MEMORANDUM

To: Massachusetts and Rhode Island Program Administrators

From: COOL SMART Impact Evaluation Team

Subject: Ductless Mini-Split Heat Pump (DMSHP) Draft Cooling Season Results

Date: April 27, 2016

The Massachusetts and Rhode Island Program Administrators (PAs) commissioned Cadmus and its subcontractors, Navigant and Tetra Tech—together, the COOL SMART impact evaluation team—to conduct an *in situ* study of ductless mini-split heat pumps (DMSHPs) in Massachusetts and Rhode Island. The team initially planned to study 132 Massachusetts homes that participated in the COOL SMART Program. However, shortly after, the PAs extended the scope of work by adding 20 Rhode Island homes that had participated in the High Efficiency Heating and Cooling Rebate Program.

The evaluation team selected the sample population from participating customers who had installed DMSHPs in the 2013 or 2014 programs. We conducted site visits beginning in late July of 2014. Prior to the site visits, we fielded a phone and web survey and conducted additional interviews at the site during meter installation.

This memo presents the 2015 summer cooling season consumption and savings analysis of the DMSHP study. A companion memo details the heating season findings, and all results will be presented at length in the final report.[1]

Objectives of Memo and Final Report

The PAs and the evaluation team identified several research questions related to the performance, efficiency, and energy savings resulting from the installation of DMSHPs through Massachusetts' COOL SMART (and through Rhode Island's High Efficiency Heating and Cooling) Program. The questions most pertinent to the cooling season analysis are:

1. How much energy is being saved with an average DMSHP installation?
2. How does the *in situ* performance correlate with DMSHP rated cooling capacity, rated SEER, rated EER, and ambient conditions?

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[1] Cadmus. *Ductless Mini-Split Heat Pump (DMSHP) Final Heating Season Results.* Memo to Massachusetts Program Administrators. October 12, 2015.

3. What are the relevant baseline equipment configurations and associated energy savings?
4. What are the average 8,760 (hourly) DMSHP run times and load shapes for a typical weather year?
5. What are the 8,760 (hourly) DMSHP savings load shapes for each baseline equipment configuration and from these data, the summer peak demand savings?

This memo addresses questions 1-2. The final report will address all research questions. For this study, we directly measured the relevant parameters needed to calculate the cooling output (including airflow and energy used by the system) on upwards of 200 units. With one-minute interval meter data of total cooling delivered and total energy consumption, we determined the seasonal average efficiency for a large portion of the metered units[2]. We also determined average efficiency at every temperature observed during the cooling season to develop efficiency versus temperature curves. The type of analysis performed in this study where performance and efficiency are calculated by directly measuring the output or delivered capacity of each DMSHP, has not been accomplished in any previous field study of greater than 10 units.

The current program is designed to encourage participants who have already made the decision to install a DMSHP to choose a high efficiency system. Savings are based on the assumption that a minimum efficiency DMSHP would have been installed in absence of the program. This memo presents cooling savings for the current program design and includes an algorithm and parameters that PAs can use to estimate forward-looking cooling savings and also shows savings estimates based on 2015 participation.

The final report will include savings for each DMSHP studied with the relevant baseline that we determined from participant surveys and on-site observations. With this information we will estimate impacts for the program in 2013 and 2014. The final report will also include parameters and algorithms so that PAs can estimate savings for any baseline scenario (e.g. DMSHP replacing electric resistance heat and window AC). In addition, the final report will include total seasonal load shapes, heating savings, and summer coincident peak demand savings. From 8,760 load shapes we will have the ability to calculate demand savings for any specified demand period (e.g. 1-5pm summer non-holiday weekdays). Lastly, the final report will include additional observations (See Discussion and Conclusions).

Technical Background

A DMSHP contains an outdoor unit, which rejects heat to the outdoor environment in cooling mode and absorbs heat from the outdoor environment in heating mode. The outdoor unit is attached to one or more indoor units via small refrigerant line sets. A compressor located in the outdoor unit drives the flow of refrigerant and heat through the line sets between the indoor and outdoor units. The indoor head contains a coil that refrigerant passes through, which provides cooling in the summer and heating in the winter by absorbing or rejecting heat. A small fan in the indoor unit assists the heat transfer to

[2] The final report will include all DMSHPs metered. At the start of the analysis process, we did not have data from all units.

and from this coil by moving air over its surface. A large fan in the outdoor unit assists the heat transfer to and from this coil in the same manner.

Figure 1 shows a typical residential-style DMSHP in a composite of four images:

(**A**) Outdoor unit;
(**B**) Indoor wall-mounted head;
(**C**) Indoor ceiling-mounted head or cartridge unit, and;
(**D**) Indoor wall-mounted head with its cover removed to expose the coil and circuit boards.

Figure 1. DMSHP Components

Airflow Delivers Heating and Cooling

Although it can be estimated by metering power draw, the quantity of air flowing through each indoor head is needed to directly calculate the delivered capacity of the DMSHP (i.e., the amount of heat delivered or removed from the conditioned space). For systems with multiple indoor units (i.e., multi-zone), the delivered capacity from each head is summed at each interval of measurement to produce the total delivered capacity for a system (i.e., for each outdoor unit and set of heads). This delivered capacity or transferred heat is determined using Equation 1 and Equation 2.

Equation 1. Heat Transfer Rate Using Mass Flow Rate of Air

$$\dot{Q} = \dot{m} \cdot \Delta h$$

Where:

$\dot{Q} = \ heat\ transfer\ rate\ \left[\frac{Btu}{hr}\right]$

$\dot{m} = mass\ flow\ rate\ of\ air\ \left[\frac{lbm\ of\ dry\ air}{hr}\right]$

$\Delta h = change\ in\ specific\ enthalpy\ of\ airflow\ \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$

Equation 2. Simplified Heat Transfer Rate Using Volumetric Flow Rate of Air

$$\dot{Q} \approx (4.5) \cdot \dot{V}\left[\frac{ft^3}{min}\right] \cdot \Delta h\ \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$$

Where:

$\dot{Q} = \ heat\ transfer\ rate\ \left[\frac{Btu}{hr}\right]$

$(4.5) =$ Unit converstion, from minutes to hours, and from cubic feet of air to pounds of air [3]

$\dot{V} = volumetric\ flow\ rate\ of\ air\ \left[\frac{ft^3}{min}, or\ CFM\right]$

$\Delta h = change\ in\ specific\ enthalpy\ of\ airflow\ \left[\frac{Btu}{lbm\ of\ dry\ air}\right]$

For this study, the evaluation team directly measured the change in enthalpy (Δh) from Equation 2 using temperature and humidity sensors.[4]

Measuring the Cooling Performance of a DMSHP

It is not practical to continuously log airflow at a DMSHP's head in a home and have that unit remain functional. For this reason we collected spot measurements of airflow and used a proxy variable correlated with airflow to log airflow for the study. We considered using (1) fan RPM and (2) the

[3] Air at standard conditions (70°F and 1 atmosphere) is assumed for this conversion factor.

[4] Enthalpy is a measure of the total heat in an airflow. It accounts for heat contained in an amount of dry air and for the heat contained in water vapor in that air. The heat in the water vapor is the amount of heat needed to vaporize that amount of water and the amount of heat needed to heat the water vapor to the dry bulb temperature of the air.

amperage drawn by the fan for a proxy variable. While RPM had been used for a field method on a single unit we found that logging RPM often required disassembling the unit, an action that could void warranties, and could potentially damage the unit. Instead, we used fan current, measured in Amperes, as a proxy variable for airflow. We established relationships for each make and model of indoor head so that we could convert logged fan amperage to airflow over the duration of the study. A companion document contains more detail on this topic.[5]

We measured temperature and humidity at multiple points in the DMSHP inlet and outlet airstream and calculated the cooling provided at one-minute intervals. On the entering face of the DMSHP outdoor unit, we deployed a weather station to capture accurate, local weather data and entering conditions for the DMSHP. We applied national weather service data from nearby stations to check or normalize these on-site weather data.

Finally, we logged total input power to the DMSHP. Our sensors captured the true power demand (including power factor and voltage effects) and energy consumption of each observed DMSHP at one-minute intervals over the logging period. These energy measurements are critical to the calculation of efficiency and can also be used to generate demand curves or load shapes that illustrate the operating profiles of the participant population.

Measurement Methods

Measuring Airflow

For each indoor unit, we used a calibrated flow hood, or balometer, to capture spot measurements of the delivered airflow at each corresponding fan setting. We also used specialized frame kits for each balometer, which modified the geometry of the instrument to better fit a typical DMSHP head. Figure 2 presents an image of a typical flow hood, with the specialized frame kit attached.

[5] Cadmus. *Ductless Mini-Split Heat Pump (DMSHP) Draft Airflow Results.* Memo to Massachusetts Program Administrators. January 8, 2016.

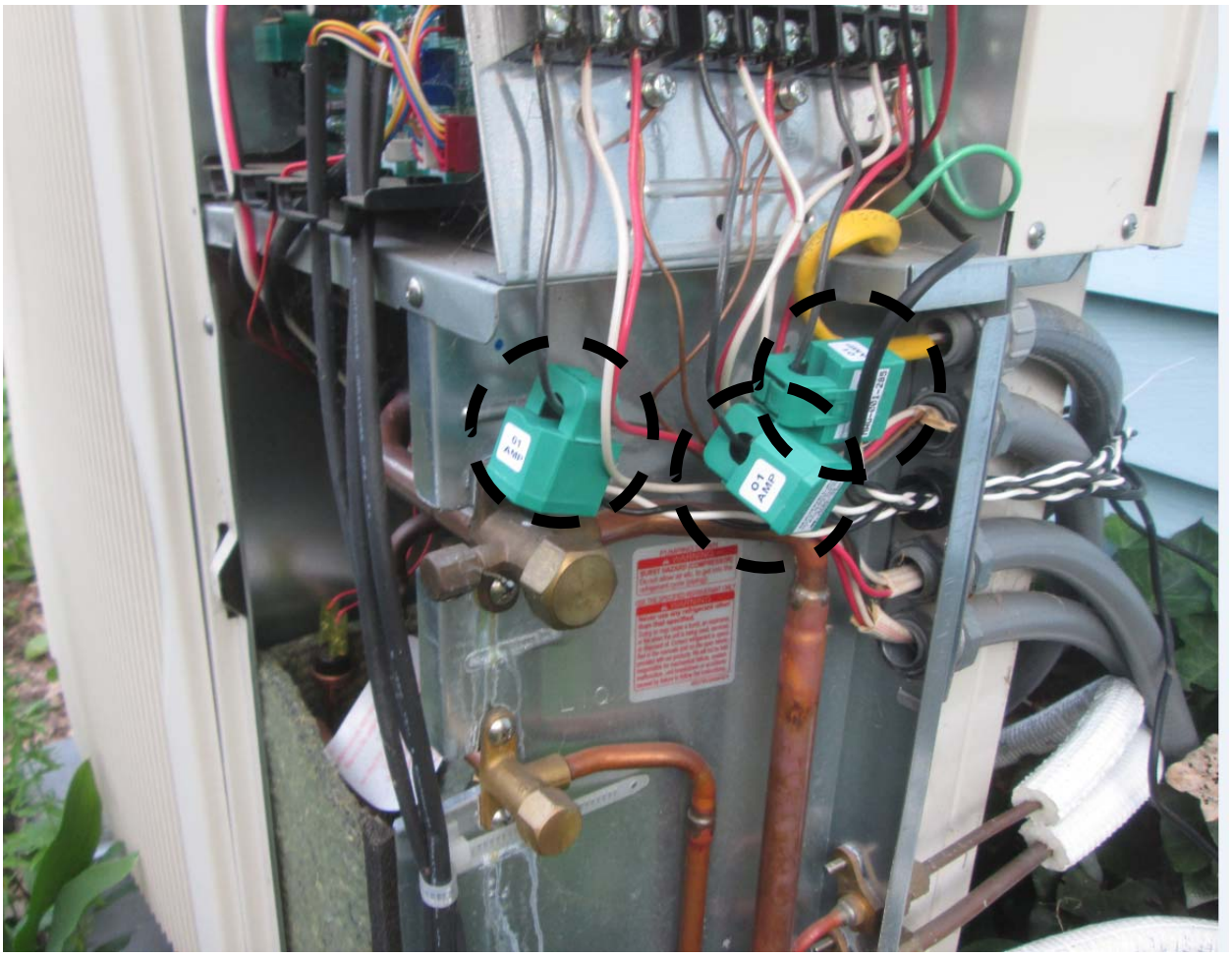
Figure 2. Balometer

We took airflow measurements at each speed setting on the indoor head's controller, collecting readings for one to three minutes depending on the fan current logging frequency. The team designed this procedure to collect a suitable number of current readings for each airflow reading.

Measuring Fan Current

We installed current transducers on the wire powering the indoor head for each unit studied. These current transducers sensed the current draw for the indoor unit at one-minute intervals for the duration of the study. For the airflow spot measurement process, we increased the fan current measurement frequency to a reading every five seconds to increase resolution. We then returned the sampling frequency to one-minute intervals after the spot test. Figure 3 is an example of a current transducer installation for a DMSHP system with three indoor heads.

Figure 3. Three Current Transducers Installed on Fan Wires



Putting Airflow and Current Together

The evaluation team used the airflow and current data to create fan performance curves and to convert the logged indoor unit amperage data into functional airflow values for the entire logged period. Figure 4 presents a graph of logged current plotted against measured airflow, with fan current on the x-axis and airflow on the y-axis. Published airflow ratings from available manufacturer literature are indicated by the horizontal dashed lines. The best fit line is defined by Equation 3.

Equation 3. Airflow as a Function of Fan Current

$$\dot{V} = b(i - c)^a$$

Where:

$\dot{V} = volumetric\ flow\ rate\ of\ air\ \left[\frac{ft^3}{min}, or\ CFM\right]$

$i = fan\ current\ [amps, or\ A]$

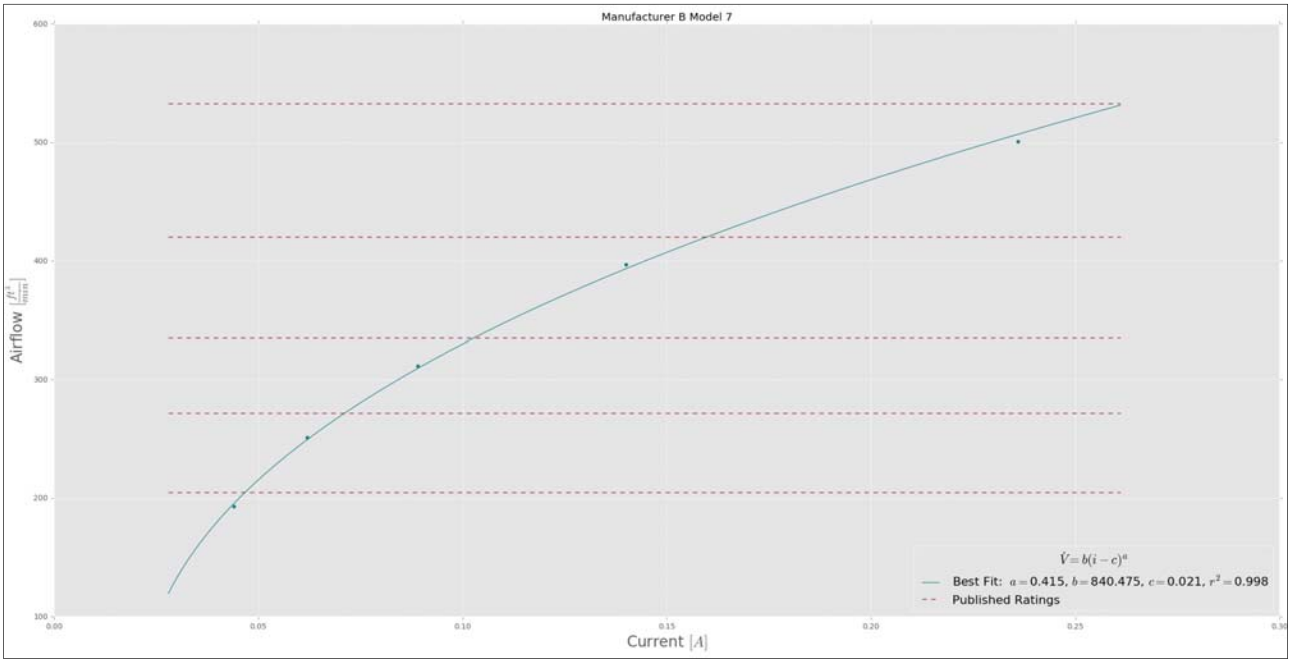
$a = the\ exponent$

$b = a\ constant$

$c = the\ nominal\ current\ draw\ for\ the\ head\ when\ the\ fan\ is\ not\ running$

$r^2 = the\ coefficient\ of\ determination$[6]

Figure 4. Example Airflow Plot



[6] r^2 is known as the coefficient of determination and is a metric used to describe how well a data set fits a given trend line or curve. This value ranges from 0 to 1; a value of 1 indicates a perfect fit of the data to the curve, and a value of 0 represents no fit at all. An r^2 value of 0.9 or higher is generally considered an excellent fit.

Measuring Delta Enthalpy

Equation 1 and Equation 2 above are functions of enthalpy (h) as well as airflow.[7] Enthalpy quantifies the total heat content of a system, and accounts for both sensible and latent heat. The change in enthalpy (Δh) of air passing over a coil (in this case, the indoor unit of the DMSHP) is the difference between the entering and leaving conditions of air.

To collect enthalpy data, our team logged dry-bulb temperature and relative humidity data and used a psychrometric conversion to produce an enthalpy value. We mounted three sensors at the leaving point and one sensor at the entering point of each DMSHP head to measure the change in enthalpy (Δh). We used multiple points of measurement for redundancy and because some models of DMSHP heads exhibit a temperature gradient across the length of the unit. This multi-point logging enabled temperature averaging where needed for certain types of units.

We deployed an indoor ambient temperature and humidity logger to provide some quality control checks on our readings. In some cases, we deployed additional temperature and humidity loggers in areas adjacent to the DMSHP head location to understand the interactions between adjacent rooms as well as to note customer behavior (i.e., the unit is operated with the door open).

Figure 5 illustrates deployment of the sensors used for the leaving conditions. We used similar sensors and loggers to collect entering air conditions, indoor ambient conditions, and outdoor ambient conditions. To meet homeowners' aesthetic concerns, we enclosed the sensor cables in wire channel.

Measuring Total Power

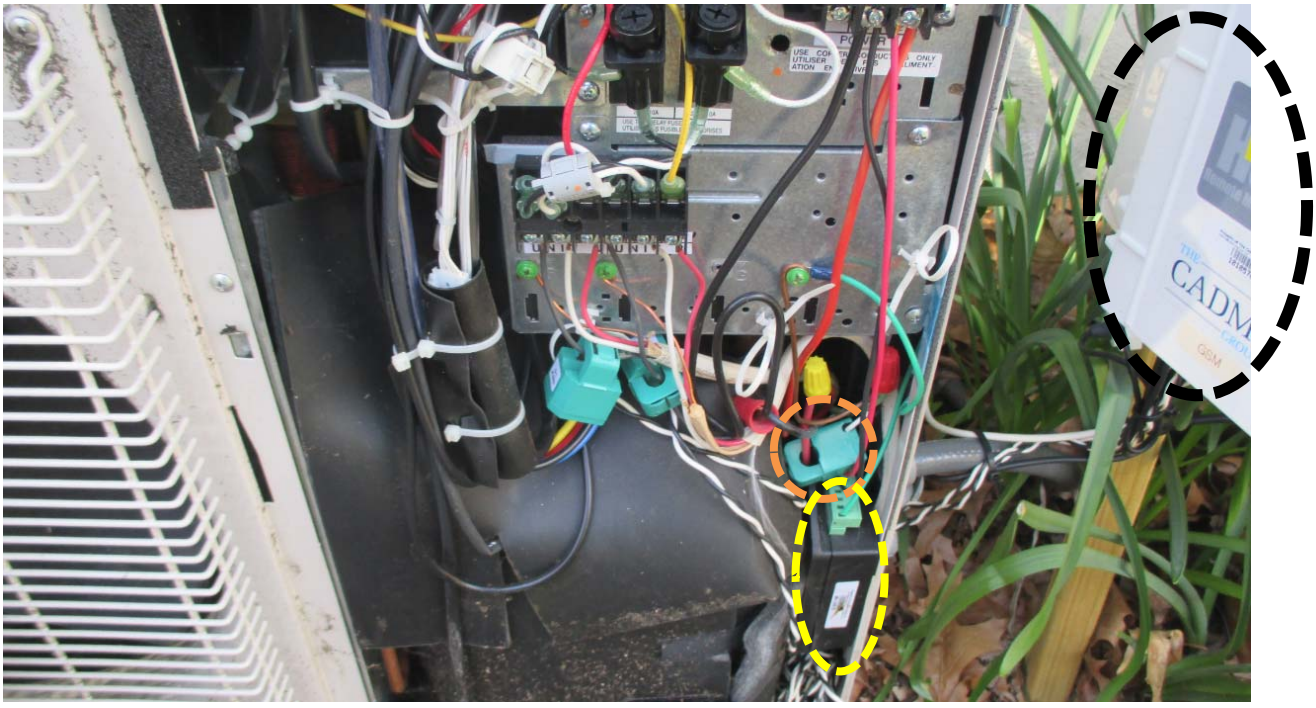
The evaluation team also needed to understand power and energy input to assess DMSHP performance and efficiency. Our team installed Watt-hour transducers on each DMSHP studied. These transducers are sensors with voltage taps and current transducers that convert true energy consumption to pulse waves. An attached logger converts the pulse waves into values and logs the data at regular intervals (in this case, one-minute intervals).

Figure 6 presents a Watt-hour transducer (yellow circle) with connected current transducer (orange circle) and associated logger installed on a DMSHP outdoor unit (black circle).

[7] Enthalpy here, and for the purposes of this memo, is actually specific enthalpy, or the enthalpy per-unit-mass of air. Specific enthalpy is expressed in units of British thermal units (Btu) per pound of air for the U.S. Inch-Pound (IP) system.

Figure 5. Leaving Air Sensors on a DMSHP Head

Figure 6. Logger, Watt-Hour Transducer, and Current Transducers Installed on Outdoor Unit



This equipment captured energy consumption at one minute intervals while also giving an average demand for that period. These demand data were then compared against the delivered capacity data to understand how much power was needed to produce an observed amount of cooling (or heating).

We combined these input power and delivered capacity data with other parameters (outdoor dry-bulb temperature, indoor ambient dry-bulb temperature, etc.) to understand customer operating behavior. For example, we plotted the outdoor conditions against the power and capacity data to understand if a customer used cooling only when it was very hot outside. We compared these data against indoor conditions to understand if the unit is keeping up with the cooling load imposed by the customer. We also identified different modes of unit operation such as "fan-only" or "dehumidification."

Calculating Delivered Cooling, Energy Consumption, and Efficiency

The evaluation team calculated delivered cooling (or heat transferred, Q $[Btu]$) for each minute of the observed period. We also logged the work input (or energy consumption) needed to deliver this cooling. We derived this value from the total logged power of the DMSHP. We then computed an instantaneous energy efficiency ratio (instEER) using Equation 4.

Equation 4. Instantaneous Energy Efficiency Ratio (instEER) for DMSHP in Cooling Mode

$$instEER = \frac{Q_{out}}{W_{in}}$$

Where:

$\mathrm{Q}_{out} = heat\ removed\ from\ space$ [Btu/hr]

$W_{in} = power\ input\ to\ system\ [Watts]$

To calculate electric energy savings, our team needed to compare our findings against baseline system performance. These baseline performances are generally in terms of Seasonal Energy Efficiency Ratio (SEER) or 'rated' EER (i.e., test conditions stipulated by Air-Conditioning, Heating, and Refrigeration Institute, or AHRI); Equation 5 and Equation 6, respectively. Equation 6 is nearly identical to Equation 4 except that it is an instantaneous rating at 95°F outdoor temperature.

Equation 5. Seasonal Energy Efficiency Ratio (SEER)

$$SEER = \frac{Q_{out}}{W_{in}}$$

Where:

$\mathrm{Q}_{out} = heat\ removed\ from\ space$ [Btu] $over\ entire\ cooling\ season$

$W_{in} = power\ input\ to\ system\ [Watts]\ over\ entire\ cooling\ season$

Equation 6. Rated Energy Efficiency Ratio (EER)

$$EER = \frac{Q_{out}}{W_{in}}$$

Where:

$$Q_{out} = heat\ removed\ from\ space\ [\text{Btu/hr}]$$

$$W_{in} = power\ input\ to\ system\ [Watts]$$

DMSHP Cooling Baseline Approach

To determine the performance of a baseline DMSHP unit, our team referenced 2012 International Energy Conservation Code (IECC) for residential,[8] Massachusetts and Rhode Island Amendments to the IECC,[9] and federal residential equipment standards to identify minimum efficiency units.[10] We compared these minimums to manufacturer product catalogs and the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) database.[11] We increased the efficiency of the prospective SEER values for a DMSHP, changing it from the code minimum of 14.0 to a value of SEER 14.5, which better reflects the minimum efficiency currently available in the marketplace. We found several examples of 14.5 SEER DMSHPs that had available performance data[12] and were among the least-cost, lowest-efficiency options available.

Our team used published performance data for the 14.5 DMSHPs and metered data from the study population to develop a temperature-dependent efficiency curve for a baseline DMSHP. We used performance data to develop three instEER versus temperature curves, as depicted in Figure 7. For this baseline system, the manufacturer provided three distinct capacity and power estimates for low, medium, and high compressor speeds. The upper and lower curves in Figure 7 represent the high and low operational range, respectively, of efficiency for this system.

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[8] Effective as of July 1, 2014, in Massachusetts and as of July 1, 2013, in Rhode Island. International Code Council. *2012 International Energy Conservation Code.* July 11, 2012. Available online: http://publicecodes.cyberregs.com/icod/iecc/2012/

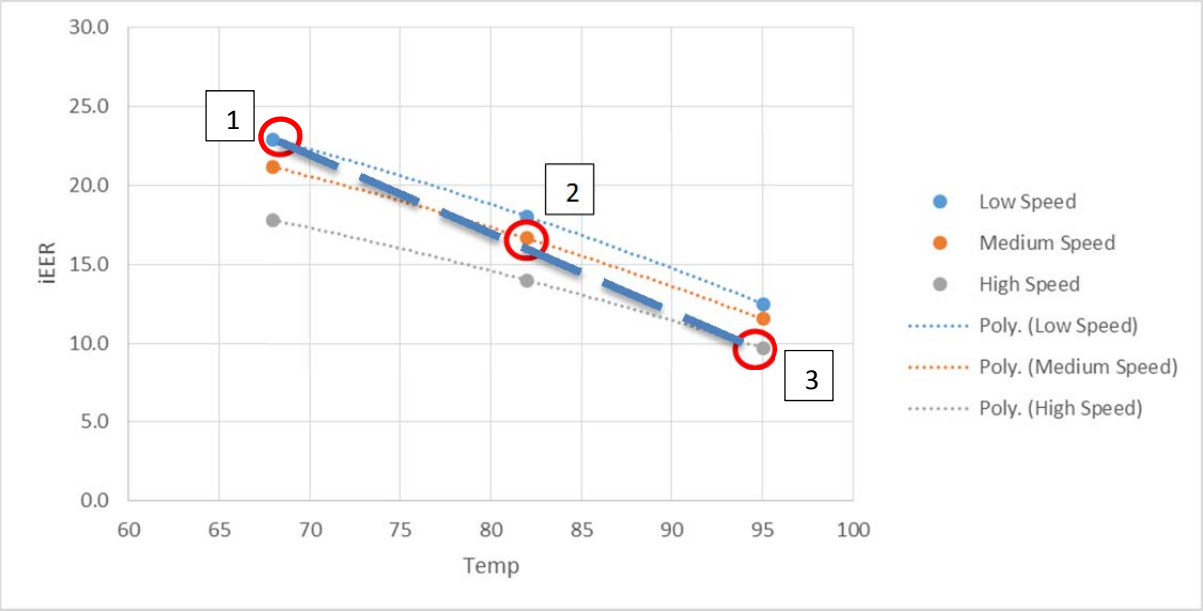
[9] Massachusetts State Board of Building Regulations and Standards. *780 CMR: Massachusetts Amendments to the International Building Code 2009.* August 8, 2010. Available online: http://www.mass.gov/eea/energy-utilities-clean-tech/energy-efficiency/policies-regs-for-ee/building-energy-codes.html. State of Rhode Island and Providence Plantations. *SBC-8 State Energy Conservation Code.* January 1, 2007. Available online: http://sos.ri.gov/documents/archives/regdocs/released/pdf/BCSC/5981.pdf

[10] Both Massachusetts and Rhode Island Technical Reference Manuals (TRMs) reflect these federal minimum values.

[11] Air-Conditioning, Heating, and Refrigeration Institute (AHRI). "Directory of Certified Product Performance." Accessed January 2016: https://www.ahridirectory.org/ahridirectory/pages/home.aspx

[12] Nameplate (AHRI) rated data is insufficient for this analysis. The manufacturers' performance data needed for this analysis shows efficiency as a function of both compressor speed and outdoor temperature.

Figure 7. Estimated Performance Curve for Baseline (14.5 SEER) System



To estimate baseline efficiency at each temperature, we constructed a single polynomial instEER vs. temperature baseline curve from the three points circled in Figure 7. This method presumes a 14.5 SEER system would operate at its:

1. Lowest speed at 70°F outdoor ambient temperature;
2. Medium speed at 80°F outdoor ambient; and
3. Highest speed at 95°F outdoor ambient.

We chose these values because our collected meter data[13] indicated the population of DMSHPs:

1. Operated at 12% of full load kW at 70°F outdoor ambient temperature;
2. Operated at approximately 30% of the full load kW at 80°F outdoor ambient; and
3. Operated at approximately 70% of the full load kW at 95°F outdoor ambient.

We chose the lowest efficiency rating for the baseline system at 95°F, because a baseline unit is more likely to run at high speed because it does not have the advanced control algorithms that most of the higher efficiency units employ.

[13] Many DMSHPs did not run at mild conditions so we looked at 20 systems that operated at the full range of conditions

Savings Calculations

The energy savings algorithm for a DMSHP from the proposed Massachusetts Technical Reference Manual (Planning submission for 2016 to 2018) is modified for cooling only savings and presented below.

Equation 7. Standard Energy Savings Algorithm

$$\Delta kWh_{COOL} = Tons \times \frac{12\ kBtu/hr}{Ton} \times Hours_C \times \left(\frac{1}{SEER_{BASE}} - \frac{1}{SEER_{EE}}\right)$$

Where:

ΔkWh_{COOL} = Reduction in annual kWh cooling consumption of heat pump (HP) equipment

$Tons = capacity\ of\ HP\ equipment$

$SEER_{BASE} = Seasonal\ efficiency\ of\ baseline\ HP\ equipment$

$SEER_{EE} = Seasonal\ efficiency\ of\ new\ HP\ equipment$

$Hours_C = Evuivalent\ Full\ Load\ Hours\ (EFLH) for\ cooling$

Equation 7 uses nameplate information and an equivalent full load hour value to determine savings. Equivalent full load hours is defined in the same TRM by Equation 8.[14]

Equation 8. Standard Equivalent Full Load Hours Algorithm

$$EFLH = \frac{Total\ Seasonal\ Energy\ Consumption\ [kWh]}{Nameplate\ Rated\ Peak\ Demand\ [kW]}$$

To calculate energy use and savings, we chose a detailed bin temperature analysis methodology to estimate cooling savings for each baseline scenario for each temperature observed during the cooling season (Equation 9). The benefits of this approach which uses detailed information from metering, include providing an accurate estimate of efficiency at each temperature, and aligning with techniques used to normalize consumption and savings to typical weather data. At the end of the document we use the results of this detailed analysis to produce an EFLH value that can be inserted into the TRM equation to generate savings.

Equation 9. Modified Energy Savings Algorithm and Weather Normalization

$$\Delta kWh_{COOL} = \sum_{i=T_L}^{T_H} \left(kWh_{METERED} \times \frac{instEER_{EE}}{instEER_{BASE}} - kWh_{METERED}\right) \times \frac{Hours_{TMY}}{Hours_{ACTUAL}}$$

[14] Sourced from current planning Technical Reference Manual for program years 2016-2018, dated October 2015.

Where:

ΔkWh_{COOL} = Reduction in annual kWh cooling consumption of heat pump (HP) equipment

$T_H = Highest\ observed\ outdoor\ drybulb\ temperature\ with\ cooling\ from\ local\ weather\ station$
$T_L = Lowest\ observed\ outdoor\ drybulb\ temperature\ with\ cooling\ from\ local\ weather\ station$

$kWh_{METERED} = logged\ energy\ consumption$

$instEER_{BASE}$
$= Instantaneous\ efficiency\ of\ baseline\ equipment\ (varies\ with\ outdoor\ conditions)$

$instEER_{EE}$
$= Instantaneous\ efficiency\ of\ installed\ equipment\ (varies\ with\ outdoor\ conditions)$

$Hours_{TMY} = Total\ count\ of\ Typical\ Meteorological\ Year\ (TMY)\ hours\ in\ each\ temperature\ bin\ from\ local\ weather\ station$

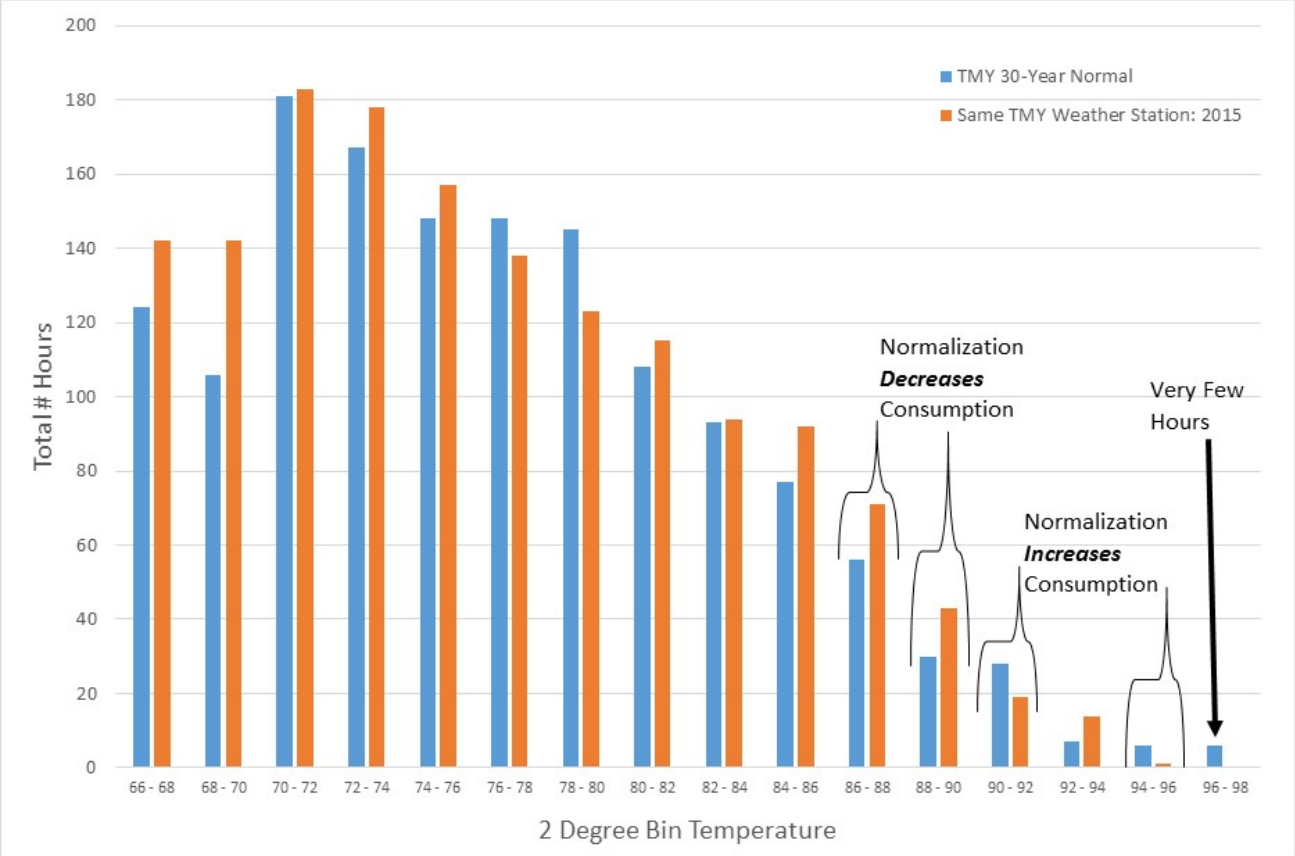
$Hours_{ACTUAL}$
$= Total\ count\ of\ observed\ hours\ in\ each\ temperature\ bin\ from\ local\ weather\ station$

In Equation 9, $instEER_{EE}$ is a function of the metered delivered cooling and metered energy consumption, and is calculated from metered parameters. Our approach assumes that the delivered cooling capacity provided by the baseline system is the same as that provided by the high efficiency DMSHP. The instantaneous efficiency of baseline equipment is based on efficiency curves that are a function of outdoor temperature.

The last term in Equation 9, the ratio of hours observed at each temperature during the metering period to TMY hours, is a weather normalization adjustment factor. This factor normalizes metered data to energy consumption and savings for a typical meteorological 30-year (TMY3). The weather normalization method (Equation 9) estimates kWh only for temperature ranges actually metered.

The 2015 cooling season was similar to TMY3 weather data, except that several weather stations never reached the highest temperatures recorded in the TMY3 datasets. This however has a very minor impact on normalized saving estimates because the MA summer was similar to TMY, the number of hours in the unmetered temperature bin was very small (about 2% of the season). Figure 8 compares the total hours in 2-degree temperature bins for TMY3 data to actual hours observed during the 2015 season for an example weather station: *Norwood Memorial Airport.* This weather station has TMY3 historical data and was one of the most commonly used in our study (it was the closest TMY weather station to 26% of homes studied). According to TMY3 data, temperatures reach 96°F for 6 hours during a typical year. In converting metered savings to TMY savings, the 6 hours are not lost, they occur at slightly lower temperature hours. The impact therefore is a possible small adjustment to roughly 2% of the season's hours – a very small impact.

Figure 8 Comparison of TMY Normal Hours to Actual Hours in 2015 (June – August)



Findings

Efficiency and Consumption during Cooling Season

For 88 single and multi-head systems with an average nameplate SEER of 22.1, we calculated a field-measured SEER of about 19, based on BTU measurements at the indoor head. Multi-head systems delivered a higher field-measured SEER than single-head units, but those same multi-head systems had a higher average nameplate efficiency. Table 1 presents these findings. These values are approximate and may change somewhat in the final report as airflow measurements are again collected at meter removal.

Table 1. Evaluated Performance and Efficiency

System Type	Nameplate SEER	Nameplate Cooling Capacity (Tons)	*In Situ* SEER	Normalized Seasonal Energy Consumption [kWh]	System Count (n =)
Single Head DMSHP systems	21.7	1.2	18	209	67
Multi-Head DMSHP systems	23.2	1.7	21	357	21
Combined	22.1	1.3	19	244	88

Figure 9 shows the distribution of weather-normalized energy consumption for 129 DHPs[15]. Figure 10 shows the distribution of equivalent full load hours, for the same DHPs.

Figure 9 Distribution of DHP Energy Consumption

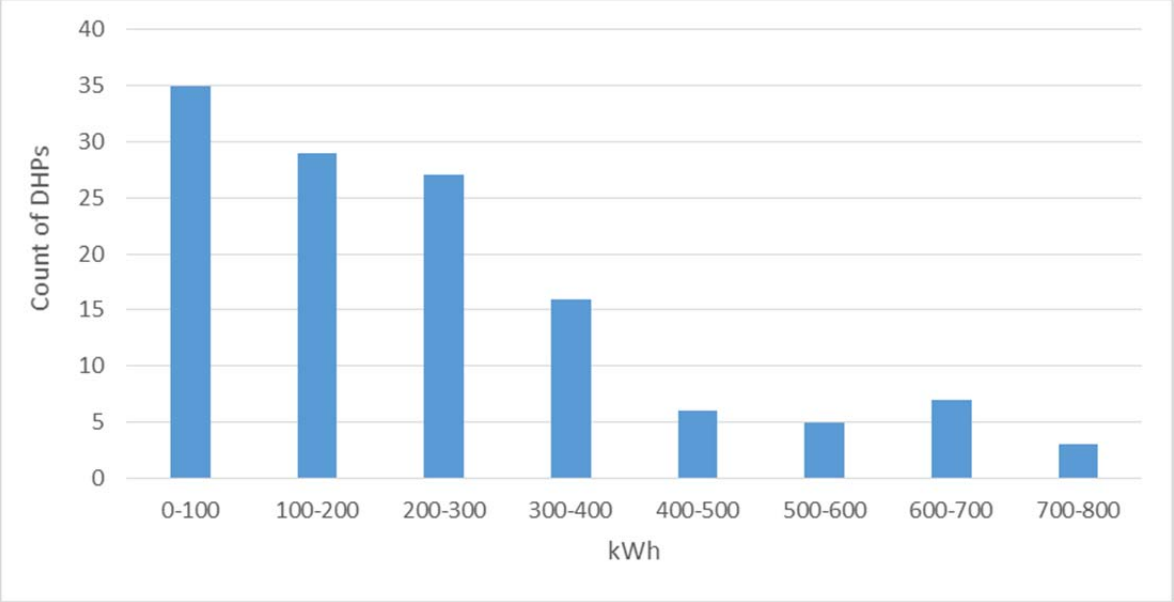
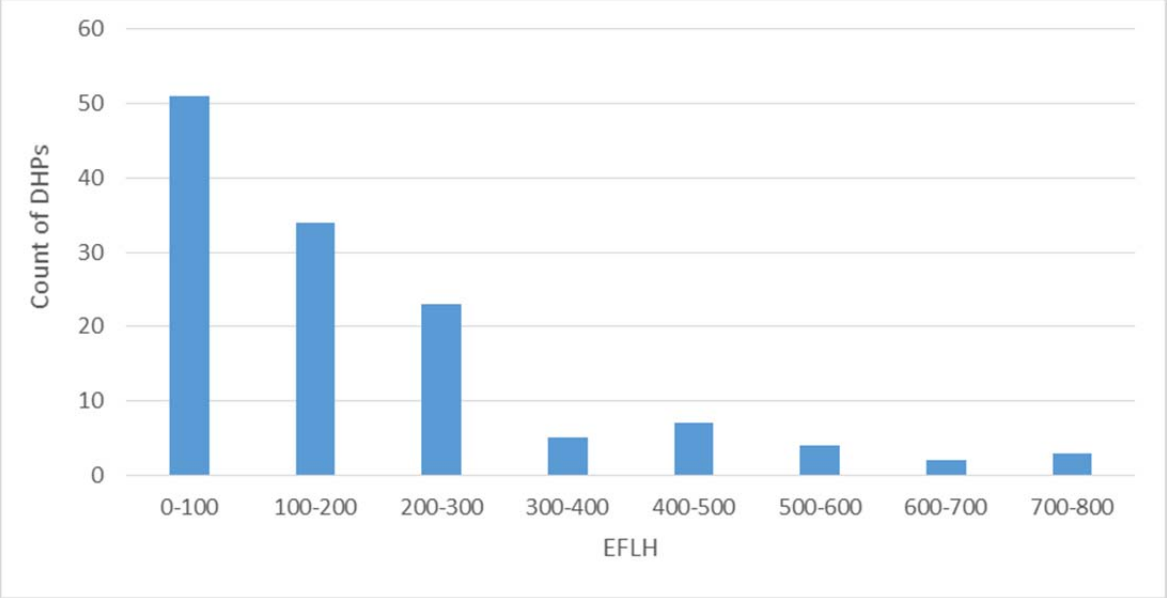


Figure 10 Distribution of DHP Equivalent Full Load Hours



[15] We did not perform a BTU balance of every DHP metered – we metered total power for all DHPs, and a BTU balance on at least one unit per house. Additionally, this sample size does not include all metered participants because some data sets had not received quality control checks at the time Cadmus performed this analysis., they will be included in the final report

Savings during Cooling Season

For 129 single and multi-head systems, we calculated cooling season electric energy savings using Equation 9, evaluating each minute of data collected. The DMSHPs metered in this study averaged 16,050 Btu/h (1.3 tons) and 22.1 SEER nameplate capacity and efficiency respectively. We found that the energy savings for a normal cooling season for these units was **98.6 kWh**. This value is based on an average unit in the study. A larger unit, or one that is more highly used would generate much larger cooling savings.

The average EFLH calculated using the definition of EFLH (Equation 8) was **265 hours**. This value, if plugged into Equation 7 would not yield fully correct savings because the nameplate SEER values are based on a standard performance testing and SEER calculation methodology[16]. Rated SEER values are based on constant indoor conditions and outdoor weather (bin temperature hours) that are different from how DMSHPs actually operate in MA and RI.

Using equation 9 methodology, we determined that on average the DMSHPs in the study saved 98.6 kWh. We then derived an EFLH value of **259 hours** by plugging that savings value into Equation 7. The following algorithm can be used to estimate cooling energy savings for the current DMSHP program:

Equation 10. Recommended Cooling Energy Savings Algorithm

$$\Delta kWh_{COOL} = Tons \times \frac{12\ kBtu/hr}{Ton} \times 259 \times \left(\frac{1}{14.5} - \frac{1}{SEER_{EE}}\right)$$

rather than tons:

Equation 11. Recommended Cooling Energy Savings Algorithm (Btu/h input)

$$\Delta kWh_{COOL} = \frac{Capacity\ Btu/hr}{1{,}000\ kBtu/Btu} \times 259 \times \left(\frac{1}{14.5} - \frac{1}{SEER_{EE}}\right)$$

Discussion and Conclusions

The design and manufacture of DHSHPs is evolving quickly, and much has changed since these units were installed in 2013 and 2014. More makers are offering DMSHPs, including Mitsubishi, Fujitsu, Friedrich, Panasonic, Daikin, Toshiba, and Carrier. Cooling SEERs as high as 33 are advertised, with most makers advertising units approaching SEER 30. These higher SEER systems will likely offer even greater cooling savings than those delivered by the population in this study (which averaged about 22 SEER). Table 2 compares the 2015 statewide program participation to the DMSHPs metered.

[16] ANSI/AHRI Standard 210/240 titled *Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment.* Online: http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/ARI/ARI_Standard_210_240-2006.pdf

Table 2. 2015 Statewide DMSHP Participation and Savings Comparison

Measure Level (Tier)	Total DHP Count	Nameplate Cooling Capacity (Tons)	Nameplate SEER	Average Cooling Energy Savings per DMSHP [kWh]
DMSHP Tier 1 (18 SEER and 9.0 HSPF)	1,298	1.8	19.7	101.8
DMSHP Tier 2 (20 SEER and 11.0 HSPF)	1,718	1.0	25.3	91.5
Combined (2015 Year)	**3,016**	**1.3**	**22.9**	**95.9**
Combined (Metering Study)	**129**	**1.3**	**22.1**	**98.6**

Compared to the metered sample and to previous population averages, the average SEER increased in 2015. Overall savings, however declined slightly because the average Tier 2 DMSHP system size was much smaller than the Tier 1 DMSHPs.

The savings found in this study are generally aligned with the TRM-derived values but are lower because our findings show that the metered DMSHP units operate at fewer full load cooling hours (265 actual hours, 259 hours used for savings) than the deemed TRM value (360 hours). This is not surprising because many users were observed to turn the units on and off for 'on-demand' cooling, rather than using them to consistently maintain a cooler space temperature. Figure 10 shows a relatively wide distribution of equivalent full load run hours for DMSHPs metered in Massachusetts and Rhode Island. Though the weather differences between MA and RI likely result in runtime differences, the variability due to other factors (e.g. user operation) is much higher. For this reason we have not segregated the sample. The final report will include state-specific results if we find statistically significant differences in runtime after normalizing by population-weighted weather data.

The final report will include analytical observations of statistical significance which may help decision makers further refine program design and marketing. Examples of helpful observations include variance in DMSHP usage due to installation location (room type) or differences in DMSHP usage for participants who have different motivations to install (e.g. purchased primarily for heating, purchased primarily for cooling).