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# SOLAR POWERED, ACDC12B, DUCTLESS MINI-SPLIT AIR CONDITIONER SYSTEM PERFORMANCE



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## EXECUTIVE SUMMARY

In support of California's strategic plan to accelerate the penetration of energy efficiency technologies, this report presents the findings of a field evaluation of solar powered, ductless mini-split air conditioning systems in a commercial setting. The work was executed by AESC, on behalf of the SCPA member utilities in conjunction with Securus Air and Hot Purple Energy, representing the vendor and installer.

**Technology Evaluation Description:** The objective of the study was to monitor and analyze the ACDC12B system, manufactured by HotSpot Energy, through the 2016 cooling season and the 2017 heating season. The goal of the analysis was to evaluate the cooling, heating, and overall system performance of the solar powered, ductless mini-split air conditioning unit. The evaluated unit is equipped with a DC inverter which allows the compressor to run on DC power converted from AC power, as well as DC power directly from solar panels. The hybrid operation utilizes solar, when available, to power the system and the utility 220VAC power source when there is insufficient power being generated from the photovoltaic (PV) system.

The evaluation, measurement and verification (EM&V) effort entailed the monitoring of five units installed within the Southern California area, with four units installed at Pasadena Unified School District (PUSD) sites, and a single unit installed in the City of Colton. The City of Colton unit was installed in an outdoor water pumping house (WPH), while PUSD had installations in various areas including a service kitchen, lobby area, and two conference rooms. Prior to the installation of the ACDC12B units, all areas, with exception to the Pasadena Education Center West Building, were not equipped with any space conditioning equipment. Points of measurement for the period spanning July 2016 to March 2017 included AC and DC power, as well as indoor and outdoor temperature and relative humidity at one-minute intervals.

**Project Findings:** The units were initially found operating without DC capability. However, the ACDC12B units were serviced soon after the discovery and have since been functioning as designed. A summary of estimated energy savings and demand reduction from the study are presented in Table 1. Note that DC power production recorded at PUSD McKinley was minimal and may not reflect the true operation of the unit.

**TABLE 1 RESULTS SUMMARY TABLE – ENERGY SAVINGS FOR ALL HOST SITES**

SITE	ESTIMATED ENERGY USAGE [kWh/Yr]	ENERGY SAVINGS FROM SOLAR PV [kWh/Yr]	% SAVINGS	DEER ON-PEAK BASE DEMAND [kW]	DEER ON-PEAK DEMAND REDUCTION [kW]	% SAVINGS
WPH	2,550	766	30%	1.06	0.24	23%
PUSD McKinley	4,810	337	7%	1.14	0.03	3%
PUSD Middle	1,070	472	44%	0.67	0.17	25%
PUSD South	-	-	-	-	-	-
PUSD West	790	266	34%	0.9	0.38	42%
<b>Total</b>	<b>2,305</b>	<b>517</b>	<b>20%</b>	<b>3.8</b>	<b>0.8</b>	<b>22%</b>

Table 2 below summarizes the overall operation of the ACDC12B units during the eight-month monitoring period. After some necessary corrections to the datasets, energy consumption and maximum demand were calculated for each site.

**TABLE 2 SUMMARY OF HEAT PUMP OPERATION**

SITE	CITY	TOTAL HOURS LOGGED [HRS]	TOTAL HOURS OF HP OPERATED [HRS]	SOLAR PV PRODUCED [KWH]	UTILITY SUPPLIED 220VAC POWER [KWH]	PV PRODUCED MAX DEMAND [KW]	UTILITY SUPPLIED MAX DEMAND [KW]
WPH	Colton	4,635	1,189	256	940	0.71	1.42
PUSD McKinley	Pasadena	4,545	3,765	209	3,339	0.19	1.52
PUSD Middle	Pasadena	3,917	719	184	393	0.58	1.40
PUSD South	Pasadena	4,597	27	10	54	0.51	1.40
PUSD West	Pasadena	4,138	441	116	402	0.70	1.42
<b>Cumulative</b>	<b>All</b>	<b>21,832</b>	<b>6,141</b>	<b>775</b>	<b>5,128</b>	<b>0.71</b>	<b>1.52</b>

Of the 21,832 total hours of logged data gathered for the period spanning July 2016 through the beginning of March 2017, the cumulative runtime of all units was 6,141 hours in which a total of 5,128 kWh of AC power was utilized from the grid. Total combined DC Power of 775 kWh was produced by the onsite solar PV systems, which supplemented approximately 13% of the required power input.

Each site experienced variable operation during the monitoring period. The Colton WPH experience nearly continuous operation during the cooling season, however only operated for a limited amount of time during the heating season with most of the operation during nighttime hours. The PUSD Education Center – South building only operated a total of 27 hours during the eight-month period, as the conference room it is serving is seldom utilized. The PUSD Education Center Middle Building experienced a cyclical usage pattern that reflected normal business hours. The unit installed at PUSD McKinley experience nearly continuous operation during the entire monitoring period. The collected data showed that the unit was undersized for the space and therefore, the space temperature often floated from the setpoint. The DC power production at this site was minimal, indicating that there may have been an issue with its solar PV. The unit installed at the PUSD Education Center West Building experience minimal operation during the cooling season, however usage increased in the heating season.

The analysis concluded that the efficiency of the ACDC12B unit increased with the aid of solar PV, although the degree of improvement varied from site to site. Regression analyses were performed to predict the annual consumption of the units at each site, and the monitored data was used to determine the system performance characteristics, as depicted in Table 3 below.

**TABLE 3 SUMMARY OF CALCULATED HEAT PUMP PERFORMANCE**

SITE	COOLING SEER		COOLING EER		HEATING HSPF	
	w/ PV	w/o PV	w/ PV	w/o PV	w/ PV	w/o PV
WPH	13	10	13	9	-	-
PUSD McKinley	10	10	17	16	10	10
PUSD Middle	16	11	15	10	15	9
PUSD South	-	-	-	-	-	-
PUSD West	-	-	22	12	11	10

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## INTRODUCTION

AESC was contracted by the Southern California Public Power Authority (SCCPA), on behalf of its member utilities, through a competitively bid solicitation to perform the evaluation, measurement and verification for select heat pump, air conditioning systems being utilized in Member service territories.

AESC is an energy engineering practice specializing in utility programs, technology assessments, demand side audits, and measurement and verification. AESC's history of developing EM&V protocol for California utilities, as demonstrated in various emerging technology study practices, enabled this effort to fit seamlessly within AESC's core expertise. SCPA is a joint powers agency created by the Publicly Owned Utilities in Southern California, with members including utilities serving the cities of Anaheim, Azusa, Banning, Burbank, Cerritos, Colton, Glendale, Los Angeles, Pasadena, Riverside, Vernon and the Imperial Irrigation District. SCPA fulfills a broad range of services for its members by providing effective forums of collaboration through committees such as Customer Service, Finance, Public Benefits, Resource Planning, Transmissions and Distribution, Engineering and Operations, Natural Gas, and Renewable Energy Resources.

Securus Air, the vendor responsible for project management of the emerging technology implementation, presented the ACDC12B ductless mini-split hybrid heat pump technology to SCPA members to be assessed for use in the various member territories. As a result of this presentation, two SCPA members, City of Colton and City of Pasadena, proceeded to install the equipment at five locations within their service territories. Four units were installed within the Pasadena service area, while a single unit was installed within the City of Colton. As part of the implementation proceedings, all SCPA members funded the EM&V effort for purposes of further investigating the impact of the technology.

Hot Purple Energy, a full service solar and HVAC contractor, was tasked with the installation of the five units at the designated sites selected by the Cities of Colton and Pasadena. Four locations within the Pasadena Unified School District (PUSD) were selected for equipment installation, including the Education Center lobby and two conference rooms, as well as the McKinley Elementary School kitchen. The City of Colton selected a water pumping facility used to house pumping systems serving the water requirements of the City. Except for the PUSD second floor conference room which was previously equipped with a window air conditioning unit and decommissioned from service as part of this effort, all locations were previously unconditioned areas.

In July of 2016, AESC commenced the EM&V effort at all five locations with the support of all stakeholders. AESC developed the M&V plan using International Performance Measurement and Verification Protocol (IPMVP) standards delegated from the Department of Energy and followed the path of "Option B – Retrofit Isolation" by measuring all parameters used for determining energy usage and system performance.

## INCUMBENT TECHNOLOGY

Ductless, mini-split heat pumps were first introduced in mass to the marketplace in the 1970s as a more efficient alternative to conventional window air conditioning units. The ductless system delivered improved performance with greater efficiencies and aesthetic appeal. The ability to remotely locate the sound-bearing condensing section of the system from the occupied space appealed to early consumers. Since the introduction of the early units, great strides have been made in technology advancement in the realms of increased capacity, temperature operational ranges, efficiency levels, and control methodologies.

The technology consists of two main components, an outdoor unit consisting of a compressor or condenser and an indoor air-handling unit. The two units are linked via a common conduit consisting of power cables, a condensate drain, refrigerant lines, and suction tubing. Depending the unit model, many systems are equipped with thermostatic set point control and scheduling capabilities. The units are powered via alternating current (AC) power input, typically from the utility grid or other AC power source.

To assess the ductless, mini-split heat pump industry, the Air Conditioning, Heating, & Refrigeration Institute (AHRI) database was consulted. AHRI provides efficiency and capacity certification of air conditioning equipment for more than 90 percent of the residential and commercial air conditioning, heating, water heating, and commercial refrigeration equipment manufactured in North America. Restricting the parameters to units similarly sized to our equipment of topic (11,500 Btu/hr cooling & 13,000 Btu/hr heating), the AHRI database certifies 920 units currently in the marketplace. Details regarding cooling and heating efficiency characteristics for these units is provided below in **Error! Reference source not found.** and Table 5, respectively. Cooling efficiency is measured as both the Energy Efficiency Ratio (EER) and Seasonal Energy Efficiency Ratio (SEER). The EER is the ratio of the cooling capacity in Btu/hr to the power input of the unit in watts. Comparatively, the SEER rating is the ratio of the total cooling output of the unit in Btu during a typical cooling season to the total energy input during the same period in watt-hours. Heating efficiency is measured as the Heating Season Performance Factor (HSPF), which is the ratio of the total heating output of the unit in Btu during a typical heating season to the total energy input during the same period in watt-hours. All three of these performance metrics characterize a system's expected operation during both cooling and heating mode, throughout different seasons.

**TABLE 4 AHRI COOLING EFFICIENCY OF COMPARABLE HEAT PUMPS IN CURRENT MARKETPLACE**

COOLING CAPACITY (BTU/HR)	MINIMUM SEER	MAXIMUM SEER	AVERAGE SEER	MINIMUM EER	MAXIMUM EER	AVERAGE EER
11,000	18.0	25.5	19.2	12.5	13.8	12.7
11,100	15.4	15.4	15.4	12.0	12.0	12.0
11,200	16.0	21.5	20.3	12.0	12.5	12.4
11,500	15.5	26.2	20.9	9.1	15.0	12.8
11,800	16.0	16.0	16.0	9.4	9.4	9.4
11,900	18.0	18.0	18.0	10.3	10.3	10.3
12,000	14.5	30.5	19.3	8.5	16.4	11.5

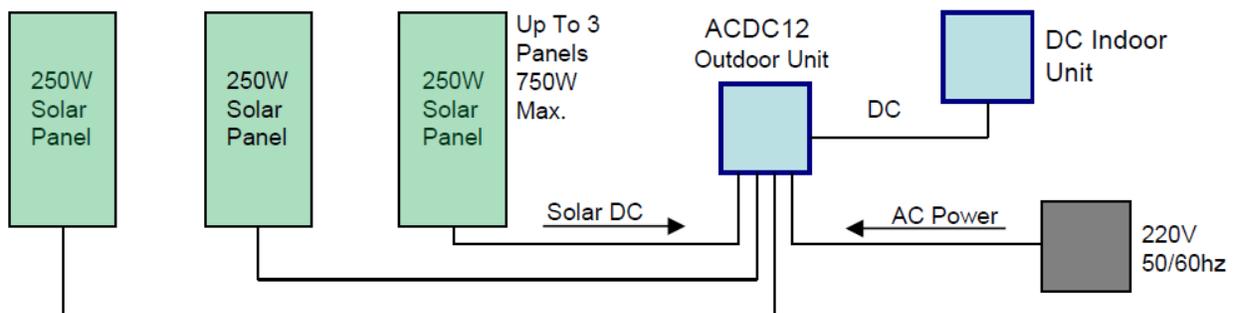
**TABLE 5 AHRI HEATING EFFICIENCY OF COMPARABLE HEAT PUMPS IN CURRENT MARKETPLACE**

HEATING CAPACITY (BTU/HR)	MINIMUM HSPF	MAXIMUM HSPF	AVERAGE HSPF
12,000	8.2	13.0	9.3
12,200	8.4	14.0	10.6
12,500	8.4	9.6	9.2
13,000	8.5	12.0	9.6
14,000	9.0	12.8	10.4

## EMERGING TECHNOLOGY DESCRIPTION

The ACDC12B unit is a ductless mini-split hybrid heat pump supplied by Securus Air. The unit contains a DC inverter which allows the compressor to run on DC power converted from AC power, as well as DC power directly from solar panels. Up to three solar panels can be connected to the AC unit via standard MC4 solar connectors. The hybrid operation utilizes solar, when available, to power the system and the utility 220VAC power source when there is insufficient power being generated from the photovoltaic (PV) system. Figure 1 is a single line diagram for the ACDC12B unit, depicting both the solar and utility grid power inputs as provided by Securus Air.

FIGURE 1 ACDC12B SOLAR AIR CONDITIONER SYSTEM CONFIGURATION<sup>1</sup>



The systems installed at the five sites were each equipped with three Hyundai HiS-M260RG solar panels, wired in a parallel configuration as is typical with most installations of the ACDC12B unit. Each panel consists of 60 multi-crystalline cells configured in a series matrix, with a manufacturer's total module efficiency of 15.9% at standard testing conditions. The power generated by the solar array is routed to a common DC disconnect for transfer to the ACDC12B unit during times the unit is operational. For situations when the unit is not operating during solar production times, the power generated by the solar array is dispersed to heat by the system. Similarly, the unit is also connected to a utility supplied 208/230-volt AC power supply to supplement the power requirements of the unit. Although the unit is equipped with dual power sources, the ACDC12B is not able to back feed to the utility grid for purposes of offsetting utility loads.

The unit utilizes 4R10A refrigerant, with operating ranges from 20°F to 122°F in cooling mode and 5°F to 86°F heating mode. The refrigerant line set is capable of traversing 82 feet, and 33 feet in elevation. Both the indoor and outdoor fans are equipped with DC powered, variable speed motors with indoor air flows between 285 to 410 CFM. The compressor is a brushless DC rotary unit with design pressure of 340 PSIG low side and 550 PSIG high side. Per the manufacturer's specification, the unit is intended for heating and cooling spaces up to 750 square feet. AHRI rating information for the ACDC12B unit is depicted in Table 6 below.

<sup>1</sup> <http://www.securusair.com/>

TABLE 6 AHRI RATED PERFORMANCE OF ACDC12B UNIT

<b>ACDC12B UNIT</b>	
<b>AHRI REFERENCE NUMBER: 7201808</b>	
Cooling Capacity (Btu/hr)	11,500
EER Rating (Cooling)	13
SEER Rating (Cooling)	21
Heating Capacity @ 47°F (Btu/hr)	13,000
HSPF Rating (Heating)	10
Heating Capacity @ 17°F (Btu/hr)	7,500

In addition to the third-party rated data for the unit, the manufacturer attests the unit efficiency increases to 35 SEER when equipped with two 230-watt or greater solar panels, and above 65 SEER when equipped with three 300-watt solar panels. Without accounting for the solar contribution, the unit falls within the average efficiency ratings for similarly sized units, as previously shown in Table 4 and Table 5.

## ASSESSMENT OBJECTIVES

The objective of the EM&V study was to monitor and analyze the ACDC12B system through the 2016 cooling season and the 2017 heating season, with the goal of evaluating the cooling, heating, and overall system performance of the solar powered heat pump. To this end several objectives were established:

- Measure and verify energy and demand usage of the ACDC12B units, as well as system performance in commercial applications.
- Examine the hourly correlations to weather conditions, effect on overall compressor runtime and cycling frequency, and annualized energy usage for each individual unit as well as the totality.
- Generate a multivariable regression equation to be deployed among various climate zone to calculate the consumption of the ACDC12B system and its effect on the grid.
- Generate a technology assessment report that follows the International Performance Measurement and Verification Protocol, Option B (IPMVP).

To accomplish these objectives, measurement devices were installed on five units within the Southern California area, with four units located at Pasadena Unified School District sites and a single unit located in the City of Colton.

## MEASUREMENT AND VERIFICATION PLAN

A measurement and verification plan was established to capture all the necessary data to estimate energy impacts and system performance of this technology. The plan followed the principles of the International Performance Measurement and Verification Protocol (IPMVP) standards and used Option B (Retrofit Isolation) M&V approaches. Retrofit isolation was exercised by monitoring the specific energy use of each unit on an interval basis along with other variables to inform regression analyses. The following sections outline the specifics of the M&V plan including host site descriptions, instrumentation, and measurement timeline.

The EM&V effort entailed the monitoring of five units installed within the Southern California area, with four units installed at Pasadena Unified School District sites and a single unit installed in the City of Colton. The Colton unit was installed in an outdoor water pumping house, and Pasadena had installations in various areas including a service kitchen, lobby area, and two conference rooms. Prior to the installation of the ACDC12B units all areas, with exception to the Pasadena Education Center West Building, were not equipped with either heating or cooling capabilities.

Energy analysis was performed by monitoring the units on a one-minute interval basis and using regressions to external variables as part of this effort. The analysis included the examination of hourly correlations to weather conditions, solar radiation, and space temperatures.

### HOST SITES

The host sites for the field evaluation within both Pasadena and Colton service territories are characterized in Table 7 below, including location type, space occupancy, conditioned area and geographical reference.

**TABLE 7 HOST SITE BUILDING CHARACTERISTICS**

CHARACTERISTIC	PUSD SOUTH	PUSD WEST	PUSD MIDDLE	PUSD MCKINLEY	COLTON WPH
Location Type	Conference Room	Conference Room	Lobby	Kitchen	Pump Storage
Space Occupancy	As needed	As needed	8AM – 5PM Mon – Fri	8AM – 5PM Mon – Fri	As needed
Conditioned Area	600 ft <sup>2</sup>	750 ft <sup>2</sup>	1,500 ft <sup>2</sup>	1,200 ft <sup>2</sup>	600 ft <sup>2</sup>
CA Climate Zone	9	9	9	9	10
Zip Code	91101	91101	91101	91101	92324

## INSTRUMENTATION

Data were collected using logging instrumentation for a period of eight months, and all measurements were taken at one-minute intervals. Dent ElitePro XC Power Meters were used to measure utility provided AC current, voltage, power factor, and true power along with solar provided DC voltage and current at all sites, with exception to the Pasadena McKinley location. The Dent power meters required that AC line voltage be connected to power the meter during the monitoring period. Unfortunately, the AC and DC disconnects at the McKinley location were installed in locations with distances that did not allow for the shared connection. At McKinley, an Onset current transducer (CT) was used to measure the utility provided AC current, with was captured on a Hobo data logger. The current measurements were used in conjunction with spot measurements of AC voltage and power factor to calculate the single-phase power input. These same Hobo loggers were used to record indoor temperature, outdoor temperature and relative humidity. Solar radiation was determined using local airport weather station data.

**TABLE 8 MONITORING INSTRUMENTATION**

DATA POINT	MEASUREMENT	INSTRUMENT	ACCURACY	LOGGING INTERVAL
AC Power	kW, A, V, pf	Dent ElitePro XC	±1%	1 minute
DC Power	kW, A, V, pf	Dent ElitePro XC	±1%	1 minute
AC Power (McKinley)	A	HOBO U12 Fluke 345	±1%	1 minute
OAT and OARH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	1 minute
INDT and INDRH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	1 minute
Solar Radiation	LY	Local Station	±0.5%	1 minute

## TIMELINE AND PARTY ROLES

The objective of the EM&V study was to monitor and analyze the ACDC12B system through the 2016 cooling season and the 2017 heating season. This monitoring effort spanned the period from July 2016 through the beginning of March 2017. The cooling season was defined as the period from July 2016 through October 2016, while the heating season was defined as the period from November 2016 through the beginning of March 2017.

Due to data storage limitations and battery lifespans, onsite visits were conducted monthly to extract data and relaunch equipment. To keep all parties informed on project progress, AESC provided interim reporting after data collection, and additional targeted analysis for the cooling and heating seasons. This effort was completed with the participation of all participating parties, including contacts from Pasadena Unified School District and the City of Colton.

## ANALYSIS

Raw, one-minute data of unit AC power, DC power, outside air temperature and relative humidity, inside air temperature and relative humidity, as well as solar radiation were culminated for each installation site. To determine the single-phase power input to the unit, the following equation was used:

$$kW = \frac{V * A}{1000} * PF$$

Where,

V = Voltage supplied to the unit for AC (utility grid) and DC (solar component)

A = Amperage supplied to the unit for AC (utility grid) and DC (solar component)

PF = AC power factor from the utility grid. Note that solar provided power input operates in unity, or a power factor of 1

To filter out the phantom power load associated with the equipment, the kW input data was plotted in a histogram to determine a baseline power input to be used as a basis to justify unit operation. For most sites, this threshold was approximately 20 to 30 watts. The unit operational data was then segregated from the population for purposes of quantifying the system performance.

System cooling performance was determined using both EER<sub>95</sub> and SEER approaches for sites, where sufficient operational data was available. EER and SEER were used instead of COP to be consistent with the AHRI rating. Additionally, these metrics allowed the analysis to account for part-load operation during each season. EER<sub>95</sub> is the equivalent methodology used for determining AHRI validated specifications, and was selected as a metric for this study to compare the measured system performance with validated performance characteristics. This approach determines the EER at the standardized testing conditions of 95°F outside air, 80°F inside air, and 50% inside air relative humidity. A ±5°F dead band was set for each of the three parameters and the data was filtered and segregated for analysis. The AC and DC kW at these conditions was plotted over time to observe the distinct operating power inputs at variable system loads, to determine the effective kW/ton metric for the 11,500 Btu/hr full cooling capacity unit. The following equations were utilized in determining the EER<sub>95</sub>:

$$Part\ Load\ Capacity\ \% = \frac{(kW_{AC} + kW_{DC})_{instantaneous}}{(kW_{AC} + kW_{DC})_{avg\ @\ full\ capacity}}$$

$$Part\ Load\ Capacity\ (tons) = \frac{Partload\ Capacity\ \% * 11,500\ Btu/hr}{12,000\ \frac{Btu/hr}{ton}}$$

$$EER_{95\ w/solar} = \frac{12}{kW_{AC}/ton}$$

$$EER_{95\ w/out\ solar} = \frac{12}{(kW_{AC} + kW_{DC})/ton}$$

The cooling SEER efficiency rating is the ratio of the total Btu of cooling output during a typical season to the total electric energy input in watt-hours during the same period. The same part load accountability methodology as mentioned above was used to determine the unit cooling capacity throughout the evaluation period. The following equations were utilized in determining the SEER rating:

$$\text{Season Cooling Output (Btu)} = \sum_{i=0}^n \text{Partload Capacity } \%_i * 11,500 \text{ Btu/hr}$$

$$\text{Season Cooling Energy Input}_{w/solar} \text{ (Wh)} = \sum_{i=0}^n \frac{(kW_{AC})_i}{1000 * 60}$$

$$\text{Season Cooling Energy Input}_{w/out solar} \text{ (Wh)} = \sum_{i=0}^n \frac{(kW_{AC} + kW_{DC})_i}{1000 * 60}$$

$$SEER_{w/solar} = \frac{\text{Season Cooling Output (Btu)}}{\text{Season Cooling Energy Input}_{w/solar} \text{ (Wh)}}$$

$$SEER_{w/out solar} = \frac{\text{Season Cooling Output (Btu)}}{\text{Season Cooling Energy Input}_{w/out solar} \text{ (Wh)}}$$

The heating efficiency is measured as the Heating Season Performance Factor (HSPF), which is the ratio of the total heating output of the unit in Btu during a typical heating season to the total energy input during the same period in watt-hours. The same part load accountability methodology as mentioned above was used to determine the unit heating capacity throughout the evaluation period; however, the full load heating capacity differs slightly at 13,000 Btu/hr. The following equations were utilized in determining the HSPF rating:

$$\text{Total Season Heating Output (Btu)} = \sum_{i=0}^n \text{Partload Capacity } \%_i * 13,000 \text{ Btu/hr}$$

$$\text{Season Heating Energy Input}_{w/solar} \text{ (Wh)} = \sum_{i=0}^n \frac{(kW_{AC})_i}{1000 * 60}$$

$$\text{Season Heating Energy Input}_{w/out solar} \text{ (Wh)} = \sum_{i=0}^n \frac{(kW_{AC} + kW_{DC})_i}{1000 * 60}$$

$$HSPF_{w/solar} = \frac{\text{Season Heating Output (Btu)}}{\text{Season Heating Energy Input}_{w/solar} \text{ (Wh)}}$$

$$HSPF_{w/out\ solar} = \frac{\text{Season Heating Output (Btu)}}{\text{Season Heating Energy Input}_{w/out\ solar} (Wh)}$$

## RESULTS

Field measurements of the ductless mini-split air conditioner systems were conducted using the instrumentation and methods described in the M&V plan. This section summarizes the field measurement results during the monitoring period and the performance of the units, from July 2016 to March 2017.

### WATER PUMPING HOUSE RESULTS

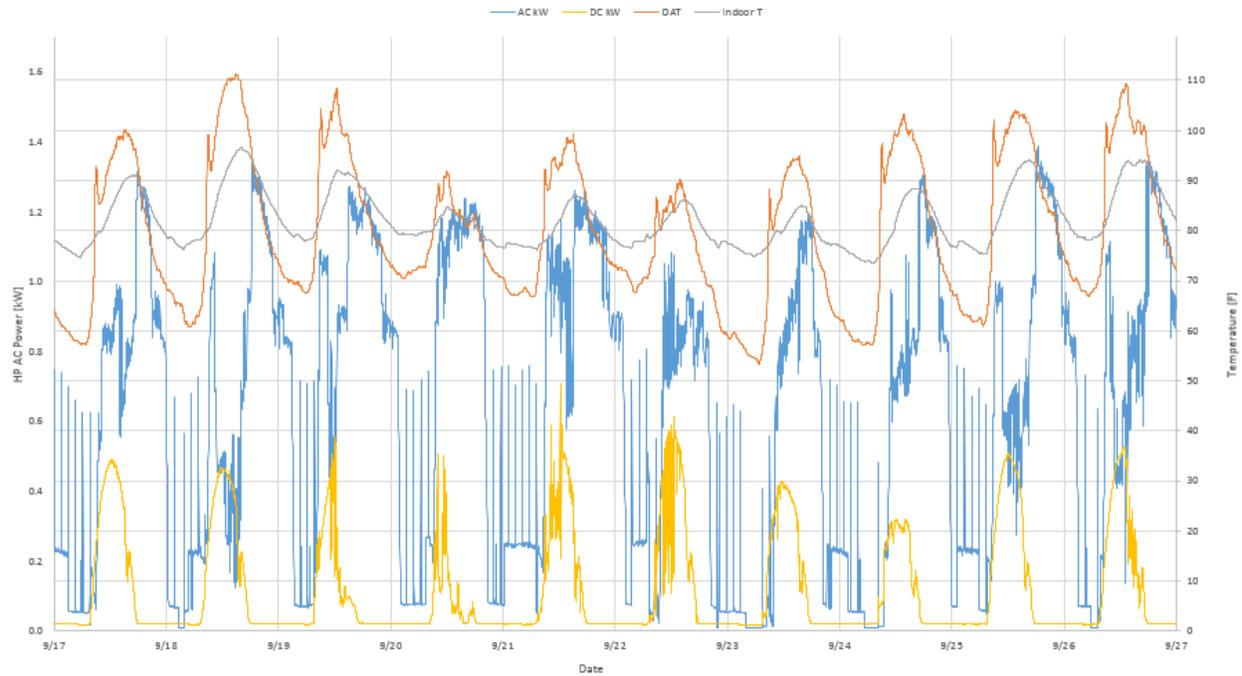
The ACDC12B unit serves the water pumping house (WPH), which is a 600 ft<sup>2</sup> building without any insulation. During the period from October through March, ten datasets were collected at the site: Heat Pump (HP) AC current draw in amps, AC voltage, AC power factor, AC true power in kW, DC current draw in amps, DC voltage, outside air temperature (OAT), outside air relative humidity, indoor space temperature in degrees Fahrenheit, and indoor space relative humidity. DC current and voltage data were then multiplied to convert to power. During the initial site visit in July 2016, AESC found that the mini-split systems were not drawing any power from solar PV system. Thus, the first few weeks of monitoring included 220VAC power only. Additionally, the analysis excludes trend data obtained from the time when the units were repaired to the time when the DC loggers were installed. Due to circumstances surrounding site specific monitoring equipment installation, complete measurements of both DC and AC draws were not initiated until September 2016.

**TABLE 9 SUMMARY OF WPH HEAT PUMP OPERATION**

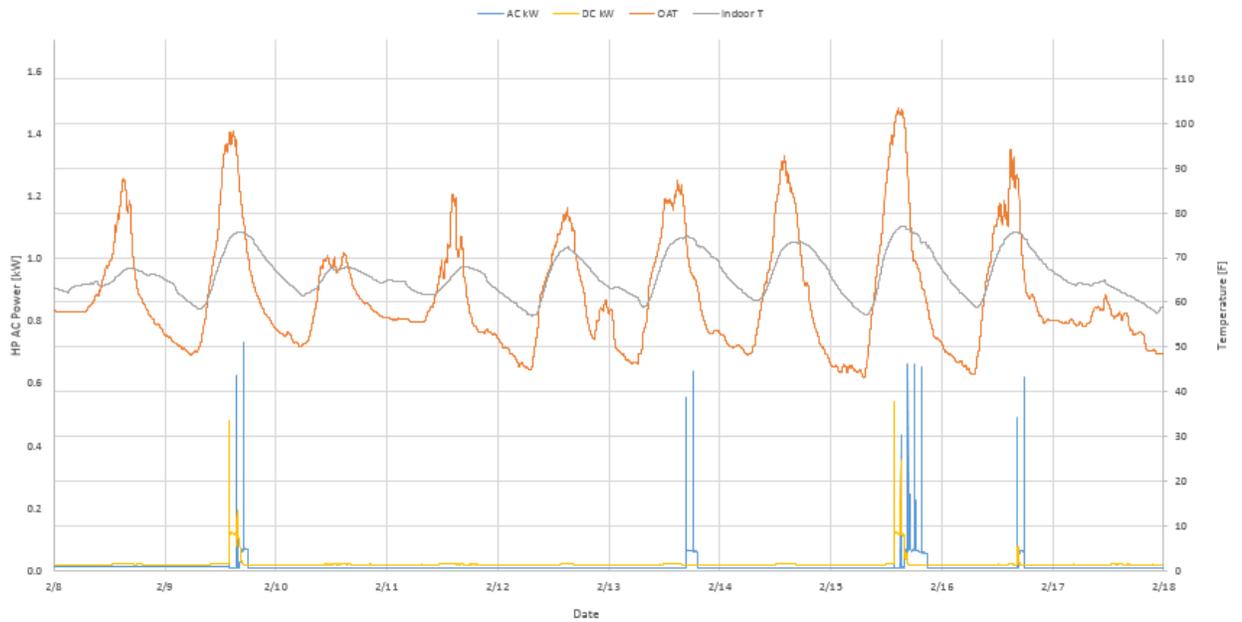
MONTH	HOURS LOGGED [Hrs]	HOURS OF HP OPERATED [Hrs]	SOLAR PV PRODUCED [kWh]	UTILITY SUPPLIED 220VAC POWER [kWh]	PV PRODUCED MAX DEMAND [kW]	UTILITY SUPPLIED MAX DEMAND [kW]
July	85	85	0	89	0.00	1.41
August	72	72	0	71	0.00	1.41
September	709	532	95	402	0.71	1.42
October	744	359	66	250	0.70	1.34
November	721	140	42	92	0.62	1.26
December	744	0	17	12	0.05	0.10
January	744	0	21	11	0.06	0.10
February	672	1	14	10	0.54	0.73
March	144	0	3	3	0.44	0.68
<b>Cumulative</b>	<b>4,635</b>	<b>1,189</b>	<b>256</b>	<b>940</b>	<b>0.71</b>	<b>1.42</b>

### RAW DATA AND PROCESSING

The figures below illustrate the operation of the unit during the monitoring period in the time lapse of the 220V AC Power (kW), DC Power (kW), OAT (°F), and indoor temperature (°F) for a typical cooling and heating period. At this site, the unit only operated in heating mode for several hours over the course of study.

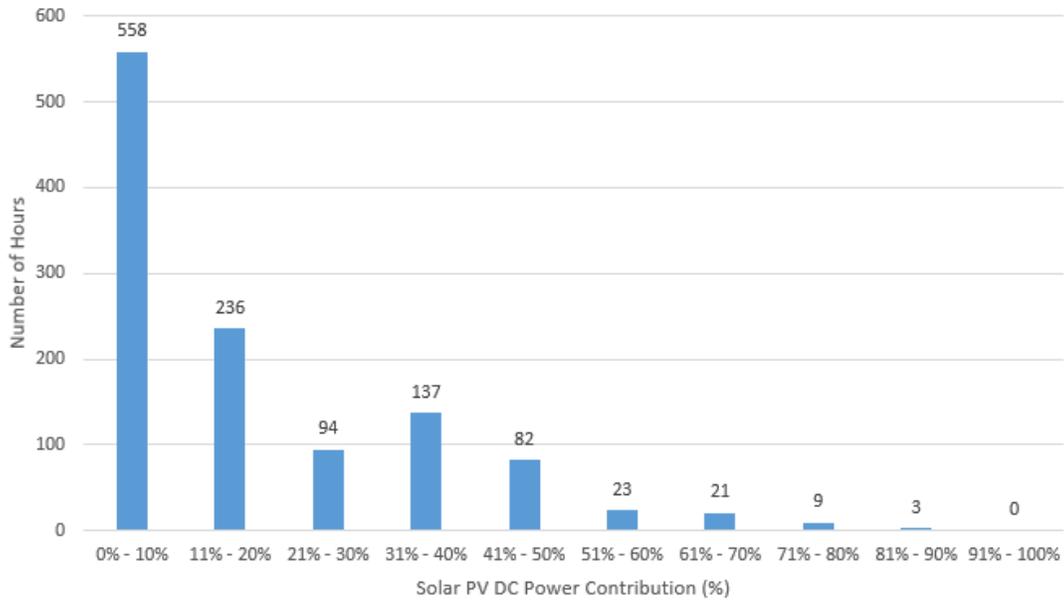


**FIGURE 2 COLTON WPH TYPICAL COOLING PERIOD OPERATING PROFILE**



**FIGURE 3 COLTON WPH TYPICAL HEATING PERIOD OPERATING PROFILE**

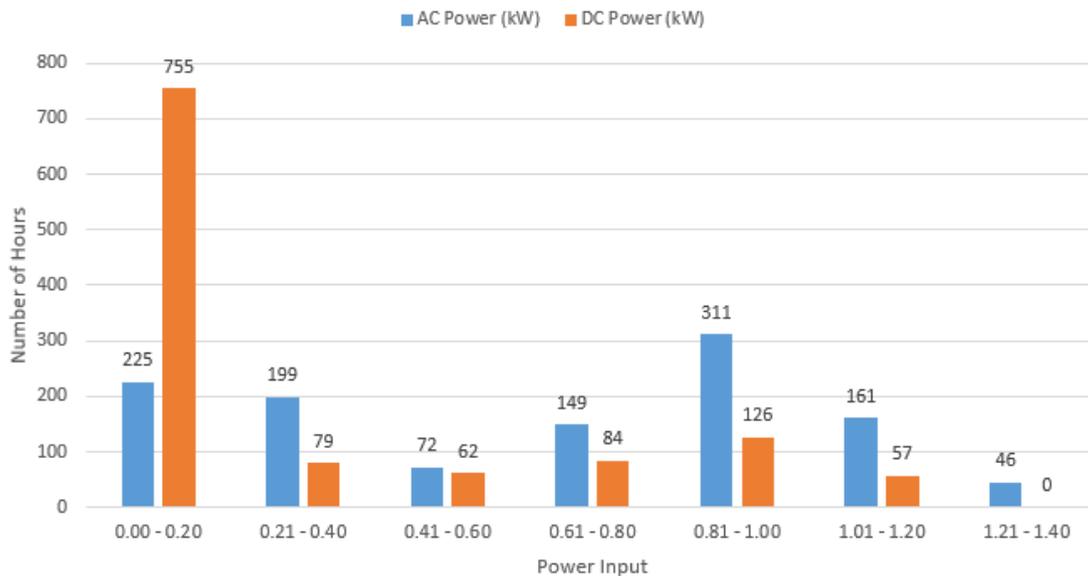
To quantify the impact of the solar PV system on the unit’s operation, the solar contribution percentage of the total power input requirement was determined. Figure 4 below illustrates the number of hours the solar PV system offset the energy requirements of the unit during operation. On average, the solar component contributed approximately 18% of the power input to the unit, with a maximum of 96%.



**FIGURE 4 COLTON WPH SOLAR PV SYSTEM CONTRIBUTION TO TOTAL POWER REQUIREMENTS**

### SYSTEM PERFORMANCE

On average the system drew 0.63 kW from the utility grid and 0.14 kW from the solar PV system, with maximum AC and DC power inputs of 1.42 kW and 0.71 kW, respectively. Figure 5 below illustrates the number of hours the unit spent in various kW operating ranges during operation only.



**FIGURE 5 COLTON WPH HOURLY BIN DATA FOR AC AND DC SYSTEM POWER INPUT**

Using the approach outlined in the Analysis section, the system operating SEER, EER<sub>95</sub>, and HSPF were calculated. Table 10 below provides details of the calculated efficiencies and manufacturer’s specification efficiencies. As can be seen in the table, the unit at this site is

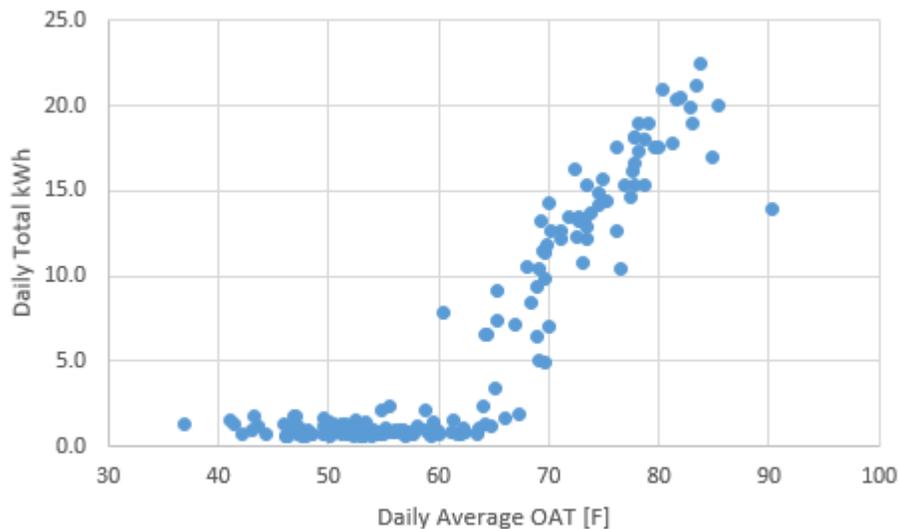
operating at efficiencies less than what was claimed by the manufacturer. Note that there are a number of unmeasurable variables that could have negatively affected the efficiencies of the unit during the in-field tests, while ARHI tests are done in the lab.

**TABLE 10 COLTON WPH CALCULATED SYSTEM EFFICIENCIES**

EFFICIENCY TYPE	CALCULATED EFFICIENCY		SPECIFICATION EFFICIENCY	
	WITH PV	WITHOUT PV	WITH PV	WITHOUT PV
Cooling SEER	13	10	N/A	21
Cooling EER <sub>95</sub>	13	9	N/A	13
Heating HSPF	N/A	N/A	N/A	10

## ENERGY AND DEMAND SAVINGS

Over the course of the monitoring period, which spanned 4,635 hours, the unit operated for approximately 1,189 hours for a calculated utilization rate of 26%. To estimate annual energy unit consumption and savings, several regression analyses were performed. Figure 6 shows the total daily consumption of the unit at this site over the course of monitoring period. As expected, the daily consumption of the unit increased with increasing average outside air temperature (OAT) at the site. The chart also shows that the unit only operated when daily average OAT exceeded approximately 60°F, indicating the unit operated solely in cooling mode even though the data collection period included the entire winter season.



**FIGURE 6 COLTON WPH DAILY UNIT CONSUMPTION DATA**

To estimate annual energy consumption of the unit in cooling mode, a linear regression model was formed between the calculated cooling degree day (CDD) and the recorded daily total unit energy consumption (kWh). The CDD is calculated as the difference between OAT and the balance point temperature, which in this case was determined as 60°F at this site

from the above data. The model revealed that the unit daily consumption was strongly correlated to the CDD, with  $R^2$  value of 0.88.

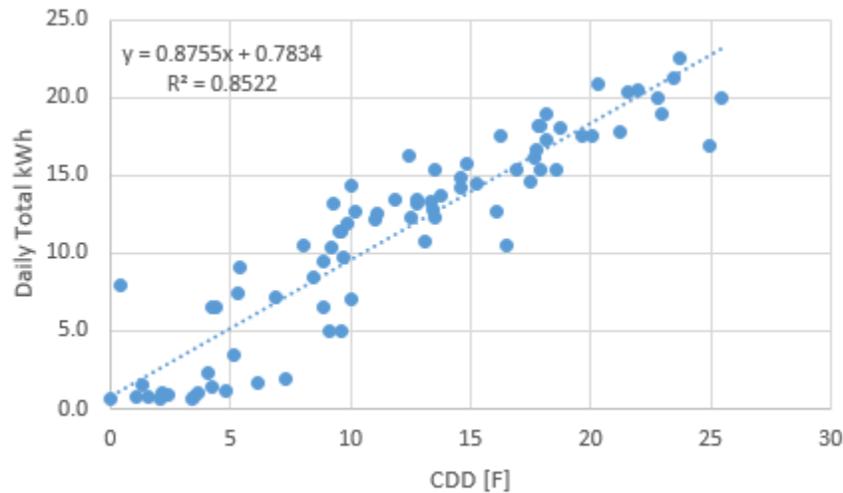


FIGURE 7 COLTON WPH DAILY UNIT CONSUMPTION VS. CDD

Next, the measured DC power was plotted against daily total solar radiation received. The solar data is publicly available from California Department of Water Resource's California Irrigation Management Information (CIMIS) website. A weather station in Riverside was selected as it is the closest from the test site. The data showed increasing daily DC power production with increasing daily total solar radiation and resulted in a reasonable correlation with  $R^2$  value of 0.55.

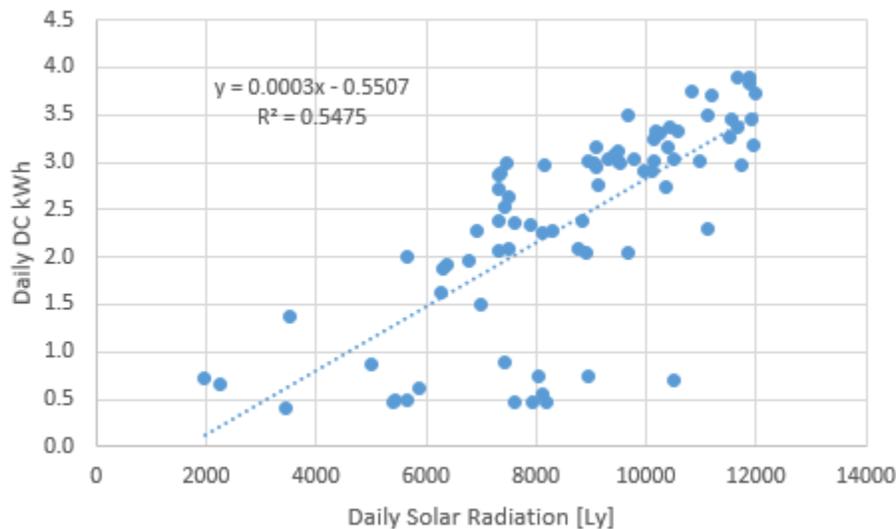


FIGURE 8 COLTON WPH DAILY DC POWER PRODUCTION AS FUNCTION OF DAILY SOLAR RADIATION

Using above regression models along with 2016 CIMI hourly weather data, the annual consumption of the unit and energy offset from the DC power production were estimated. The expected total combined AC and DC energy usage of the unit during the year is 2,530 kWh, of which 766 kWh is supplied by the solar PV system in the form of DC power. For a standard AC power only unit, this additional 766 kWh, or 30% of total consumed energy, would have been provided by the utility grid.

The DEER peak demand period is specified as the period from 2:00PM to 5:00PM during the hottest three-day period of the year. Using the bin operating data during the specified timeframe in September, it is estimated that the unit will be drawing on average 0.82 kW from the utility grid and 0.24 kW provided by the solar. Therefore, the ACDC12B saves 0.24 kW over a standard unit. A summary of estimated energy and demand savings is summarized in Table 17 below.

**TABLE 11 COLTON WPH CALCULATED ENERGY AND DEMAND SAVINGS**

<b>SAVINGS METRIC</b>	<b>CALCULATED SAVINGS</b>
Estimated Annual Unit Consumption (kWh)	2,550
Annual Energy Savings (kWh)	766
Peak Demand Savings (kW)	0.24
Estimated Annual Cost Savings (\$)*	\$115

\*Cost savings use an estimated cost per kWh of \$0.15.

## McKINLEY MIDDLE SCHOOL RESULTS

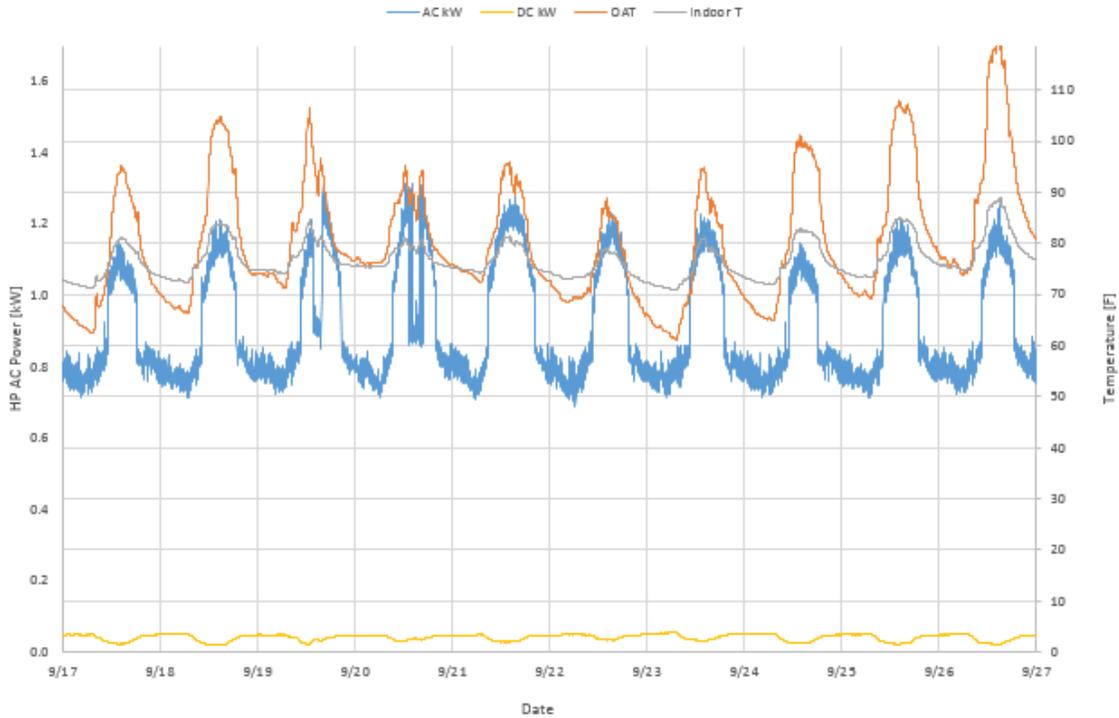
The ACDC12B unit serves the lobby area of the Pasadena Unified School District (PUSD) – McKinley School Kitchen. During the period from October through March, ten datasets were collected at the site: Heat Pump (HP) AC current draw in amps, AC voltage, AC power factor, AC true power in kW, DC current draw in amps, DC voltage, outside air temperature (OAT), outside air relative humidity, indoor space temperature in degrees Fahrenheit, and indoor space relative humidity. DC current and voltage data were then multiplied to convert to power. During the initial site visit in July 2016, AESC found that the mini-split systems were not drawing any power from solar PV system. Thus, the first few weeks of monitoring included 220VAC power only. Additionally, the analysis excludes trend data obtained from the time when the units were repaired to the time when the DC loggers were installed. Due to circumstances surrounding site specific monitoring equipment installation, complete measurements of both DC and AC draws were not initiated until September 2016.

TABLE 12 PUSD McKINLEY MIDDLE SCHOOL OPERATIONAL DATA

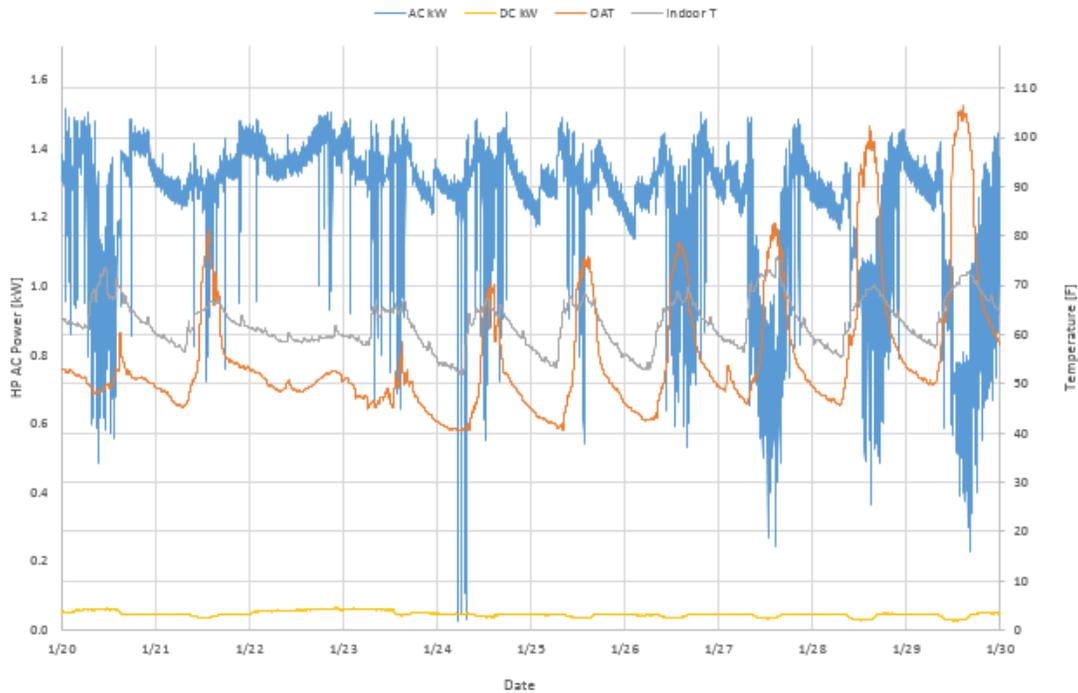
MONTH	HOURS LOGGED [Hrs]	HOURS OF HP OPERATED [Hrs]	SOLAR PV PRODUCED [kWh]	UTILITY SUPPLIED 220VAC POWER [kWh]	PV PRODUCED MAX DEMAND [kW]	UTILITY SUPPLIED MAX DEMAND [kW]
July	105	6	0	8	0.00	1.08
August	348	71	0	81	0.00	1.04
September	346	346	14	313	0.05	1.32
October	744	676	35	460	0.08	1.31
November	721	408	36	292	0.19	1.50
December	744	743	43	630	0.10	1.50
January	744	738	43	795	0.14	1.52
February	672	661	33	653	0.07	1.52
March	120	116	6	107	0.06	1.52
<b>Cumulative</b>	<b>4,545</b>	<b>3,765</b>	<b>209</b>	<b>3,339</b>	<b>0.19</b>	<b>1.52</b>

### RAW DATA AND PROCESSING

The figures below illustrate the operation of the unit during the monitoring period in the time lapse of the 220V AC Power (kW), DC Power (kW), OAT (°F), and indoor temperature (°F) for a typical cooling and heating period.



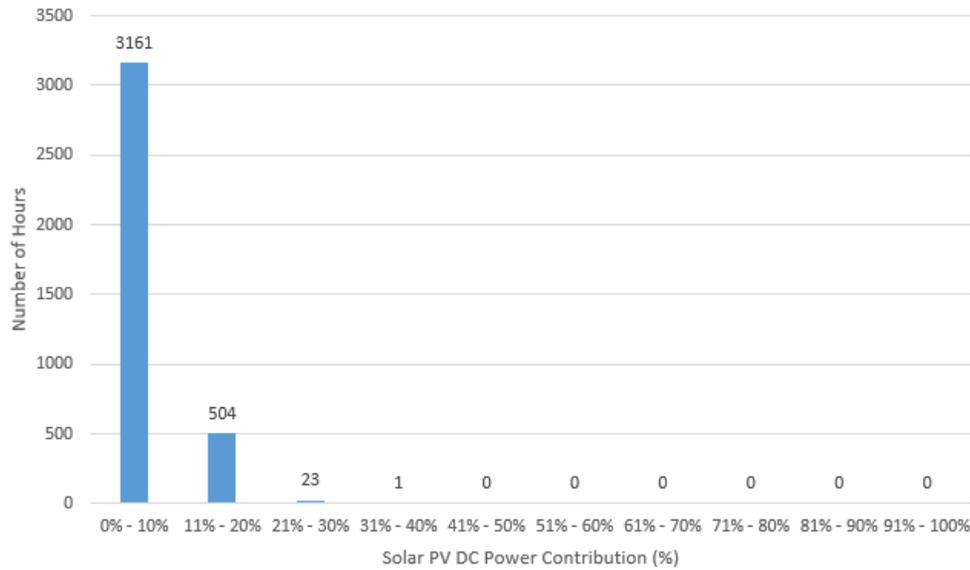
**FIGURE 9 PUSD MCKINLEY MIDDLE SCHOOL TYPICAL COOLING PERIOD OPERATING PROFILE**



**FIGURE 10 PUSD MCKINLEY MIDDLE SCHOOL TYPICAL HEATING PERIOD OPERATING PROFILE**

To quantify the impact of the solar PV system on the unit’s operation, the solar contribution percentage of the total power input requirement was determined. Figure 11 below illustrates the number of hours the solar PV system offset the energy requirements of the unit during

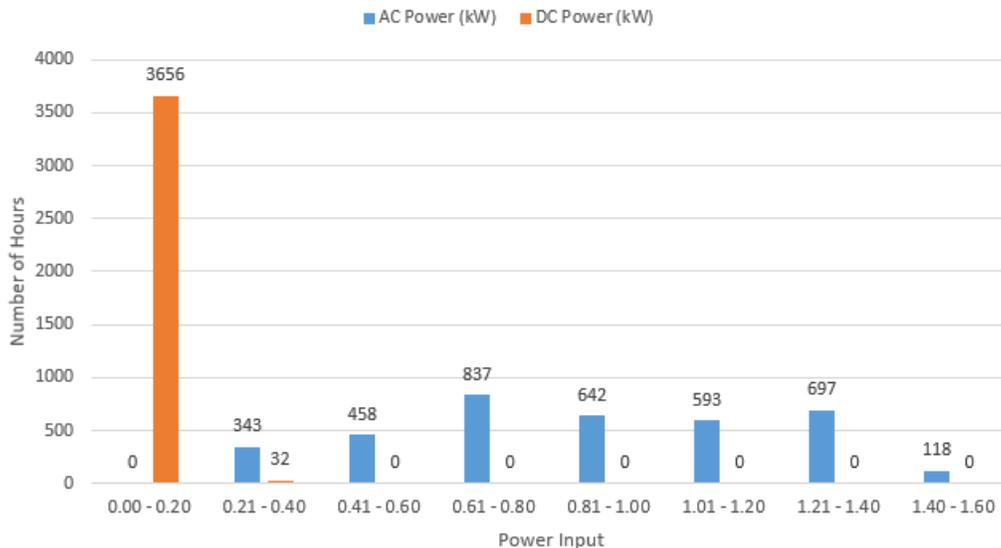
operation. At this site, solar PV power was barely utilized. On average, the solar component contributed approximately 7% of the power input to the unit, with a maximum of 25%.



**FIGURE 11 PUSD MCKINLEY MIDDLE SCHOOL SOLAR PV SYSTEM CONTRIBUTION TO TOTAL POWER REQUIREMENTS**

### SYSTEM PERFORMANCE

On average the system drew 0.87 kW from the utility grid and 0.05 kW from the solar PV system, with maximum AC and DC power inputs of 1.52 kW and 0.14 kW, respectively. Figure 12 below illustrates the number of hours the unit spent in various kW operating ranges during operation only.



**FIGURE 12 PUSD MCKINLEY MIDDLE SCHOOL HOURLY BIN DATA FOR AC AND DC SYSTEM POWER INPUT**

Using the approach outlined in the Analysis section, the system operating SEER, EER<sub>95</sub>, and HSPF were calculated. Table 13 below provides details of the calculated efficiencies and

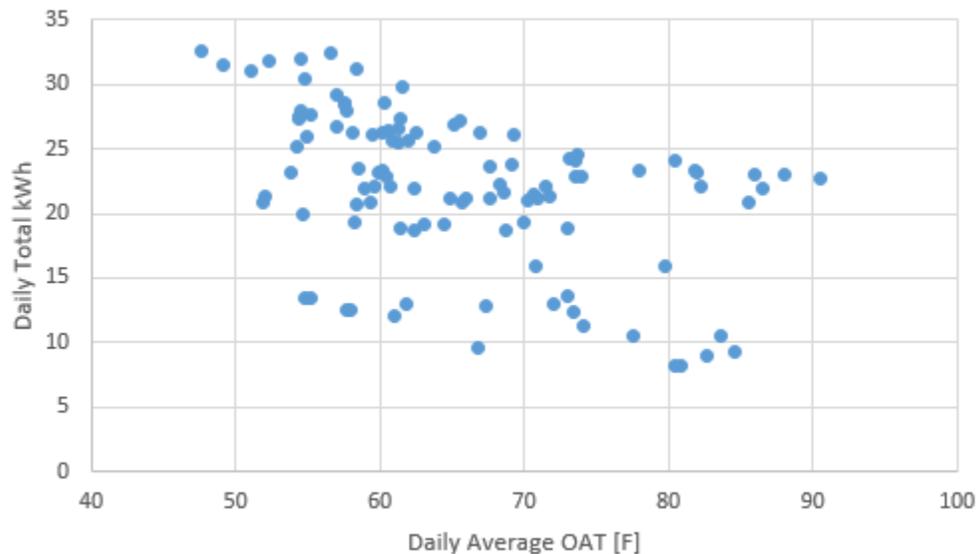
manufacturer's specification efficiencies. As can be seen in the table, the unit at his site is operating at efficiencies greater than manufacturer claimed values.

**TABLE 13 PUSD MCKINLEY MIDDLE SCHOOL CALCULATED SYSTEM EFFICIENCIES**

EFFICIENCY TYPE	CALCULATED EFFICIENCY		SPECIFICATION EFFICIENCY	
	WITH PV	WITHOUT PV	WITH PV	WITHOUT PV
Cooling SEER	10	10	N/A	21
Cooling EER <sub>95</sub>	17	16	N/A	13
Heating HSPF	10	10	N/A	10

## ENERGY AND DEMAND SAVINGS

Over the course of the monitoring period, which spanned 4,545 hours, the unit operated for approximately 3,765 hours for a calculated utilization rate of 83%. To estimate annual energy unit consumption and savings, several regression analyses were performed. Figure 13 shows the total daily consumption of the unit at this site over the course of monitoring period. The figure shows that the unit operated in both cooling and heating mode. The daily consumption of the unit doesn't increase with increasing or decreasing OAT conditions. Additionally, the minute by minute data above showed that the unit operated all the time with large fluctuations in indoor temperatures, which indicates that the unit was undersized for the space.



**FIGURE 13 MCKINLEY MIDDLE SCHOOL DAILY UNIT CONSUMPTION DATA**

Due to lack of relationship between OAT and the unit operation, the annual usage for this unit was estimated with the above calculated utilization rate and average hourly unit consumption. The expected total combined AC and DC energy usage of the unit during the year is 4,810 kWh. The DC power production at this site was very minimal and therefore, it was not feasible to perform a regression analysis to estimate the DC power production based on solar radiation. The estimated savings of 337 kWh was calculated based on the average percent contribution calculated for the entire monitoring period. For a standard AC

power only unit, this additional 337 kWh of energy would have been provided by the utility grid.

The DEER peak demand period is specified as the period from 2:00PM to 5:00PM during the hottest three-day period of the year. Using the bin operating data during the September timeframe, it is estimated that the unit will be drawing on average 1.11 kW from the utility grid and 0.03 kW provided by the solar. Therefore, the demand savings of the solar ACDC12B versus a standard unit is 0.03 kW. A summary of estimated energy and demand savings is summarized in Table 14 below.

**TABLE 14 PUSD EDUCATION CENTER – WEST BUILDING CALCULATED ENERGY AND DEMAND SAVINGS**

<b>SAVINGS METRIC</b>	<b>CALCULATED SAVINGS</b>
Estimated Annual Unit Consumption (kWh)	4,810
Annual Energy Savings (kWh)	337
Peak Demand Savings (kW)	0.03
Estimated Annual Cost Savings (\$)*	\$51

\*Cost savings use an estimated cost per kWh of \$0.15.

## PUSD EDUCATION CENTER - MIDDLE BUILDING DATA AND PROCESSING

The ACDC12B unit serves the lobby area of the Pasadena Unified School District (PUSD) – Education Center Middle Building. During the period from October through March, ten datasets were collected at the site: Heat Pump (HP) AC current draw in amps, AC voltage, AC power factor, AC true power in kW, DC current draw in amps, DC voltage, outside air temperature (OAT), outside air relative humidity, indoor space temperature in degrees Fahrenheit, and indoor space relative humidity. DC current and voltage data were then multiplied to convert to power. During the initial site visit in July 2016, AESC found that the mini-split systems were not drawing any power from solar PV system. Thus, the first few weeks of monitoring included 220VAC power only. Additionally, the analysis excludes trend data obtained from the time when the units were repaired to the time when the DC loggers were installed. Due to circumstances surrounding site specific monitoring equipment installation, complete measurements of both DC and AC draws were not initiated until September 2016.

On November 9, 2016 at approximately 8:35 AM, AESC’s data logging equipment was disconnected to accommodate the installation of a new wall-mounted air conditioning unit near the logging equipment. The interruption of logging was not made known to AESC until December 7, 2016 when the Engineer returned to the site to gather the logged data. Therefore, data was not available for the period from 8:35 AM on November 9, 2016 to 1:56 PM on December 7, 2016.

**TABLE 15 PUSD EDUCATION CENTER – MIDDLE BUILDING OPERATIONAL DATA**

MONTH	HOURS LOGGED [Hrs]	HOURS OF HP OPERATED [Hrs]	SOLAR PV PRODUCED [kWh]	UTILITY SUPPLIED 220VAC POWER [kWh]	PV PRODUCED MAX DEMAND [kW]	UTILITY SUPPLIED MAX DEMAND [kW]
July	106	28	0	33	0.00	1.30
August	348	121	0	123	0.00	1.24
September	394	86	30	69	0.54	1.14
October	744	90	36	35	0.45	0.87
November	202	0	5	0	0.00	0.00
December	586	85	25	20	0.55	1.35
January	744	163	42	56	0.57	1.40
February	672	122	37	52	0.58	1.40
March	120	23	8	4	0.37	0.23
<b>Cumulative</b>	<b>3,917</b>	<b>719</b>	<b>184</b>	<b>393</b>	<b>0.58</b>	<b>1.40</b>

### RAW DATA AND PROCESSING

The figures below illustrate the operation of the unit during the monitoring period in the time lapse of the 220V AC Power (kW), DC Power (kW), OAT (°F), and indoor temperature (°F) for a typical cooling and heating period.

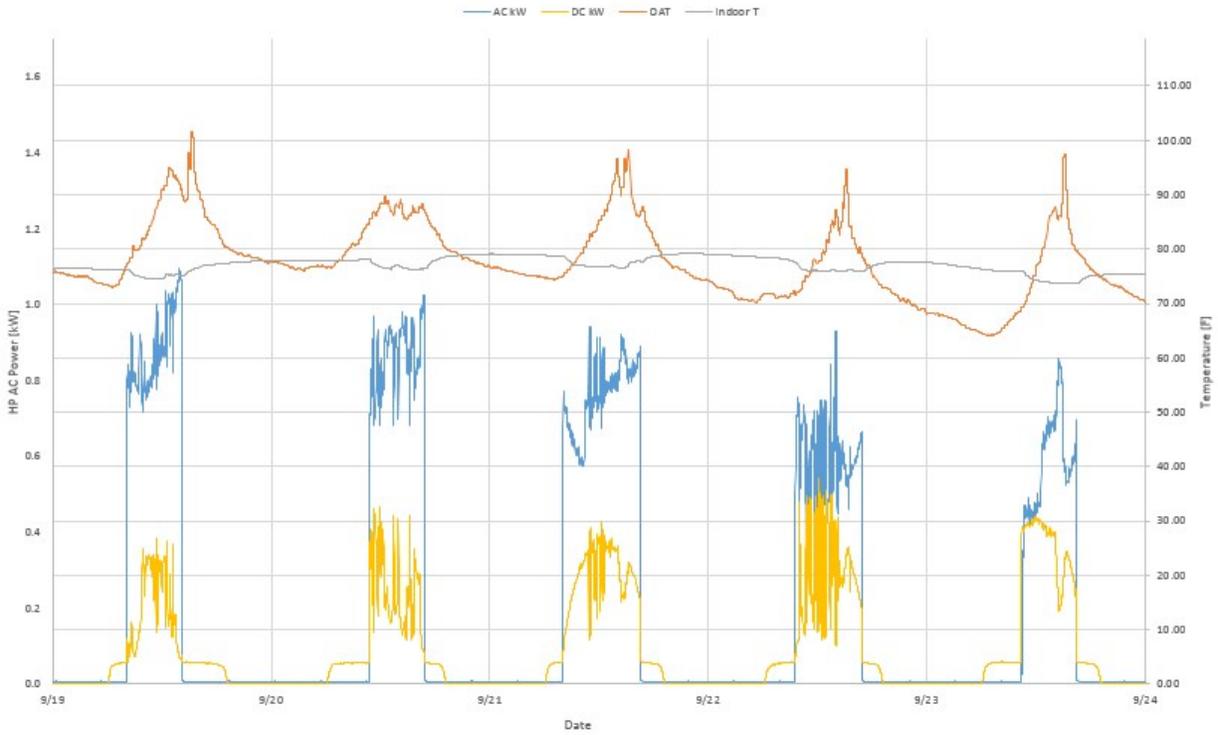


FIGURE 14 PUSD EDUCATION CENTER – MIDDLE BUILDING TYPICAL COOLING PERIOD OPERATING PROFILE

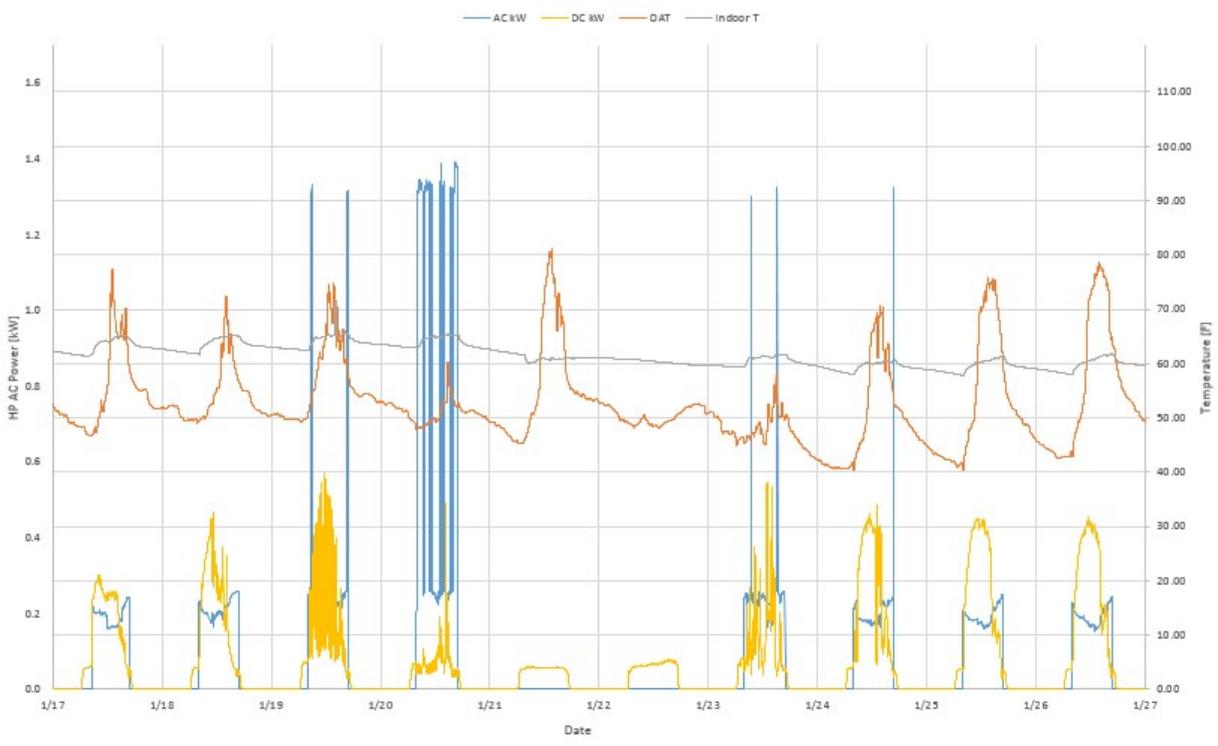
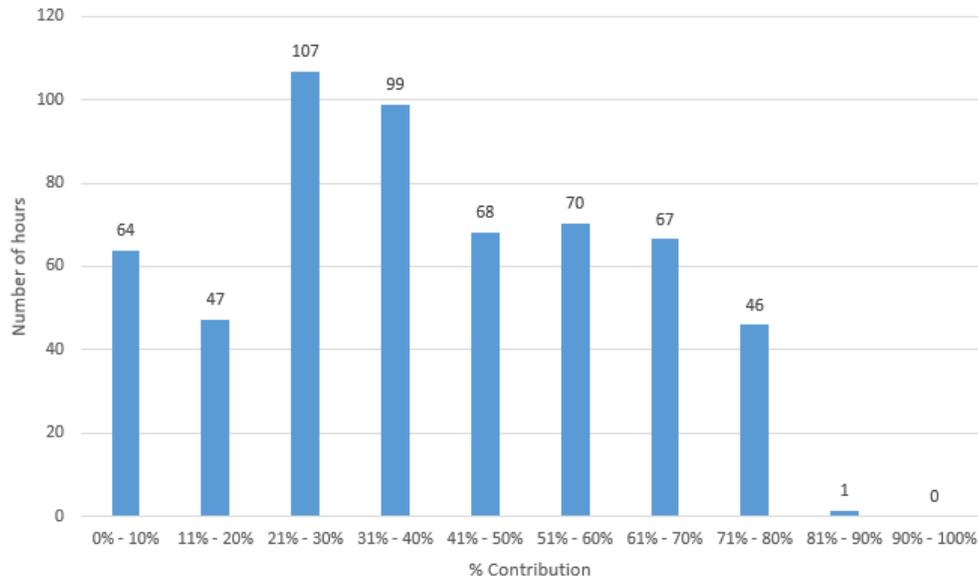


FIGURE 15 PUSD EDUCATION CENTER – MIDDLE BUILDING TYPICAL HEATING PERIOD OPERATING PROFILE

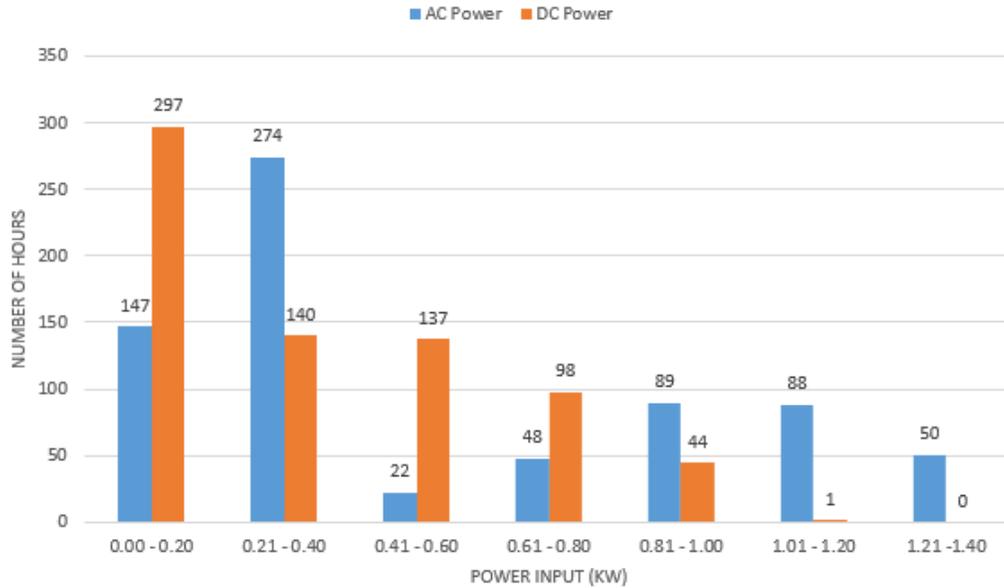
To quantify the impact of the solar PV system on the unit's operation, the solar contribution percentage of the total power input requirement was determined. Figure 16 below illustrates the number of hours the solar PV system offset the energy requirements of the unit during operation. On average, the solar component contributed approximately 38% of the power input to the unit, with a maximum of 84%.



**FIGURE 16 PUSD EDUCATION CENTER – MIDDLE BUILDING SOLAR PV SYSTEM CONTRIBUTION TO TOTAL POWER REQUIREMENTS**

## SYSTEM PERFORMANCE

On average the system drew 0.53 kW from the utility grid and 0.16 kW from the solar PV system, with maximum AC and DC power inputs of 1.40 kW and 0.58 kW, respectively. Figure 17 below illustrates the number of hours the unit spent in various kW operating ranges during operation only.



**FIGURE 17 PUSD EDUCATION CENTER – MIDDLE BUILDING HOURLY BIN DATA FOR AC AND DC SYSTEM POWER INPUT**

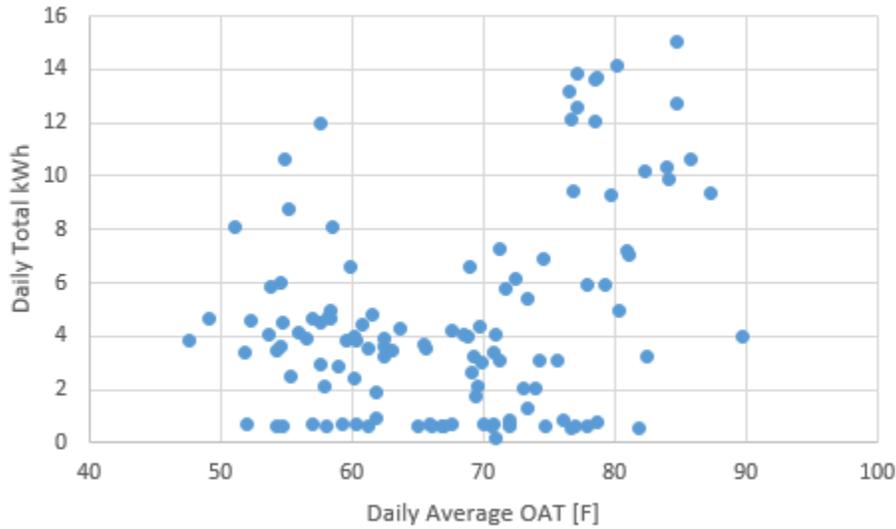
Using the approach outlined in the Analysis section, the system operating SEER, EER<sub>95</sub>, and HSPF were calculated. Table 16 below provides details of the calculated efficiencies and manufacturer’s specification efficiencies. As can be seen in the table, the unit at this site is operating at efficiencies less than that claimed by the manufacturer. Note that there are many unmeasurable variables that could have negatively affected the efficiencies of the unit during the in-field tests, while ARHI tests are done in the lab.

**TABLE 16 PUSD EDUCATION CENTER – MIDDLE BUILDING CALCULATED SYSTEM EFFICIENCIES**

EFFICIENCY TYPE	CALCULATED EFFICIENCY		SPECIFICATION EFFICIENCY	
	WITH PV	WITHOUT PV	WITH PV	WITHOUT PV
Cooling SEER	16	11	N/A	21
Cooling EER <sub>95</sub>	15	10	N/A	13
Heating HSPF	15	9	N/A	10

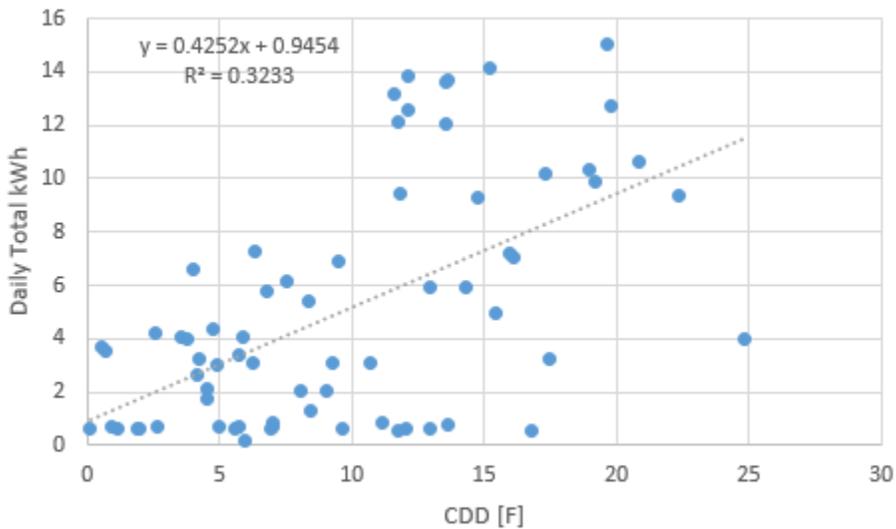
### ENERGY AND DEMAND SAVINGS

Over the course of the monitoring period, which spanned 3,917 hours, the unit operated for approximately 719 hours for a calculated utilization rate of 18%. To estimate annual energy unit consumption and savings, several regression analyses were performed. Figure 18 shows the total daily consumption of the unit at this site over the course of monitoring period. The chart shows that the unit operated in both cooling and heating mode with a balance point temperature of approximately 65°F. As expected, the daily consumption of the unit increased as OAT moved further away from the balance point temperature. Note that the unit didn’t operate during the weekends and therefore, the data below reflects only weekday operations.



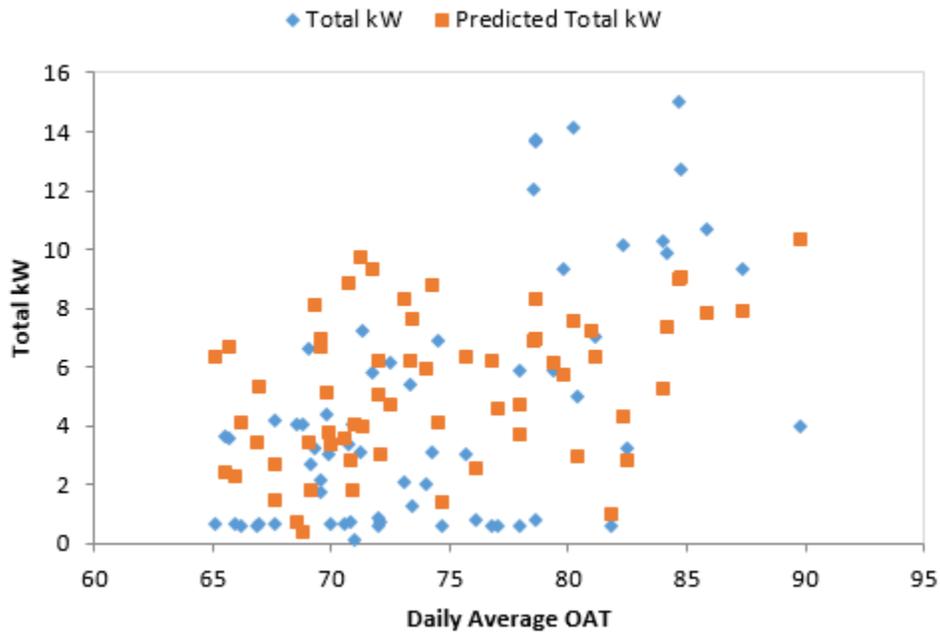
**FIGURE 18 PUSD EDUCATION CENTER – MIDDLE BUILDING DAILY UNIT CONSUMPTION DATA**

To estimate annual energy consumption of the unit in cooling mode, a linear regression model was formed between the calculated cooling degree day (CDD) and the recorded daily total unit energy consumption (kWh). The CDD is calculated as the difference between OAT and the balance point temperature, which in this case was determined as 65°F from the above data. The model revealed that the unit daily consumption didn't show strong correlation to the CDD, with R<sup>2</sup> value of 0.32. Thus, a multivariable regression was run with OAT and OAT<sup>2</sup>, which resulted in acceptable multiple R value of 0.57.



**FIGURE 19 PUSD EDUCATION CENTER – MIDDLE BUILDING DAILY UNIT CONSUMPTION VS. CDD**

<i>Regression Statistics</i>	
Multiple R	0.57
R Square	0.33
Adjusted R Square	0.31
Standard Error	3.72
Observations	69



**FIGURE 20 PUSD EDUCATION CENTER – MULTIVARIABLE REGRESSION ANALYSIS RESULTS**

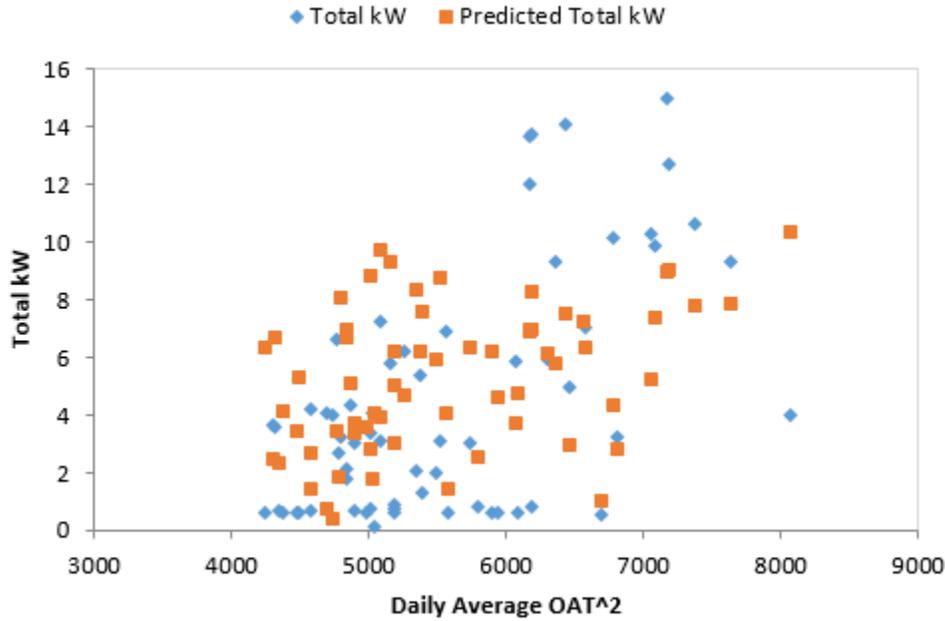
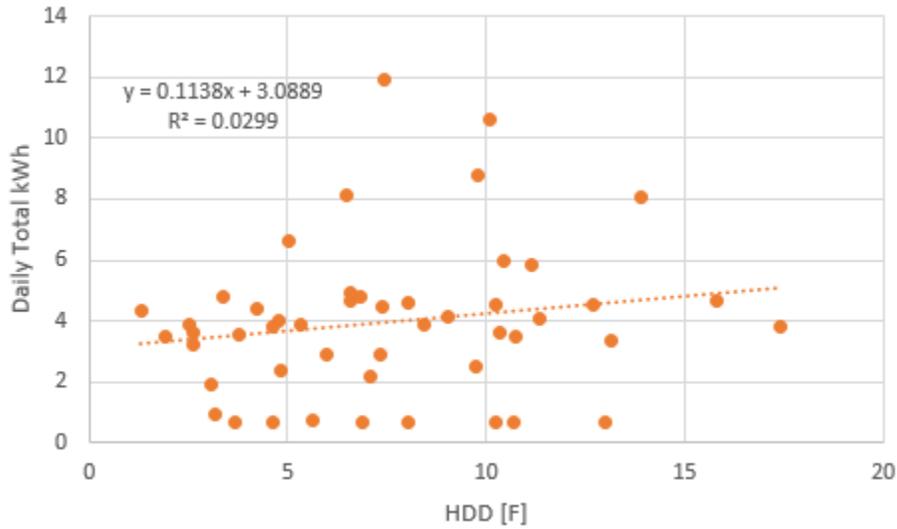


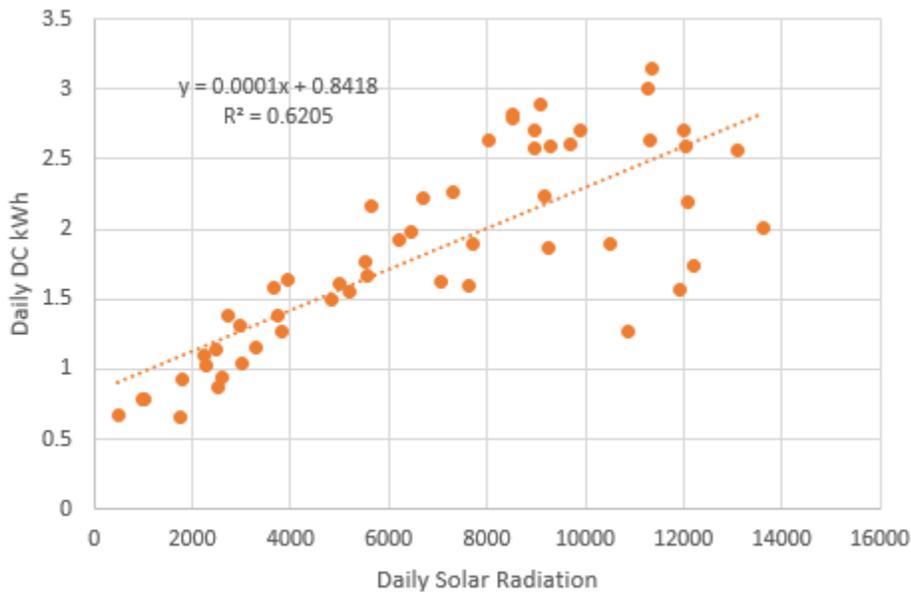
FIGURE 21 PUSD EDUCATION CENTER –AVERAGE DAILY OAT LINE FIT PLOT (MIDDLE), AND OAT<sup>2</sup> LINE FIT PLOT

A similar analysis was performed in heating mode. To estimate annual energy consumption of the unit in cooling mode, a linear regression model was formed between the calculated heating degree day (HDD) and the recorded daily total unit energy consumption (kWh). The HDD is calculated as the difference between the balance point temperature, which in this case was determined as 65°F from the above data and OAT. The model revealed that the unit daily consumption didn't show any correlation to the HDD, with R<sup>2</sup> value of 0.03. Several multi-variable regression analyses were also performed, but failed to achieve usable results. Thus, for the purpose of estimating annual consumption, the unit was assumed to consume a flat rate of 3.9 kWh per day, the average consumption of the unit in heating mode.



**FIGURE 22 PUSD EDUCATION CENTER – MIDDLE BUILDING DAILY UNIT CONSUMPTION VS. HDD**

Next, the measured DC power consumption was plotted against daily and hourly total solar radiation received. The solar data is publicly available from California Department of Water Resource’s California Irrigation Management Information (CIMIS) website. A weather station in Monrovia was selected as it is the closest from the test site. The data showed increasing daily DC power production with increasing daily total solar radiation and resulted in a good correlation with  $R^2$  value of 0.62.



**FIGURE 23 PUSD EDUCATION CENTER – MIDDLE BUILDING DAILY DC POWER PRODUCTION AS FUNCTION OF DAILY SOLAR RADIATION**

Using the above regression models along with the 2016 CIMI hourly weather data, the annual consumption of the unit and energy offset from the DC power production were estimated. The expected total combined AC and DC combined energy usage of the unit

during the year is 1,070 kWh, of which 697 kWh is supplied by the solar PV system in the form of DC power. For a standard AC power only unit, this additional 472 kWh, or 44% of total consumed energy, would have been provided by the utility grid.

The DEER peak demand period is specified as the period from 2:00PM to 5:00PM during the hottest three-day period of the year. Using the bin operating data during the specified timeframe in September, it is estimated that the unit will be drawing on average 0.50 kW from the utility grid and 0.17 kW provided by the solar. Therefore, the ACDC12B saves 0.17 kW over a standard unit. A summary of estimated energy and demand savings is summarized in Table 17 below.

**TABLE 17 PUSD EDUCATION CENTER – MIDDLE BUILDING CALCULATED ENERGY AND DEMAND SAVINGS**

<b>SAVINGS METRIC</b>	<b>CALCULATED SAVINGS</b>
Estimated Annual Unit Consumption (kWh)	1,070
Annual Energy Savings (kWh)	472
Peak Demand Savings (kW)	0.17
Estimated Annual Cost Savings (\$)*	\$105

\*Cost savings use an estimated cost per kWh of \$0.15.

## PUSD EDUCATION CENTER - SOUTH BUILDING DATA AND PROCESSING

The ACDC12B unit serves the third-floor conference room of the Pasadena Unified School District (PUSD) – Education Center South Building. During the period from September through March, ten datasets were collected at the site: Heat Pump (HP) AC current draw in amps, AC voltage, AC power factor, AC true power in kW, DC current draw in amps, DC voltage, outside air temperature (OAT), outside air relative humidity, indoor space temperature in degrees Fahrenheit, and indoor space relative humidity. DC current and voltage data were then multiplied to convert to power. During the initial site visit in July 2016, AESC found that the mini-split systems were not drawing any power from solar PV system. Thus, the first few weeks of monitoring included 220VAC power only. Additionally, the analysis excludes trend data obtained from the time when the units were repaired to the time when the DC loggers were installed. Due to circumstances surrounding site specific monitoring equipment installation, complete measurements of both DC and AC draws were not initiated until September 2016.

**TABLE 18 PUSD EDUCATION CENTER – SOUTH BUILDING OPERATIONAL DATA**

MONTH	HOURS LOGGED [Hrs]	HOURS OF HP OPERATED [Hrs]	SOLAR PV PRODUCED [kWh]	UTILITY SUPPLIED 220VAC POWER [kWh]	PV PRODUCED MAX DEMAND [kW]	UTILITY SUPPLIED MAX DEMAND [kW]
July	109	1	0	6	0.00	1.18
August	348	0	0	16	0.00	0.99
September	396	0	1	2	0.35	0.54
October	744	20	3	12	0.32	0.89
November	721	3	2	5	0.31	0.92
December	744	0	1	3	0.00	0.01
January	744	3	2	6	0.51	1.40
February	672	0	1	3	0.00	0.01
March	120	0	0	1	0.00	0.01
<b>Cumulative</b>	<b>4,597</b>	<b>27</b>	<b>10</b>	<b>54</b>	<b>0.51</b>	<b>1.40</b>

### RAW DATA AND PROCESSING

The figures below illustrate the operation of the unit during the monitoring period in the time lapse of the 220V AC Power (kW), DC Power (kW), OAT (°F), and indoor temperature (°F) for a typical cooling and heating period.

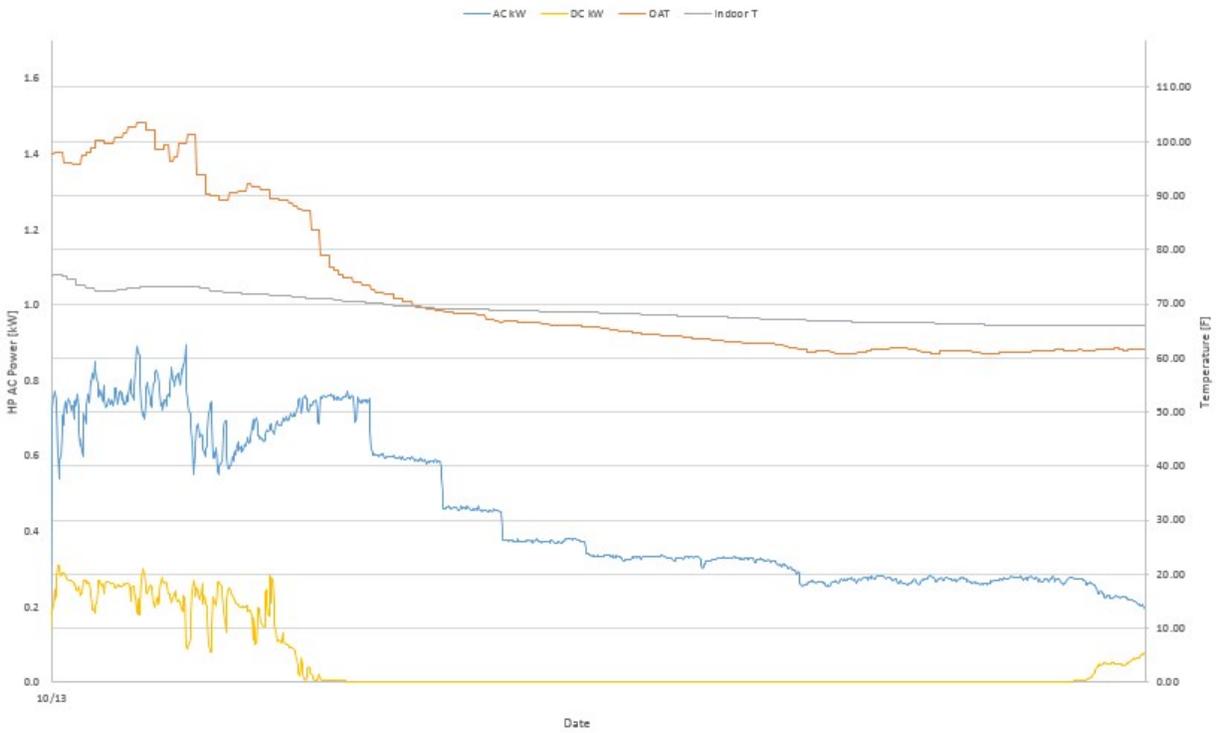


FIGURE 24 PUSD EDUCATION CENTER – SOUTH BUILDING TYPICAL COOLING PERIOD OPERATING PROFILE

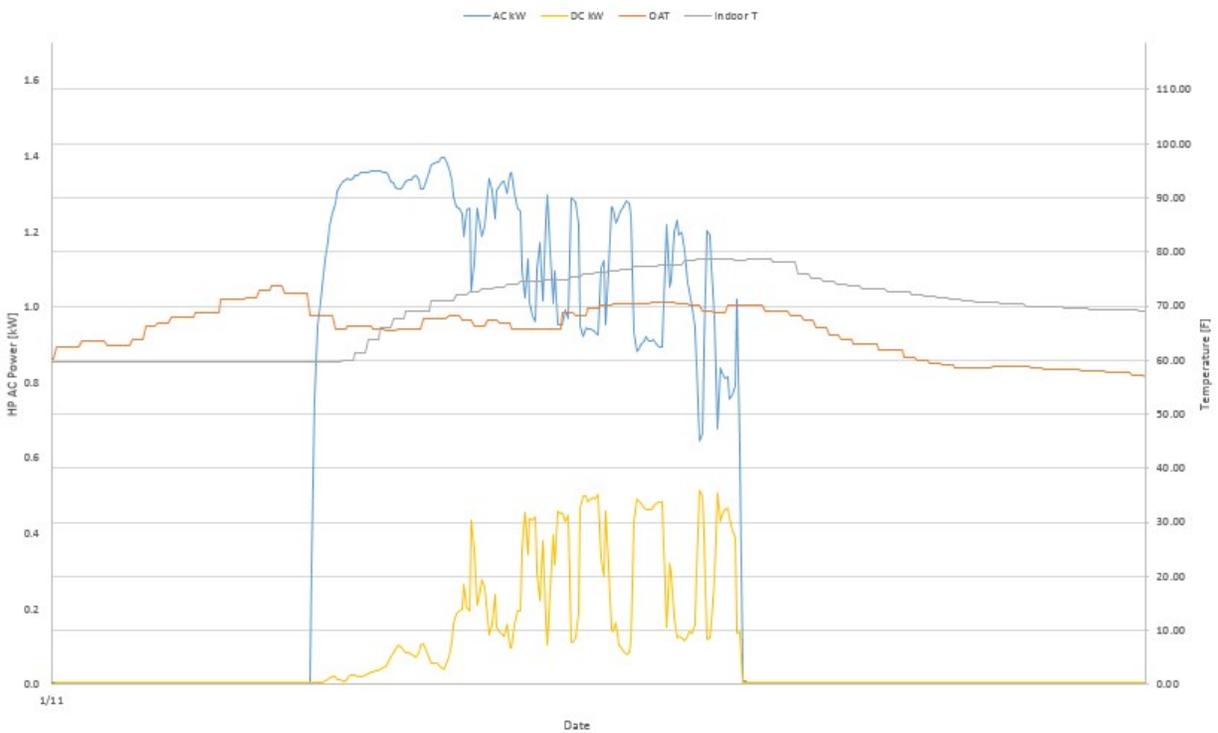
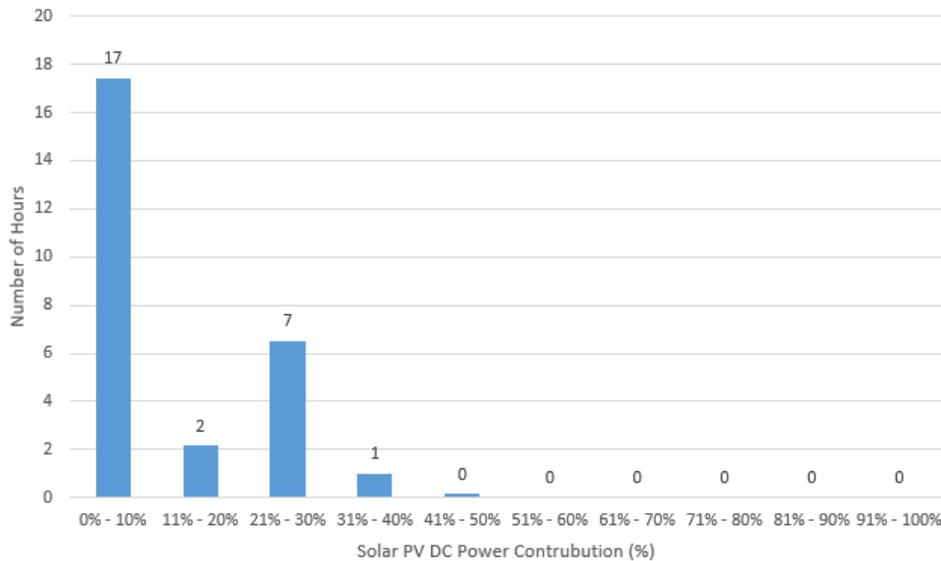


FIGURE 25 PUSD EDUCATION CENTER – SOUTH BUILDING TYPICAL HEATING PERIOD OPERATING PROFILE

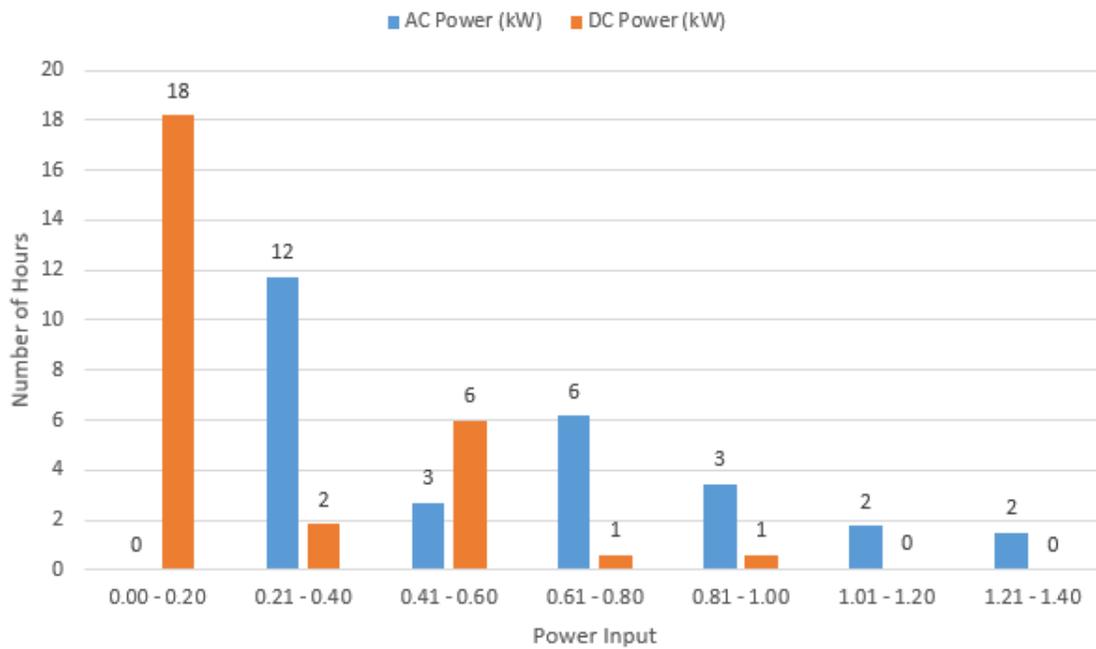
To quantify the impact of the solar PV system on the unit's operation, the solar contribution percentage of the total power input requirement was determined. Figure 26 below illustrates the number of hours the solar PV system offset the energy requirements of the unit during operation. On average, the solar component contributed approximately 9% of the power input to the unit, with a maximum of 61%.



**FIGURE 26 PUSD EDUCATION CENTER – SOUTH BUILDING SOLAR PV SYSTEM CONTRIBUTION TO TOTAL POWER REQUIREMENTS**

## SYSTEM PERFORMANCE

On average the system drew 0.60 kW from the utility grid and 0.09 kW from the solar PV system, with maximum AC and DC power inputs of 1.40 kW and 0.51 kW, respectively. Figure 27 below illustrates the number of hours the unit spent in various kW operating ranges during operation only.



**FIGURE 27 PUSD EDUCATION CENTER – SOUTH BUILDING HOURLY BIN DATA FOR AC AND DC SYSTEM POWER INPUT**

### ENERGY AND DEMAND SAVINGS

Due to the limited amount of operational data obtained from this site, the SEER, EER<sub>95</sub>, and HSPF performance values as well as energy and demand savings could not be accurately determined.

## PUSD EDUCATION CENTER - WEST BUILDING BASELINE DATA AND PROCESSING

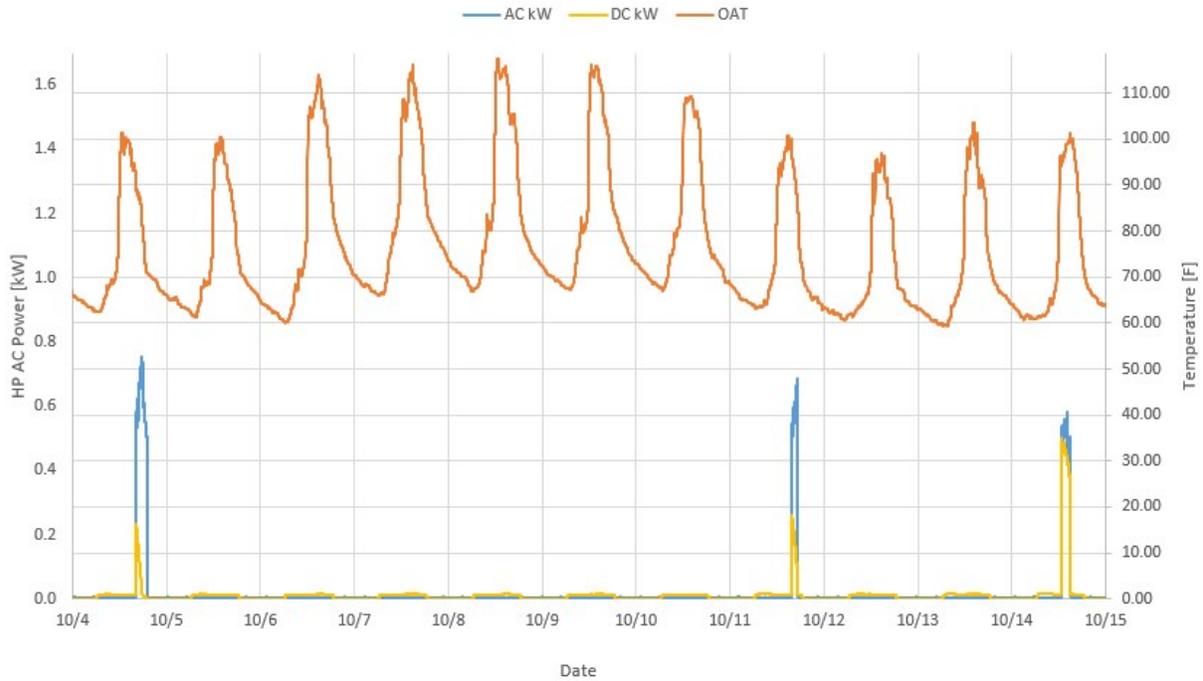
The ACDC12B unit serves the conference room on the second floor of the Pasadena Unified School District (PUSD) – Education Center West Building. During the period from September through March, ten datasets were collected at the site: Heat Pump (HP) AC current draw in amps, AC voltage, AC power factor, AC true power in kW, DC current draw in amps, DC voltage, outside air temperature (OAT), outside air relative humidity, indoor space temperature in degrees Fahrenheit, and indoor space relative humidity. Due to circumstances surrounding site specific monitoring equipment installation, complete measurements of both DC and AC draws were not initiated until September 2016.

**TABLE 19 PUSD EDUCATION CENTER – WEST BUILDING OPERATIONAL DATA**

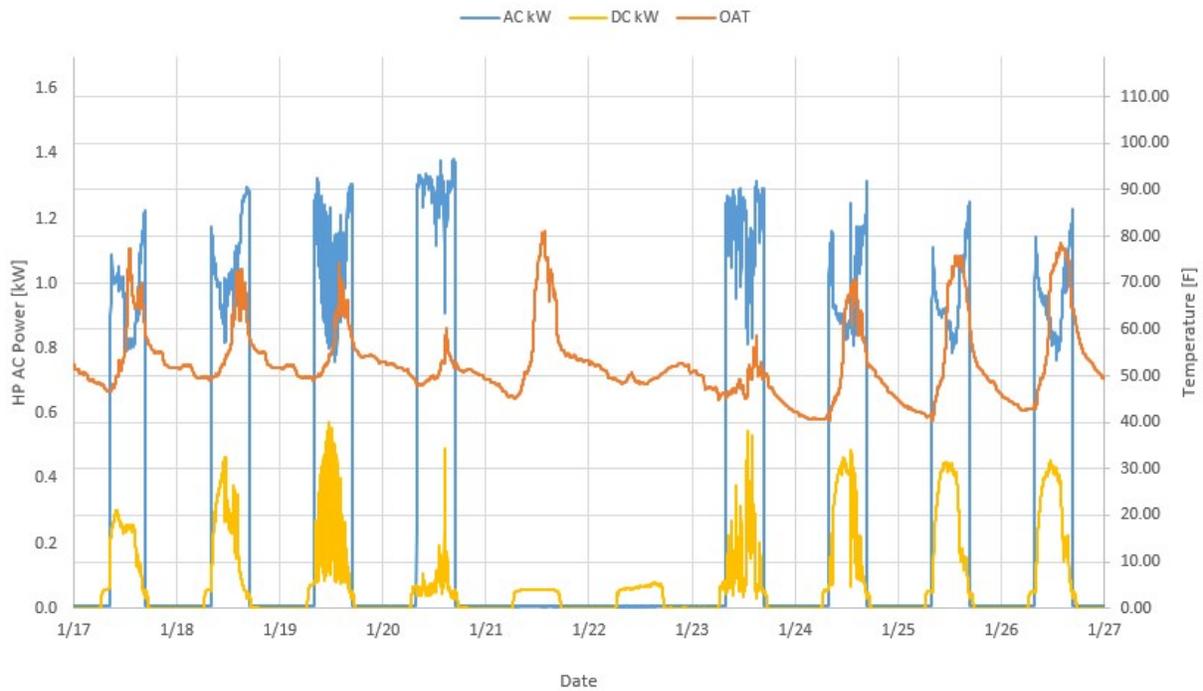
MONTH	HOURS LOGGED [Hrs]	HOURS OF HP OPERATED [Hrs]	SOLAR PV PRODUCED [kWh]	UTILITY SUPPLIED 220VAC POWER [kWh]	PV PRODUCED MAX DEMAND [kW]	UTILITY SUPPLIED MAX DEMAND [kW]
July	0	0	0	0	0.00	0.00
August	0	0	0	0	0.00	0.00
September	394	2	3	4	0.70	1.06
October	744	83	11	16	0.64	1.05
November	721	0	4	3	0.51	0.09
December	744	45	10	42	0.56	1.42
January	744	164	42	181	0.57	1.39
February	672	123	37	136	0.58	1.39
March	120	24	8	20	0.37	1.15
<b>Cumulative</b>	<b>4,138</b>	<b>441</b>	<b>116</b>	<b>402</b>	<b>0.70</b>	<b>1.42</b>

### RAW DATA AND PROCESSING

The figures below illustrate the operation of the unit during the monitoring period in the time lapse of the 220V AC Power (kW), DC Power (kW), OAT (°F), and indoor temperature (°F) for a typical cooling and heating period.



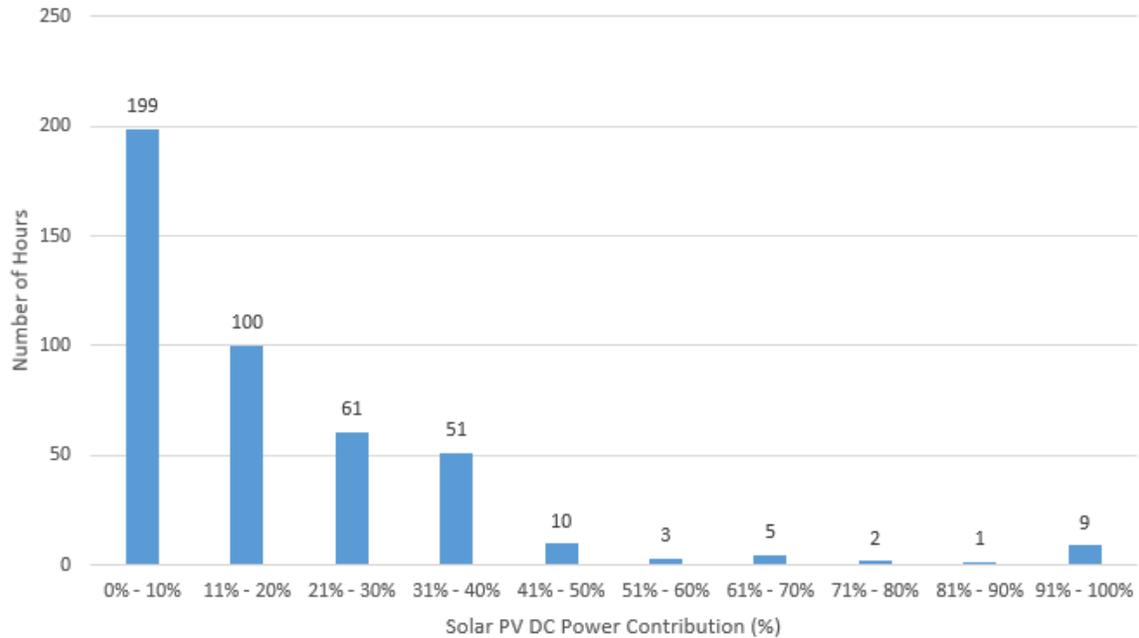
**FIGURE 28 PUSD EDUCATION CENTER – WEST BUILDING TYPICAL COOLING PERIOD OPERATING PROFILE**



**FIGURE 29 PUSD EDUCATION CENTER – WEST BUILDING TYPICAL HEATING PERIOD OPERATING PROFILE**

To quantify the impact of the solar PV system on the unit’s operation, the solar contribution percentage of the total power input requirement was determined. Figure 30 below illustrates the number of hours the solar PV system offset the energy requirements of the unit during

operation. On average, the solar component contributed approximately 17% of the power input to the unit, with a maximum of 99%.



**FIGURE 30 PUSD EDUCATION CENTER – WEST BUILDING SOLAR PV SYSTEM CONTRIBUTION TO TOTAL POWER REQUIREMENTS**

## SYSTEM PERFORMANCE

On average the system drew 0.88 kW from the utility grid and 0.17 kW from the solar PV system, with maximum AC and DC power inputs of 1.42 kW and 0.70 kW, respectively. Figure 31 below illustrates the number of hours the unit spent in various kW operating ranges during operation only.

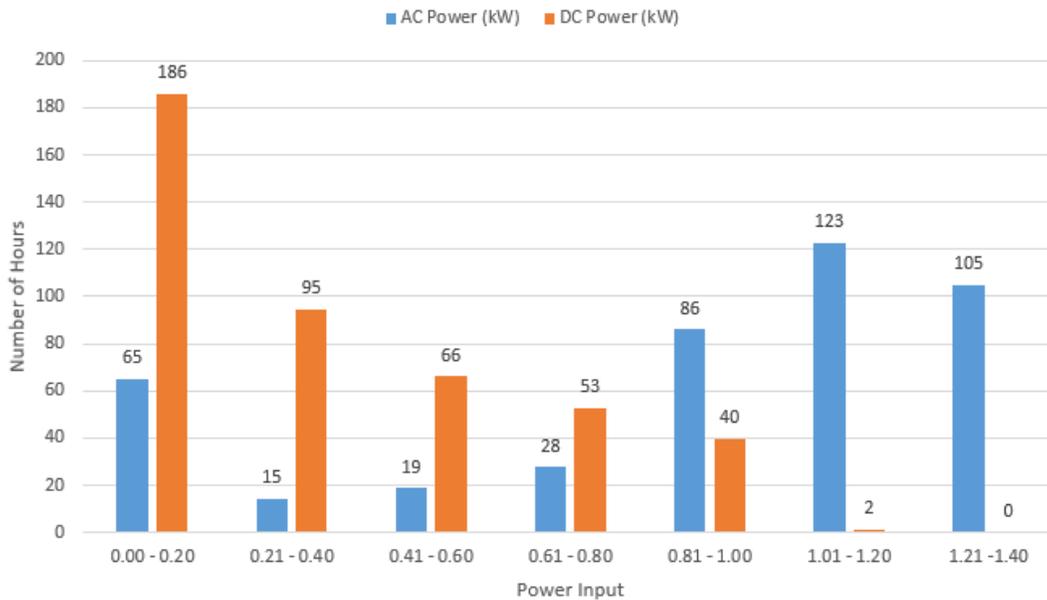


FIGURE 31 PUSD EDUCATION CENTER – WEST BUILDING HOURLY BIN DATA FOR AC AND DC SYSTEM POWER INPUT

Using the approach outlined in the Analysis section, the system operating SEER, EER<sub>95</sub>, and HSPF were calculated. Table 20 below provides details of the calculated efficiencies and manufacturer's specification efficiencies. As can be seen in the table, the unit at this site is operating at comparable efficiencies as claimed by the manufacturer. During the cooling season the unit only operated for a limited 85 hours; therefore, sufficient data was not obtained to accurately depict the seasonal operation efficiency (SEER) for the this site.

TABLE 20 PUSD EDUCATION CENTER – WEST BUILDING CALCULATED SYSTEM EFFICIENCIES

EFFICIENCY TYPE	CALCULATED EFFICIENCY		SPECIFICATION EFFICIENCY	
	WITH PV	WITHOUT PV	WITH PV	WITHOUT PV
Cooling SEER	Insufficient Data		N/A	21
Cooling EER <sub>95</sub>	22	12	N/A	13
Heating HSPF	11	10	N/A	10

## ENERGY AND DEMAND SAVINGS

Over the course of the monitoring period, which spanned 4,138 hours, the unit operated for approximately 441 hours for a calculated utilization rate of 10.7%. The unit serves a conference room that is seldom used and is only operated on an as needed basis. Thus, the consumption of the unit largely depends on when the space is occupied. In fact, the unit only turned on for the total of 85 hours during the entire cooling season. The daily consumption of the unit was plotted against average OAT and shown in Figure 32. The figure shows that unit operated mostly in heating mode when OAT is below 65°F.

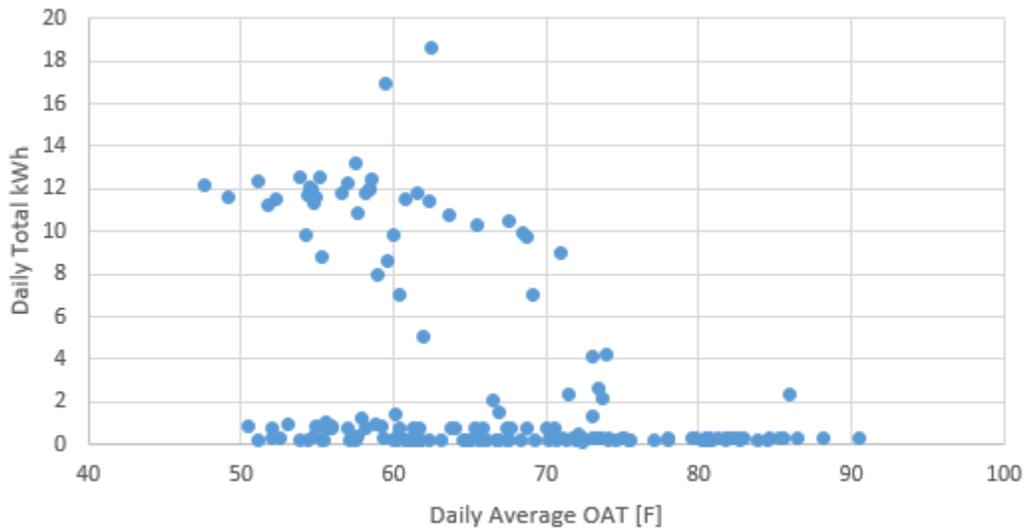


FIGURE 32 PUSD EDUCATION CENTER – WEST BUILDING DAILY UNIT CONSUMPTION DATA

Several unsuccessful attempts were made to predict the heating operation of the unit by the day of week, the hour of day, OAT, and HDD. For example, no correlation was found between HDD and the daily total consumption of the unit during the weekday, as illustrated in Figure 33. The result is expected because the unit does not follow any set schedule and only operated when the space was occupied.

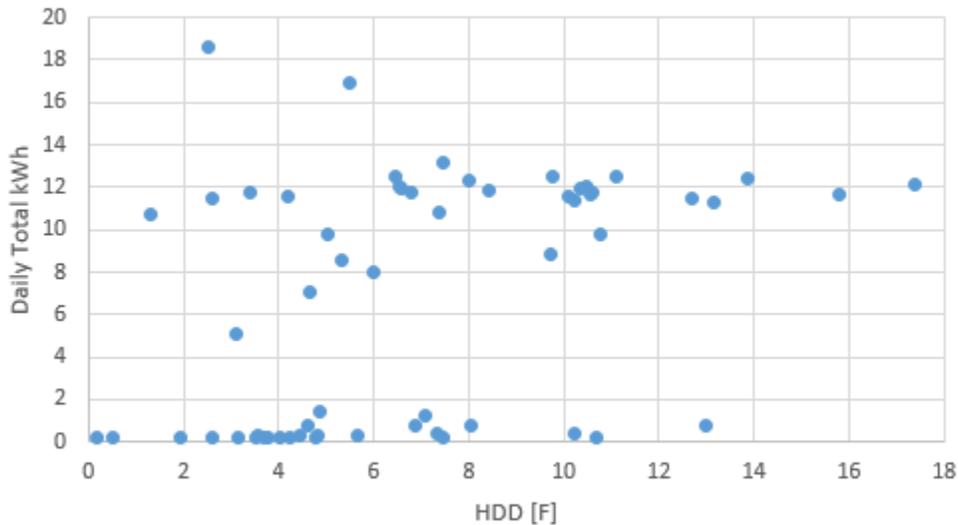
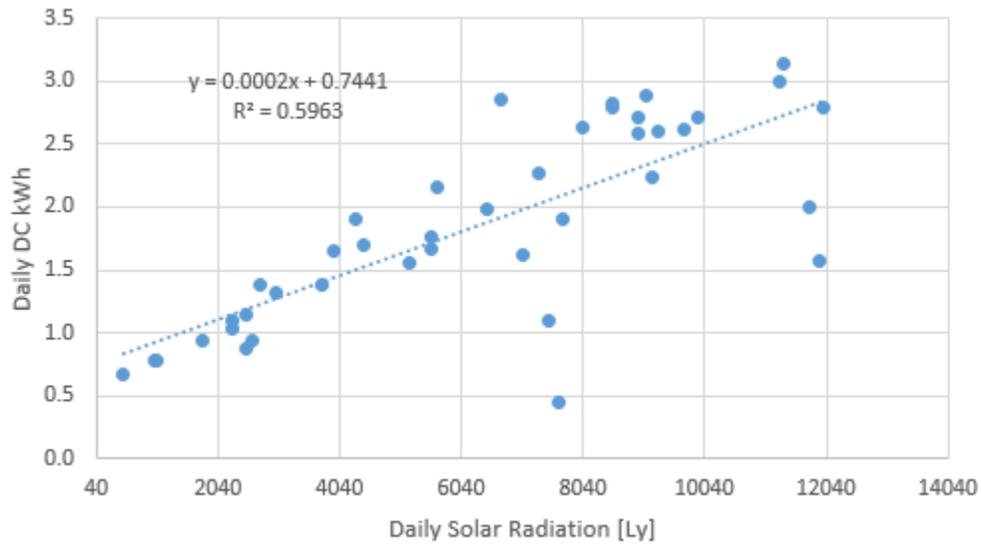


FIGURE 33 PUSD EDUCATION CENTER – WEST BUILDING DAILY UNIT CONSUMPTION VS. HDD

Next, the daily DC power during unit operation was plotted against daily total solar radiation received. The solar data is publicly available from California Department of Water Resource's California Irrigation Management Information (CIMIS) website. A weather station in Monrovia was selected as it is the closest from the test site. The data showed increasing daily DC power production with increasing daily total solar radiation and resulted in a reasonable correlation with  $R^2$  value of 0.60.



**FIGURE 34 PUSD EDUCATION CENTER – WEST BUILDING DAILY DC POWER PRODUCTION AS FUNCTION OF DAILY SOLAR RADIATION**

Due to lack of data during the cooling season and the unpredictable nature of unit operation, which serves a conference room and is turned on as needed, the annual usage for this unit was estimated with the calculated utilization rate of 10.7% and the average daily consumption of the unit during heating mode. The expected total combined AC and DC energy usage of the unit during the year is 790 kWh, assuming the unit only operates in heating mode and that it draws the average of 6.8 kWh of per day.

Using above regression models along with 2016 CIMI hourly weather data, the annual energy offset by the DC power production was estimated. The PV system is expected to supply 266 kWh in the form of DC power. For a standard AC power only unit, this additional 266 kWh, or 34% of total consumed energy, would have been provided by the utility grid.

The DEER peak demand period is specified as the period from 2:00PM to 5:00PM during the hottest three-day period of the year. Using the bin operating data during the specified timeframe, it is estimated that the unit will be drawing on average 0.52 kW from the utility grid and 0.38 kW provided by the solar. Therefore, the demand savings of the solar ACDC12B versus a standard unit is 0.38 kW. A summary of estimated energy and demand savings is summarized in Table 21 below.

**TABLE 21 PUSD EDUCATION CENTER – WEST BUILDING CALCULATED ENERGY AND DEMAND SAVINGS**

SAVINGS METRIC	CALCULATED SAVINGS
Estimated Annual Unit Consumption (kWh)	790
Annual Energy Savings (kWh)	266
Peak Demand Savings (kW)	0.38
Estimated Annual Cost Savings (\$)*	\$119

## DISCUSSION AND CONCLUSION

Of the 21,832 total hours of logged data gathered for the period spanning July 2016 through the beginning of March 2017, the cumulative runtime of all units was 6,141 hours in which a total of 5,128 kWh of AC power was utilized from the grid. Total combined DC Power of 775 kWh was produced by the onsite solar PV systems, which supplemented approximately 13% of the required power input.

The unit operation varied at each site. At the WHP in Colton, the unit operated 24/7. Since the building is poorly insulated and sealed, the unit could not meet the cooling load during the hottest summer days. Additionally, the unit experienced reduced operation in heating mode for the entire heating season, with most of the operation during nighttime hours. The unit installed in PUSD McKinley also operated 24/7. The collected data showed that the unit was undersized for the space and therefore, the space temperature often floated from the setpoint. The DC power production at this site was minimal, indicating that there may have been an issue with its solar PV. At PUSD Middle, the unit provided conditioning to the lobby area and operated mostly during the normal business hours. The unit installed at PUSD South only operated 27 hours during the entire monitoring period because the unit served a conference room that was rarely used. The unit at PUSD West didn't operate much during the cooling season but saw a large increase in utilization during the heating season.

Regression analyses were performed to predict the annual consumption of the units at each site. The results showed that the DC power from the solar could offset as much as 65% of the total annual estimated consumption. Though due to the small size of the unit, energy consumption itself is relatively small, which limits the magnitude of savings. It is expected that percent energy savings become proportionally smaller with longer unit operating hours at night since the DC power production from solar PV is only possible during the day. The percent peak demand reduction averaged 22% for all units. The analysis also concluded that the efficiency of the ACDC12B unit increased with the aid of solar PV, although the degree of improvement varied from site to site.

The field test results showed that calculated EERs were comparable to AHRI specified values, while SEER differed greatly. A few factors were considered for this noticeable difference. For one, EER<sub>95</sub> was evaluated using a narrow band of OAT conditions ( $95 \pm 5^\circ\text{F}$ ). Since the unit was mostly operating at full load at the OAT condition, the load didn't have to be calculated. However, SEER values were evaluated using the data from the entire cooling season. Since the load was not measured, and therefore needed to be estimated from power, the degree of uncertainty increased. Additionally, the cooling season for this study only included data from September through October, which may have skewed the results. Finally, calculated efficiency values are based on field measured data, which included uncontrollable factors such as relative humidity, weather, occupancy and other load variations that lab testing in a controlled environment would not have experienced. As such, when reviewing the performance data, it is more appropriate to consider the calculated EER<sub>95</sub> when comparing to the manufacturer's specification efficiency for the cooling season.

## RECOMMENDATIONS

Although the ACDC12B unit has potential to reduce utility energy use, it appears that site selection and commissioning is essential for the proper operation of the unit. As discussed previously, all units were found to operate without utilizing the DC power in the beginning of study. Additionally, the data revealed that the units installed at the Colton WHP and PUSD McKinley were undersized for the space and the DC power subsidized only 7% of total energy consumed by the PUSD McKinley unit due to poor solar PV production. It is not certain if the system deficiency is due to the unit size issue or the solar panels themselves. However, it is recommended that the unit to be re-commissioned at the PUSD McKinley site. The savings can be maximized if the unit is installed for the space that requires air conditioning during the daylight hours and if the solar PV system is installed in an optimal location to maximize the DC power supply.

The most appropriate program designs are likely rebates or direct installs based on deemed energy savings values. If implemented, the program should require the commission of the unit before rebate payment. Since the available market for this unit is small commercial and residential customers, the potential for success, energy savings, and demand reduction is apparent. Further program development and analysis would be needed to determine which program and customers would be best suited for the technology.

To support the implementation and penetration of this technology, several things could be done including the following items:

- Follow-up study using a pre- and post-installation approach to compare results with the findings here.
- Follow-up study at residential sites, if the program intends to encompass residential market.
- A program design that requires commissioning of the unit before rebate payment.
- The unit utilization should be considered. For instance, the rebate should only be given to those units that meet the minimum daylight operating hours, as set by the program.