the following:

- Controller senses demand for heat
    - 10s delay
    - Controller closes relay to heat pump stage to run

- Heat pump fan and pump start

- After an approximately 4-minute further delay; heat pump compressor runs

Minimum ON time: 10min

Minimum OFF time: 10min

Minimum time between (2) stage starts: 10s

Heat pump(s) are turned off when (T4) ENTERING WATER TEMPERATURE TO HEAT PUMPS reaches setpoint per standard SANCO2 sequence of operations.

- Alarm broadcasting via ema & SMS

Test Procedure

The test procedure is designed with two goals:

1. Demonstrate and document that the controller is operating as intended and posturing the system according to the sequence of operations
2. Demonstrate that alarms are generated and reported out correctly when their triggering events occur

System Configuration

All manufacturer recommendations shall be undertaken when installing equipment.

Heat pump plant utilized for testing consists of 10 heat pump units. Each stage in the controller is connected to two heat pump units.

Take controller through the procedure listed below. Whenever an alarm is generated, whether locally at the units or through email and/or SMS, the message and time shall be noted.

Prior to testing per the procedures below, fully charge all storage tanks and heat pump piping loops with water and bleed air at system high point.

Testing Steps

DRAW-DOWN TEST:
Start test with plant in normal operating mode, and with HPWH units not currently engaged.

Open at least six nearby bathtubs / showers to full hot water flow.

The controller should eventually see PRIMARY STORAGE TEMPERATURE [T1] below setpoint and should engage stage 1.

Verify that only stage 1 is initially powered on.

Note time delays as they occur.

If system recovers with stage 1 running only, open more hot water fixtures until such time that all stages have been called to run.

If reasonable flowrates cannot be provided to force on multiple stages, strategically pick stage 1 equipment for interruption testing in next sections to verify stage sequencing.

OBSERVATIONS:
System was fully charged with hot water at beginning of test. T1 reading was 135°F and no heat pumps were running.

All hot water fixtures in (4) units (tub, bathroom lavatory and kitchen sink) were *fully opened for a period of 30 minutes to induce hot water load onto the plant. [Roughly 10:30AM]*

10:38AM: heat pumps 9/10 [stage 5] are engaged; typical controller and equipment delays were observed for each heat pump activation. "Engaged" refers to controller calling on, equipment delays, and eventual pump / fan / compressor running.

10:41AM: T1 has fallen to value below the lowest set-point. All subsequent stages of heat pumps are engaged after typical delays noted above.

POWER INTERRUPTION AND REESTABLISHMENT TO HEAT PUMP UNIT:

This step should be undertaken when heat pumps are running to meet demand imposed on system during #1 above.

Note time and interrupt power to a unit currently running. Note any alarms that are shown locally at the controller and verify email / SMS messages have been generated according to controller setup.

Re-establish power via disconnect to heat pump. Note time-delay from power reestablishment to error clearing locally.

Note what controller does with paired heat pump unit when power interrupted to one heat pump in a stage.

OBSERVATIONS:

10:43AM: Power is interrupted at disconnect to HPWH-9 [NOTE disconnect interrupted power to only HPWH-9, not the controller stage that would correspond to both HPWH 9/10]. No alarm is generated at controller.

10:45AM: Power is re-established to HPWH-9.

10:46AM: HPWH-9 fan is rotating.

10:47AM: HPWH-9 compressor and pump are running.

Note that during the test, the paired heat pump, HPWH-10, continued to run.

AIR FLOW RESTRICTION:

This step should be undertaken when heat pumps are running.

Introduce airflow restriction to suction side of a unit that is currently running in increments of 25% of area, starting from bottom, and retain blocking material plumb to ground. Allow the unit to operate for a minimum of 5 minutes between increasing airflow restriction. Upon alarm generation and unit shut down, record blockage percentage and error codes shown locally at the controller. Note email or SMS errors if received.

Remove airflow restriction and record the time it takes for the HPWH to turn back on.

OBSERVATIONS:

10:56AM: Airflow blockage of roughly 25% is added to HPWH-6. Unit still operates as normal.

11:01AM: Airflow blockage is increased to roughly 50%. Unit still operates as normal.

11:07AM: Airflow blockage is increased to roughly 75%. Unit still operates as normal.

11:15AM: All possible areas are blocked off as much as possible. Air is still felt exiting the unit on the discharge side, though notably not as cold as nearby units. Fan speed is notably higher on HPWH-6 compared to nearby units, likely a sign of the unit trying to maintain normal operating parameters.

Internal temperatures were not available to more fully document equipment response.

11:20AM: Airflow blockages were removed. Unit continues to operate normally.

11:25AM: Fan speed of HPWH-6 is back in line with adjacent units.

Controller did not generate any alarms or change staging of units throughout the test.

COMMUNICATION INTERRUPTION:
This step should be undertaken when heat pumps are running.

Interrupt the communications for a unit that is currently running. Note any alarms generated on controller or broadcast out.

After 5 minutes re-establish communications.

OBSERVATIONS:
10:50AM: HPWH-1 communication line is interrupted in the controller enclosure. The unit immediately starts it shut-down cycle: compressor immediately off, fan / pump run for several minutes.

10:55AM: HPWH-1 communication is re-established. Unit starts up immediately.

Controller did not generate any alarms during this test.

An ad hoc test was devised after this test to force an alarm condition. Each heat pump unit utilizes a resistor to simulate a call for heat from a temperature sensor, as if it were paired one-to-one with a single storage tank / single temperature sensor. The controller simply provides a contact closure to complete the circuit and allow the unit to run. By disconnecting this resistor, the heat pump unit will go into alarm. This alarm should be sent to the controller.

(Times not recorded for this ad hoc test):

- *Resistor is disconnected from one terminal within the enclosure of HPWH-6. An alarm is immediately visible at the unit and is seen on the LCD screen of the controller. No communications were available to the controller at the time of testing; therefore email/SMS verification was not possible.*
- *Upon resistor being re-connected HPWH-6 immediately re-engaged.*

ALARMING– WATER FLOW RESTRICTION:
This step should be undertaken when heat pumps are running.

Close the isolation valve associated with one heat pump that is currently running. Note any alarms that are shown locally and verify email / SMS messages have been generated according to controller setup.

After 5 minutes, open isolation valve closed in previous step. If unit starts back up, note time-delay from valve opening to unit restarting.

Once both heat pumps have powered back on, repeat steps a-c with a second heat pump.

OBSERVATIONS:
Per recommendation of Small Planet Supply controls representative test was altered slightly to not fully close valve, and to do so in ~25% increments.

11:08AM: Water restriction consistent with valve position at 50% applied to HPWH-3.

11:19AM: Valve position moved to 75%.

11:33AM: HPWH-3 has turned off.

11:36AM: HPWH-3 fan is running.

11:38AM: HPWH-3 has turned off. Unit continues through cycle consistent with equipment start-up sequence, several times. No alarm is generated at controller. Out of caution to avoid damaging equipment, isolation valve is fully opened.

11:45AM: HPWH-3 is back on.

Controller did not generate any alarms or change staging of units throughout the test. It is believed that the unit was cycling through start-up and shut-down cycles and would likely continue to do this indefinitely with little useful output produced, but no alarm to alert maintenance staff. Since the on-board programming of the unit is maintaining this cycle and not producing an error, the controller cannot be alerted to this error. The controller is only sending a signal to run and does not know if the unit is running or not, so even programming internal to the controller to check for short cycling is not a possibility. This test highlighted the shortcomings of the communication protocol between the unit and the controller.

POWER INTERRUPTION AND REESTABLISHMENT TO CONTROLLER:

This step should be undertaken when heat pump units are currently being run.

Remove power to controller.

Note how heat pump units respond. Note status of all heat pumps before power interruption, and their status directly after power interruption.

Wait a minimum of 10 minutes.

Re-establish power to controller. Note delay for controller to power on and regain communication with heat pumps.

OBSERVATIONS:

12:01PM – Power is disconnected within enclosure by opening up fuse connection.

All units were running at time of power interruption. All units turn off upon controller power interruption.

12:03PM – Power is reconnected.

12:04PM – All units are back on.