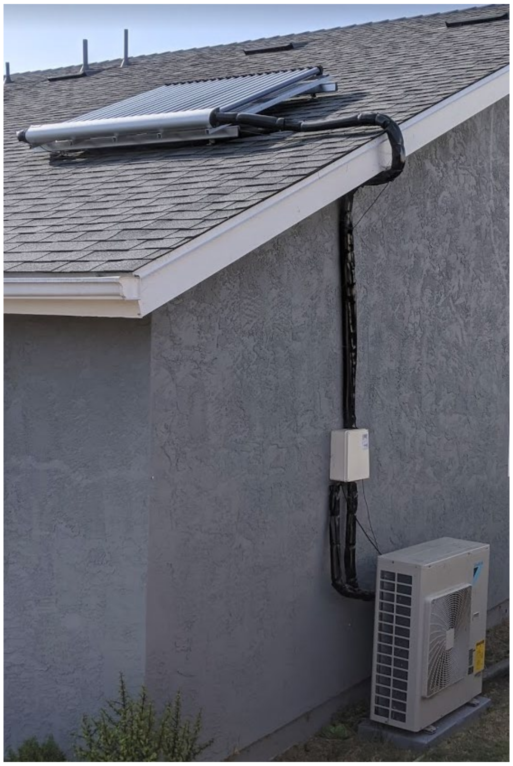
Emerging Technologies Program

Solar Assisted DX System

ET19SDG7011 Report



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EXECUTIVE SUMMARY

The goal of this project is to assess the energy and demand savings resulting from a solar assisted direct expansion (DX) system.

A field test was conducted in a 1,600 sq. ft. single-story residential home located within SDG&E territory. In this test, an emerging technology that consists of a solar thermal collector, a bypass valve, and a controller was added onto a new 2-ton variable-speed split heat pump. Since the technology was installed onto the new heat pump, baseline operation was simulated by bypassing the solar thermal collector. The technology performance was recorded in between November 2019 to April 2020, alternating the technology on and off weekly. The heat pump operated in both cooling and heating modes during the testing period.

The field test observed no apparent savings either in cooling or heating mode. However, the study was limited in scope and the following next steps were recommended:

- Although this field test did not result in savings, the manufacturer of tested technology lists numerous case studies exhibiting notable savings with larger systems in commercial applications, including refrigeration systems. Since the field test was done on a small residential unit, an additional study is recommended to evaluate the demand and energy savings potentials of the technology in commercial applications such as larger packaged unit and/or refrigeration system.
- The effectiveness of the technology with the heat pump in heating mode was inconclusive due to lack of low ambient temperature conditions at the test site. A testing in a climate with more heating hours is recommended to further investigate the saving potential in heating mode.
- Only one manufacturer model was examined in this test while there exist a few variations of the same technology. Thus, it is recommended that an additional study be performed to evaluate the demand and energy savings potential of the other technology vendors in commercial applications.

ABBREVIATIONS AND ACRONYMS

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BMS	Building Management System
CDD	Cooling Degree Days
CEC	California Energy Commission
CT	Current Transformer
CZ	Climate Zone
DEER	Database for Energy-Efficient Resources
DX	Direct Expansion
EE	Energy Efficiency
EER	Energy Efficiency Ratio
ET	Emerging Technology
HDD	Heating Degree Days
HP	Heat Pump
HVAC	Heating Ventilation and Air Conditioning
IPMVP	International Performance Measurement and Verification Protocol
LED	Light Emitting Diode
M&V	Measurement and Verification
OAT	Outside Air Temperature

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INTRODUCTION

A direct expansion (DX) system is a vapor-compression refrigeration system that consists of a compressor, a condenser, an expansion valve, and an evaporator, where refrigerant directly cools the targeted medium (i.e. air). Examples of DX air conditioning systems include packaged units, split units, and window units, and are widely used to air condition residential and commercial buildings.

The emerging technology studied in this report – a solar assisted DX system – uses solar thermal energy to offset a portion of the thermal energy input to the refrigeration cycle that would normally be generated by the compressor.

The technology typically consists of a solar thermal collector, a bypass valve, and a controller that is added onto an existing DX system with a variable-speed compressor. The technology can work both in cooling and heating modes when applied to a heat pump and can, in theory, provide savings to both modes of operation.

The technology is of great interest because the potential savings could coincide with the time when the air conditioning unit is in cooling mode and at its highest demand during the afternoon. Additionally, the savings in heating mode may incent many people to switch from gas furnaces to heat pumps with this technology, contributing to greenhouse gas (GHG) reduction.

Since the technology is relatively new, the energy savings of this technology in the field have not been studied extensively. In this study, a field test was conducted to evaluate the energy saving potential of a commercially available solar assisted DX heat pump.

BACKGROUND

The evaluated technology is a solar assisted DX system, which generally consists of a solar thermal collector and a controller that adds on to an existing direct expansion (DX) system with multi-stage or variable speed compressor(s). The technology uses an evacuated-tube solar thermal collector to convert solar radiation to heat, offsetting a portion of the thermal energy that is otherwise generated by the compressor. As a result, the technology saves energy by reducing the speed of the compressor(s) when the solar radiation energy is available.

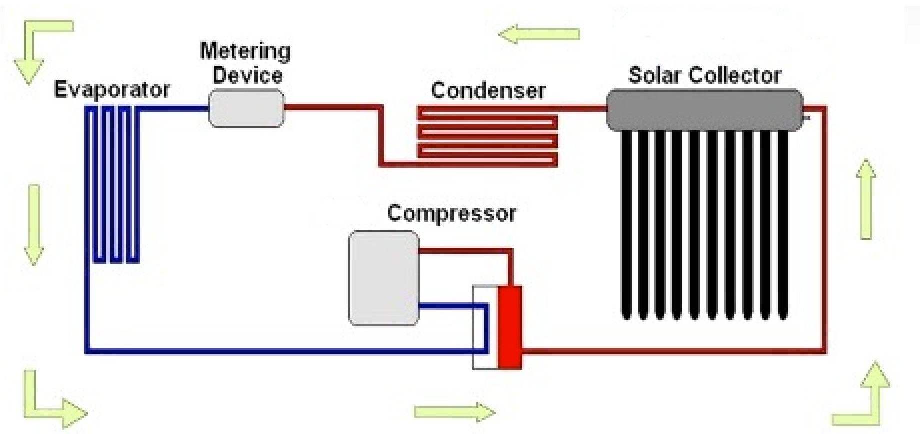

FIGURE 1: THE COMPONENTS OF SOLAR ASSISTED DX AIR CONDITIONER

The energy savings potential of this technology has not been studied extensively, largely due to the lack of commercially available products in the market. However, several studies have been done to estimate the energy savings experimentally and theoretically using computer simulations with varying results. One study predicted the energy savings from mathematical models and experimental data using a transient simulation tool (TRNSYS16). The technology in this study consisted of a DX air conditioner, a solar vacuum collector, and a hot water storage tank, which was used as a heat exchanger to transfer heat to the refrigerant, as shown in Figure 2. Although the configuration is slightly different, the process is the same as the emerging technology studied in this report with one exception: in this configuration, the technology not only controlled the refrigeration flow through the hot water storage tank but also the condenser airflow. The study reported that the computer simulation resulted in compressor savings by as much as 14% at steady state with the average energy savings of 7.1% over four summer months (Q.P. Ha & V. Vakiloroaya, 2014).

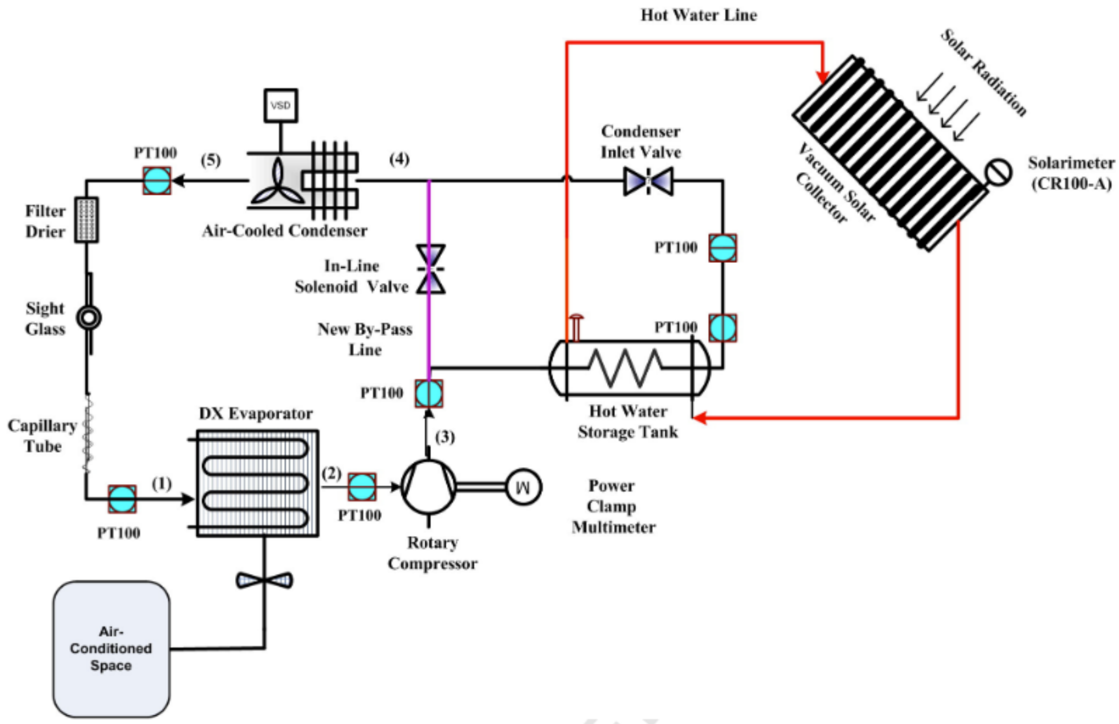

FIGURE 2: THE TECHNOLOGY CONFIGURATION

In another study, a proportional three-way control valve was installed after the compressor to regulate the refrigerant flow to the condenser and to the solar thermal collector. In this experimental setup, the solar thermal collector was replaced with an electrical heater to simulate a wide range of solar radiation and to avoid weather fluctuations during testing. In this controlled environment, the COP of the system with the technology was observed to be 10% more efficient than the conventional system (Mohammed & Abduljabbar, 2018).

EMERGING TECHNOLOGY/PRODUCT

The emerging technology product assessed in this study is an add-on unit that consists of an evacuated solar thermal collector, a bypass valve, and a controller. This product can be added on to any direct expansion unit with multi-staged or variable-speed compressor, from small split system for residential application to commercial refrigeration system. The solar thermal collector is installed after the compressor(s) to add thermal energy to the refrigerant. The bypass valve is used to ensure that the temperature of refrigerant does not decrease through the solar thermal collector by blocking the refrigerant flow to the collector during cooler periods (nighttime or rainy day, for example).

During the installation, the refrigerant must be removed and then readded in a slighter higher volume due to the increased pipe length. Most refrigerants, by the manufacturer[1], are well suited for this technology.

[1] https://www.solxenergy.com/index.php

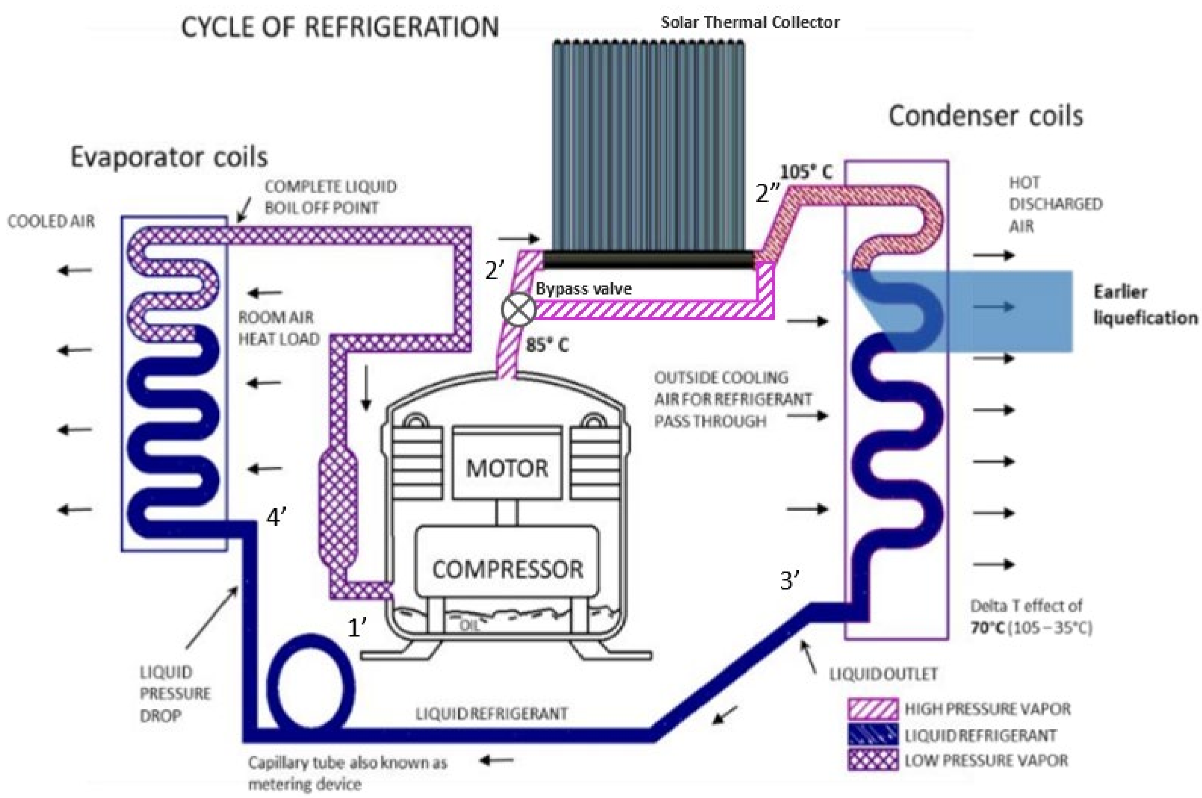

FIGURE 3: THE SIMPLE DIAGRAM OF VAPOR COMPRESSION CYCLE WITH THE EMERGING TECHNOLOGY[2]

The solar assisted cooling system might save compressor energy by allowing the compressor(s) to slow down to its lowest possible design point while ensuring the total thermal energy in the system stays within the manufacturer's specifications. The energy savings are possible because, with modern DX units, temperature sensors rather than pressure sensors are used to control compressors. Via thermistor sensors, the logic controller recognizes the combined thermal energy from compressor and solar thermal collector is more than sufficient to meet the system's overall requirements and signals the compressors to slow down or drop stages.

The pressure-enthalpy diagram below illustrates how the technology can reduce the compressor work by adding thermal energy to the refrigerant. In a traditional setting, the refrigeration cycle follows steps 1-2-3-4 highlighted in blue. When compressor(s) is fully loaded, the refrigerant is compressed from point 1 to 2, which is specified by the compressor exit pressure or temperature in the case of modern DX units. The refrigerant is then condensed through an air-cooled condenser, following line 2-3.

With the emerging technology, the refrigerant cycle follows steps 1'-2'-2"-3'-4' highlighted in red. When solar thermal energy is available, the refrigerant is compressed to a lower pressure (2') than the traditional system, saving compressor energy. Next, the solar thermal collector continues to add thermal

[2] Original image excerpted from: https://www.solxenergy.com/images/solxenergy/downloads/Case-Studies/Case-Study-Whitehorse.pdf

energy to the refrigerant until it reaches point 2”, following isobaric line. As indicated in the diagram, the refrigerant temperature at the outlet of solar thermal collector is 175.6˚F, which is in line with the system’s design temperature of 172˚F (2) even though the compressor is running part load at 75%. As added bonus, the refrigerant is superheated at this point (2”) and therefore increases heat transfer efficiency at the condenser (2”-3’) although the amount of heat that needs to be rejected is greater than the traditional system due to added thermal energy. According to the manufacturer, this also improves the quantity of liquid flow through the expansion valve (3’-4’) and provides higher cooling capacity within the evaporator (4’-1’).

The compressor(s) slow down when solar thermal energy is available, which usually corresponds to periods when reducing air conditioning electricity consumption could be most valuable (both to the grid by reducing load, and to the customer as these are typically the periods with the highest energy rates).

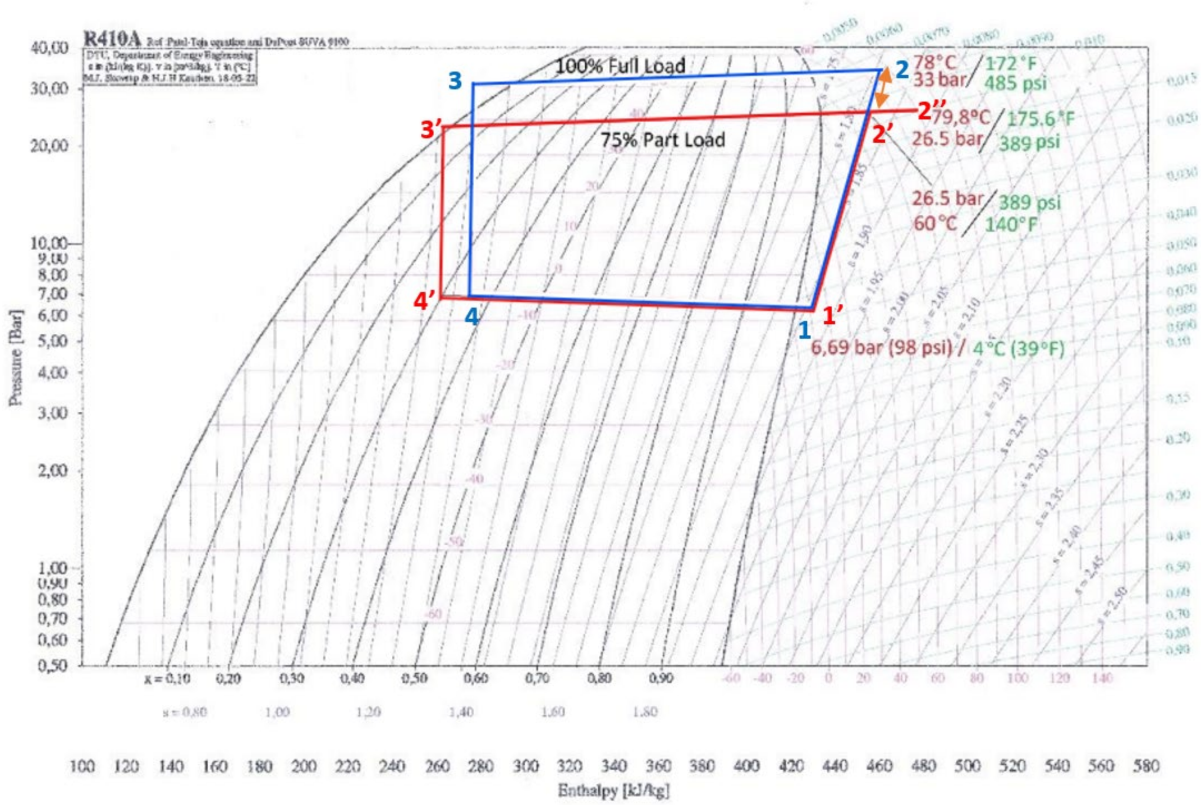

FIGURE 4: THE PRESSURE-ENTHALPY DIAGRAM SHOWING AN INVERTER COMPRESSOR WITH THE TECHNOLOGY RUNNING AT 75% CAPACITY VS. THE STAND-ALONE INVERTER COMPRESSOR RUNNING AT 100%[3]

[3] Image excerpted from manufacturer’s website

MARKET POTENTIAL AND BARRIERS

The emerging technology can be added onto any air-cooled DX system with multiple-stage and/or variable-speed compressor(s). According to the California Commercial Saturation Survey (CPUC, 2014), DX cooling constitutes more than 80% of all HVAC units in commercial buildings and heat pumps make up 31% of heating equipment in CA. Additionally, over half of surveyed equipment was 12 years old. Therefore, the technology has great potential to be added on to new unit as well as relatively new existing units that meets the installation criteria.

The largest market barrier for this technology is the additional cost compared to the traditional vapor compressor cycle and the lack of knowledge and skepticism from both the public and the experts alike. The following are some of the market barriers for this technology:

- Not readily available: The technology is new and has not been widely commercialized in the US.
- Unknown savings: There is no clear understanding of how much savings can be achieved.
- Solar availability: The technology only works if the irradiation from the sun is available where the solar collector is mounted.
- Space requirement: The technology requires additional space for a solar collector
- Costs: The additional pieces of equipment make the installation more complex compared to a traditional unit.

ASSESSMENT OBJECTIVES

The goal of this technology assessment is to identify the demand and energy savings of a solar assisted HVAC system. The emerging technology is an equipment add-on to traditional vapor compression cycle HVAC heat pumps. The system is expected to reduce consumption during hot summer days when demand is high, and the sun is shining. Energy consumption is also expected during colder winter days when the sun is shining, and the evacuated tubes can collect the solar radiation without dissipating much heat through convection with the cold air. As part of the study the objectives were to:

- Evaluate existing heat pump energy usage to establish a baseline case,
- Monitor heat pump energy usage after the technology is installed to establish a post-installation case,
- Quantify potential demand and energy savings resulting from the technology,
- Document and research existing market potential and barriers,
- Generate an assessment report that can be used as a case study for future upgrade opportunities, deemed workpaper development, and utility incentive program design.

To accomplish these objectives, AESC designed a Measurement and Verification (M&V) plan that adheres to IPMVP principles. The M&V plan is outlined in the following section and was designed to directly measure energy effects, as well as relevant factors and performance characteristics.

TECHNICAL APPROACH/TEST METHODOLOGY

A field-testing of the emerging technology was conducted in a single-family residence, located in SDG&E territory Climate Zone 7.

TEST PLAN

A test plan was developed to help achieve the assessment objectives. The plan included a field testing of the technology at single-family home in SDG&E territory. A field study was chosen over a laboratory study because the energy saving of this technology is dependent on the occupant behavior, which cannot be mimicked in the lab. A single vendor's product was tested for this study partly due to the lack of other compatible and cost-effective solutions available in the market.

The data collection was performed following IPMVP Option B (Retrofit Isolation: all Parameter Measurement).

FIELD TESTING OF TECHNOLOGY

To test the energy saving potential of solar assisted heat recovery unit, the solar thermal collector was installed on the roof of a 1,600 sq. ft. single-family residential home located in Oceanside, CA. The host site characteristics are listed in the table below.

TABLE 1: HOST SITE CHARACTERISTICS

CHARACTERISTICS	CARLSBAD SITE
Building Type	Single-family Residence
Conditioned Floor Area [ft^2]	1,595
Year Built	1988
Number of Floors	1
Typical Number of Occupants	2
CA Climate Zone	7

FIGURE 5: THE INSTALLED TECHNOLOGY

The solar collector is an add-on unit and therefore the baseline is either a newly installed heat pump unit that meets current Title 24 code requirements or an existing multi-speed or variable-speed heat pump with remaining useful life greater than five years. For this test, the baseline system consists of a newly installed split heat pump with a variable speed compressor because the heat pump was installed at the same time with the technology. The home previously had central gas heating only. The characteristics of the new heat pump are listed in table below.

TABLE 2: HEAT PUMP CHARACTERISTICS

CHARACTERISTICS	HP3
Outdoor Model	RZQ24TAVJU
Indoor Model	FTQ24TAVJU
Compressor Type	Variable-Speed Swing
Compressor RLA	15.3 A
Rated Cooling Capacity	24,000 Btu/hr
Rated Heating Capacity	27,000 Btu/hr
Rated Efficiency	15.2 SEER/10.3 EER
Supply Fan CFM (at 3 speeds)	800/680/560
Supply Fan HP	½ HP

The typical temperature setpoints during the test period were between 72°F and 76°F for cooling while varied between 68°F and 72°F for heating. To simulate a typical baseline configuration (with a heat pump unit without a solar collector), the refrigerant flow to the solar collector was bypassed at the controller box. In this configuration, the refrigerant goes straight from the compressor to the condenser coil as in any traditional air-cooled DX system would. No other changes were made to run the heat pump as baseline condition When the bypass valve is open, the hot refrigerant gas goes from the compressor to the collector, where it is further heated before traveling to the condenser coil.

INSTRUMENTATION PLAN

Data were collected using logging instrumentation listed in Table 3. The measured variables in the table were continuously monitored and logged on an interval basis. All data were captured in one-minute intervals to capture any compressor or fan cycling that may have occurred. A spot measurement of voltage and power factor was also performed.

The logging started immediately after collector installation was completed on October 17th, 2019. Cooling tests were conducted in October 2019 (during a heat wave) and in May 2020 (during a heat wave), while heating tests were conducted in December 2019, January and February of 2020.

TABLE 3: LOGGING INSTRUMENTATION DETAILS

DATA POINT	MEASUREMENT	INSTRUMENT	ACCURACY	LOGGING INTERVAL
Indoor Unit Fan Current	Amps	Panoramic Power	<2%	1 minute
Outdoor Unit Current	Amps	Panoramic Power	<2%	1 minute
Compressor Discharge Temperature	T	HOBO U12	±0.63°F	1 minute
Collector Outlet Temperature	T	HOBO U12	±0.63°F	1 minute
Supply Air Temperature	T/RH	HOBO MX2305	±0.45°F, ±2.5% RH	1 minute
Return Air Temperature	T/RH	HOBO MX2305	±0.45°F, ±2.5% RH	1 minute
Indoor Air Temperature	T/RH	HOBO U12	±0.63°F, ±2.5% RH	1 minute
Outside Air Temperature	T	HOBO U12	±0.63°F	1 minute

RESULTS

No savings were observed from the technology, either in cooling mode or heating mode through the field testing. A few adjustments to the valve controller were made by the installer, but without effect on the energy savings. The following sections include the details.

COOLING MODE

As discussed previously, temperatures rather than pressures are used in modern DX systems to ensure the thermal energy in the system stays within the manufacturer's design conditions. The technology offsets some of compressor energy by using its solar collector to increase the refrigerant temperature to the design temperature that is required to reject heat. Thus, compressor energy as well as refrigerant temperatures before and after the solar collector were recorded to ensure that the refrigerant was picking up thermal energy from the collector. The chart below illustrates the temperatures of refrigerant before and after the solar collector, the current draw of the outdoor heat pump unit, and outdoor air temperature over the course of three relatively warm days. As shown, the refrigerant temperature at the outlet of collector increased as soon as the unit turned on when the refrigerant was allowed to flow through the collector. Since the thermal energy was accumulated during the day, the refrigeration temperature at the outlet of collector increased greatly shortly after the unit was turned on. After the initial temperature spike, however, the thermal collector increased refrigerant temperature consistently, as much as 50°F depending on the solar availability.

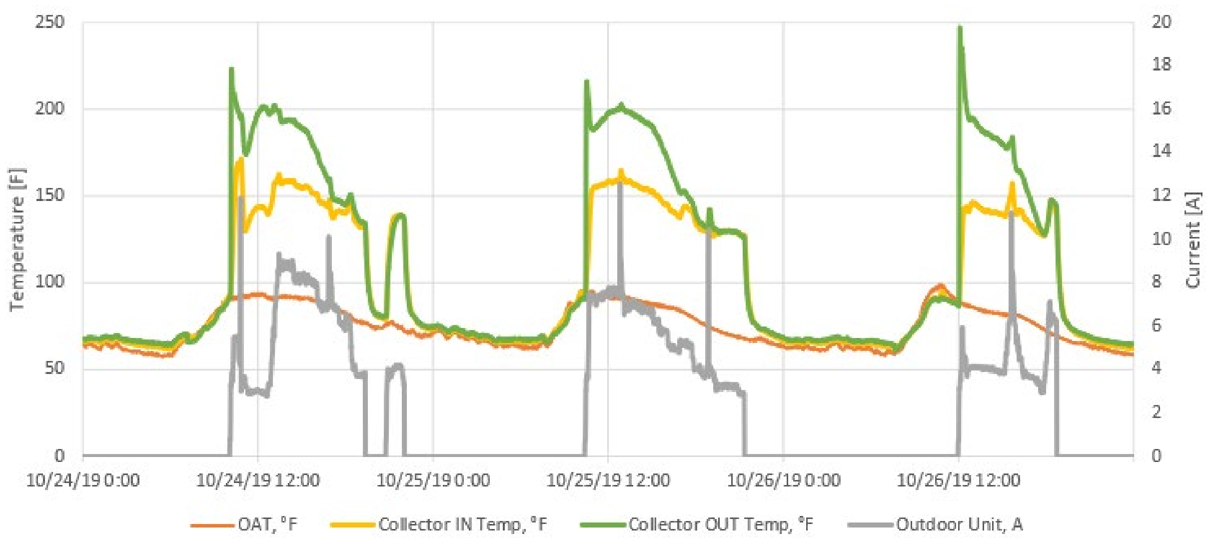

FIGURE 6: TYPICAL HEAT PUMP OPERATION IN COOLING MODE WHEN THE TECHNOLOGY IS ENABLED

To understand the performance of heat pump with and without technology, hourly averaged total heat pump demands, which includes both the indoor supply fan and outdoor unit demands, were plotted against hourly averaged loads to the compressor (Figure 7: Total power as function of cooling loadFigure 7). The load to the compressor was calculated using the measured supply air temperature (SAT), return air temperature (RAT) and supply fan CFM as following:

$$Compressor\ Load\ (ton) = 1.08\ \cdot Supply\ Fan\ CFM \cdot \frac{(RAT - SAT)}{12{,}000}$$

The formula only account for sensible load, but in the area where the study was conducted, the latent load is minimal and for that reason was neglected consistently in the pre and post calculation for simplicity.

EQUATION 1. COMPRESSOR LOAD

The total heat pump demand increased with increasing load, as expected. However, no significant difference was found between periods when the technology was enabled with the refrigerant flowing through the collector ("ON") and when the technology was disabled and the refrigerant bypassing the collector ("OFF").

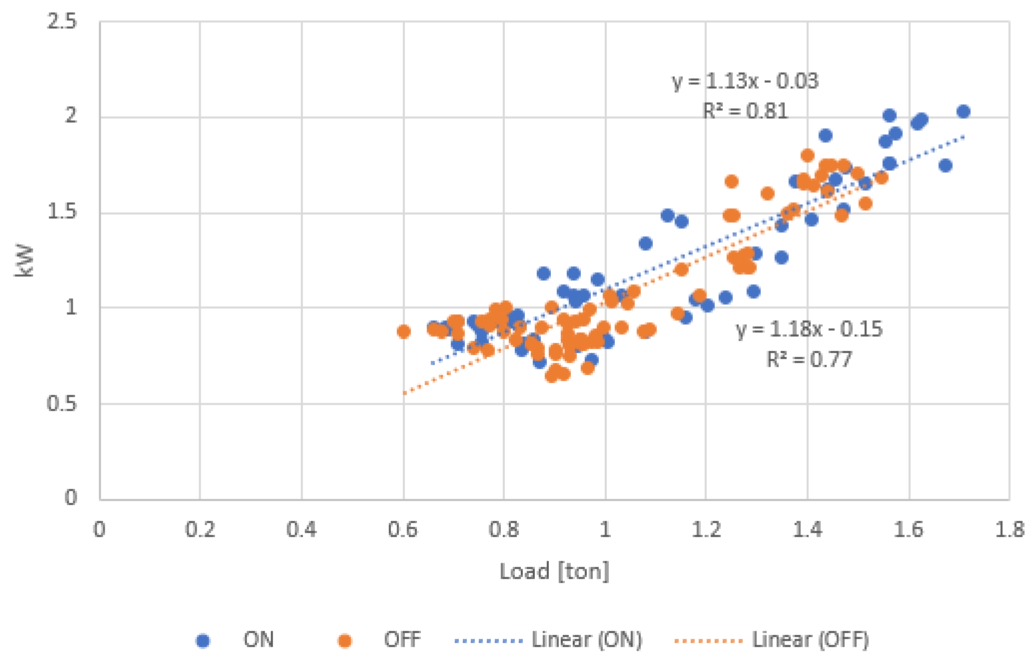

FIGURE 7: TOTAL POWER AS FUNCTION OF COOLING LOAD

The technology claims to save energy by adding energy to the refrigerant gas through the solar thermal collector, which would have otherwise been supplied by the compressor. Therefore, the refrigerant temperature at the compressor outlet is expected to be lower when the technology was turned "ON". However, as shown in Figure below, the field testing results did not exhibit this behavior and no significant difference was observed between the two operating states.

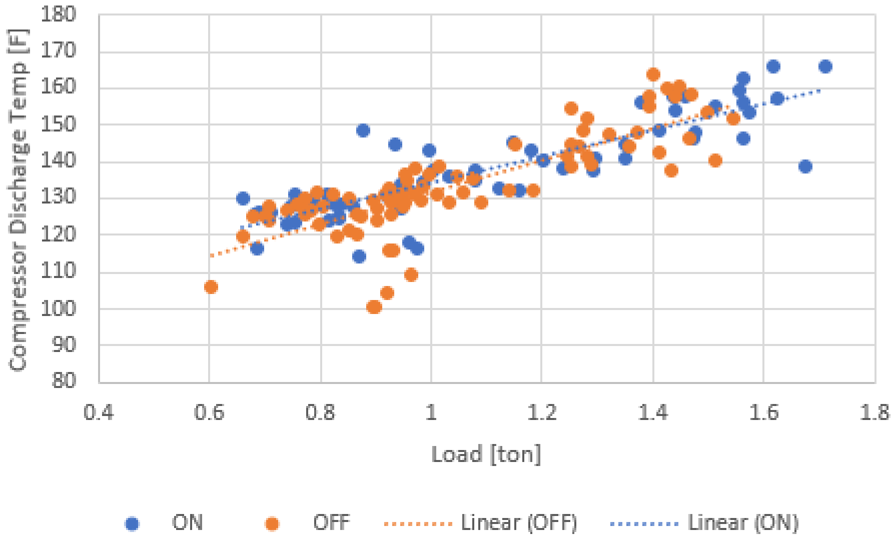

FIGURE 8: COMPRESSOR DISCHARGE TEMPERATURE AS FUNCTION OF COOLING LOAD

In summary, while the solar collector did increase the temperature of the refrigerant gas, the compressor did not vary its speed to save energy while the heat pump was in cooling mode.

HEATING MODE

The chart below illustrates the heat pump's performance in heating mode when the technology was enabled over the course of three relatively cool days. As shown in Figure 11, the refrigerant temperature increased through the solar collector during the day when enough thermal energy from the solar collector was available.

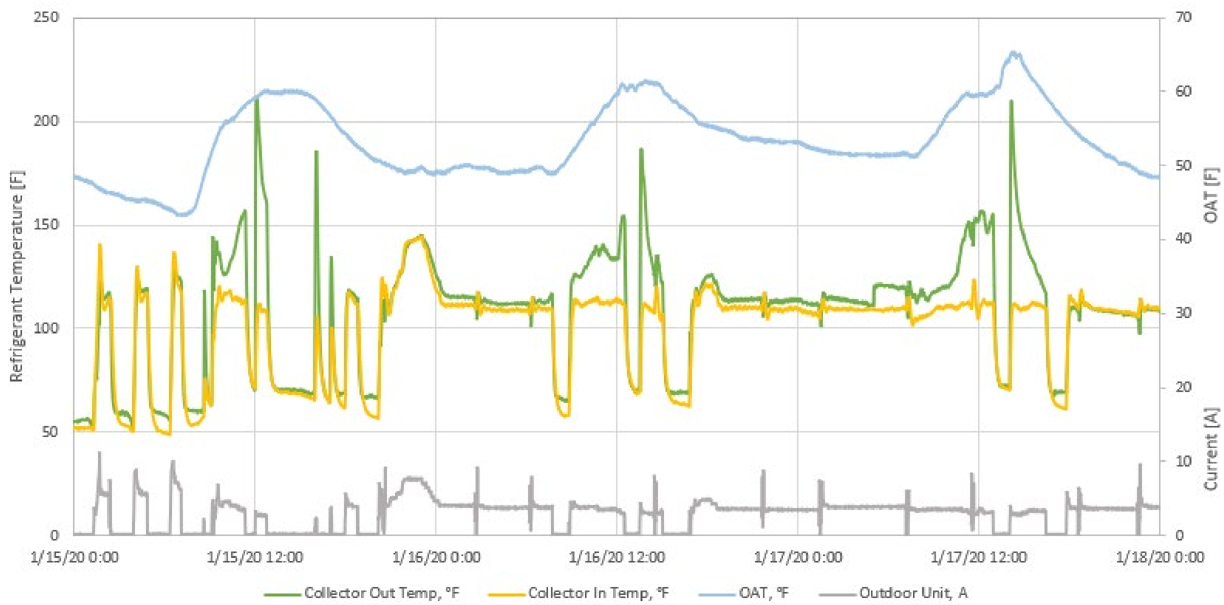

FIGURE 8: TYPICAL HEAT PUMP OPERATION IN HEATING MODE WHEN THE TECHNOLOGY IS ENABLED

Total heat pump demand increased with increasing load to the unit, as expected. However, similar to cooling mode, no significant difference in was found between periods when the technology was enabled with the refrigerant flowing through the collector ("ON") and when the technology was disabled and the refrigerant bypassing the collector ("OFF").

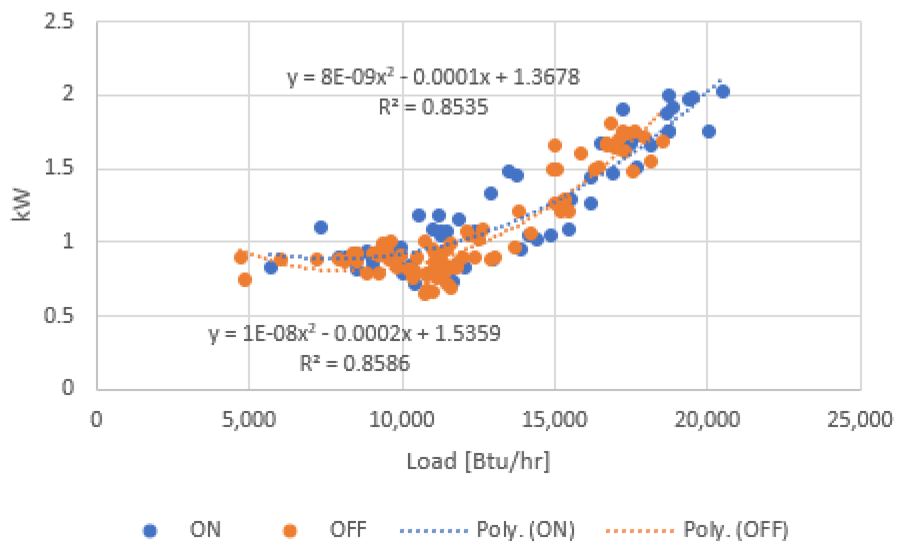

FIGURE 0: TOTAL POWER AS FUNCTION OF HEATING LOAD

To compare the heat pump efficiency between the technology's "ON" and "OFF" modes, the COP was plotted against hourly average OAT in Figure 9 below.

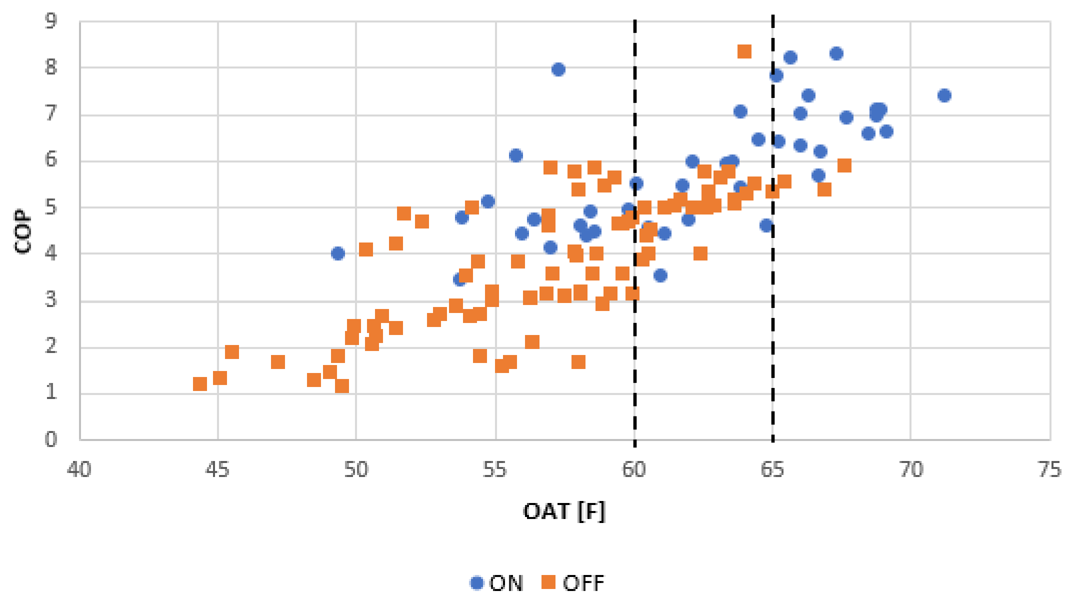

FIGURE 9: COP AS FUNCTION OF OUTDOOR AIR TEMPERATURE

No significant difference was found between the two modes of operation. However, a few observations were made:

- Although the unit appears to have performed better with technology "ON" with higher COP when outdoor air temperature exceeded 65˚F, a fair comparison could not be made between the two operating modes because the unit operated only a few hours with the technology "OFF" above 65˚F. Additionally, there was little heating load to the unit when OAT was above 65˚F.

- The unit performed similarly when the outdoor air temperature was between 60˚F and 65˚F regardless of the technology's ON/OFF status.
- The COP of the unit appears to be slightly higher with the technology "ON" when outdoor air temperature was below 60°F. However, the result is inconclusive because the unit operated only several hours with the technology "ON" and below 60°F.

The unit operated very few hours with the technology "ON" at outdoor air temperatures below 60˚F because solar was not available at this test site in the early mornings and late evenings when outdoor temperature dipped below 60˚F. The figure below illustrates that the outdoor air temperature rose to 58˚F by the time adequate amount of solar thermal energy became available for the technology to utilize, as indicated by the green shaded area.

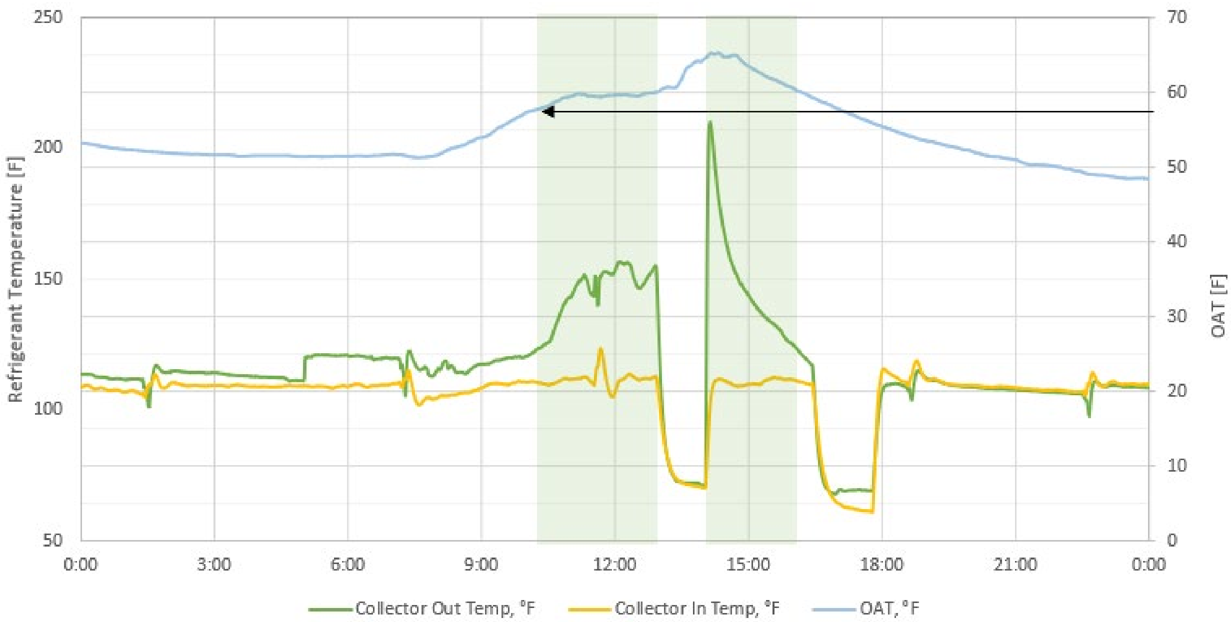

FIGURE 10: THE RELATIONSHIP BETWEEN THE SOLAR THERMAL ENERGY AVAILABILITY AND OUTDOOR AIR TEMPERATURE DURING HEATING MODE. THE GREEN SHADED AREA REPRESENTS PERIODS WHEN ADEQUATE SOLAR THERMAL ENERGY WAS HARVESTED AND MADE AVAILABLE BY THE TECHNOLOGY.

DISCUSSION & CONCLUSIONS

The results of this study, while limited in scope, showed no significant savings in cooling mode. In heating mode, however, the data suggested that the technology may have successfully slowed down the compressor when the solar radiation was available. A firm conclusion could not be drawn because not enough data was collected due to a lack of conditions where low ambient temperature and sufficient solar thermal energy were simultaneously available at the test site.

In the literature review, others also reported that adding thermal energy to the refrigerant in a heat pump system resulted in energy savings only in heating mode and not in cooling mode (ASHRAE, 2020). There is a tradeoff between compressor and condenser energy uses as indicated by another study, which stated that a larger condenser was required for the technology to work because the increased condensing requirement decreased efficiency (Q.P. Ha & V. Vakiloroaya, 2014).

If the technology is indeed able to reduce electrical consumption of a heat pump in heating mode, it could help with the reduction of greenhouse gas by having users switch from gas furnace package (or split) units to solar assisted heat pumps.

RECOMMENDATIONS

The results showed that solar assisted heat pump may have potential to save energy in heating mode. Following items are recommended before considering the adoption of this emerging technology into an EE program:

- This study was performed on a small residential unit with limited cooling and heating loads. Therefore, additional study is recommended in commercial applications such as larger packaged unit and/or refrigeration system with more consistent load to the system.
- The effectiveness of the technology in heating mode was inconclusive due to the lack of sufficiently low ambient temperature conditions at the test site. A test in a region with more heating load as well as ample solar radiation, such as in CZ10, is recommended to further investigate the saving potential in heating mode.
- Only one manufacturer model was examined in this test while there exist a few variations of the same technology. It is recommended that an additional study be performed to evaluate the demand and energy savings potential of other manufacturers of the technology in commercial applications. A laboratory setting could provide constant load to the unit, so, while the sun radiation cannot be simulated, at least the unit could have the desired amount of load when the sunshine.
- The cost effectiveness of the technology should be investigated when the technology is installed at a larger scale. The cost of installation on a two-ton split heat pump at a single-family residential was around $5,000, commensurate to the price of the heat pump unit itself. Thus, even with significant heating savings, the simple payback on a smaller installation would be longer than the heat pump's useful life. Commercial applications with extensive operating hours would only justify the additional investment unless the technology's cost is significantly reduced. Additionally, it should be noted that there is an economy of scale as the solar collector size increase and therefore 7.5 ton and higher size heat pumps seem to have a potential for payback.

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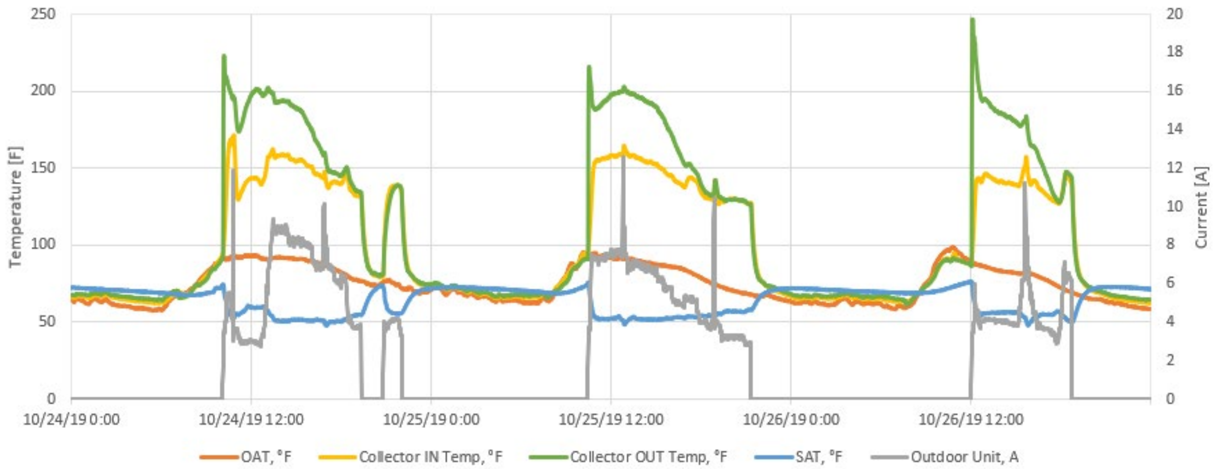
APPENDIX


250
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Temperature [F]
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10/26/19 0:00
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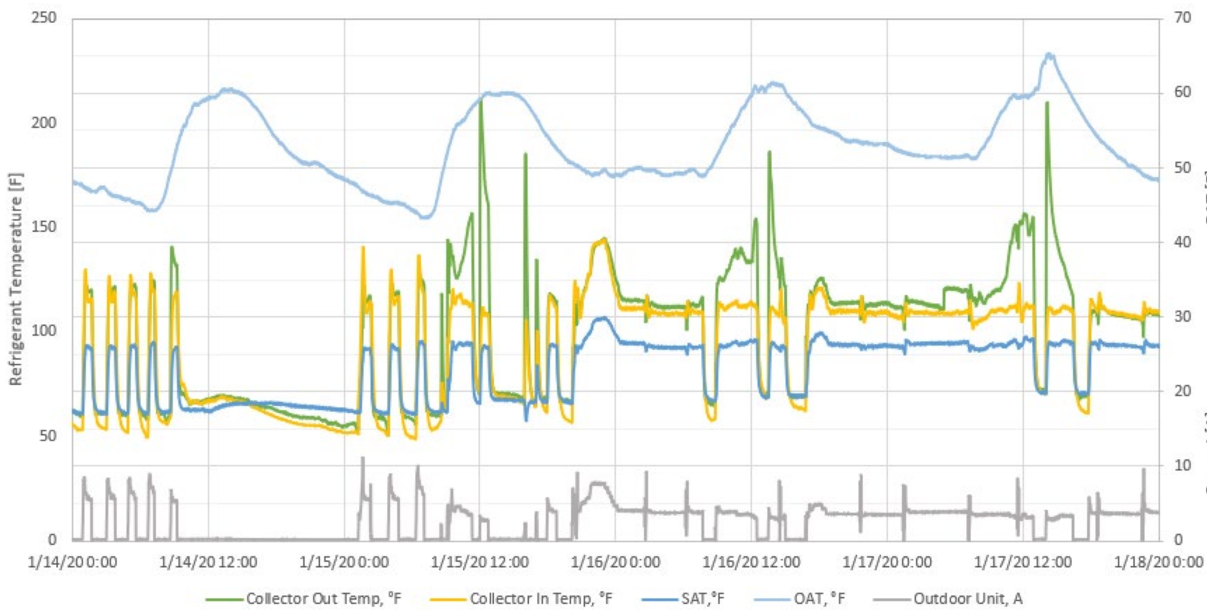
OAT, °F
Collector IN Temp, °F
Collector OUT Temp, °F
SAT, °F
Outdoor Unit, A


250
200
150
100
50
0
Refrigerant Temperature [F]
70
60
50
40
30
20
10
0
OAT [F]
Current [A]
1/14/20 0:00
1/14/20 12:00
1/15/20 0:00
1/15/20 12:00
1/16/20 0:00
1/16/20 12:00
1/17/20 0:00
1/17/20 12:00
1/18/20 0:00
Collector Out Temp, °F
Collector In Temp, °F
SAT, °F
OAT, °F
Outdoor Unit, A