CalNEXT
ENERGIZING CALIFORNIA'S FUTURE

Water-Cooled Chillers Market Assessment and Performance Evaluation

Final Report

ET23SWE0025

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December 4, 2023

Acknowledgements

The project team is grateful to all water chiller manufacturers and distributors who spent a considerable amount of time discussing program design issues and providing equipment data in support of this project.

Executive Summary

This report addresses the shortcomings of the current Water-Cooled Chiller (WCC) measure package (SWHC005) in the California Technical Forum (Cal TF) Electronic Technical Reference Manual (eTRM), where WCC Tiers of California Public Utilities Commission (CPUC)'s Database for Energy-Efficiency Resources (DEER) do not match market conditions. The Tier 1 full-load efficiency (FLE, measured in kW/ton) of (10%/10%) requirement contrasts with the Tier 2 part-load efficiency (PLE) requirement of (15%/15%). WCCs modeled in DEER are based on the same performance curves. This project aims to add more granularity to the performance maps so that part-load performance is better correlated to the unit Integrated Part-Load Value (IPLV) ratings for systems with variable speed compressors.

While a reasonable percentage of equipment can meet CPUC DEER Tier 1 (10%/10%) above Title 24, it is very rare for equipment to meet DEER Tier 2 (15%/15%) efficiency levels. Full-load efficiency (FLE) and part-load efficiency (PLE) improvements should at the very least be "decoupled" or even better – change in an "inverse" relationship, meaning that as PLE requirements increase from Tier 1 to Tier 2, FLE requirements could decrease slightly. Therefore, having accurate technical performance in the existing measure is crucial to seeing any energy savings in this measure. WCCs modeled i n DEER are based on the same performance curves. However, this project aims to add more granularity to the performance maps so that part-load performance is better correlated to the unit Integrated Part-Load Value (IPLV) ratings for systems with variable speed compressors.

This effort was started in 2019 and data was presented to the CPUC, resulting in the less restrictive full-load efficiency (FLE) requirements in Section D3 of CPUC Resolution E-5152 of the DEER in 2023. Nevertheless, these recent policies have not yet been integrated into the eTRM.

Between 2019 and 2023, two major trends emerged within the product category of WCCs:

1. Upcoming California Air Resources Board (CARB) and Environmental Protection Agency (EPA) regulations requiring low-GWP refrigerants.
2. The emergence of waste heat recovery chillers (HRC) to offset or replace natural gas boiler usage. The 2019 vintage dataset was collected mainly for high-GWP refrigerant equipment and didn't include any data for heat recovery chillers.

The ultimate goal of this initiative is to update the eTRM with new high-IPLV offerings for cooling-only WCCs within SWHC005 and to develop a new measure package for HRCs[1] (This requires a separate measure package due to the assumption that an HRC measure package would be a Fuel Substitution). However, 2023 is not an appropriate year to undertake such a time-intensive effort because the modeling engine is in the process of being moved from DOE-2 to EnergyPlus. The current effort of this report is expected to be completed by December 2023.

Because of this reality, this project was scoped to achieve the following specific tasks in the interim so that the goal of achieving updates to measure package SWHC005 and writing and submitting a

[1] This requires a separate measure package due to the assumption that an HRC measure package would be a Fuel Substitution.

new HRC measure package could be achieved in 2024. This project's objectives and achievements are described below.

1. Investigate whether the WCC data works with the Low-Global Warming Potential (GWP) refrigerants by working with manufacturers.
    a. This objective was achieved by modeling the low GWP refrigerant (R1233zd) data in EnergyPlus.
2. Collect performance maps for HRCs this year from manufacturers and/or distributors.
    a. This objective was achieved by collecting performance maps of three HRCs and providing modeling performance using EnergyPlus.
3. Ascertain that the previously collected technical performance 2019 WCC data can be modeled in EnergyPlus.
    a. This objective was achieved by modeling the data of R1233zd data that was collected in 2019.
4. Write the measure package plans this year for CPUC consideration and feedback for potential execution in 2024:
    a. Updating current measure package for WCC measure package SWHC005.
    b. New measure package plan for HRCs.
    c. Both the above measure packages are submitted separately with the report.

This report documents the background research, and analysis of the data collected from manufacturers and distributors and presents information that fulfills all the above objectives.

Technical Limitations and Future Considerations

The project team contacted six distributors to collect performance maps of WCCs and HRCs using low GWP refrigerants and was able to collect one map for WCC and three maps for HRCs with low GWP refrigerants. Unfortunately, the data availability was limited because distributors don't yet have access to the software for low GWP refrigerants.

Further literature review revealed that there is a drop in capacity and/or efficiency in various retrofit systems using new low-GWP refrigerants. The project team expects that all such issues will be addressed fully by the manufacturers before a new product is launched onto the market. We would inevitably use performance maps for chillers that employ various low GWP refrigerants as long as the efficiency performance is equivalent to earlier systems.

Currently, EnergyPlus contains two models for HRCs but both use water-cooled condensers, while the data that manufacturers supplied us on dedicated HRCs use air-cooled condensers. Therefore, there is a gap between the EnergyPlus existing models and the available manufacturer data. This technical discrepancy is outside the scope of this project and may be addressed in collaboration with Lawrence Berkeley National Laboratory in the future.

Abbreviations and Acronyms

Acronym	Meaning
CARB	California Air Resources Board
CPUC	California Public Utilities Commission
CET	Cost-Effectiveness Tool
CSD	Constant Speed Drive
DEER	Database for Energy-Efficiency Resources
ECWT	Entering condenser water temperature
eTRM	Electronic Technical Reference Manual
FLE	Full Load Efficiency
EPA	Environmental Protection Agency
EUL	Effective Useful Life
HRC	Heat-Recovery Chiller
IPLV	Integrated Part Load Value
LChWT	Leaving chilled water temperature
LEWT	Leaving evaporator water temperature
PLE	Pat Load Efficiency
PLR	Part Load Ratio
VSD	Variable Speed Drive
WCC	Water-Cooled Chillers
IOU	Investor-Owned Utilities

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Introduction

The current measure package for water-cooled chillers (WCC) has several shortcomings that have been identified, most notably an unrealistic Tier 1 full-load efficiency (FLE, in kW/ton) requirement of (10%/10%) to go along with the Tier 2 part-load efficiency (PLE) requirement of (15%/15%). Current WCC measures are restrictive requiring 10 percent above-code efficiency for both full and part-load ratings, while most equipment is optimized for one or the other metric. Therefore, having accurate technical performance in the existing measure is crucial to seeing any energy savings in this measure. This issue was studied in-depth by Southern California Edison (SCE) and Energy Solutions in 2019 and 2020, culminating in collecting 25 detailed WCC performance maps and efficiency rating pairings (i.e., FLE and PLE scores) for dozens of additional chillers to show where the market is regarding WCC efficiency trends.

The current Database for Energy Efficient Resources (DEER) tiers, California Public Utilities Commission (CPUC) Energy Department proposed update, and latest SCE proposal is shown on the 'WCC Heat Map' below in Figure 1. This heat map delineates measure tiers, where:

- Boxes outlined in black are the current DEER2017 WCC tiers.
- Boxes outlined in green are the DEER2023 E-5152 WCC tiers.

WCC Path B	FLE – Full-load efficiency improvement over Title 24										
PLE – Part-load efficiency improvement over Title 24	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
5%	50%	44%	37%	32%	29%	22%	18%	12%	7%	4%	2%
6%	50%	44%	37%	32%	29%	22%	18%	12%	7%	4%	2%
7%	49%	44%	37%	32%	29%	22%	18%	12%	7%	4%	2%
8%	47%	43%	37%	32%	29%	22%	18%	12%	7%	4%	2%
9%	43%	39%	36%	32%	29%	22%	18%	12%	7%	4%	2%
10%	40%	37%	35%	31%	28%	21%	18%	12%	7%	4%	2%
11%	38%	36%	34%	30%	27%	21%	18%	12%	7%	4%	2%
12%	31%	30%	29%	26%	24%	19%	16%	12%	7%	4%	2%
13%	26%	24%	23%	20%	20%	17%	14%	11%	6%	3%	1%
14%	20%	19%	18%	16%	16%	13%	13%	10%	6%	3%	1%
15%	15%	14%	13%	11%	11%	9%	9%	7%	4%	2%	1%
16%	14%	13%	12%	10%	10%	7%	7%	7%	4%	2%	1%
17%	6%	6%	6%	5%	5%	3%	3%	3%	2%	2%	1%
18%	6%	6%	6%	5%	5%	3%	3%	3%	2%	2%	1%
19%	4%	4%	4%	3%	3%	2%	2%	2%	2%	2%	1%
20%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%

Figure 1: WCC heat map, showing latest tier proposals

This data was presented to the California Public Utilities Commission (CPUC) which resulted in the less restrictive FLE requirements in Section D3 of Resolution E-5152 of the Database for Energy Efficiency (DEER) in 2023. Nevertheless, these recent policies have not yet been integrated into the Electronic Technical Reference Manual (eTRM) measure package SWHC005, nor have they been included in a new standalone measure package. Therefore, the overall objective of this CalNEXT project is to update eTRM with new technical performance for energy savings in this measure.

While the overall goal is to update measure package SWHC005 in the CA eTRM, the measure package can only be completed and delivered in 2024 after the CPUC has moved their modeling engine from DOE-2 to EnergyPlus. That transition effort should be completed by the end of 2023.

Therefore, the project team has undertaken a study in 2023 with the following supplementary tasks:

1. Investigate whether the WCC data works with the Low-Global Warming Potential (GWP) refrigerants by working with manufacturers
2. Collect performance maps for heat recovery chillers this year from manufacturers and/or distributors
3. Ascertain that the previously collected technical performance 2019 WCC data can be modeled in EnergyPlus
4. Write a measure package plan this year for CPUC consideration and feedback for potential execution in 2024

This project leverages newly collected data as well as previously collected technical performance data, completing an effort begun in 2019, to update the existing measure package on WCC (SWHC005) and development of a new measure package for HRC in the California eTRM in 2024.

Background

Water-Cooled Chillers

Water cooled chillers are vapor compression-based systems that chill water at the evaporator of the system and distribute it to air handlers to cool air and dissipate building cooling demand. The chillers use a condenser water loop and cooling towers to reject heat from the refrigeration cycle, generally achieving higher efficiencies relative to air-cooled systems. WCCs are common in commercial and industrial applications and are available in a wide range of capacities, generally from 75 to several thousand tons. Electrically operated water-cooled chillers are categorized by compressor type and tonnage capacity in efficiency standards such as ASHRAE 90.1 2022 and the *2022 Building Energy Efficiency Standards (Title 24, Parts 6 and 11)*. Compressor technologies include positive displacement (reciprocating, rotary, screw or scroll) and centrifugal.

The efficiency ratings for a water-cooled chiller are based on the unit operating under standard test conditions, normally determined by the manufacturer in accordance with AHRI Standard 550/590 – 2020. Chillers have two different measures of rated energy usage: full load usage (kW/ton), which is the reciprocal of efficiency (ton/kW), and part load usage represented by the integrated part load value which also carries units of kW/ton.

Low-GWP Refrigerant Considerations in Chillers

Chillers have customarily used high-efficiency but high-GWP refrigerants (such as R134a). However, due to the recent changes in regulations and enforcement of environmentally friendly technologies, there has been a slow but significant transition toward the use of low-GWP refrigerants to replace some of these high-GWP refrigerants in chillers. *As per the ruling of the US Environmental Protection*

Agency (EPA), all high-GWP HydroFluroCarbons, including R134a, R404A and R410A, will be banned in most new refrigeration equipment from January 1, 2025 [EPA (2022)]. The maximum GWP value of a refrigerant to be used in a chiller must be less than 700.

In the pursuit of the worldwide phase-down of high GWP refrigerants [Richard 2021], there are many different types of chillers, however in terms of the refrigerant, they can be categorized into three types: low, medium, and high pressure.

LOW PRESSURE REFRIGERANTS

Historically, the low-pressure refrigerant chillers originally used the CFC R11, which was replaced by the B1 safety class HCFC R123, but due to the low GWP legislation requirement, these have now been replaced by very low GWP refrigerants R514A (GWP=2) and R1233zd (GWP 4.5), both belonging to A1 safety class. They are only applied typically for large centrifugal compressors.

MEDIUM PRESSURE REFRIGERANTS

This sector has been dominated by R134a since it was introduced back in the early 1990s as a replacement for the CFC R12. There are several alternatives of R134a, including R513A, R515B, and R-1234ze(E).

- R513A, a non-flammable refrigerant with a GWP of 631, has been quickly adopted by several manufacturers and can easily be used for retrofitting R134a systems, with very similar cooling capacity and performance but with about a two percent to three percent reduction in full and part-load values (IPLV), although performance can vary by the model type.
- R515B is a new blend introduced to the market in 2020 with A1 (non-flammable) classification and a GWP of 292. However, it is not a retrofit option for R134a as it suffers with large capacity degradation by up to 37 percent for most applications with about a two percent loss in full and part-load efficiency.
- R-1234ze(E) is also not suitable as a retrofit for R134a systems due to its lower cooling capacity (by 25 percent). While it offers better energy efficiency than R134a, it would require engineering work to match existing capacity and meet safety standards due to its A2L rating.

HIGH PRESSURE REFRIGERANTS

For over 15 years, R410A has been the predominant high-pressure refrigerant in chillers. However, R454B is now emerging as its alternative with a GWP of 466 with several manufacturers as it is a close match to R410A in terms of operating performance.

It may be noted that these alternative refrigerants have their own unique properties and offer certain advantages and disadvantages depending upon the system type, operating conditions, and usage domain. For example, carbon dioxide (CO_2) is an excellent refrigerant in large commercial air-source heat pump water heating systems due to its efficient performance at low ambient conditions but at relatively high capital cost.

An insightful comparative performance of these refrigerants is shown in 1, and further explanation of refrigerant flammability level is described in **Figure 2**.

Table 1: Comparative insights of various refrigerants for their application in Chillers

New Refrigerant	GWP	Flammability Level	System Availability	Performance Notes
R-514A	2	A1	Commercially available: Centrifugal	*Low pressure Ref*; similar capacity as R123
R-1233zd(E)	4.3	A1	Commercially available: Centrifugal, Screw	*Low pressure Refrigerant*
R-513A	630	A1	Commercially available: Screw, Scroll, Centrifugal	*Medium Pressure ref*; 4% higher capacity; 4 - 6% and sometimes 24% drop in efficiency compared with R134a;
R-515B	292	A1	Commercially available: Scroll, Screw, Centrifugal	*Medium Pressure Ref*; Requires 37% increase in displacement to replace R134a
R-1234ze(E)	<1	A2L	Commercially available: Screw	*Medium Pressure Ref*: About 25% Lower capacity compared with R134a
R-454B	466	A2L	Commercially available; Scroll	*High Pressure Ref*- Matches R410 performance;
CO_2	1	A1	Under Development	High Pressure Ref

	lower toxicity	higher toxicity	
higher flammability	A3	B3	LFL ≤ 0.10 kg/m³ or heat of combustion ≥19 000kj/kg
lower flammability	A2 A2L*	B2 B2L*	LFL ≤ 0.10 kg/m³ and heat of combustion ≥19 000kj/kg
no flame propagation	A1	B1	no LFL based on modified ASTM E681-85 test
	no identified toxicity at concentrations ≤400 ppm	evidence of toxicity below 400 ppm (based on data for TLV-TWA or consistent indices)	

*A2L and B2L are lower flammability refrigerants with a maximum burning velocity of < 10 cm/s.

Figure 2: Refrigerant safety classifications from ASHRAE Standard 34 (Agency n.d.)

CAVEATS AND LIMITATIONS

It may be noted from the information presented in 1 that most refrigerant alternatives to R-410A, R-134a, or R123 suffer from a drop in either efficiency or capacity in retrofits. However, for the new machines, it is expected that the manufacturers will address these issues before a new product is launched onto the market that would offer at least the same efficiency and capacity, if not better, than the units being replaced. This may involve modification involving several design variables, including compressor displacement, heat exchanger area and other components sizing, and optimization of the refrigerant charge. Consequently, we can inevitably use performance maps for chillers that use different refrigerants as long as the efficiency performance is equivalent.

Since the availability of the data involving low GWP refrigerants from distributors was quite limited, this research investigates the performance of some specific refrigerants in WCCs, including R454B, R513A, and R1233zd (E).

Mechanical Heat Recovery

The term “mechanical heat recovery” refers to any piece of equipment that uses the vapor-compression cycle to simultaneously provide space cooling and space and/or domestic hot water heating. This technology option can produce HVAC systems that achieve very high coefficients of performance, because the energy transferred across the evaporator as well as the condenser “counts” in the numerator of the ratio. This contrasts with a regular chiller that can only “count” the evaporator energy since the condenser energy is waste heat. This benefit is reflected in the higher minimum coefficients of performance requirements that were recently added for heat recovery chiller equipment. For example, for the < 75-ton positive displacement equipment with a 120 °F leaving hot water temperature, the heat pump heating coefficients of performance must meet or exceed 3.68, while for the same size category and leaving hot water temperature for heat recovery, the coefficients of performance must achieve 6.41 or greater. This is a result of the benefit of mechanical heat recovery, again, the productive use of both energy eliminated from a chilled water stream by the evaporator and added to the hot water stream by the condenser.

Water source heat recovery chillers are a well-established product in the market. Historically, the equipment was primarily marketed as a water-cooled chiller with heat recovery capabilities, implying that the cooling function takes priority over heating. Figure 2 provides a snapshot of some existing heat recovery chiller products.

		
Trane CenTraVac with Heat Recovery	York YK Centrifugal with Heat Recovery	Carrier AquaForce 30HX, 30XW

Figure 3: Heat recovery chiller product offerings

"Double bundle" heat recovery chillers are an established technology that is offered by major chiller manufacturers. The term "double bundle" refers to the fact that there are two condenser coils, one for sending excess energy to a cooling tower, the other for returning energy to the building. Sometimes this equipment is referred to in the industry as "6-pipe" units. Manufacturers produce "application guides" and other documentation regarding heat recovery chillers, which are highly valuable documents. Trane discusses water-side heat recovery in this 2007 newsletter, and Carrier publishes a variety of materials on its heat recovery homepage, including white papers for both air-source and water-source heat recovery equipment.

A rapidly growing category of heat recovery chillers can be classified as "dedicated" or "modular" equipment. This market is dominated by manufacturers such as Aermec, Multistack, and ClimaCool, and some example products are shown in 3.

Both the "double bundle" heat recovery chillers and dedicated/modular heat recovery chillers are largely accomplishing the same task, namely, delivering condenser heat to the building and absorbing energy from the building in the evaporator, but the differences stem from sizing, controls, and amount of heat recovery capability. A double bundle chiller may only be able to provide "partial" heat recovery, depending on the capacity of its second heat exchanger. This means that the refrigerant doesn't fully condense in the heat recovery portion and must send the remainder of its waste heat to the condenser loop/cooling tower.

		
Multistack VME II	Aermec NXP	ClimaCool UCH

Figure 4: Examples of dedicated heat recovery chillers

Heat recovery chillers can be in the condenser water or chilled water loops (in both cases, delivering hot water). A heat recovery chiller can recover condenser waste heat by being in the condenser loop, or they can also recover building waste heat by being placed in the chilled water return loop. This configuration is slightly more efficient, because the heat recovery chiller can offload the regular WCC chiller by cooling down the return chilled water temperature before it hits the cooling only WCC equipment. Generally, heat recovery chillers are most effective when they are first in the loading order, which ensures that the heat recovery is maximized throughout the year.

Novel Heat Recovery Chillers

This report delves into the performance analysis of two specific chillers that are energy efficient and environmentally friendly and use low GWP refrigerants. The Energy Solutions team received the performance data on these units from the distributors. The selection of these two chillers underscores their novelty in the market and their heat-recovery capabilities.

YMAE Inverter Scroll Modular Heat Pump Chiller: 35-140 Ton

York has engineered an Inverter Scroll Modular Heat Pump Chiller, an air-to-water heat pump, shown in Figure 4, to achieve decarbonization goal as a stand-alone heating and cooling solution for offices and schools to multi-unit residential buildings, hotels, and healthcare facilities. The modular design allows for single point power and offers an ideal solution to replace boilers with high-performance electric heat pump technology. The YMAE offers a broad operating range and delivers up to 140 °F (60 °C) water in heating capacities up to 443 MBH (heating only mode) and 546 MBH (simultaneous heating and cooling mode). It uses R454B low GWP refrigerant reducing direct emissions by up to 78 percent, and its high IPLV of ~20.1 exceeds ASHRAE 90.1-2022 by 54 percent.

Figure 5: York Inverter Modular heat pump chiller

SMARDT T-Class Water Cooled Chiller: 60–3200 Ton

The oil-free centrifugal chillers from Smardt use magnetic bearings and a variable speed drive to deliver IPLV efficiencies that far surpass those of conventional oil-lubricated centrifugal, reciprocating, scroll, and screw chillers. The oil-free operation delivers significant chiller energy savings with an extended service life without the efficiency decrease compared with standard chillers. These chillers (shown in Figure 5) come in various sizes ranging from 60 Ton to 3200 Ton. T-class chillers can be equipped with up to eight oil-free compressors running with low GWP refrigerant R513A. Smardt's T-Class chillers find applications in a variety of markets, including commercial, data center, pharmaceutical, hospital, higher education, district cooling, hotels, malls, and manufacturing.

Figure 6: Smardt Oil free water cooled chillers

Objectives

The objectives of this CalNEXT research are four-fold, as below:

1. Ascertain that the previously collected technical performance 2019 WCC data can be modeled in EnergyPlus.
2. Investigate whether the WCC data works with the Low-GWP refrigerants by working with manufacturers.
3. Collect performance maps for heat recovery chillers this year from manufacturers and/or distributors.
4. Write a measure package plan this year for CPUC consideration and feedback for potential execution in 2024.

This project leverages on the newly collected data as well as previously collected performance data, completing an effort begun in 2019, to update the existing measure package for WCC (SWHC005) and development of a new measure package of HRC in the CA eTRM in 2024.

Methodology & Approach

Interviews with WCC Distributors and Data Collection

The project team prepared a list of WCC Distributors and connected with them via email for a meeting to discuss the overall project goals and seek project participation.

Following the email, the project team connected with each distributor over the phone and presented the pitch deck (Appendix A) to each distributor individually to introduce the CalNEXT project, the efforts of the California Technical Forum (CalTF), the eTRM as a repository of energy measures and the request for specific data for performance maps of water-cooled chillers, and waste heat recovery chillers.

Following this, the project team prepared specific Excel sheets for the data request for both the water-cooled chillers, as well as the waste heat recovery chillers (Appendix B).

Data Request for Constant Speed Drive Chiller

In order to model the chillers and develop their performance maps under various operating conditions, the project team distributed a template (as shown in Appendix B) to manufacturers and distributors requesting data for chillers. The intent was to collect data covering a wide range of parameters, including refrigerant and compressor types, water flow rates, entering water temperature to the condenser and leaving water temperature to the evaporator. The input variables include the entering condenser water temperature and leaving evaporator water temperature for a fixed value of evaporator and condenser water flow rates. The requested outputs include the net evaporator capacity (tons) and input power (kW).

Data Request for Variable Speed Drive (VSD) Chiller

For a given chiller make and model, the first data request included the total capacity of the chiller (tons) and input power (kW) at full load (i.e., 100 percent capacity) with entering condenser water temperature varying between 120, 130 and 140 °F; and for each of these, with evaporator water leaving temperature or leaving chilled water temperature at 40 °F, 44 °F and 48 °F respectively.

For part load conditions, specific data was requested in different tables with load varying from 100 to 10 percent, while entering condenser water temperature and evaporator water leaving temperature being fixed at specific values, say 120°F and 40°F respectively; followed by 120°F and 44 °F, 120 °F and 48 °F, 110 °F and 40 °F, 110 °F, and 44 °F, and 110 °F and 48 °F. The requested outputs included chiller capacity (tons) and input power (kW).

Practical Limitations with Data Collection

Gathering data from manufacturers presented some difficulties due to the unavailability of data software for distributors dealing with low GWP refrigerants for both WCC and HRC at this time. The project team anticipates that more data will become accessible in early 2024.

Data Comprehensiveness of Market Study

The team surveyed the landscape of available heat recovery chiller technologies, and we believe that the collected data is representative of the major categories of commercially available heat recovery chillers. These major categories include water-source units that function similarly to traditional WCCs but possess the ability to deliver hotter water temperatures on the condenser side, enabling DHW and space heating use cases with that water stream. But they are fundamentally cooling-oriented units that can control output to a cooling setpoint. The other major branch of heat recovery chillers in the market are the modular "dedicated" units that are more flexible and enable equipment to be controlled to a cooling or heating setpoint. Both major categories of heat recovery chillers were investigated as part of this effort.

Modeling in EnergyPlus

The project team dedicated efforts to model WCC and HRC performance in EnergyPlus (Energy Plus, 2020). This initiative aligns with the anticipated 2024 eTRM transition of the model engine from DOE-2 to EnergyPlus. This transition offered the opportunity to use the “reformulated” version of the chiller object, which mainly switches from the entering condenser water temperature to the leaving condenser water temperature. This adjustment is anticipated to enhance the model's accuracy by closely tracking the condenser saturation temperature. However, it is important to note that this transition carries a drawback and the data collected in 2019 will become outdated as a result. The implementation of this change is contingent upon the approval of CPUC, Cal TF, and the IOUs.

Water-Cooled Chiller

The EnergyPlus chiller model (object name Chiller:Electric:EIR) uses performance information at reference conditions along with three curve fits for cooling capacity and efficiency to determine chiller operation at off-reference conditions. Chiller performance curves can be generated by fitting manufacturer’s catalog data. The three performance curves are summarized in the following section.

Cooling Capacity Function of Temperature Curve

Cooling capacity performance curve is a biquadratic performance curve that parameterizes the variation of the cooling capacity as a function of the leaving chilled water temperature and the entering condenser fluid temperature. The data utilized to model these curves was supplied by the distributors and manufacturers interviewed. -Supplementary data is listed in the chiller performance manuals. The output of this curve is multiplied by the reference capacity to give the cooling capacity at specific temperature operating conditions. The reference capacity is listed in the manufacturer's catalog under the AHRI rated conditions (AHRI 210/240).

$$ChillerCapFTemp = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)(ECWT)$$

Equation 1: Cooling Capacity as Function of Temperature

Where:

$ChillerCapFTemp$ is Cooling capacity factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C).

$ECWT$ is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Electric Input to Cooling Output Ratio Function of Temperature Curve

The first energy input ratio (EIR) performance cure is a biquadratic performance curve that parameterizes the variation of the energy input to cooling output ratio (EIR) as a function of the leaving chilled water temperature and the entering condenser fluid temperature.

$$ChillerEIRFTemp = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)\,(ECWT)$$

Equation 2: Electric Input to Cooling Output Ratio Function of Temperature

Where:

$ChillerEIRFTemp$ is Energy input to cooling output factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C).

$ECWT$ is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Electric Input to Cooling Output Ratio Function of Part Load Ratio Curve

The second energy input ratio (EIR) performance curve is a quadratic performance curve (ref: Performance Curves) that parameterizes the variation of the EIR as a function of the part-load ratio.

$$ChillerEIRFPLR = a + b\,(PLR) + c\,(PLR)^2$$

Equation 3: Electric Input to Cooling Output Ratio

Where:

$ChillerEIRFPLR$ is the energy input to cooling output factor, equal to 1 at reference conditions.

Water-Cooled Heat Recovery Chillers

Double-Bundled Heat Recovery Chiller

As per EnergyPlus engineering reference, this chiller object Chiller:Electric:EIR can also model heat recovery where part of its condenser section is connected to a heat recovery loop for what is commonly known as a double bundled chiller or single condenser with split bundles. The heat recovery chiller is simulated as a standard vapor compression refrigeration cycle with a double bundled condenser. A double bundle condenser involves two separate flow paths through a split condenser. One of these paths is condenser water typically connected to a standard cooling tower; the other path is hot water connected to a heat recovery loop. After leaving the compressor, the refrigerant is condensed to liquid in a refrigerant to water condenser. In a split bundle, the chiller's internal controls will direct a part of the refrigerant to heat recovery condenser bundle and/or to the tower water condenser bundle depending on the chilled water load, the condenser inlet temperatures, and internal chiller controls (and possibly a leaving hot water temperature setpoint). The refrigerant pressure is then dropped through a throttling valve so that fluid can evaporate at a low pressure that provides cooling to the evaporator.

The algorithm for the heat recovery portion of the chiller needs to be determined from relatively simple inputs to estimate the amount of the heat that is recovered and then send the rest of the heat to the cooling tower.

Design Heat Recovery Water Flow Rate

This is the design flow rate used if the heat recovery option is being simulated. Note that heat recovery is only available with CondenserType = WaterCooled.

Condenser Heat Recovery Relative Capacity Fraction

This fraction describes the relative capacity of the heat recovery bundle of a split condenser compared to the nominal, full load heat rejection rate of the chiller. This fraction will be applied to the full heat rejection when operating at nominal capacity and nominal COP to model a capacity limit for the heat rejection. If this field is not entered, the capacity fraction is set to 1.0.

Dedicated Heat Recovery Chiller

The EnergyPlus object (*CHILLERHEATERPERFORMANCE:ELECTRIC:EIR*) simulates the performance of a chiller-heater which can receive pre-cooled or pre-heated water from the source loop, and provide cooling, heating, or simultaneous cooling-heating. The object needs to work with the Central Heat Pump System object to be controlled properly. This model does not simulate thermal performance or the power consumption of associated pumps or cooling towers. The Central Heat Pump System object holds the input/output nodes connection of the chiller-heater and its control scheme once the chiller-heater is properly referred.

The model uses user-input performance information at design conditions along with three performance curves (curve objects) for cooling capacity and efficiency to determine chiller operation at off-design conditions. Three additional performance curves for heating capacity and efficiency are used when the chiller is operating in a heating-only mode or simultaneous cooling-heating mode.

Cooling-only Mode

Cooling Mode Cooling Capacity Function of Temperature Curve

The Cooling model Cooling Capacity Function of Temperature Curve represents the fraction of the cooling capacity of the chiller-heater as it varies by temperature. The curve should have a value of 1.0 at the reference conditions. The output of a bi-quadratic curve with the input variables being the leaving chilled water temperature and either the entering or leaving condenser water temperature is given by:

$$EvapCapFTclg = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\ (LChWT)(ECWT)$$

Equation 4: Cooling Capacity as Function of Temperature

Where:

$EvapCapFTclg$ is Cooling capacity factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C).

$ECWT$ is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Cooling Mode Electric Input to Cooling Output Ratio Function of Temperature Curve

The Cooling Mode Electric Input to Cooling Output Ratio Function of Temperature curve represents the fraction of electricity to the chiller-heater at full load as it varies by temperature. The output of a bi-quadratic curve with the input variables being the leaving chilled water temperature and either the entering or leaving condenser water temperature is given by:

$$EIRFT\text{clg} = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)\,(ECWT)$$

Equation 5: Electric Input to Cooling Output Ratio Function of Temperature

Where:

$EIRFTclg$ is Energy input to cooling output factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C)

ECWT is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Heating-only mode and Simultaneous cooling-heating mode

Heating Mode Cooling Capacity Function of Temperature Curve

The output of a Heating Mode Cooling Capacity Function of Temperature curve with the input variables being the leaving chilled water temperature and either the entering or leaving condenser water temperature is given by:

$$EvapCapFThtg = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)(ECWT)$$

Equation 6: Cooling Capacity as Function of Temperature

Where:

$EvapCapFThtg$ is heat mode Cooling capacity factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C).

$ECWT$ is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Heating Mode Electric Input to Cooling Output Ratio Function of Temperature Curve

The output of a Heating Mode Cooling Output Ratio Function of Temperature curve with the input variables being the leaving chilled water temperature and either the entering or leaving condenser water temperature is given by:

$$EIRFThtg = a + b(LChWT) + c(LChWT)^2 + d(ECWT) + e(ECWT)^2 + f\,(LChWT)\,(ECWT)$$

Equation 7: Electric Input to Cooling Output Ratio Function of Temperature

Where:

$EIRFThtg$ is Energy input to cooling output factor, equal to 1 at reference conditions.

$LChWT$ is Leaving chilled water setpoint temperature (°C)

ECWT is Entering condenser fluid temperature (°C). For a water-cooled condenser this will be the water temperature returning from the condenser loop (e.g., leaving the cooling tower).

Findings

Manufacturer Interviews

Water-cooled chiller manufacturers were contacted and interviewed by the project team with the intention of learning about product offerings as well as requesting data for energy modeling. These interviews revealed that various chiller manufacturers offer products with different compressor types and models for different applications, influenced by refrigerant choices for efficiency and environmental impact. However, obtaining accurate performance data can be challenging. The industry is shifting towards low-GWP refrigerants with a focus on environmental sustainability. Challenges include varying heat recovery effectiveness, refrigerant safety, and compressor selection.

Conversations highlighted the risk that common WCCs (i.e., non-HRCs) may qualify for HRC incentives, highlighting the importance of a diverse chiller product range to cater to varying customer needs. A prevalent challenge revolves around distinguishing between cooling-only and heat-recovery applications. Accurate specification and operation of chillers hinge on this distinction. A proposed solution involves creating unique model numbers for HR chiller variations. However, enforcing the use of these models on non-heat recovery applications remains a substantial hurdle. This finding underscores the need for robust control mechanisms and standardized labeling to address this issue effectively.

Discussions went on to highlight that most chillers currently utilize R-513A refrigerant, serving as a bridge to future alternatives since it tends to offer four to six percent lower efficiency than R134a. The refrigerant choice imposes limitations on the maximum water temperature that can be achieved.

Several manufacturers highlighted the prevalence of custom elements in water-cooled chillers, indicating their inherent complexity. This complexity underscores the importance of tailored solutions to meet specific customer requirements. It also highlights the challenges in qualifying these units for incentives due to customizations that often bypass deemed measures. Custom measure applications are notoriously difficult.

Concerns regarding refrigerant limitations were raised in two interviews. R-513A refrigerant is commonly used, but it imposes restrictions on achieving high water temperatures. This limitation has a significant impact on high-temperature applications, emphasizing the need for ongoing research and development in refrigerant technology to meet evolving environmental and performance requirements.

A further perspective highlighted the shortage of chillers capable of high-temperature operation (greater than 140°F). In contrast, standard chillers were identified as being capable of operating at high-temperature condensers, providing a practical alternative in many scenarios. This insight informs decision-makers about available options when dealing with high-temperature applications, contributing to more informed choices.

Another distributor dispelled a common misconception regarding centrifugal heat pumps, which typically achieve temperatures up to 120 °F , not 130 °F. Additionally, the observation that legacy chillers unload to 50 percent of their design loads has implications for efficiency and operational strategies, highlighting potential areas for improvement.

These insights further delved into the capacity for simultaneous heating and cooling in chiller systems, with Coefficient of Performance (COP) values for combined heating/cooling systems ranging from 5.5 to 6.3. This information provides valuable guidance for optimizing energy usage in various applications, encouraging the adoption of more efficient and sustainable heating and cooling practices.

Emphasizing the limitations of Heat Pump Chillers (HPC), it was noted that that distributors and manufacturers cannot fulfill all heating needs, particularly in cases without significant simultaneous heating/cooling loads or in hot climates. This finding underscores the importance of considering alternative solutions such as thermal heating energy storage or electric-resistant boilers with attention to efficiency.

Finally, it was pointed out that terminology discrepancies among supply chain actors regarding “heat recovery”. Some define HR as a machine controlling both cooling and heating set points, while others consider it as the process of producing residual heat without active control. This led to the introduction of the term “heat recovery machine” for the latter, highlighting the need for clarity and consistency in industry communication.

The insights gathered from interviews within the HRC and WCC supply chain highlight the complexity and evolving nature of these technologies. The findings emphasize the need for continued innovation, close collaboration between manufacturers and end-users, and careful consideration of refrigerant options and compressor types. These insights will aid industry stakeholders in navigating the challenges and opportunities presented by HRCs and WCCs in an ever-changing market landscape.

Technical Analysis of Manufacturer Data

The project team secured four valuable data sets from manufacturers to meet the project's objectives. Furthermore, the team also explored data from the 2019 Water Cooled Chiller study as part of research efforts.

The project team has conducted analysis on the following four datasets, including:

1. Variable Speed WCC by Manufacturer 2
2. Constant-speed HRC
   a. Manufacturer 1, using low GWP refrigerant R454B and Scroll Compressor
   b. Manufacturer 2
3. Variable Speed HRC
   a. Manufacturer 3 (Unit 1)
   b. Manufacturer 3 (Unit 2)

The following sections provide further detail as to the findings for each of these datasets.

Variable Speed Water-Cooled Chiller

Sample manufacturer data can be seen for the Variable Speed WCC, using low-GWP refrigerant R-1233 zd (E) in Table 3. The data below reflects a PLR down to 0.3.

The manufacturer performance data was analyzed (as shown in Table 2), and curve-fitting was conducted to determine curve coefficients (using Equation 1, Equation 2, and Equation 3) as shown in Table 3. Two performance curves were plotted for Cooling Capacity and Energy Input Ratio in Figure 7 and Figure 8 respectively. As expected, the cooling capacity of the water-cooled chiller (as shown in Figure 7) decreases at higher entering condenser water temperature due to the increasing temperature lift between the evaporator and the condenser. Consequently, the energy input ratio (as shown in Figure 8) of the water-cooled chiller increases with increasing entering condenser water temperature and part load ratio. As a result, the water-cooled chiller becomes less efficient.

Table 2: Manufacturer Performance Data

PLR	Cooling Capacity (tons)	kW/ton	Input Power (kW)	$T_{cond,e}$ (°F)	$T_{cw,l}$ (°F)	EIR
1.00	268	0.6544776	175.4	85	44	0.18609
0.90	241.2	0.6011609	145	85	44	0.17093
0.80	214.4	0.5806903	124.5	85	44	0.16511
0.70	187.6	0.5836887	109.5	85	44	0.165962
0.60	160.8	0.6256219	100.6	85	44	0.177885
0.50	134	0.6902985	92.5	85	44	0.196275
0.40	107.2	0.8470149	90.8	85	44	0.240835
0.30	80.4	1.028607	82.7	85	44	0.292467

Table 3: Water-Cooled Chiller Performance Curve Coefficients

Performance Curve	Performance Curve Coefficients					
	a	b	c	d	e	f
Cap f(LChWT, EWT)	0.359044	0.018563	0.000047	0.000110	(0.000028)	(0.000019)
EIR f(LChWT, EWT)	0.832268	0.002776	0.000187	(0.002332)	0.000161	(0.000341)

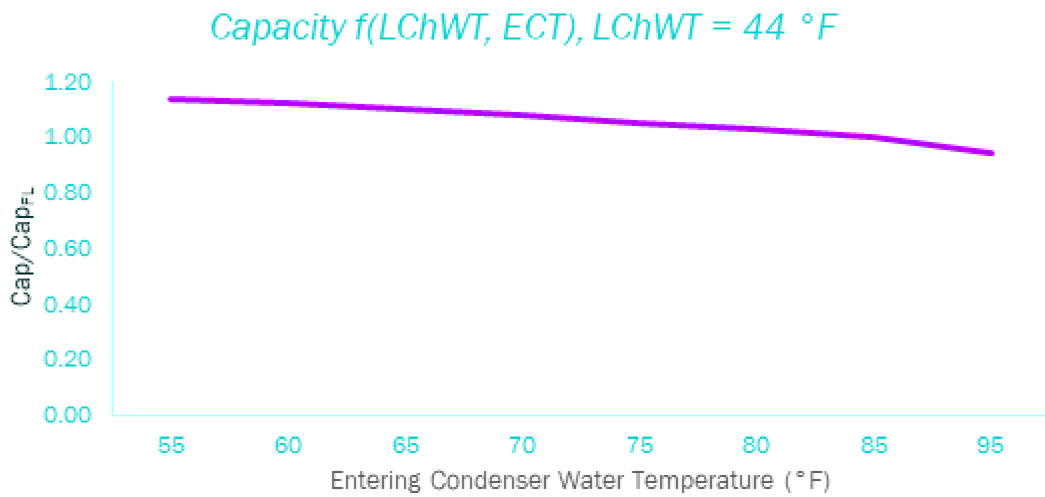

Figure 7: Cooling Capacity as Function of Temperature Curve

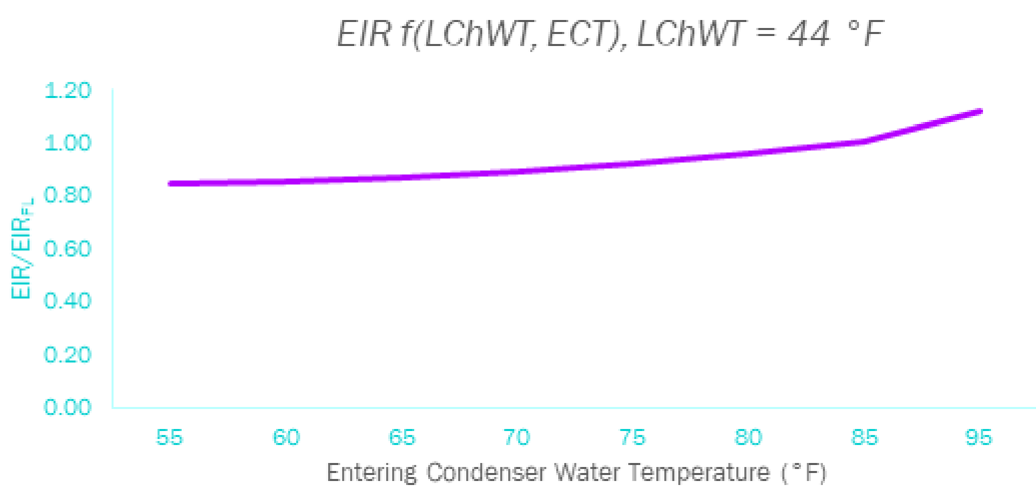

Figure 8: Electric Input to Cooling Output Ratio Function of Temperature Curve

Constant Speed Heat Recovery Chillers

For Manufacturer 1 and Manufacturer 2's constant-speed HRCs, sample manufacturer data can be seen in Table 4 and Table 5 respectively. The entering hot water temperature (EWT) is typically between 110 ºF and 140 ºF. the leaving chilled water temperature ranges from 40 ºF to 48 ºF. This unit used low GWP refrigerant R454B and a Scroll Compressor. Table 8 presents the reference conditions for curve fitting. Based on the manufacture catalog data, the curve coefficients are listed in Table 6 and Table 7. Figures 9 to 12 depict respectively the performance curves for cooling capacity and EIR for Manufacturer 1 and Manufacturer 2.

Table 4: Constant speed water-cooled heat recovery chiller from Manufacturer 1

PLR	Cooling Capacity (tons)	kW/ton	Input Power (kW)	$T_{cond,e}$ (°F)	$T_{cw,l}$ (°F)	EIR	Heating (mBH)
1.00	216.28	1.45	313.36	120	40	0.41	3658
1.00	232.92	1.36	316.20	120	44	0.39	3867
1.00	250.88	1.27	319.32	120	48	0.36	4093
1.00	198.92	1.76	351.04	130	40	0.50	3578
1.00	214.64	1.65	353.36	130	44	0.47	3775
1.00	231.40	1.54	356.16	130	48	0.44	3985

Table 5: Constant speed water-cooled heat recovery chiller from Manufacturer 2

PLR	Cooling Capacity (tons)	kW/ton	Input Power (kW)	Tcond,e (°F)	Tcw,l (°F)	EIR	Heating (mBH)
1.00	33	1.22	40.3	120	40	0.35	539
1.00	33	1.22	40.3	120	44	0.35	539
1.00	33	1.22	40.3	120	48	0.35	539
1.00	31.7	1.38	43.9	130	40	0.39	533
1.00	31.7	1.38	43.9	130	44	0.39	533
1.00	31.7	1.38	43.9	130	48	0.39	533
1.00	30.1	1.58	47.5	140	40	0.45	525
1.00	30.1	1.58	47.5	140	44	0.45	525
1.00	30.1	1.58	47.5	140	48	0.45	525

Table 6: Reference Conditions for Constant Speed Heat Recovery Chiller Curve-fitting

Reference condition	Manufacturer 1	JCI
Reference Cooling COP (W/W)	2.59	2.88
Reference Leaving Chilled Water Temperature (F)	44	44
Reference Entering Condenser Fluid Temperature (C)	120	120

Table 7: Manufacturer 1 Heat Recovery Chiller Performance Curve Coefficients

Curve	Curve Coefficient					
	a	b	c	d	e	f
ChillerCap Temp	0.655699	0.018290	0.000158	0.000000	-0.000012	-0.000114
ChillerEIR Temp	-0.276437	0.020402	0.000206	0.000000	0.000166	-0.000456

Table 8: Manufacturer 2 Heat Recovery Chiller Performance Curve Coefficients

Curve	Curve Coefficient					
	a	b	c	d	e	f
Capacity f(LChWT, ECT)	0.763636	0.000000	0.000000	0.007424	-0.000045	0.000000
EIR f(LChWT, ECT)	1.280574	0.000000	0.000000	-0.016866	0.000121	0.000000

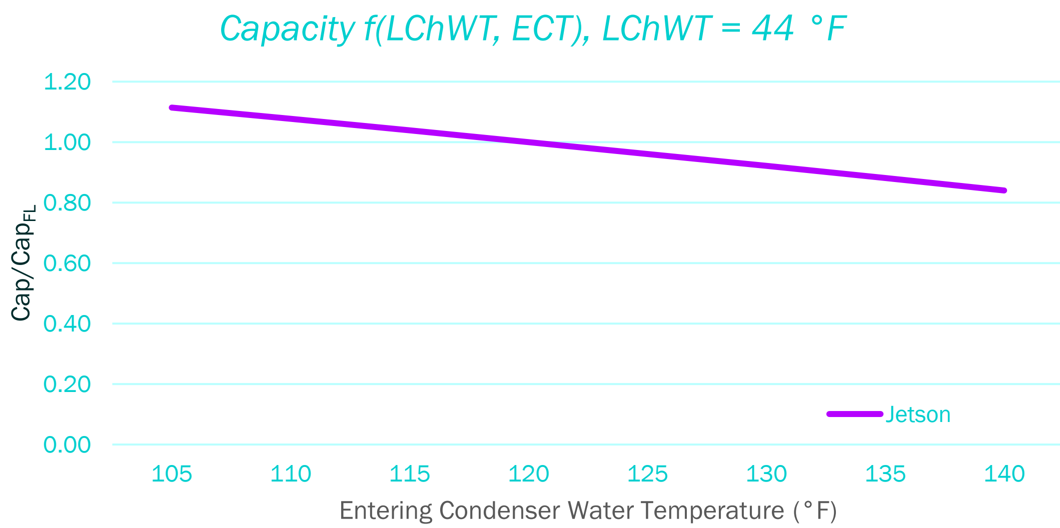

Figure 9: Manufacturer 1 Heat Recovery Chiller Cooling Capacity as Function of Temperature Curve

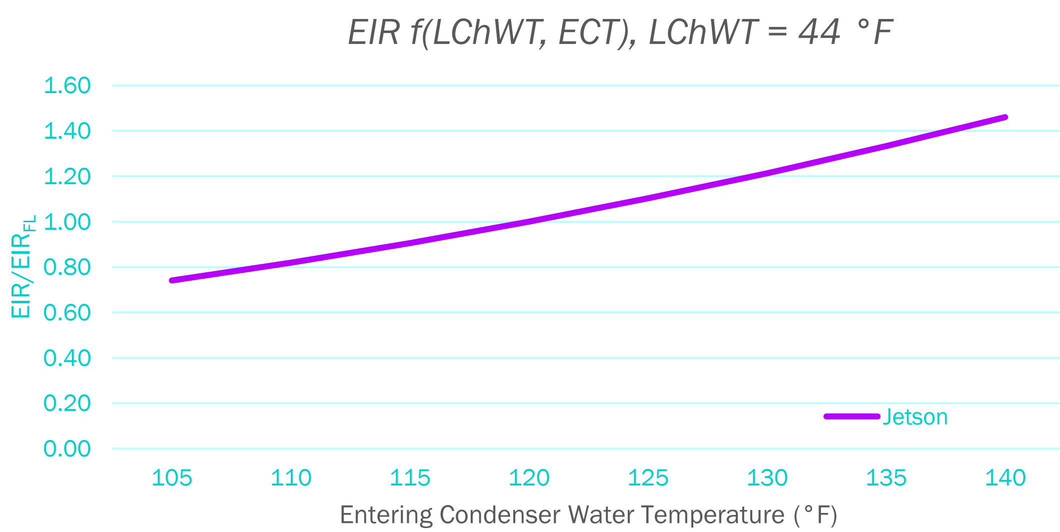

Figure 10: Manufacturer 1 Heat Recovery Chiller Cooling EIR as Function of Temperature Curve

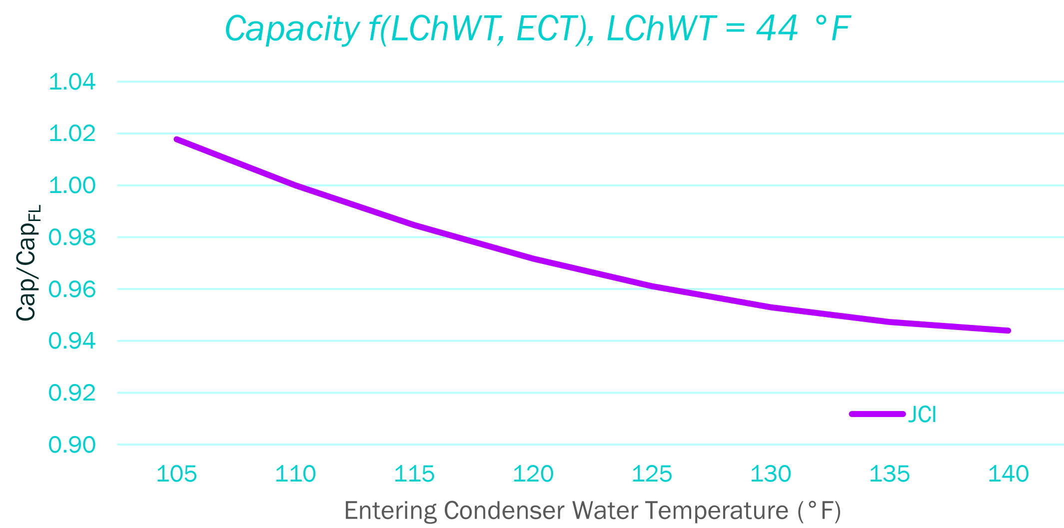

Figure 11: Manufacturer 2 Heat Recovery Chiller Cooling Capacity as Function of Temperature Curve

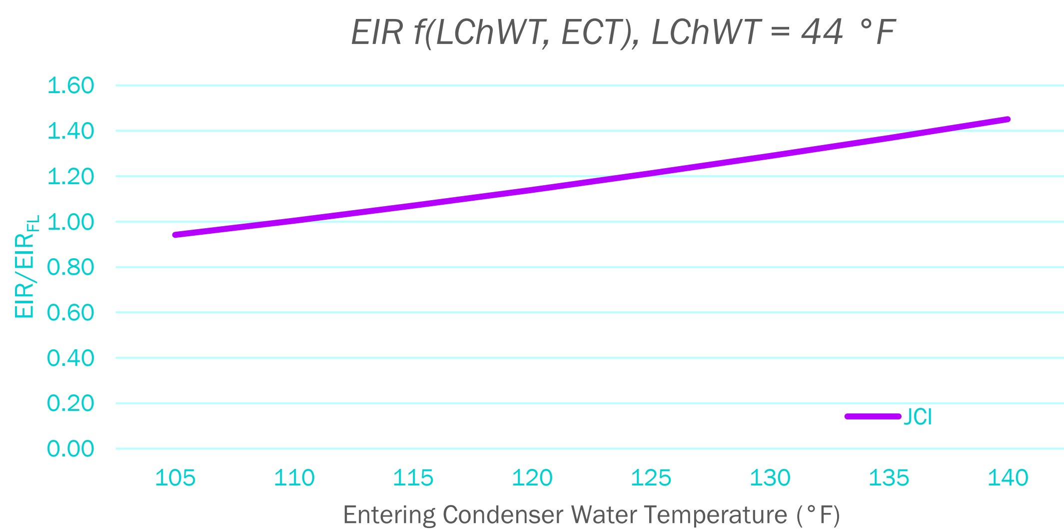

Figure 12: Manufacturer 2 Heat Recovery Chiller Cooling EIR as Function of Temperature Curve

Variable Speed Heat Recovery Chillers

For variable speed heat recovery chiller, sample manufacturer data can be seen in Appendix D in Table 12 and Table 13. For the unit Manufacturer 3 (Unit 2) with standard lift compressor, the entering hot water temperature (EWT) is typically between 100 °F and 110 °F and the leaving chilled water temperature is in the range of 40 °F to 48 °F. For Manufacturer 3 (Unit 1) with high lift compressor, the entering hot water temperature (EWT) is typically between 120 °F and 130 °F and the leaving chilled water temperature is the range of 40 °F to 48 °F.

For EnergyPlus modeling, the reference conditions are specified in Table 9. At the reference condition, the correction factor is equal to one for the capacity and energy input ration curves. Based on the manufacture catalog data, the curve coefficients are listed in Tables 10 and 11. Figures 13 - 14 and Figures 15 - 16 depict respectively the performance curves for cooling capacity and EIR for Manufacturer 3 (Unit 2) and Manufacturer 3 (Unit 1). In general, the cooling capacities decrease with the increase of the entering hot water temperature. However, the EIR increases with higher entering hot-water temperature.

Table 9: Reference Conditions for Heat Recovery Chiller Curve Fitting

Reference condition	Manufacturer 3 (Unit 2)*	Manufacturer 3 (Unit 1)
Reference Cooling COP (W/W)	3.93	2.85
Reference Leaving Chilled Water Temperature (F)	44	44
Reference Entering Condenser Fluid Temperature (C)	110	120

* Heat recovery chiller with a standard lift compressor has entering condenser fluid temperature between 100 °F and 110°F.

Table 10: Manufacturer 3 (Unit 2) heat recovery chiller performance curve coefficients

Curve	Curve Coefficient					
	a	b	c	d	e	f
Capacity f(LChWT, ECT)	0.416516	0.017405	0.000396	0.000000	0.000048	-0.000316
EIR f(LChWT, ECT)	0.590781	0.000055	-0.000106	0.000000	0.000066	-0.000038

Table 11: Manufacturer 3 (Unit 1) Heat Recovery Chiller Performance Curve Coefficient

Curve	Curve Coefficient					
	a	b	c	d	e	f
Capacity f(LChWT, ECT)	-1.69462	0.118543	-0.001186	0.000553	-0.00002	0
EIR f(LChWT, ECT)	-1.01658	0.086576	-0.000968	-0.00081	0.000033	-5.5E-05

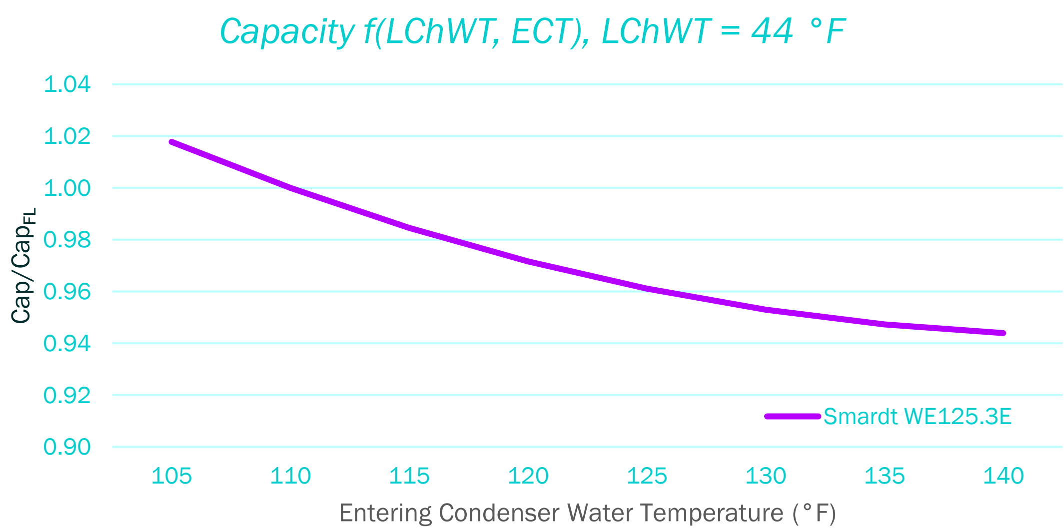

Figure 13: Manufacturer 3 (Unit 2) Heat Recovery Chiller Cooling Capacity as Function of Temperature Curve

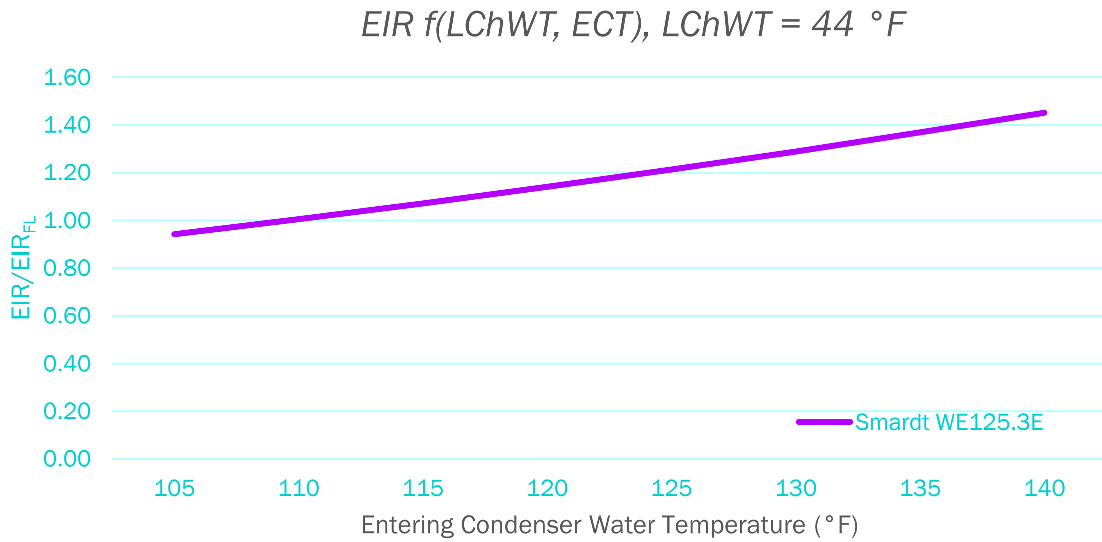

Figure 14: Manufacturer 3 (Unit 2) Heat Recovery Chiller Cooling EIR as Function of Temperature Curve (Manufacturer 2)

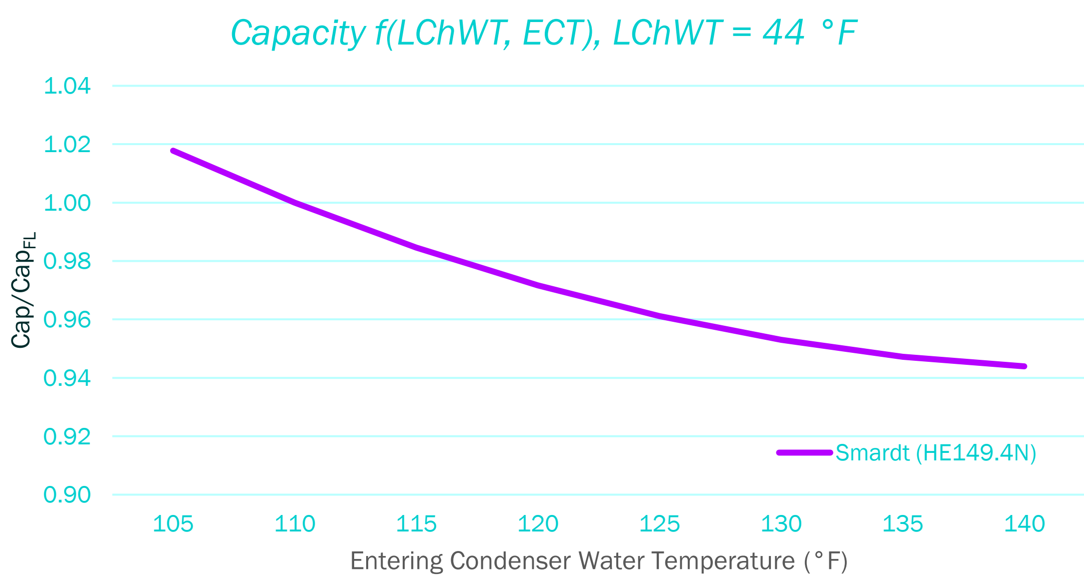

Figure 15: Manufacturer 3 (Unit 1) Heat Recovery Chiller Cooling Capacity as Function of Temperature Curve

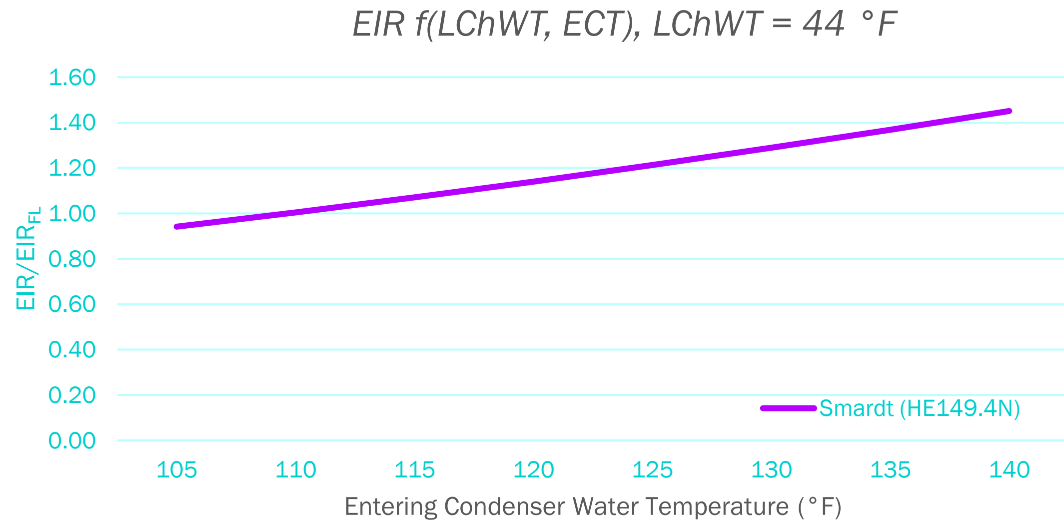

Figure 16: Manufacturer 3 (Unit 1) Heat Recovery Chiller Cooling EIR as Function of Temperature Curve

LIMITATIONS OF AVAILABLE PERFORMANCE DATA AND MODELLING TOOLS

As mentioned in the previous section Modeling in EnergyPlus, EnergyPlus currently has two models for heat recovery chillers including double bundled or split bundled Heat Recovery Chiller (Chiller:Electric:EIR) and dedicated heat recovery chiller (ChillerHeaterPerformance:Electric:EIR). Both these models have water-cooled condensers. However, the manufacturer data collected so far on dedicated heat recovery chiller belongs to air-cooled condensers. Therefore, there is a gap between the EnergyPlus existing models and the available manufacturer data. This issue is not something that can be fixed by the Energy Solutions team and therefore, the Lawrence Berkley National Laboratory team has been requested to resolve this matter in the future.

Stakeholder Feedback

The SDG&E Engineer PA team was contacted to provide feedback on the project and project-handoff processes. SDG&E leaders have suggested that the project team make a second presentation before the Cal TF Measure Screening Committee. With the understanding that Energy Solutions is facilitating this work, the group recommends that the project team resubmit the project to the Measure Screening Committee, ensuring the completion and submission of Measure Package Plans to the Cal TF. Once this step is completed, the SDG&E Engineering Group will take over the project.

A key stakeholder in the WCCs measure updates is Solaris, responsible for managing eTRM Measure SWHC005. The project team contacted key members of the Solaris team to receive their feedback. Solaris team is now aware of our work and are cooperative in this endeavor.

In addition to this, other stakeholders, including manufacturers who were contacted for supply chain interviews and HVAC subject matter experts, were approached for feedback on the findings. Several recommendations were offered by these stakeholders to enhance the clarity of language in describing technologies and findings, but no substantial concerns were raised regarding project methods, approach, or results.

Conclusions

As a result of the research performed on WCC and HRC, following main conclusions may be drawn:

Low GWP refrigerant R1233zd data in Water Cooler Chiller was modelled in Energy Plus and performance curves were generate. A Measure Package Plan has been developed to update the current measure package WCC (SWHC005) in the ETRM,

Data on low GWP refrigerants R513A, R454B, and R1233zd in HRC was collected from chiller distributors, and performance maps were generated using Energy Plus. A new measure package plan has been developed for HRC, for CPUC consideration and feedback for potential execution in 2024,

There were numerous limitations that were experienced during this research that include the following major points:

1. The availability of performance data with low GWP refrigerants in WCCs and HRCs was limited because distributors don't yet have access to the software with low GWP refrigerants.
2. There is a drop in capacity and/or efficiency in various retrofit systems using new low–GWP refrigerants. The project team expects that all such issues will be addressed fully by the manufacturers before a new product is launched into the market. The performance maps for chillers using various low GWP refrigerants would be used as long as the efficiency performance is equivalent to earlier systems.
3. There is a gap between the EnergyPlus existing models and the available manufacturer data. This technical glitch is outside the scope of this research and may be addressed in collaboration with Lawrence Berkeley National Laboratory in the future.

Recommendations

Due to the limitations of time and software unavailability for distributors of HRCs working with low GWP refrigerants, the data collected was compromised. The project team recommends that:

- More data sets of HRCs with low GWP refrigerants be collected and performance maps developed using EnergyPlus,
- New fuel substitution measure packages be created for heat recovery chillers. Program design ideas/data from this report provide the starting point.
- Update SWHC005 using 2019 WCC performance data with new tiers made permissible by DEER E-5152.

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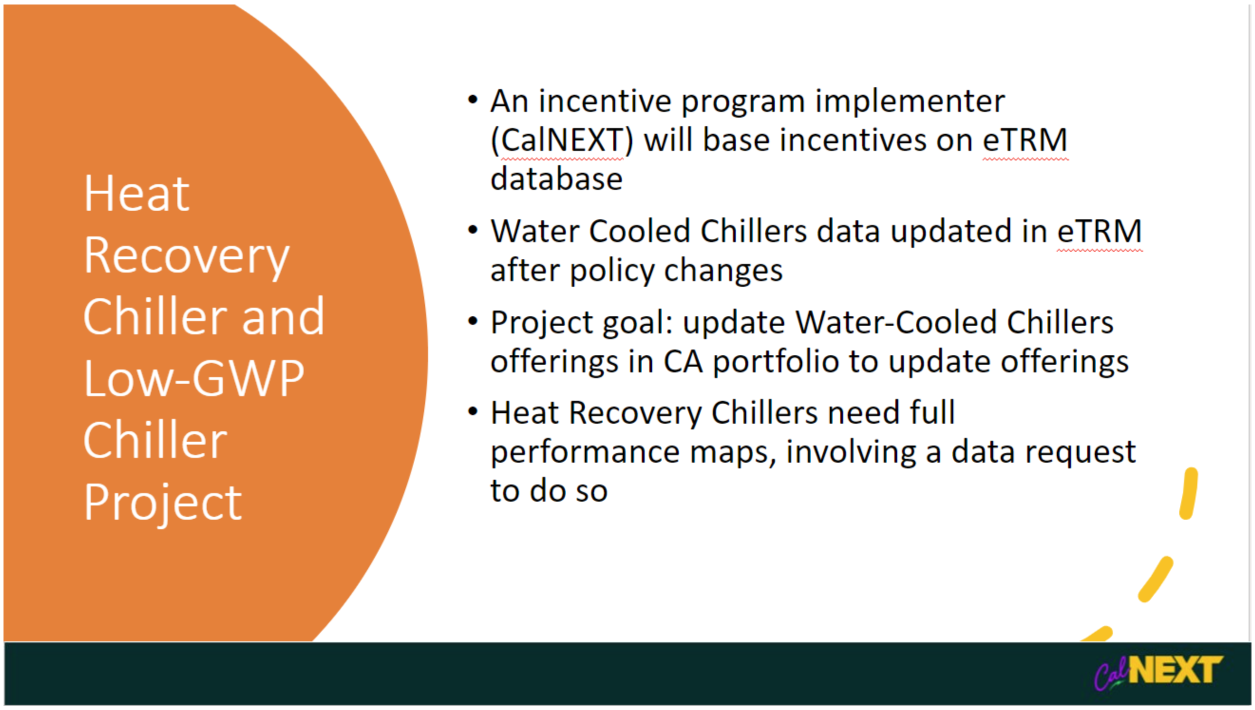
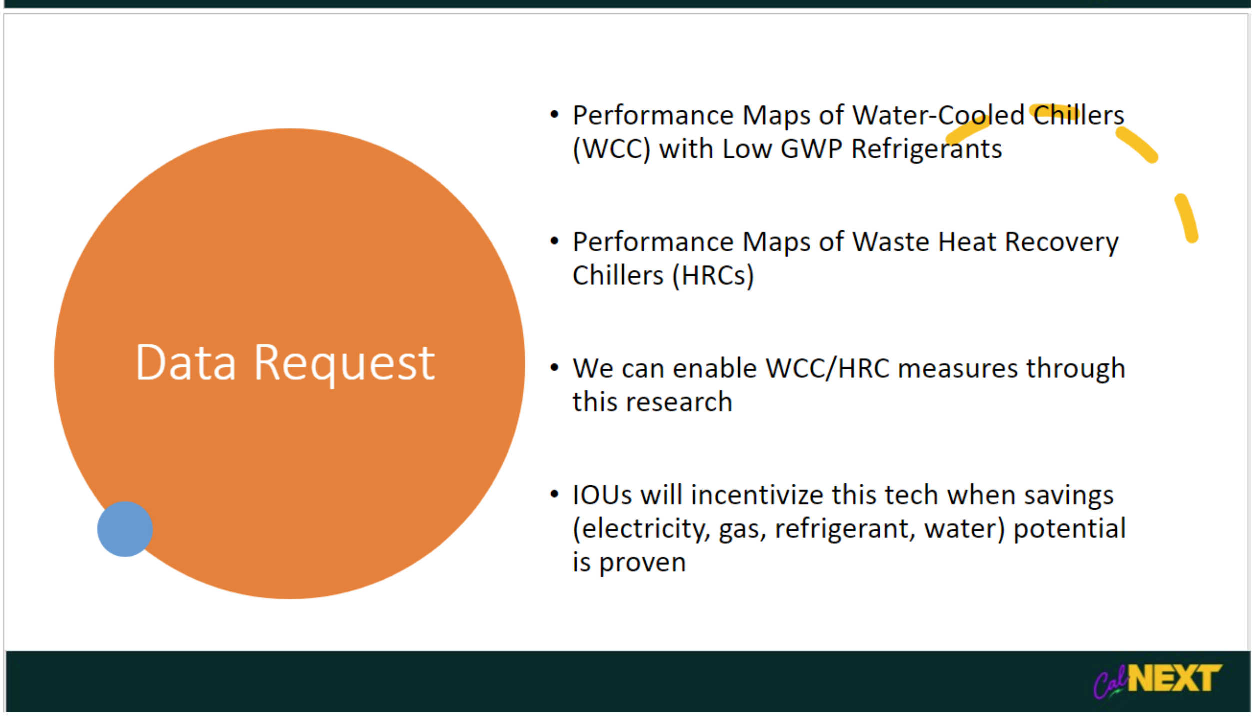
Appendix A: Distributor Interview Pitch Deck

The information about the project and slide deck to introduce the project and request for specific dataset for Water-Cooled Chillers as well as Waste Heat Recovery Chillers.





Appendix B: Details of Excel Template with Data request

RS0001: Liquid-Cooled Chiller				
Data Grou	**Data Element**	**Value**	**Units**	**Required**
metadata				✓
	data_model			✓
	schema			✓
	schema_version			✓
	description			✓
	id			✓
	data_timestamp			✓
	data_version			✓
	data_source			
	disclaimer			
	notes			
description				
description.product_information				
	refrigerant			
	rated_capacity (ton)			
	rated_COP			
	rated_leaving chilled water temperature (F)			
	rated entering condenser fluid temperature (F)			
	rated chilled water flow rate (gpm)			
	rated condenser water flow rate (gpm)			
	Design Heat Recovery Water Flow Rate (gpm)			
	Condenser Heat Recovery Relative Capacity Fraction			
	Heat Recovery Inlet High Temperature Limit (F)			
	liquid_data_source	CoolProp		
	hot_gas_bypass_installed	FALSE		
	compressor_type	CENTRIFUGAL		
performance				✓
performance.evaporator_liquid_type				✓
performance.evaporator_liquid_type.liquid_componen		$liquid_components		✓
	concentration_type	BY_VOLUME		✓
performance.condenser_liquid_type				✓
performance.condenser_liquid_type.liquid_component		$liquid_components0		✓
	concentration_type	BY_VOLUME		✓
	evaporator_fouling_factor	0	m2-K/W	✓
	condenser_fouling_factor	0	m2-K/W	✓
	compressor_speed_control_type	CONTINUOUS		✓
	maximum_power	112875.4136	W	
	cycling_degradation_coefficient	0	-	✓
performance.performance_map_cooling		$performance_map_cooling		✓
performance.performance_map_standby		$performance_map_standby		✓

	A	B	C	D	E	F	G	H	I
3	net_evaporator_capacity	input_power	condenser_water_entering_temperatu	evaporator_water_leaving_temperatu	condenser_water_volumetric_flow_ra	condenser_water_leaving_temperatur	evaporator_water_volumetric_flow_ra	evaporator_water_entering_temperatu	%Load
4	tons	kw	°F	°F	gpm	°F	gpm	°F	
5			120	40	A		X		100%
6			120	44	A		X		
7			120	48	A		X		
8			130	40	A		X		
9			130	44	A		X		
10			130	48	A		X		
11			140	40	A		X		
12			140	44	A		X		
13			140	48	A		X		
14			120	40	B		X		
15			120	44	B		X		
16			120	48	B		X		
17			130	40	B		X		
18			130	44	B		X		
19			130	48	B		X		
20			140	40	B		X		
21			140	44	B		X		
22			140	48	B		X		
23			120	40	C		X		
24			120	44	C		X		
25			120	48	C		X		
26			130	40	C		X		
27			130	44	C		X		
28			130	48	C		X		
29			140	40	C		X		
30			140	44	C		X		
31			140	48	C		X		
32									
33			120	40	A		y		
34			120	44	A		y		
35			120	48	A		y		
36			130	40	A		y		
37			130	44	A		y		
38			130	48	A		y		
39			140	40	A		y		
40			140	44	A		y		
41			140	48	A		y		

This is for constant speed chillers

Please highlight rated condition

Please add additional evaporator and condenser water temperatures if you have them

A,B,C are condenser flow rates and X,Y,Z are evaporator flow rates.

Appendix C: Sample Dataset of low GWP refrigerants

YORK

Project: WCC-11
Unit Tag:
Engineer:
Customer:

Rating Program: XEngine 1.0.7186
Software Version: YW 19.04b
Date: 10/01/2019 13:49:44

SALES REPORT

Unit Specifications			
Model	YZ-MA058BV052P078HA	Refrigerant	R-1233zd(E)
Specified Net Capacity (Tons)	500.0	Refrigerant Charge (lb)	1130
Rated Net Capacity (Tons)	500.0	Variable Orifice	4
Heat Rejection Capacity (MBtu/h)	6.910		
Full Load (kW/Ton.R)	0.5121	Isolation Valve	Y
IPLV.IP (kW/Ton.R)	0.3223	OptiSound Control	Y
Input Power (kW)	256.0	Voltage / Hz	460 / 60.0
Starter Type	P078HA	FLA (Amps)	337
Compressor	MA058-BV052	A-Weighted SPL (dBA)	81
Evaporator	FC3914-A3M-641-2*	Min Circuit Ampacity	421
Condenser	CB2914-C2Z-491-2*	Max Circuit Breaker Amps	700
Motor	MA058		
Starter Type Specifying	VSD w/ Filter		

	Evaporator	Condenser
Fluid	Water*	Water*
Tube MTI No.	641*	491* / 491
Passes	2*	2*
Fouling Factor (hr-ft²-°F/Btu)	0.000100*	0.000250*
Entering Fluid Temp (°F)	54.00*	85.00*
Leaving Fluid Temp (°F)	44.00*	94.30*
Fluid Flow (gpm)	1196	1495
Fluid Pressure Drop (ft H2O)	13.9	12.8

(*) Designates User Specified Input

IPLV.IP CALCULATION:

$$IPLV.IP = \frac{1}{\frac{0.01}{A} + \frac{0.42}{B} + \frac{0.45}{C} + \frac{0.12}{D}} \qquad IPLV.IP = \frac{1}{3.103} \qquad 0.3223$$

A = kW/Ton.R AT 100% NET CAPACITY
B = kW/Ton.R AT 75% NET CAPACITY
C = kW/Ton.R AT 50% NET CAPACITY
D = kW/Ton.R AT 25% NET CAPACITY

Certified in accordance with the AHRI Water-Cooled Water Chilling and Heat Pump Water-Heating Packages Using Vapor Compressor Cycle Certification Program, which is based on AHRI Standard 550/590 (I-P) and AHRI 551/591 (SI). Certified units may be found in the AHRI Directory at www.ahridirectory.org. Auxiliary components included in total kW: Chiller Controls.
Compliant with ASHRAE 90.1-2004.
Compliant with ASHRAE 90.1-2007.
Compliant with ASHRAE 90.1-2010.
Compliant with ASHRAE 90.1-2013.
Compliant with ASHRAE 90.1-2016.
Compliant with the requirements of the LEED Energy and Atmosphere Enhanced Refrigerant

AHRI CERTIFIED®

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YORK

Project: WCC-11
Unit Tag:
Engineer:
Customer:

Rating Program: XEngine 1.0.7186
Software Version: YW 19.04b
Date: 10/01/2019 13:49:44

SALES REPORT

Unit Specifications			
Model	YZ-MA058BV052P078HA	Refrigerant	R-1233zd(E)
Specified Net Capacity (Tons)	500.0	Refrigerant Charge (lb)	1130
Rated Net Capacity (Tons)	500.0	Variable Orifice	4
Heat Rejection Capacity (MBtu/h)	6.910		
Full Load (kW/Ton.R)	0.5121	Isolation Valve	Y
IPLV.IP (kW/Ton.R)	0.3223	OptiSound Control	Y
Input Power (kW)	256.0	Voltage / Hz	460 / 60.0
Starter Type	P078HA	FLA (Amps)	337
Compressor	MA058-BV052	A-Weighted SPL (dBA)	81
Evaporator	FC3914-A3M-641-2*	Min Circuit Ampacity	421
Condenser	CB2914-C2Z-491-2*	Max Circuit Breaker Amps	700
Motor	MA058		
Starter Type Specifying	VSD w/ Filter		

	Evaporator	Condenser
Fluid	Water*	Water*
Tube MTI No.	641*	491* / 491
Passes	2*	2*
Fouling Factor (hr-ft²-°F/Btu)	0.000100*	0.000250*
Entering Fluid Temp (°F)	54.00*	85.00*
Leaving Fluid Temp (°F)	44.00*	94.30*
Fluid Flow (gpm)	1196	1495
Fluid Pressure Drop (ft H2O)	13.9	12.8

(*) Designates User Specified Input

IPLV.IP CALCULATION:

$$IPLV.IP = \frac{1}{\frac{0.01}{A} + \frac{0.42}{B} + \frac{0.45}{C} + \frac{0.12}{D}} \qquad IPLV.IP = \frac{1}{3.103} \quad 0.3223$$

A = kW/Ton.R AT 100% NET CAPACITY
B = kW/Ton.R AT 75% NET CAPACITY
C = kW/Ton.R AT 50% NET CAPACITY
D = kW/Ton.R AT 25% NET CAPACITY

Certified in accordance with the AHRI Water-Cooled Water Chilling and Heat Pump Water-Heating Packages Using Vapor Compressor Cycle Certification Program, which is based on AHRI Standard 550/590 (I-P) and AHRI 551/591 (SI). Certified units may be found in the AHRI Directory at www.ahridirectory.org. Auxiliary components included in total kW: Chiller Controls.
Compliant with ASHRAE 90.1-2004.
Compliant with ASHRAE 90.1-2007.
Compliant with ASHRAE 90.1-2010.
Compliant with ASHRAE 90.1-2013.
Compliant with ASHRAE 90.1-2016.
Compliant with the requirements of the LEED Energy and Atmosphere Enhanced Refrigerant

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Appendix D: Variable-Speed Water-Cooled HRC Data Tables

Table 12: Variable speed water-cooled heat recovery chiller - Manufacturer 3 (Unit 2)

PLR	Cooling Capacity (tons)	kW/ton	Input Power (kW)	$T_{cond,e}$ (°F)	$T_{cw,l}$ (°F)	EIR	Heating (mBH)
1.00	370	0.95	350.7	110	40	0.27	5,637
0.90	333	0.90	300.2	110	40	0.26	5,020
0.80	296	0.87	258.2	110	40	0.25	4,433
0.70	259	0.86	222.3	110	40	0.24	3,866
0.60	222	0.84	186.6	110	40	0.24	3,301
0.50	185	0.81	150	110	40	0.23	2,732
0.40	148	0.82	121.4	110	40	0.23	2,190
0.30	111	0.77	85.84	110	40	0.22	1,625
0.20	74	0.77	56.78	110	40	0.22	1,082

0.10	37	1.24	45.92	110	40	0.35	601
1.00	395	0.89	353.5	110	44	0.25	5,946
0.90	355	0.84	299.9	110	44	0.24	5,283
0.80	316	0.81	256.4	110	44	0.23	4,667
0.70	276	0.79	218.7	110	44	0.23	4,058
0.60	237	0.79	186.6	110	44	0.22	3,481
0.50	197	0.75	147.8	110	44	0.21	2,868
0.40	158	0.75	118.3	110	44	0.21	2,300
0.30	118	0.72	85.15	110	44	0.21	1,707
0.20	79	0.70	55.17	110	44	0.20	1,136
0.10	39	1.06	41.22	110	44	0.30	609
1.00	425	0.85	361.8	110	48	0.24	6,334

0.90	382	0.80	304.4	110	48	0.23	5,623
0.80	340	0.76	257.9	110	48	0.22	4,960
0.70	297	0.73	217.8	110	48	0.21	4,307
0.60	255	0.72	184.8	110	48	0.21	3,691
0.50	212	0.70	147.7	110	48	0.20	3,048
0.40	170	0.68	116.3	110	48	0.19	2,437
0.30	127	0.68	86.13	110	48	0.19	1,818
0.20	85	0.64	54.13	110	48	0.18	1,205
0.10	42	0.88	36.98	110	48	0.25	630
1.00	380	0.83	316.5	100	40	0.24	5,640
0.90	342	0.78	267.4	100	40	0.22	5,016
0.80	304	0.75	226.6	100	40	0.21	4,421

0.70	266	0.72	192.2	100	40	0.21	3,848
0.60	228	0.72	163.1	100	40	0.20	3,292
0.50	190	0.69	130.3	100	40	0.19	2,725
0.40	152	0.68	102.7	100	40	0.19	2,174
0.30	114	0.67	76.05	100	40	0.19	1,627
0.20	76	0.63	47.82	100	40	0.18	1,075
0.10	38	0.87	33.19	100	40	0.25	569
1.00	410	0.79	325.4	100	44	0.23	6,030
0.90	369	0.74	272.5	100	44	0.21	5,358
0.80	328	0.70	228.7	100	44	0.20	4,716
0.70	287	0.67	191.9	100	44	0.19	4,099
0.60	246	0.65	161	100	44	0.19	3,501

0.50	205	0.64	130.7	100	44	0.18	2,906
0.40	164	0.62	101.2	100	44	0.18	2,313
0.30	123	0.63	77.22	100	44	0.18	1,739
0.20	82	0.57	47.02	100	44	0.16	1,144
0.10	41	0.69	28.49	100	44	0.20	589
1.00	445	0.74	328.9	100	48	0.21	6,462
0.90	400	0.69	275.4	100	48	0.20	5,740
0.80	356	0.65	231.5	100	48	0.18	5,062
0.70	311	0.62	193.5	100	48	0.18	4,392
0.60	267	0.61	162.5	100	48	0.17	3,758
0.50	222	0.59	131.1	100	48	0.17	3,111
0.40	178	0.57	101.6	100	48	0.16	2,483

0.30	133	0.58	77.03	100	48	0.16	1,859
0.20	89	0.53	46.98	100	48	0.15	1,228
0.10	44	0.68	30.11	100	48	0.19	631

Table 13: Variable speed water-cooled heat recovery chiller Manufacturer 3 (Unit 1)

PLR	Cooling Capacity (tons)	kW/ton	Input Power (kW)	$T_{cond,e}$ (°F)	$T_{cw,l}$ (°F)	EIR	Heating (mBH)
1.00	385	1.30	501.5	130	40	0.37	6,331
0.90	346	1.21	418.4	130	40	0.34	5,580
0.80	308	1.15	353.2	130	40	0.33	4,901
0.70	269	1.12	302.4	130	40	0.32	4,260
0.60	231	1.10	253.7	130	40	0.31	3,638
0.50	192	1.08	208	130	40	0.31	3,014

0.40	154	1.05	161	130	40	0.30	2,397
0.30	115	1.07	122.9	130	40	0.30	1,799
0.20	77	0.98	75.15	130	40	0.28	1,180
0.10	38	1.43	54.43	130	40	0.41	642
1.00	420	1.30	544	130	44	0.37	6,896
0.90	377.9	1.19	449.8	130	44	0.34	6,070
0.80	336	1.11	371.8	130	44	0.31	5,301
0.70	294	1.06	311.5	130	44	0.30	4,591
0.60	252	1.06	267	130	44	0.30	3,935
0.50	210	1.01	212.6	130	44	0.29	3,245
0.40	168	1.01	169.3	130	44	0.29	2,594
0.30	126	0.98	123.1	130	44	0.28	1,932

0.20	84	0.94	78.65	130	44	0.27	1,276
0.10	42	1.16	48.88	130	44	0.33	671
1.00	435	1.24	541.2	130	48	0.35	7,067
0.90	390.9	1.14	443.7	130	48	0.32	6,205
0.80	348	1.05	366	130	48	0.30	5,425
0.70	304	1.00	304.4	130	48	0.28	4,687
0.60	261	0.99	259.4	130	48	0.28	4,017
0.50	217	0.95	207	130	48	0.27	3,310
0.40	174	0.96	166.5	130	48	0.27	2,656
0.30	130	0.91	118.9	130	48	0.26	1,966
0.20	87	0.89	77.11	130	48	0.25	1,307
0.10	43	1.06	45.49	130	48	0.30	671

1.00	405.1	1.24	501.3	120	40	0.35	6,572
0.90	364	1.13	410.8	120	40	0.32	5,770
0.80	324	1.04	337.7	120	40	0.30	5,040
0.70	283	0.99	279.5	120	40	0.28	4,350
0.60	243	0.98	237.3	120	40	0.28	3,726
0.50	202	0.94	189.9	120	40	0.27	3,072
0.40	162	0.95	153.8	120	40	0.27	2,469
0.30	121	0.90	108.8	120	40	0.26	1,823
0.20	81	0.88	71.46	120	40	0.25	1,216
0.10	40	1.04	41.69	120	40	0.30	622
1.00	440.1	1.24	543.8	120	44	0.35	7,137
0.90	395.9	1.12	443.5	120	44	0.32	6,264

0.80	352	1.02	358.2	120	44	0.29	5,446
0.70	308	0.95	291.3	120	44	0.27	4,690
0.60	264	0.91	241.1	120	44	0.26	3,991
0.50	220	0.89	196.5	120	44	0.25	3,310
0.40	176	0.88	155.5	120	44	0.25	2,643
0.30	132	0.84	110.9	120	44	0.24	1,962
0.20	88	0.86	75.35	120	44	0.24	1,313
0.10	44	0.90	39.47	120	44	0.26	663
1.00	455	1.19	540.2	120	48	0.34	7,303
0.90	409	1.07	436.4	120	48	0.30	6,397
0.80	364	0.97	352.1	120	48	0.28	5,569
0.70	318	0.90	285.3	120	48	0.26	4,789

0.60	273	0.86	234.7	120	48	0.24	4,077
0.50	227	0.84	191.6	120	48	0.24	3,378
0.40	182	0.83	150.3	120	48	0.23	2,697
0.30	136	0.79	107.4	120	48	0.22	1,998
0.20	91	0.81	73.75	120	48	0.23	1,344
0.10	45	0.82	36.7	120	48	0.23	665
1.00	425	1.19	504.6	110	40	0.34	6,822
0.90	382	1.07	408.4	110	40	0.30	5,977
0.80	340	0.96	328	110	40	0.27	5,199
0.70	297	0.89	263.3	110	40	0.25	4,462
0.60	255	0.85	215.6	110	40	0.24	3,796
0.50	212	0.83	176.8	110	40	0.24	3,147

0.40	170	0.81	137.6	110	40	0.23	2,509
0.30	127	0.78	98.76	110	40	0.22	1,861
0.20	85	0.81	69.16	110	40	0.23	1,256
0.10	42	0.80	33.58	110	40	0.23	619
1.00	455	1.18	535	110	44	0.33	7,285
0.90	409.1	1.05	430.8	110	44	0.30	6,379
0.80	364	0.94	342.5	110	44	0.27	5,537
0.70	318	0.85	271.3	110	44	0.24	4,742
0.60	273	0.80	218.6	110	44	0.23	4,022
0.50	227	0.79	178.2	110	44	0.22	3,332
0.40	182	0.76	137.8	110	44	0.22	2,654
0.30	136	0.74	100	110	44	0.21	1,973

0.20	91	0.76	69.04	110	44	0.22	1,328
0.10	45	0.72	32.23	110	44	0.20	650
1.00	475	1.14	541.4	110	48	0.32	7,547
0.90	426.9	1.01	433.1	110	48	0.29	6,601
0.80	380	0.90	342.6	110	48	0.26	5,729
0.70	332	0.81	269.9	110	48	0.23	4,905
0.60	285	0.76	215.9	110	48	0.22	4,157
0.50	237	0.73	174.1	110	48	0.21	3,438
0.40	190	0.71	135.1	110	48	0.20	2,741
0.30	142	0.69	98.6	110	48	0.20	2,040
0.20	95	0.70	66.2	110	48	0.20	1,366
0.10	47	0.65	30.71	110	48	0.19	669