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FINAL PROJECT REPORT

Development of an Advanced High-Temperature Heat Pump for the Efficient Recovery of Low-Grade Industrial Waste Heat:

Innovative Technology for Industrial Decarbonization

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Finally, EPRI would like to dedicate this final report in memory of Professor Predrag "Pega" S Hrnjak, who passed away in August 2022. Pega was the Director of the Air Conditioning and Refrigeration Center at the University of Illinois, Urbana-Champaign, and the CEO of CTS and CTS4CA. On this project, Pega led the CTS and CTS4CA teams in the development and management of the high-temperature heat pump technology. The project team acknowledges Pega for his significant contributions to the project.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Development of an Advanced High-Temperature Heat Pump for the Efficient Recovery of Low-Grade Industrial Waste Heat: Innovative Technology for Industrial Decarbonization is the final report for the project EPC-19-024 conducted by the Electric Power Research Institute. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

According to the U.S. Department of Energy, it is estimated that approximately 35 percent of industrial energy input for process heating is lost as waste heat in the form of exhaust gases, cooling water, and heat loss from product heating. The waste heat inventory in the industrial sector in the United States is estimated to be on the order of 1,500–3,000 trillion British thermal units per year (1.58–3.17 exajoules). This project was aimed at developing an industrial heat pump that can capture low-grade industrial waste heat (around 158–176°F [70–80°C]) and transform it into high-temperature useful heat, specifically in the form of steam. This report also discusses the use of a low global warming potential refrigerant (R1233zd(E)) that can provide a temperature lift of at least 104°F (40°C), thereby producing steam, with a coefficient of performance greater than 3.4. Industries such as food processing, chemicals, paper, and textile industries can make use of this steam. Results from the prototype laboratory testing show that, with the newer and emerging refrigerants, efficient compressors, and innovative control designs, a higher coefficient of performance heat pump that can effectively recover waste heat from the industrial processes is achievable. The industrial waste heat recovery heat pumps offer multiple benefits to industrial customers: firstly, they produce useful heat in the form of steam; secondly, they lower fossil fuel energy use by reusing the otherwise wasted heat energy and thereby reduce emissions due to combustion; and, finally, by using clean energy electricity, they additionally lower emissions and help in industrial decarbonization. In summary, even though there is no one "silver bullet" solution for industrial decarbonization, industrial high-temperature heat pumps offer a great pathway for industries to achieve their carbon reduction targets. Governments around the world should fund more research to develop high-performance refrigerants and innovations in heat pump technology design that could potentially combat the climate crisis more effectively and efficiently.

Keywords: industrial heat pump, waste heat recovery, steam-producing heat pump, high temperature, food manufacturing, chemical manufacturing, pulp and paper manufacturing

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TABLE OF CONTENTS

Acknowledgements i

Preface ii

Abstract iii

Executive Summary 1

Introduction or Background 1
Project Purpose 1
Project Approach 2
Project Results 3
Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market) 4
Key Advantages of the HTHP Design 6
Benefits to California 6

CHAPTER 1: Introduction 10

Overview 10
Project Goals and Objectives 11
Project Task Description 11
Benefits to California 12
Lead Organization, Partners, and Technical Advisory Committee 13
Chapter Organization 14

CHAPTER 2: Breadboard System Design and Test Plan 15

Refrigerant Selection 15
Breadboard System Design 17
Breadboard System Components 18
Test Plan Description 20

Inputs, Outputs, and Other Key Parameters 23

CHAPTER 3: Performance Testing of the Breadboard 24

Instrumentation 24

Controls and LabVIEW Arrangement 25

Data Collection and Analysis 26

Calculation of Balances 30

Results 31

Effect of Relative Compressor Size 31
Effect of Water Source Temperatures for Various Steam Conditions 34

Conclusion 36

CHAPTER 4: Prototype Development and Testing 38
Design of the Prototype 38
Test Methodology of the Prototype 41
Heating capacity (Q_h) 42
Data Analysis 43
M&V of the Data Analysis 43
Conclusion 47
CHAPTER 5: Evaluation of Project Benefits 48
Technology Potential Benefit 48
Lower Cost 48
Lower Maintenance 48
Economic Development 49
Environmental Benefits 49
Energy Efficiency 49
CHAPTER 6: Technology/Knowledge Transfer Activities 50
Market Characterization 50
Total Addressable Market 50
Path to Commercialization 50
Market Barriers 51
Product Availability and Economics 51
Overcoming Safety Concerns 51
Well-Documented Performance History 51
Sales and Service Support 52
Technology Transfer Conduits 52
Retailers 55
Government 55
Codes and Standards 55
Utilities 56
Technology Transfer 56
Fact Sheet 56
Industry Conferences and Journals 57
EPRI Activities 60
Utility Incentive Programs and Applicable Codes and Standards 60
Utility Incentive Programs 61
Applicable Codes and Standards 61
CHAPTER 7: Production Readiness Plan 62

System Features 62
Boundary Conditions 62
Refrigerant 62
Compressors 63
Heat Pump Configuration 63
Production Requirements 64
Condensers 64
Evaporators 65
Compressors 65
Expansion Valve 66
Configurations and Control System 67
Estimated Cost of Production 67
Expected Investment Needed to Launch a Commercial Product 69
Getting to Scale 69
Conclusion 71
CHAPTER 8: Concluding Remarks 72
List of Terms/Glossary 73
References 76
Appendix A: List of Input, Output, and Instrumentation Used in Prototype Testing A-1
Input, Output, and Other Key Parameters A-1
List of Instruments A-2
Appendix B: Details of the HTHP Market B-1
Overview of Market Size B-1
Commercial Heat Pump Models Available in the Market Today, by Heating Capacity and Temperature Range B-2
Appendix C: Supplemental Technology Transfer Content C-1
Applicability of HTHPs for California C-1
The State-of-the-Art of the IHP Technology and Ranges of Temperatures Achieved by Demonstration Projects Around the World C-3
Understanding The Potential Market Barriers to HTHP Manufacturing and Adoption C-5
Lack of Commercial HTHP Product Availability and Awareness C-5
Slow Rate of Replacement of Legacy Boiler Systems C-5
Customer Payback Period Expectations for Adopting New Technologies C-5

LIST OF FIGURES

Figure ES-1: Comparison of COP for a Given Heating Capacity Between R245fa, R1233zd(E) and R1336mzz(Z) 3
Figure 1: Project Team – Organization Chart 14
Figure 2: Simplified Schematic of the Heat Pump Cart 17
Figure 3: Schematic Drawing of the Breadboard Components 19
Figure 4: The Heat Pump Cart, Front View 19
Figure 5: The Heat Pump Cart, Rear View 20
Figure 6: The Heat Pump Breadboard System in the Laboratory 20
Figure 7: The LabVIEW Main Screen 26
Figure 8: Comparison of COP for a Given Q_h Between R245fa, R1233zd(E), and R1336mzz(Z) 31
Figure 9: Comparison of Compressor Efficiency for a Given Speed Between R245fa, R1233zd(E), and R1336mzz(Z) 32
Figure 10: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R245fa 33
Figure 11: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R1233zd(E) 33
Figure 12: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R1336mzz(Z) 34
Figure 13: Sensitivities of System Performance Based on Delivered Steam Conditions 35
Figure 14: Installation of Heat Pump Enclosure on the Electrical Panel Side of the Prototype System 39
Figure 15: Installation of an Electrical Panel on a New Enclosure of the Prototype System 40
Figure 16: Heat Pump Prototype With Enclosure 41
Figure 17: Schematic Diagram of the Prototype System 42
Figure 18: Heating Capacity (Left) and COP (Right) of Prototype System at 60 Hz Compressor Speed 43
Figure 19: Heating Capacity (Left) and COP (Right) of Prototype System at 80 Hz Compressor Speed 43
Figure 20: The Influence of Each Key Component in an HTHP 64
Figure 21: Condenser Unit of an HTHP With the Compressor 65
Figure 22: Reciprocating Compressor 66
Figure 23: Expansion Valve 66
Figure 24: Control Board for the Heat Pump Unit 67

Figure 25: The Cost per Kilowatt Based on the Mean Temperature Lift 68
Figure 26: The Cost per Kilowatt Based on Supply Temperature 69
Figure 27: Schematic Overview of the Aspects Impacting Technology Development Toward Market Deployment 70
Figure 28: Illustration of the Ways for End-Users to Put Together Their Energy Supply 71
Figure B-1: Current Installations of Industrial Heat Pumps in the European Union B-1
Figure B-2: Current Installations of IHPs in Japan B-2
Figure C-1: Industrial Natural Gas End-Use for California C-1
Figure C-2: Industrial Natural Gas Consumption in California (by 2-Digit Standard Industry Classification (SIC) Grouping) C-2

LIST OF TABLES

Table ES-1: Technoeconomic Metrics 4
Table 1: Thermophysical Properties, Compared With R245fa 15
Table 2: ASHRAE Standard 34 – Refrigerant Safety Group Classifications 16
Table 3: Refrigerant Performances Based on Vapor-Compression Cycle Simulation 16
Table 4: Compressor Speeds When Evaluating the Relative Size of the Compressor 21
Table 5: Temperatures of the Heat Source (Water) and the Steam to Evaluate Their Effect on HTHP Performance 22
Table 6: Input Parameters Used in the Breadboard System Testing 23
Table 7: Output Parameters Used in the Breadboard System Testing 23
Table 8: Key Parameters Used in Performance Calculations of the Breadboard System Testing 23
Table 9: Instrumentation Specifications* 24
Table 10: Overview of the Controls 25
Table 11: Experimental Data Collected During the Breadboard Testing 28
Table 12: M&V of Heating Capacity of the Prototype Heat Pump 45
Table 13: M&V of Compressor Input Work of the Prototype Heat Pump 45
Table 14: M&V of COP of the Prototype Heat Pump 46
Table 15: Conferences, Meetings, and Other Events Where Project Information Was Showcased 53

Table 16: Heat Pump Conferences for Technology Transfer Efforts 57

Table 17: Industries and Their Associated Conferences That Could Benefit From HTHP Technologies 58

Table A-1: Input Parameters A-1

Table A-2: Output Parameters A-1

Table A-3: Other Key Measurement Parameters A-1

Table A-4: Pressure Transducers A-2

Table A-5: Thermocouples A-2

Table A-6: Watt Transducer A-2

Table B-1: Overview of HTHP Products Available Worldwide B-4

Table C-1: Industrial Sectors with the Greatest Steam Use and Steam Temperature Distribution C-2

Table C-2: State-of-the-Art for the Industrial HTHP Technology Around the World C-3

EXECUTIVE SUMMARY

Introduction or Background

Low-temperature waste heat streams account for most of the industrial waste heat inventory. Waste heat is abundant at low temperatures in the range of 158–176˚F (70–80˚C), coming from cooling devices such as chillers (condensing heat), from open cooling processes, or from return condensate from steam applications, to mention just a few. A vast majority of industry needs for the low-pressure steam is in the range of 248–257˚F (120–125˚C). Industries such as food manufacturing, paper, chemicals, and textiles, can make use of this low-pressure steam.

Heat pumps can be used effectively for recovering waste heat. However, commercially available heat pumps currently cannot take advantage of high-temperature industrial processes, as they have an upper temperature range limit below 212°F (100°C). Moreover, heat pumps available today use mostly refrigerants with high global warming potential (GWP) (besides some carbon dioxide and ammonia). High-GWP refrigerants have a greater contribution to climate change, resulting in regulations requiring a significant reduction in the GWP of fluids used in air-conditioning and refrigeration equipment (UN Environment 2016). Currently, there is no commercially available high-temperature heat pump (HTHP) technology in the United States (and very few around the world) that uses a low-GWP refrigerant that can cost effectively recover low-grade heat from industrial processes to transform it into useful heat such as low-pressure steam. Such heat pumps offer an ideal solution for the decarbonization of industry in California, as well as around the country and the world.

Project Purpose

This project's HTHP generates low-pressure steam at 248–257˚F (120–125˚C) in an energy-efficient and environmentally friendly way. The technology features:

- A new control strategy specifically for new near-zero refrigerants in the HTHP applications.
- Modified compressors with a much higher ratio of displacement versus motor power.
- A modified brazed plate heat exchanger (a heat exchanger with corrugated plates that combine to create channels through which a hot medium and a cold medium can be distributed) with different channels on the water and refrigerant side.

The advantages of this heat pump design are two-fold. First, it provides an immediate high-impact heat-pump-based decarbonization solution to industries in California. Second, the heat pump reclaims the waste heat from industry and uses it in the industrial processes, thereby increasing plant productivity and lowering energy intensity (reduced energy per pound of product produced). In addition to the system advantages, the industrial plant could also potentially reduce operation and maintenance costs associated with the fossil-fueled boiler. Such a demonstration project supports the technology transfer of such decarbonization

technology to other industries in the state of California and helps meet the overall statewide greenhouse gas (GHG) emission goals.

The goals and objectives of this project were to:

- Develop a single-stage HTHP that uses low-GWP refrigerant to recover waste heat from a heat source at 176˚F (80˚C) and provide a temperature lift of at least 104˚F (40°C) to a more useful temperature, in the form of low-pressure steam at 248˚F (120°C) or higher, with a coefficient of performance (COP), a measure of heat pump efficiency, greater than 3.4.
- Select an optimal refrigerant and optimize the control system.
- Test and optimize components of the breadboard (a foundation to construct and prototype) to develop them into an operational prototype in the laboratory to ensure that the technology is suitable for pilot-scale demonstration.
- Complete a thorough measurement and verification of the system to ensure that it meets the reliability, safety, and efficiency metrics.
- Through multiple technology-transfer efforts, impart the findings of the project to stakeholders and the public to stimulate adoption of the technology.

Project Approach

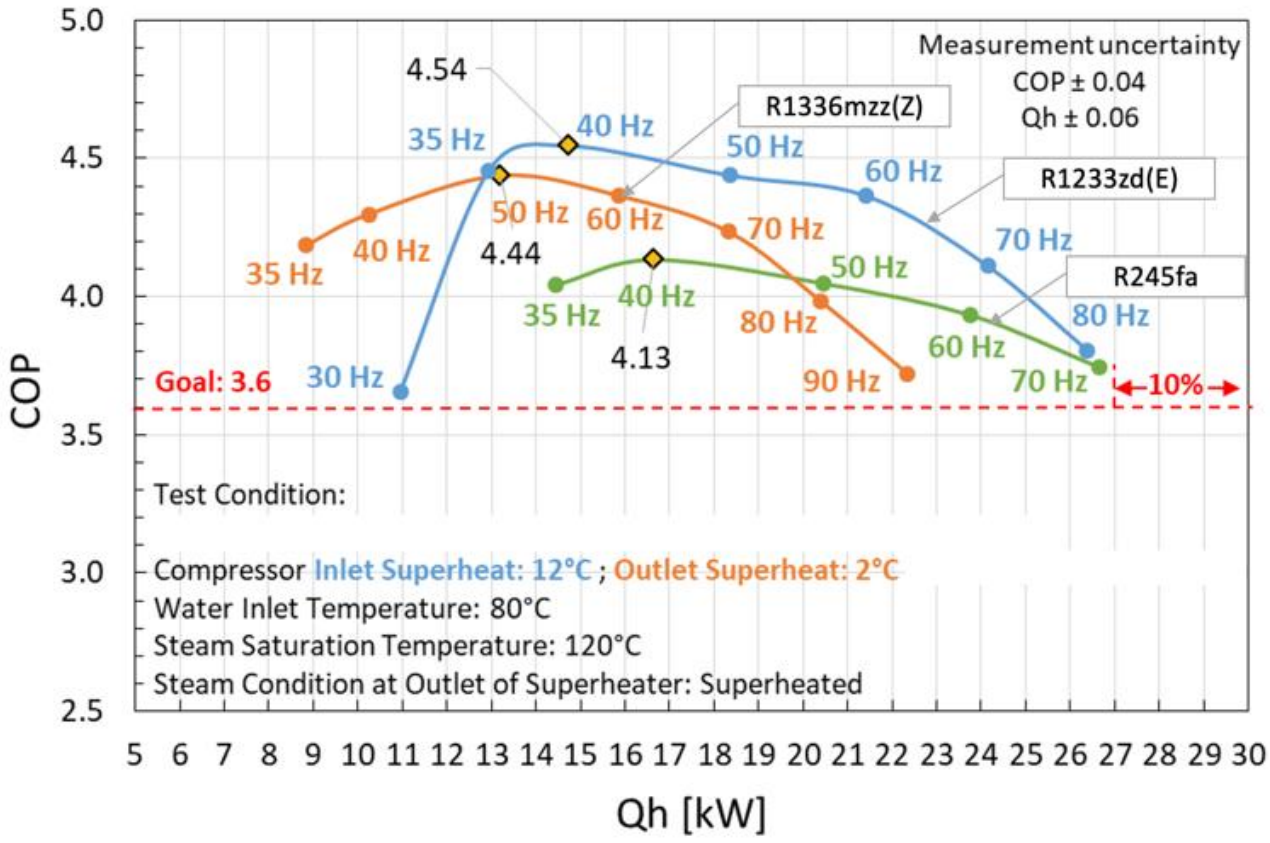
The project was divided into six stages: engineering design and prototype development, laboratory testing, performance evaluation, benefit evaluation, technology transfer, and commercialization/production readiness. In the engineering design and prototype development phase, Creative Thermal Solutions for California (CTS4CA) led the engineering design effort and assembled a prototype from breadboard components, including the selection of refrigerants. In the laboratory testing phase, CTS4CA and Electric Power Research Institute (EPRI) tested the prototype in the lab for 6 to 12 months, optimized the control system and the operational parameters, and gathered lab data for further analysis. The data has been processed and tabulated to obtain a full characterization of performance. In the performance evaluation phase, the team analyzed the lab data to ensure that the key performance indicators were met. In the benefit evaluation phase, EPRI determined and quantified benefits to California ratepayers, including energy cost reduction, operations and maintenance cost reduction, emissions reduction, increased reliability, improved safety, and improved efficiency. In the technology transfer phase, EPRI worked closely with world-class research organizations such as Électricité de France, to bring emerging heat pump design concepts from Europe to this research. This will help the project team identify cost-effective, reliable, safe, and proven solutions to be brought to the industries in California. In the commercialization phase, EPRI worked with world-renowned heat pump manufacturers such as Mayekawa in Japan to identify a path toward commercialization of the technology concept and to increase market adoption. Finally, an end-user, like La Habra Bakery (part of Kroger), provided project guidance on customer adoption and use.

Project Results

The chart shown in Figure ES-1 compares the test results for various refrigerants: R245fa (pentafluoropropane refrigerant, shown in green), R1233zd(E) (Solstice zd refrigerant, shown in blue), and R1336mzz(Z) (Opteon SF 33 refrigerant, shown in orange). The data shows that R1233zd(E) achieves the highest overall COP of 4.54, with a variable frequency drive (a type of AC motor drive that controls speed and torque by varying the frequency of the input electricity) set point of 40 hertz (`rated compressor speed). The x-axis represents the heating capacity (Q_h) (in kilowatts, kW, of the heat pump, and the y-axis represents the COP of the heat pump. The curves plotted for each refrigerant represent the COP of the system at various load conditions.

Based on these results, R1233zd(E) has been chosen as the refrigerant for this HTHP, based on its high capacity, high COP, below-5 GWP, and lower risk of air leaking into the system.

Figure ES-1: Comparison of COP for a Given Heating Capacity Between R245fa, R1233zd(E) and R1336mzz(Z)



Heating efficiency is plotted against heating capacity for various refrigerants tested.

Source: Prepared by CTS4CA for EPRI.

Following are the key findings from the laboratory testing of this HTHP.

- The COP shows that a higher value of 4.54 COP was achieved at 15 kW (20 horsepower [HP]).

- Repeatability: The HTHP system produced consistent test results under similar repeated test conditions. The heat pump was tested on an average of six to eight hours per day for five days a week continuously over six months.
- The system has been optimized to achieve an average COP of 3.6 at an average heating capacity of 25 kW (33.5 HP) (Q_h), and a COP of 4.0 was easily achieved at an average heating capacity of 20 kW (26.8 HP) (Q_h).

The results from the laboratory testing show that, with the newer and emerging refrigerants, efficient compressors, and innovative control designs, a higher COP heat pump (COP 3.6) that can effectively recover waste heat from the industrial processes is achievable. The industrial waste heat recovery heat pumps offer multiple benefits to industrial customers. They produce useful heat in the form of steam and they lower fossil fuel energy use by reusing the otherwise wasted heat energy, thereby reducing combustion emissions. And finally, if clean energy sources are used, it helps in industrial decarbonization.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The most dominant existing technology for steam production is gas-fired boilers. Such boilers have a significant carbon footprint. In comparison, industrial heat pumps that run on electric power have no onsite emissions. Also, their higher operational efficiency by a factor >3 (greater than three) makes them a highly promising technology for cost savings in industrial manufacturing facilities. Please see Table ES-1 for detailed technoeconomic metrics.

Table ES-1: Technoeconomic Metrics

Parameter	Industrial Heat Pump	Electrode Boiler	Natural Gas Boiler
Capital Cost	$785/kW	$90/kW	$14,500/MMBtu/h
Operation Cost	$335/kW	$35/kW	$6,200 MMBtu/h
Installation Cost	$1120/kW	$125/kW	$20,700/ MMBtu/h ($70/kW)
GHG Emission Factor (New)		0.063 mg/J for electricity generation; zero onsite emissions	0.05 mg/J
Operational Efficiency	COP = 3.4	98%	80%
Annual Energy Usage for 100 kW unit or 0.5 MMBtu/h	178,500 kWh	438,500 kWh	3,250 MMBtu
Annual Energy Cost $13.6/MMBtu of gas, $0.19/kWh electricity	$34,000	$84,000	$45,000

MMBtu/h = millions of British thermal units per hour; mg/J = milligrams per joule

The challenge is to bring down the cost of heat pumps, so that it is closer to boiler costs. The current projected costs (in the literature) are about an order of magnitude higher. In this project, efforts have been made to reduce the upfront cost by using heat pump components and configuration that are more cost-effective than the existing commercially available heat pump designs. One example is that a single-stage compressor has been used instead of a multi-stage compressor, and the compressor has a built-in control strategy specifically for new near-zero refrigerants in the HTHP applications.

Technology Readiness Level Discussion

Before the project began, the high-temperature heat pump (HTHP) concept was at an early stage of development, roughly technology readiness level 3. It had been validated only through simulations and basic breadboard testing, with no integrated prototype or field demonstration. The technology was considered promising, but it lacked proof of performance, reliability, and safety in a relevant environment.

After completion of the project, the HTHP advanced to approximately technology readiness level 5–6. A fully assembled prototype was designed, built, and tested in a controlled laboratory environment for six months, achieving and exceeding key performance targets (COP greater or equal to 3.4, steam at 120–125°C [248–257°F]). The system demonstrated stable operation, repeatability, and reliability under industrially relevant conditions, positioning it for pilot-scale field demonstration and paving the way toward commercialization.

Another aspect of this project was to transfer knowledge gained widely. EPRI presented the details of this work at several key conferences that are of particular interest to HTHP technology transfer efforts. The various U.S. and international conferences included those of the American Council of Energy Efficient Engineers, the International Energy Agency, and the Emerging Technologies Coordinating Council. EPRI also showcased the details of this work in other EPRI-led events, such as the Electrification Conference and the EPRI Heat Pump Symposium.

There are several organizations around the world that are involved in developing HTHPs. For example, in Japan, Fuji Electric has developed an early commercial heat pump prototype that is capable of producing steam from waste heat. This heat pump is a 30 kW/40.2 HP exhaust heat recovery type steam-generating heat pump system that can produce 248˚F (120˚C) saturated steam[1] by means of efficiently recovering hot wastewater of less than 212˚F (100˚C) (Fuji Electric Global, n.d.). Similarly, in the Netherlands, a high-lift heat pump with a four-cylinder double acting alpha design configuration was designed having a rated heat output of 750 kW for industrial applications with sink temperatures up to 392°F (200°C). This heat pump utilizes waste heat between 32°F (0°C) and 212°F (100°C) as a source and can perform temperature lifts of up to 270°F (150°C) (Högnabba et al. 2024; Peureux et al. 2014). Also, MAN Energy Solutions has developed a heat pump solution that operates on N-Butane (R-600) refrigerant and delivers medium pressure steam between 5 and 13 bars; it is suitable for many industrial processes (Toebben et al. 2024). Industrial heat pump research is a hot research area, and many heat pump manufacturers headquartered outside the U.S. — such as

[1] Note, saturated steam is steam at the boiling point for its pressure — fully vaporized but not heated beyond that point.

GEA, Oilon, and Armstrong — are attempting to bring their products into the U.S., which is helping to promote this research. At the same time, a few U.S. manufacturers are attempting to break through in the industrial heat pump space, such as Skyven Technologies, Atmos Zero, and Thar Energy.

By analyzing recent research projects focused on industrial heat pump technologies, the project team identified several insights that inform commercialization strategies and installation considerations. These projects provided real-world data and case studies that revealed key market drivers and technical challenges. First, industrial facilities are more likely to adopt energy efficiency technologies when they can achieve operational cost savings, typically aiming for a two- to-three-year simple payback on capital investments. However, research findings show that, even when cost savings are limited, companies may pursue heat pump adoption for nonfinancial benefits, such as reducing carbon dioxide emissions and improving air quality (e.g., lowering SOx and NOx). Another insight from these projects is that site-specific physical constraints can significantly affect installation feasibility and costs. Additionally, accurate knowledge of process heat demand is critical for sizing heat pumps correctly; research demonstrated that boilers are often oversized, leading to overestimated heat pump capacity and higher costs. Finally, the projects highlighted the importance of increasing awareness of high-temperature heat pump capabilities among stakeholders — users, consultants, designers, and installers — through targeted training and knowledge-sharing events.

Key Advantages of the HTHP Design

The advantages of this CEC-funded HTHP design are two-fold. Firstly, the heat pump design offers significant energy efficiency improvements compared to traditional boilers. Traditional methods of producing steam using natural gas or electricity can reach up to a maximum of 100-percent efficiency; however, the electric HTHP can reach a COP of 300 percent or greater. The HTHP discussed in this paper was able to achieve a COP of 3.6 (efficiency of 360 percent) at the rated conditions. The energy efficiency advantage lies in the fact that heat pumps operate by transferring heat from a low-temperature source to a higher-temperature sink. Instead of directly generating heat, they leverage the principles of thermodynamics to move heat against the temperature gradient. This process requires less energy compared to traditional heating or cooling methods that rely on direct heat generation or mechanical cooling. Hence, this HTHP provides an immediate, high-impact, high-efficiency decarbonization solution to industries such as chemicals, textiles, and food processing. Secondly, the heat pump will reclaim the waste heat from the industry and use it by returning it back to the industrial processes and reducing fossil-fuel consumption. Therefore, the heat pump reduces overall emissions associated with combustion.

Benefits to California

This project will benefit California investor-owned utility electricity ratepayers by demonstrating the potential of energy efficiency, emission reductions, and cost savings generated by the innovative heat recovery HTHP system, which uses a near-zero GWP

refrigerant solution for electrifying heating loads in industrial facilities. The specific benefits to be realized with this project are as follows.

- Lower costs: The system is lower in cost, as compared to other similar systems that are under development. It also provides energy savings over conventional boiler systems. Compared to the traditional boilers used for steam generation, the cost savings across three industries (food, chemical, and paper), where the HTHP has broader application, is estimated to be around $56 million per year.

  The industrial steam use from the three industries (food, paper and chemical) is estimated at about 359 million therms of natural gas consumption; this is approximately 11 percent of natural gas used in California industries for process heating and steam, based on 3,376 million therms of natural gas annually used in the industrial sectors across California to generate process heating or used in boilers to generate steam or hot water for industrial processes. This represents the total potential market, and this is a conservative estimate as it does not include contributions from other industries such as textiles, wood products, or plastics, where this technology could also be used. The annual energy equivalent used for steam generation across the three industries if HTHP were used, with the COP of 3.4 and the boiler efficiency of 80 percent, is 2,334 gigawatt-hours (GWh) per year (approximately equal to 80 million therms per year, where 1 million therms equals 29.30 GWh).

  Cost savings are estimated by assuming a natural gas price of $0.92 per therm and an electricity price of $0.1175 per kWh for industrial customers. The cost savings represent the savings from the chemical, food, and paper industries. The annual energy cost for steam production with conventional boilers is $330,280,000 per year (based on usage of 359 million therms per year). The equivalent annual electric energy usage with HTHP is $274,245,000 per year (based on 2,334 GWh per year). This results in a total cost savings across the three industries for the state of California of $56,035,020 per year.

  Such savings will flow into the economy and provide value to California investor-owned utility ratepayers.

- Environmental benefits: The potential greenhouse gas savings through the system integration and implementation at industrial facilities could prevent 1.37 million metric tons of carbon dioxide equivalent ($MTCO_2e$) per year in California. This can reduce the impacts from GHG emissions in California.

  To calculate the GHG savings, it is assumed that the natural gas emissions rate is 0.00531 $MTCO_2$ e per therm and the electricity grid emissions rate is 0.2278 $MTCO_2e$ per megawatt-hour. Based on 359 million therms of annual boiler energy usage, the equivalent electric energy usage from the HTHP with a COP of 3.6 is 2334 GWh per year. For the selected three industries, the annual GHG emissions from boiler usage for steam production is 1,906,290 $MTCO_2e$. The equivalent HTHP GHG emissions are just 531,903 $MTCO_2e$ annually. Therefore, the resulting emissions savings comparing electric HTHP to natural gas boilers is 1,374,387 $MTCO_2e$ per year. This is a

conservative value, which will go up when the electric sector incorporates more renewables in the later years.

- Potentially lower maintenance: The potential for reduced maintenance in industrial heat pumps comes from the absence of components that typically drive the maintenance effort in combustion-based systems, such as burner assemblies, fuel delivery lines, flue-gas exhaust handling, and periodic cleaning of heat-transfer surfaces due to fouling and corrosion from combustion byproducts. Heat pumps, instead, rely on sealed refrigeration circuits and electrically driven compressors, which require different (and often more predictable) maintenance, such as refrigerant leak checks, compressor monitoring, and pressure/temperature control validation. While the project team didn't have sufficient operating data from this project due to its R&D nature, early indicators — supported by field experience from other industrial heat pump deployments — suggest fewer unplanned outages related to fuel handling, burner tuning, and emissions compliance (citation). However, pump and compressor maintenance remains critical and may require skilled technicians familiar with high-pressure refrigeration systems.
- Energy security: Heat pumps transfer heat from a source fluid stream to a second, output fluid stream. This process of transferring heat is more efficient than the process used in fossil-fuel-fired boilers where heat is created by burning the fuel. Hence the COP for an industrial heat pump is greater than 1. For the HTHP developed in this project, hot water at 176˚F (80˚C) can be supplied to the heat pump, and output steam of 248°F (120˚C) can be obtained at a COP of 3.4 or greater. This lowers overall energy dependence and results in conservative energy savings of about 351 million therms (37 petajoules) per year for the three industries. The use of industrial heat pumps as the primary energy source for steam generation also means that existing gas-fired boiler installations may need to be used only in backup circumstances. Additionally, industrial heat pumps can be paired with renewable energy generation sources, unlike fossil fuel fired boilers, which can further reduce dependence on fossil fuels and enhance the resilience of the energy grid. These aspects improve energy security from the perspective of industrial facilities as well as electric utilities.
- Economic development: The prototype system, once commercialized, can be easily deployed across several industries in California. It will create local manufacturing jobs as well as a robust supply chain in the state and across the country. The development and field testing of this advanced industrial high-temperature heat pump prototype is a critical step toward building a robust, domestic supply chain for next-generation thermal decarbonization technologies. By demonstrating reliable performance under real industrial conditions, the project reduces market and technology risk, creating clear demand signals for U.S. manufacturers and component suppliers. Prototype deployment enables early identification of key supply needs — including high-pressure compressors, advanced heat exchangers, and control systems — while establishing partnerships and redundancy among vendors. In parallel, hands-on engagement with installers, operators, and service technicians helps build the skilled workforce needed for broad adoption. The insights from this project also inform standards, codes, and safety requirements that streamline future commercialization. Together, these actions help

accelerate scaling, strengthen domestic manufacturing capability, and ensure resilient supply chain readiness to meet emerging industrial electrification needs.

CHAPTER 1: Introduction

Overview

Low-temperature waste heat streams account for the majority of the industrial waste heat inventory. There is an abundance of waste heat at low temperatures in the range of 158–176˚F (70–80°C), coming from cooling devices such as chillers (condensing heat), from open cooling processes, from return condensate from steam applications, and so on. The vast majority of industry needs for steam is in the range of 248–257˚F (120–125˚C). Industries such as food manufacturing, paper, chemicals, and textiles can make use of this low-pressure steam.

Heat pumps can be effectively used for recovering waste heat. However, commercially available heat pumps currently cannot take advantage of high-temperature industrial processes, as they have an upper temperature range limit below 212°F (100°C). Moreover, heat pumps available today use mostly refrigerants with high global warming potential (GWP) (besides some carbon dioxide [CO_2] and ammonia [NH3]), whose leakage into the atmosphere has the potential to offset any gains made in decarbonization through electrification. Currently, there is no commercially available high-temperature heat pump (HTHP) technology in the United States that uses a low-GWP refrigerant that can cost effectively recover low-grade heat from industrial processes to transform it into useful heat, such as low-pressure steam. Such heat pumps offer an ideal solution for the decarbonization of industry in California, as well as around the world.

The HTHP prototype developed under this project can generate low-pressure steam at 248–257˚F (120–125˚C) in an energy-efficient and environmentally friendly way. The HTHP technology features:

- A new control strategy specifically for new near-zero refrigerants in the HTHP applications. This advanced control strategy allows the superheat to occur at the compressor discharge stage rather than superheat exiting the evaporator. This prevents liquid from entering the compressor. This advanced control strategy, which regulates superheat at the compressor discharge rather than the evaporator outlet, offers significant benefits for HTHPs using new refrigerants. Ensuring that only vapor enters the compressor minimizes the risk of liquid slugging, thereby enhancing compressor reliability, longevity, and safety. It also provides better adaptability to the unique thermodynamic properties of low-GWP refrigerants and improves performance under dynamic conditions. This approach enables more accurate, responsive, and efficient system control, especially in applications with variable loads and high-temperature lifts.
- Modified compressors with a much higher ratio of displacement versus motor power. Such a modified compressor allows the heat pump to move more refrigerant per unit of motor input, improving efficiency and performance — especially under high-lift and low-suction conditions. This design reduces motor stress, enhances volumetric efficiency,

and enables better handling of low-density or low-pressure refrigerants, resulting in a higher coefficient of performance (COP), greater reliability, and improved suitability for HTHP applications using next-generation refrigerants.

- A modified heat exchanger, a brazed plate heat exchanger, with different channels on the water and refrigerant sides. The modified brazed plate heat exchanger offers enhanced thermal performance and pressure handling for HTHP applications. By optimizing flow distribution and turbulence separately for each fluid, it improves heat transfer efficiency, reduces pressure drop, and allows for compact design, even under high operating temperatures and pressures. This tailored configuration enhances system COP, supports stable operation with new refrigerants, and increases overall reliability compared to traditional symmetric-channel designs.

The advantages of this heat pump design are two-fold. First, it will provide an immediate high-impact, heat-pump-based decarbonization solution to the industries in California. Second, the heat pump will reclaim the waste heat from industry and use it in the industrial processes, thereby increasing plant productivity and lowering energy intensity (reduced energy per pound of product produced). In addition to the system advantages, the industrial plant could also potentially reduce the operating and maintenance costs associated with fossil-fueled boilers. Such a demonstration project will support the technology transfer of such decarbonization technology to other industries in the state of California and help meet the overall statewide greenhouse gas (GHG) emission goals.

Project Goals and Objectives

The goals and objectives of this project were to:

- Develop a single-stage HTHP that uses low-GWP refrigerant to recover waste heat from a heat source at 176°F (80°C) and provide a temperature lift of at least 104°F (40°C), to a more useful temperature, in the form of low-pressure steam at 248°F (120°C) or higher, with a COP greater than 3.4.
- Select an optimal refrigerant and optimize the control system.
- Test and optimize the breadboard components to develop into an operational prototype in the laboratory to ensure that the technology is suitable for pilot-scale demonstration.
- Complete a thorough measurement and verification (M&V) of the system to ensure that it meets the reliability, safety, and efficiency metrics.
- Through multiple technology-transfer efforts, impart the findings of the project to stakeholders and the public to stimulate the adoption of the technology.

Project Task Description

The project was divided into six stages: engineering design and prototype development, laboratory testing, performance evaluation, benefit evaluation, technology transfer, and commercialization/production readiness. The project was led by the Electric Power Research Institute (EPRI) and conducted jointly with Creative Thermal Solutions for California (CTS4CA)

and Électricité de France (EDF) (a list of the organizations involved is included in the section titled "Lead Organization, Partners, and Technical Advisory Committee"). In the engineering design and prototype development phase, CTS4CA led the engineering design effort and assembled a prototype from breadboard components, including the selection of refrigerants. In the laboratory testing phase, CTS4CA and EPRI tested the prototype in the lab for 6 to 12 months, optimized the control system and the operational parameters, and gathered lab data for further analysis. The data was processed and tabulated to obtain a full characterization of performance. In the performance evaluation phase, the team analyzed the lab data to ensure that the key performance indicators were met. In the benefit evaluation phase, EPRI determined and quantified benefits to California ratepayers, including energy cost reduction, operations, and maintenance cost reduction, emissions reduction, increased reliability, improved safety, and improved efficiency. In the technology transfer phase, EPRI worked closely with the world-class research organization EDF, to bring the cutting-edge heat pump designs that have been successfully implemented in Europe to this research. This helped the project team identify cost-effective, reliable, safe, and proven solutions to be applied to the industries in California. In the commercialization phase, EPRI worked with world-renowned heat pump manufacturers (such as Mayekawa in Japan) to identify a path toward commercialization of the technology concept and to increase market adoption.

Benefits to California

This project benefits California investor-owned utility electricity ratepayers by demonstrating the potential of energy, emissions, and cost savings generated by the innovative heat recovery HTHP system, which uses a near-zero GWP refrigerant solution for electrifying heating loads in the industrial facilities. The specific benefits realized with this project are as follows.

- Lower costs: The developed heat pump system provides energy savings over conventional boiler systems. Compared to the traditional boilers used for steam generation, the cost savings across three industries (food, chemicals, and paper) where the HTHP has broader application is $56 million per year. Savings can be transferred to California investor-owned utility ratepayers.
- Greater reliability for the electric grid: When replacing electrode boilers, the heat pump system helps cut peak electricity demand for heating, easing pressure on limited-capacity grid networks and improving overall system reliability.
- Increased safety: Electricity provides inherent safety benefits to the end-use customers. Heat pump technology is a clean-energy technology that is safer than the baseline natural gas boiler because there is no combustion involved.
- Economic development: The proposed system, once commercialized, will create local manufacturing jobs, as well as provide potential energy cost savings of $56 million per year in California that will flow into the economy, assuming full market penetration.
- Environmental benefits: The potential GHG savings through system integration and implementation at the industrial facilities could prevent 1.17 million metric tons of carbon dioxide equivalent ($MTCO_2e$) per year in California.

- Public health: The efficiency improvement of the system and its ability to reuse waste heat efficiently and the potential to limit or eliminate natural gas boilers can reduce overall emissions of the electricity industry by 1.17 million $MTCO_2e$ per year. This can significantly improve air quality for California ratepayers.
- Consumer appeal: In light of wildfires in recent years in California, more consumers are aware of the need for action against global warming. The heat pump system developed in this project provides them with a green, decarbonizing solution that can reduce their overall environmental and carbon footprint.
- Energy security: This heat pump system is at least 360 percent more efficient in producing low-pressure steam than the baseline gas boiler technology, and it very efficiently extracts low-grade waste heat from industrial facilities. This lowers the overall energy dependence and results in conservative energy savings of about 351 million therms (37 petajoules [PJ]) per year for the three industries, thus improving energy security.

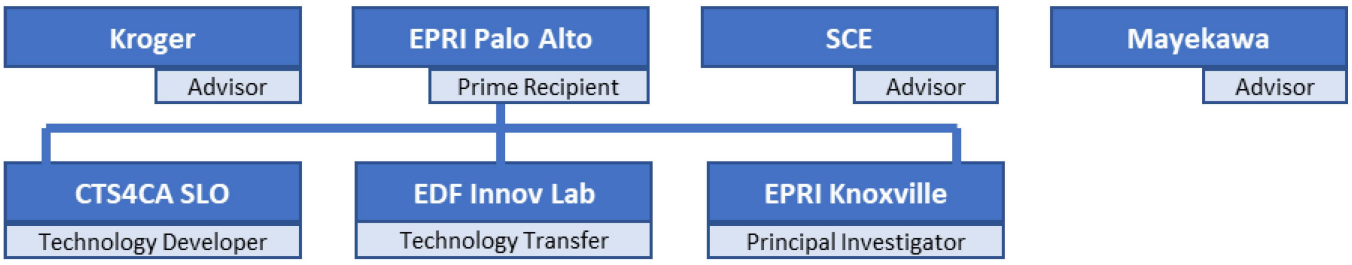
Lead Organization, Partners, and Technical Advisory Committee

The lead organization of this project, EPRI, conducts research and development relating to the generation, delivery, and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety, and the environment. In addition, EPRI's members comprise 90 percent of all electricity used in the U.S. and 35 percent of all electricity used in the rest of the world. EPRI's engagement with the utility industry is comprehensive and nationwide for capturing strategic elements for the research and development of advanced technologies.

Figure 1 shows the project's organizational structure. The multidisciplinary project team combined strong, leading organizations with expertise in heat pumps, industrial processes, beverage processing, waste heat recovery, and energy management. EPRI (located in Palo Alto, California), the prime recipient, was responsible for managing the research and coordinating interactions between researchers at its Knoxville, Tennessee facility, subcontractors, and industry advisors.

The supporting research was conducted at the CTS4CA facilities, located in Harmony, California. EDF Innovation Laboratory, located in Los Altos, California, primarily focused on technology transfer and market facilitation efforts. EDF is a France-based electric utility — one of the world's largest — and a leader in heat pump research and development. Southern California Edison (SCE) and Southern Company provided the utility advisory support, while Mayekawa (equipment manufacturer) and Kroger (end-user) closely advised EPRI on the research progress.

Figure 1: Project Team – Organization Chart



Source: EPRI

CTS4CA (a subsidiary of Creative Thermal Solutions [CTS] Illinois), led by the late Professor Pega Hrnjak, has arguably the most influential history of research and development in industrial heat pump technology in the U.S., with a focus on efficient, modern, and low-GWP and natural-refrigerants-based energy conversion systems. CTS has had a great history of tackling challenging thermal problems and providing unique and creative solutions. In addition to analysis and software development work, CTS provides custom design, assembly, and testing of various prototypes of heat pumps to meet client-specific heating and cooling needs. Mayekawa has been a world leader in the manufacture of ultra-efficient industrial heat pumps. The company focuses on moving new technologies to the laboratory to manufacturing. Finally, Kroger is one of the largest food processing/food service companies in the U.S. Its La Habra bakery is an industrial facility providing baked products to Kroger supermarkets.

Chapter Organization

There are eight main chapters in this report. The first chapter provides a brief overview of the industry and the motivation behind this project. Chapter 2 provides details about the breadboard design and test plan. Chapter 3 provides the performance testing summary and results of the breadboard design. Chapter 4 provides the development of a prototype design from the breadboard; it also provides the detailed performance testing results. Chapter 5 provides details about the project's benefits. Chapter 6 provides a summary of all the technology transfer activities. Chapter 7 provides the production readiness plan summary. Chapter 8 provides the conclusion and next steps.

CHAPTER 2:
Breadboard System Design and Test Plan

Refrigerant Selection

Selection of the appropriate refrigerant for the HTHP is of utmost importance for the successful implementation of the concept. In earlier days, R245fa (pentafluoropropane refrigerant) would have been the refrigerant of choice but, due to its environmental characteristics, it is used only as a baseline for this project.

The CTS4CA and EPRI team identified two refrigerants as possible replacement fluids for R245fa:

1. R1233zd(E) or Solstice zd, belonging to the category of hyrochloroflouroolefin (HCFO) refrigerants.
2. R1336mzz(Z) or Opteon SF 33, belonging to the category of hydrofluoroolefin (HFO) refrigerants.

Both pass the environmental criteria and, according to the manufacturers, are non-toxic. Table 1 provides the thermophysical properties of the three refrigerants.

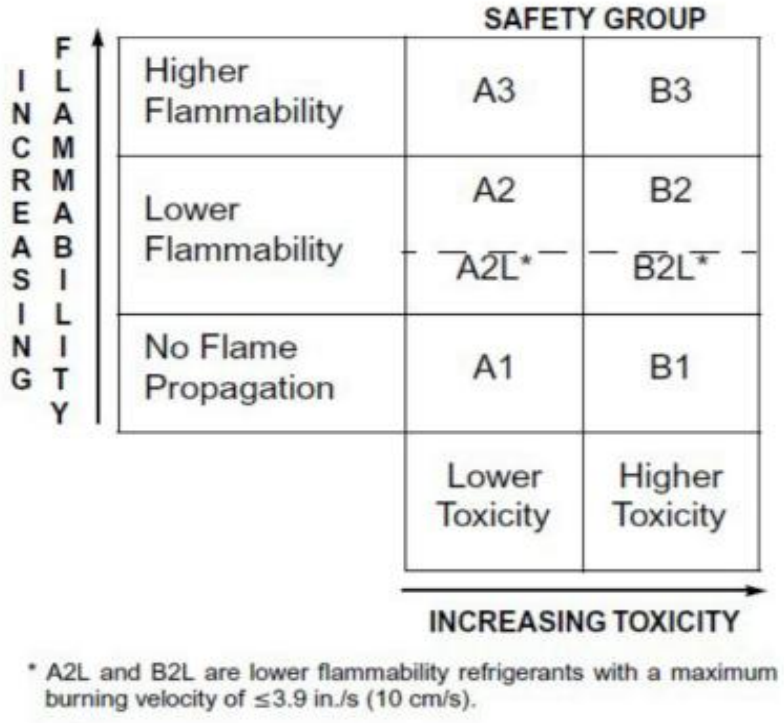
Table 1: Thermophysical Properties, Compared With R245fa

Refrigerant	Molecular Weight [g/mol]	Critical Temperature (Tcrit) [C]	Critical Pressure (Pcrit) [MPa]	Vaporization Heat [kJ/kg] at 125 [C]	Saturated Vapor Density [kg/m3] at 75 [C]	Ozone Depletion Potential (ODP) [-]	Global Warming Potential (GWP) [-]	ASHRAE Standard 34 Safety Class [-]
R245fa	134.0	153.9	3.65	105.1	38.3	0	858	B1
R1233zd(E)	130.5	166.5	3.62	117.6	30.7	0.00034	1	A1
R1336mzz(z)	164.1	171.4	2.90	107.1	24.4	0	2	A1

Key: g/mol = grams per mole, MPa = megapascal, kJ/kg = kilojoules per kilogram, kg/m^3 = kilograms per cubic meter, ODP = ozone depletion potential, GWP = global warming potential; ASHRAE = American Society for Heating, Refrigerating and Air Conditioning Engineers
Source: Arpagaus et al. 2018.

Both refrigerant candidates, R1233zd(E) and R1336mzz(Z), are acceptable from the perspective of the U.S. Environmental Protection Agency (EPA) and per ASHRAE safety group classifications shown in Table 2. To determine which of the two refrigerants performs better, they were evaluated by simulating an enhanced vapor compression cycle (enhanced through the presence of additional components in the cycle, compared to a conventional vapor compression cycle) and later validated using the breadboard design system.

Table 2: ASHRAE Standard 34 – Refrigerant Safety Group Classifications



Source: Safety group classification, according to ASHRAE Standard 34.

The results from the simulation are presented in Table 3. The first three rows show the absolute values based on the simulation, while the last three columns show the results of the alternative refrigerant simulation relative to the baseline R245fa-refrigerant-based cycle. It is seen that, for the baseline cycle, the total delivered capacity was 128 kilojoules per kilogram (kJ/kg) (55 British thermal units per pound [Btu/lb]), while the total power consumption was 34 kJ/kg (14.6 Btu/lb), yielding a COP of 3.73. In comparison, the R1233zd(E) refrigerant cycle had a 5-percent higher COP, and the R1336mzz(Z) refrigerant cycle had a 3.1-percent higher COP.

Table 3: Refrigerant Performances Based on Vapor-Compression Cycle Simulation

Refrigerants	Total heat output (q_tot) [kJ/kg]	Total heat output (q_tot) [kJ/m3]	Total thermal work (w_th) [kJ/kg]	Total electrical work (w_elec) [kJ/kg]	Thermal COP (COP_th)	Net COP
R245fa	128.11	4614.43	27.71	34.38	4.62	3.73
R1233zd(E)	138.83	4027.04	28.60	35.48	4.85	3.91
R1336mzz(z)	116.92	2706.68	24.54	30.44	4.77	3.84

Source: Testing performed at CTS4CA laboratory as part of this project.

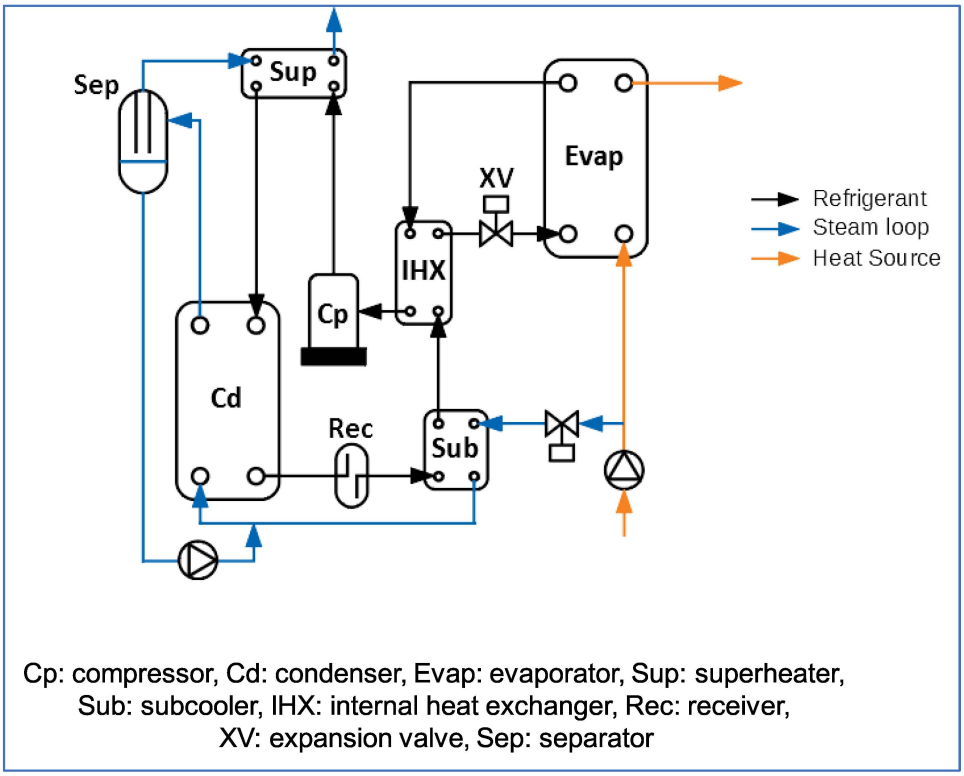
These results are very promising, considering that new refrigerants R1233zd(E) and R1336mzz(Z) show better results than R245fa, with the R1233zd(E) having the highest COP among all three refrigerants.

Breadboard System Design

The simplified schematic design of the breadboard system is shown in Figure 2. Refrigerant lines are shown in black while water lines are shown in blue.

The project team opted to use a regular, single-stage compressor while designing the HTHP to reach and exceed the targeted performance required by the contract. The compressor (indicated as Cp in Figure 2) discharges refrigerant to a superheater (Sup). The superheater serves to superheat the steam generated in the condenser (Cd). After the superheater, the refrigerant flows to the condenser (Cd) to be condensed. In that process, water on the other side is evaporated. The mixture of steam and water droplets goes to the separator (Sep), which sends saturated vapor to the superheater to be additionally heated and effectively prepared for supplying to the user. The condensed refrigerant flows to the high-pressure receiver (Rec) liquid after the receiver is subcooled in the subcooler (Sub); in the process, water is heated that will later be evaporated in the condenser. The recuperative "internal heat exchanger" (IHX) improves the performance of the system, taking care of the dry-out in the evaporator, and it increases the reliability of the compressor by reducing the chance of sending liquid to the compressor. The expansion valve (EXV) controls the flow of the refrigerant through the evaporator (Evap), which will generate refrigerant vapor to be sent to the suction of the compressor. This describes the refrigerant flow loop and the entire flow of water to be evaporated and turned into the superheated steam.

Figure 2: Simplified Schematic of the Heat Pump Cart



A diagram showing the components of the heat pump cart of the breadboard

Source: Prepared by CTS4CA.

The selection of components and the sizing of pipes are described in the following sections. The design is intended to maximize efficiency for a capacity in the range of 15–25 kilowatts (kW) (20.1–33.5 horsepower [HP]) in the required nominal temperature range of 176–248˚F (80–20˚C).

Breadboard System Components

The project team made the breadboard system design flexible in such a way as to:

1. Evaluate various refrigerants and select the most suitable refrigerant.
2. Evaluate the potential elimination of come components.
3. Evaluate the potential effect of the separation of the droplets from the steam.

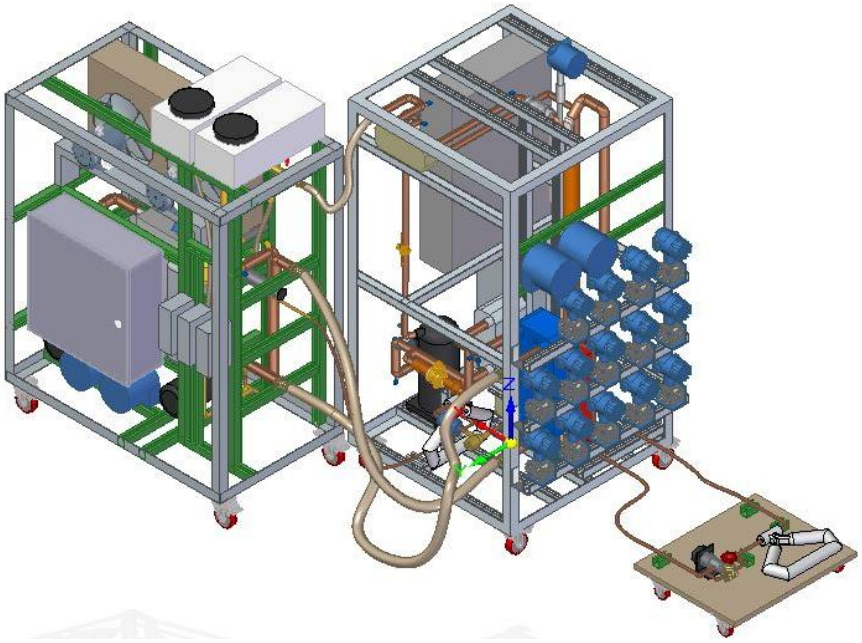
In addition, the project team designed the system in four major parts, as follows.

- Heat Pump Cart. The entire refrigerant and the heat pump system were in this cart. The cart was sized in such a way that it is reasonable when considering the physical size of a potential product. It provides the housing for the instruments needed to characterize the performances of components and the system as a whole. These instruments would eventually be removed during the prototype stage, once sufficient data was collected and analyzed. The cart had a full electric panel with only one variable frequency drive (VFD), for the compressor, being outside.
- Load Cart. The purpose of the load cart was to supply the necessary load that helps to condense the steam once it is generated and to recirculate it back to the system. The state points of the generated steam (pressure, temperature, mass flow rate, and so on) are measured in the load cart. Recirculation of steam helps to save energy and water. Like the heat pump cart, the electric panel for the components in the load cart is also an integral part of the cart.
- Water Cart. This was a small cart with a system to recirculate and measure the flow rate in the steam-generating loop. Eventually, this was removed during the prototype stage.
- Data Logger. A data logger and computer monitoring system were included in the breadboard system.

All instrumentation was attached to the appropriate cart. A compressor with hermetic construction was selected, providing the possibility for minimal refrigerant leak and fully automated operation. Besides, the hermetic design retained the heat of the motor in the system, increasing efficiency, assuming the motor is capable of operating at given temperatures. An Emerson (Copeland) scroll compressor was selected and was a robust and efficient option. All heat exchangers were of brazed plate design (a heat exchanger with corrugated plates that combine to create channels, through which a hot medium and a cold medium can be distributed), except the one that rejects the excess heat to the surrounding air. They were compact and cost-effective and could possibly be chemically cleaned if ever needed. The frames were made of sturdy angular iron construction with the Unistrut (iron

frame) system internally to create a flexible breadboard design in which the components could be easily replaced if needed. Figure 3, Figure 4, and Figure 5 show the schematic drawings, while Figure 6 shows the actual assembled breadboard system.

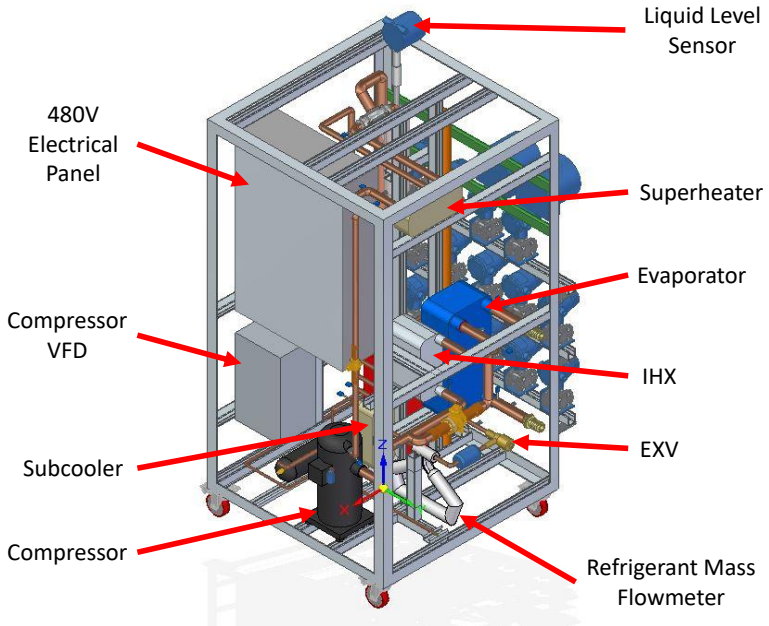
Figure 3: Schematic Drawing of the Breadboard Components



Load cart (left), heat pump cart (center), and water card (right)

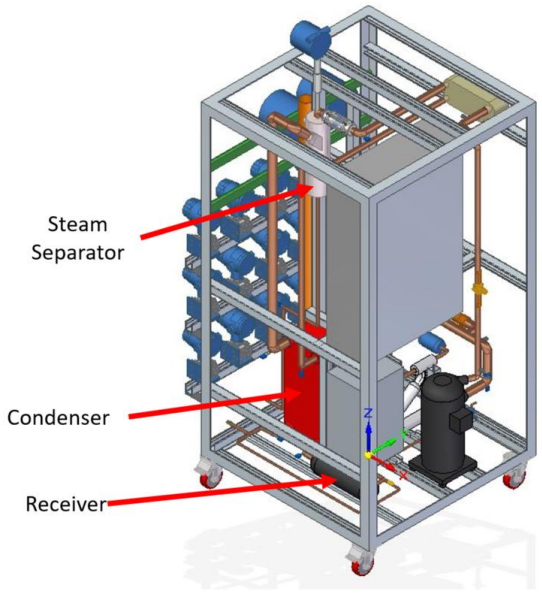
Source: Prepared by CTS4CA.

Figure 4: The Heat Pump Cart, Front View



Source: Prepared by CTS4CA.

Figure 5: The Heat Pump Cart, Rear View



Source: Prepared by CTS4CA.

Figure 6: The Heat Pump Breadboard System in the Laboratory



Heat pump cart (left), load cart (center), and water cart (right)

Source: Images taken at CTS4CA

Test Plan Description

The instrumentation and data loggers installed in the breadboard allowed the project team to measure system performance more accurately. The purpose of the breadboard/prototype testing was to evaluate the performance of the two refrigerants, R1233zd(E) and R1366mzz(Z), and to compare the COP to the currently available industry standard, hydrofluorocarbon (HFC) refrigerant, R245fa. The requirement of the project as per the California Energy Commission (CEC) award was to achieve a COP greater or equal to 3.4 when testing with a water source temperature of 176°F (80°C) and creating a 104°F (40°C) temperature lift, to create low-pressure steam at 248°F (120°C).

To provide a good balance, measurements were conducted in a steady state. Starting from room temperature, it typically took about one to one and one-half (1.5) hours for the HTHP to heat the water source to 176°F (80°C). Electric heaters boosted the source temperature. A manual pressure control valve set the steam saturation temperature to the required value. The EXV controlled the superheat at the inlet of the compressor, set at 54°F (12°C) for all tests. The steam loop pump controlled the steam mass flow rate. When a steady state was achieved, 10 minutes of data was recorded and stored in an Excel file. Mean values in time were taken from this data and used for further analysis. Among other variables, the analysis provided the COP for each test, which was determined by the equation:

$$COP = Q_h / W_{cp}$$

where Q_h is the heating capacity derived from the average of the water side and refrigerant side heating capacities, while W_{cp} is the measured compressor power (electrical unit).

In addition to the data required for this project, the team also evaluated two major empirical insights, namely:

1. The effect of the relative size of the compressor versus heat exchangers, which was evaluated through the variation of the compressor speed (size).
2. The effect of water source temperature for various steam conditions.

For that purpose, two test matrices were developed, as presented in Table 4 and Table 5.

1. Table 4: Compressor speeds when evaluating the relative size of the compressor
2. Table 5: Temperatures of the heat source (water) and the steam to evaluate their effect on the HTHP performance

Table 4: Compressor Speeds When Evaluating the Relative Size of the Compressor

Testing Variable	Objective	Constants	Variable Value (Frequency)
Compressor Speed	Evaluate the effect of the relative size of the compressor	$T_{satsupso}$=248°F (120°C) SH_{cpri}=53.6°F (12°C), T_{subwi}=176°F (80°C), SH_{supso}=superheated	30 hertz (Hz)
			35 Hz
			40 Hz
			50 Hz
			60 Hz
			70 Hz
			80 Hz
			90 Hz

Source: Prepared by CTS4CA.

Table 5: Temperatures of the Heat Source (Water) and the Steam to Evaluate Their Effect on HTHP Performance

Testing Variable	Objective	Constants	Steam Saturation Temperature [°F] (°C)	Water Source Temperature [°F] (°C)
Steam Saturation Temp and Water Source Temp	Sensitivity of performance on system inlet and outlet temperatures	Comp Speed (Frequency)=40Hz SH_{cpri}=12°C (53.6°F), SH_{supso}=superheated	221 (105)	176 (80)
			230 (110)	140 (60)
				158 (70)
				176 (80)
				194 (90)
			239 (115)	176 (80)
			248 (120)	140 (60)
				149 (65)
				158 (70)
				167 (75)
				176 (80)
				185 (85)
				194 (90)
			257 (125)	176 (80)
			266 (130)	140 (60)
				158 (70)
				176 (80)
				194 (90)
			275 (135	176 (80)
		Comp Speed (Frequency) =60Hz SH_{cpri}=12°C (53.6°F), SH_{supso}=superheated	221 (105)	176 (80)
			230 (110)	140 (60)
				158 (70)
			239 (115)	176 (80)
			248 (120)	140 (60)
				149 (65)
				158 (70)
				167 (75)
				176 (80)
			257 (125)	176 (80)
			266 (130)	140 (60)
				158 (70)
			275 (135)	176 (80)

Source: Testing performed at CTS4CA laboratory.

Inputs, Outputs, and Other Key Parameters

The inputs, outputs, and other key parameters measured and monitored are provided in Table 6, Table 7, and Table 8.

Table 6: Input Parameters Used in the Breadboard System Testing

Input	Input Name	Range	Description
Water source temperature (waste heat temp)	T_{subwi}	140-194°F (60–90°C)	Water temperature at the inlet of the subcooler
Low-pressure steam saturation temperature	$T_{satsupso}$	221-275°F (105–135°C)	Saturation temperature of superheated steam at exit of superheater
Compressor speed	N/A	30–90Hz	Speed of compressor in Hz

Source: Testing performed at CTS4CA laboratory.

Table 7: Output Parameters Used in the Breadboard System Testing

Output	Output Name	Description	Target
Heating capacity	Q_h	Amount of heat taken from high side heat exchangers and put into the steam loop	30 kW
Heating performance factor	HPF	Energy efficiency of heat pump system	>3.4

Source: Prepared by CTS4CA.

Table 8: Key Parameters Used in Performance Calculations of the Breadboard System Testing

Key Parameters	Parameter Name	Description
Compressor inlet superheat	SH_{cpri}	Amount of superheat at compressor suction
Steam separator water level	$level_{sepw}$	Saturated liquid level in steam separator
Steam superheat	SH_{supso}	Amount of superheat at exit of superheater
Temperature lift	N/A	Difference between water source temperature and steam saturation temperature

Source: Testing performed at CTS4CA laboratory.

CHAPTER 3:
Performance Testing of the Breadboard

This chapter details the instrumentation that was used for testing the breadboard design for the industrial heat pump. It also provides details of the performance testing that was conducted and the data analysis performed.

Instrumentation

The heat pump system contains the compressor (Cp) and various heat exchangers: Sup (superheater), Cd (condenser), Sub (subcooler), IHX (internal heat exchanger), and Evap (evaporator). Rec (receiver) is a refrigerant storage tank, while Sep (separator) helps to send only saturated vapor to the superheater. Instrumentation is presented mainly as boxes where T represents temperature, P–pressure, DP–pressure difference, and m–mass flow rate. Subscripts denote locations with the first letter(s): e–evaporator, cp–compressor, sup–superheater, c–condenser, sub–subcooler. The second letter in subscript denotes fluid: r–refrigerant, w–water, while the third denotes locations: i–inlet and o–outlet. Table 9 lists all the instruments with their respective uncertainties.

Table 9: Instrumentation Specifications*

Name	Range	Model	Uncertainty
P_{atm}	30 to 110 kPa (4.3 to 15.9 PSI)	BMP280+Arduino DUE R3 Board	±0.1 kPa
P_{cri}	0 to 2900 kPa (0 to 420.5 PSI)	Rosemount 1151GP8	±0.25% span
P_{ero}	0 to 1400 kPa (0 to 203 PSI)	Rosemount 1151GP8	±0.25% span
P_{cwo}	0 to 400 kPa (0 to58 PSI)	Rosemount 1151AP6	±0.25% span
DP_{supr}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{cr}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{recr}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{subr}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{IHXl}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{IHXv}	-37 to 37 kPa (-5.3 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{er}	0 to 76 kPa (0 to 11 PSI)	Rosemount 1151DP5	±0.25% span
DP_{supw}	0 to 7.5 kPa (0 to 1 PSI)	Rosemount 1151DP3	±0.25% span
DP_{cw}	0 to 37 kPa (0 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
DP_{subw}	0 to 7.5 kPa (0 to 1 PSI)	Rosemount 1151DP3	±0.25% span
DP_{ew}	0 to 37 kPa (0 to 5.3 PSI)	Rosemount 1151DP4	±0.25% span
m_r	0 to 300 g/s (0-0.6 lbs/s)	Micro Motion CFM050	±0.1%
m_{subw}	0 to 30 g/s (0-0.06 lbs/s)	Micro Motion CFM010	±0.1%

Name	Range	Model	Uncertainty
m_{sepwo}	0 to 100 g/s (0-0.22 lbs/s)	Micro Motion CFM050	±0.1%
m_{ew}	0 to 3000 g/s (0-6.6lbs/s)	Micro Motion F100	±0.1%
T	68 to 266°F (20 to 130°C)	Omega T type, 0.062" OD, 6" L	±0.1°C (after CTS calibration)
Wc_p	0 to 8 Kw (0 to 10.73 HP)	OSI PC5-015C, 3ph, 380-550V, 0-10A	±0.5% span
Ic_p	0 to 50 A	OSI CT5-1E	±0.25% span

* Please see legend for symbols and subscripts in the List of Terms/Glossary at the end of the report.
Source: Prepared by CTS4CA.

Controls and LabVIEW Arrangement

The system was designed to work automatically, controlled through the data logging software LabVIEW. The software recorded the signals coming from the measuring instruments. The VFD that controlled the speed of the compressor regulated refrigeration capacity by controlling the refrigerant mass flow rate. Two different control schemes were used because of the different characteristics of each refrigerant and the system architecture. For R1233zd(E), the condition at the suction of the compressor was controlled by the EXV, while for R1336mzz(Z) the discharge of the compressor was controlled by the EXV. That and other controls are presented in Table 10.

Table 10: Overview of the Controls

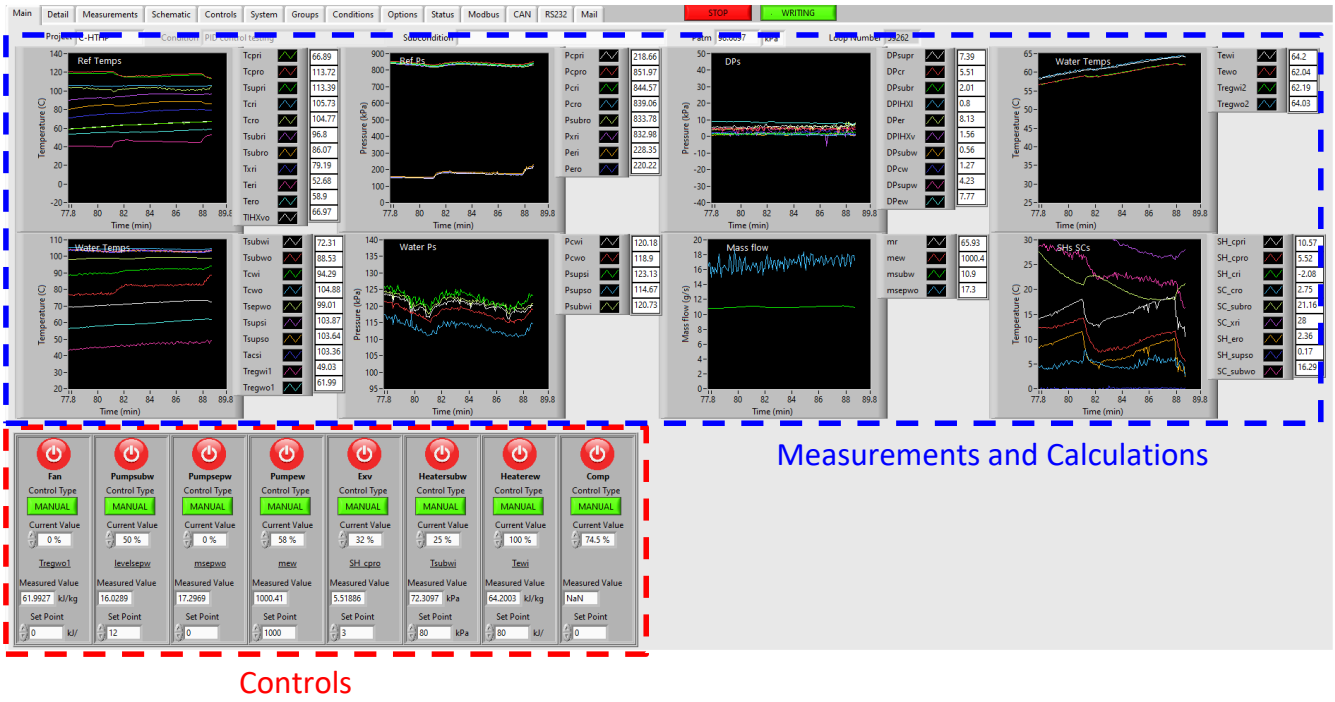
Name	Component	Parameter Under Control	Description	Automatic Control
Fan	Aircooler Fans	Tregwo1	Regulates water temperature at the outlet of the regenerator on the steam loop side	No
Pumpsubw	Steam Loop Pump	levelsepw	Regulates water level inside the steam separator	No
Pumpsepw	Separator Water Loop Pump	msepwo	Regulates mass flow in separator water loop	No
Pumpew	Evaporator Water Loop Pump	mew	Regulates superheat at suction of discharge of compressor	Yes
Exv	Refrigerant Expansion Valve	SH_cpri / SH_cpro	Regulates superheat at suction or discharge of compressor	Yes

Name	Component	Parameter Under Control	Description	Automatic Control
Heatersubw	Steam Loop Heater	Tsubwi	Regulates water temperature at inlet of subcooler	Yes
Heaterew	Evaporator Water Loop Heater	Tewi	Regulates water temperature at inlet of evaporator	Yes
Comp	Compressor	N/A	Controls compressor speed	No

Source: Prepared by CTS4CA.

Figure 7 presents the main screen of the LabVIEW program that was used during the data collection, with the control panel at the bottom and the graphs of the main measured values at the top. These graphs are good indicators of the level of steady state but also the actual values of the measured parameters.

Figure 7: The LabVIEW Main Screen



An image of the screen on the computer showing the LabView app running

Source: Image taken at CTS4CA

Data Collection and Analysis

Table 11 shows the data collected from the breadboard testing per the test plan discussed in Chapter 2.

The measurements shown include compressor speed; state points (temperatures, pressures) of the refrigerant at various points in the thermodynamic cycle; the water and steam temperatures and pressures; and refrigerant mass flow rates. Calculated values of capacity and COP are also shown, based on these measurements in the same table. The data is shown for all three refrigerants that were tested using the breadboard design.

Table 11: Experimental Data Collected During the Breadboard Testing

Refrigerant	Speed_cp	Tsat_supso	Tsubwi	T_supso	m_r	m_subw	SH_cpri	SH_cpro	SC_cro	Tsat_er	Tsat_cr	Pd/Ps	W_cp	eta_cp	Q_h	COP
	[Hz]	[C] (F)	[C] (F)	[C] (F)	[g/s] (lbs/s)	[g/s] (lbs/s)	[C] (F)	[C] (F)	[C] (F)	[C] (F)	[C] (F)	[-]	[kW] (HP)	[-]	[kW] (HP)	[-]
R245fa	70	120.1 (248.1)	79.9 (26.6)	133.3 (56.6)	210.6 (0.46)	10.7 (0.023)	12.2 (53.9)	8.5 (47.3)	1.4 (34.5)	72.9 (163.2)	124.4 (255.9)	3.4	7.1 (9.5)	0.67	26.6 (35.6)	3.74
	60	119.9 (247.8)	80.0 (176.0)	131.4 (268.5)	189.9 (0.42)	9.6 (0.021)	11.8 (53.2)	7.0 (44.6)	1.7 (35.0)	73.2 (163.8)	124.0 (255.2)	3.3	6.0 (8.0)	0.69	23.8 (31.9)	3.93
	50	120.0 (248.0)	79.9 (175.8)	130.8 (267.4)	162.4 (0.36)	8.2 (0.018)	12.0 (53.6)	7.2 (44.9)	1.8 (35.2)	74.0 (165.2)	123.6 (254.5)	3.2	5.1 (6.8)	0.68	20.5 (27.5)	4.05
	40	120.0 (248.0)	79.9 (175.8)	129.9 (265.8)	131.1 (0.29)	6.7 (0.014)	12.2 (53.9)	7.8 (46.0)	1.9 (35.4)	75.2 (167.4)	122.9 (253.2)	3.0	4.0 (5.4)	0.66	16.6 (22.2)	4.13
	35	119.9 (247.8)	79.9 (175.8)	129.2 (264.5)	113.9 (0.25)	5.8 (0.012)	11.6 (52.8)	7.6 (45.6)	2.0 (35.6)	75.5 (167.9)	122.7 (252.9)	2.9	3.6 (4.8)	0.64	14.5 (19.4)	4.04
R1233zd(E)	80	120.1 (248.1)	80.0 (176.0)	136.0 (276.7)	188.7 (0.42)	10.6 (0.023)	12.3 (54.1)	10.8 (51.4)	2.2 (36.0)	71.7 (161.1)	124.5 (256.1)	3.5	6.9 (9.2)	0.66	26.4 (35.4)	3.81
	70	120.1 (248.1)	80.0 (176.0)	134.5 (274.0)	174.4 (0.38)	9.7 (0.021)	12.0 (53.6)	9.3 (48.7)	2.8 (37.0)	73.0 (163.4)	124.6 (256.3)	3.3	5.9 (7.9)	0.69	24.1 (32.3)	4.11
	60	119.9 (247.8)	79.9 (175.8)	133.0 (271.3)	155.1 (0.34)	8.6 (0.018)	12.0 (53.6)	8.9 (48.0)	2.4 (36.3)	73.6 (164.5)	123.7 (254.7)	3.2	4.9 (6.6)	0.71	21.4 (28.7)	4.36
	50	120.1 (248.1)	79.9 (175.8)	131.7 (269.3)	133.4 (2.94)	7.4 (0.016)	11.5 (52.7)	8.2 (46.7)	2.8 (37.0)	74.7 (166.5)	123.4 (254.1)	3.0	4.1 (5.5)	0.69	18.4 (24.7)	4.44
	40	**120.0 (248.0)**	**80.0 (176.0)**	**130.8 (267.4)**	**107.3 (0.23)**	**5.9 (0.013)**	**12.3 (54.1)**	**8.5 (47.3)**	**2.4 (36.3)**	**75.3 (167.5)**	**122.8 (253.0)**	**2.9**	**3.2 (4.3)**	**0.69**	**14.8 (19.8)**	**4.54**
	35	120.0 (248.0)	79.9 (175.8)	130.2 (266.3)	93.9 (0.20)	5.2 (0.011)	11.6 (52.8)	8.4 (47.1)	2.1 (35.7)	75.8 (168.4)	122.6 (252.7)	2.9	2.9 (3.9)	0.66	12.9 (17.3)	4.46
	30	120.0 (248.0)	79.9 (175.8)	133.5 (272.2)	76.9 (0.16)	4.3 (0.009)	11.2 (52.1)	12.9 (55.2)	1.7 (35.0)	76.3 (169.3)	122.2 (252.0)	2.8	3.0 (4.0)	0.51	10.9 (14.6)	3.66

Refrigerant	Speed_cp	Tsat_supso	Tsubwi	T_supso	m_r	m_subw	SH_cpri	SH_cpro	SC_cro	Tsat_er	Tsat_cr	Pd/Ps	W_cp	eta_cp	Q_h	COP
	[Hz]	[C] (F)	[C] (F)	[C] (F)	[g/s] (lbs/s)	[g/s] (lbs/s)	[C] (F)	[C] (F)	[C] (F)	[C] (F)	[C] (F)	[-]	[kW] (HP)	[-]	[kW] (HP)	[-]
R1336mzz(Z)	90	120.0 (248.0)	80.3 (176.5)	125.3 (257.5)	184.6 (0.40)	8.8 (0.019)	7.5 (45.5)	2.4 (36.3)	6.2 (43.1)	74.7 (166.5)	126.1 (259.0)	3.7	6.0 (8.0)	0.60	22.3 (29.9)	3.72
	80	119.9 (247.8)	80.2 (176.3)	127.1 (260.7)	165.5 (0.36)	8.1 (0.017)	9.8 (49.6)	2.3 (36.1)	6.0 (42.8)	74.6 (166.3)	125.7 (258.3)	3.6	5.1 (6.8)	0.63	20.4 (27.3)	3.98
	70	120.0 (248.0)	80.0 (176.0)	127.7 (261.8)	148.5 (0.32)	7.3 (0.016)	10.6 (51.0)	1.8 (35.2)	5.9 (42.6)	75.0 (167.0)	125.5 (257.9)	3.5	4.3 (5.8)	0.66	18.3 (24.5)	4.23
	60	120.0 (248.0)	79.9 (175.8)	126.5 (259.6)	127.2 (0.28)	6.3 (0.013)	14.0 (57.2)	2.1 (35.7)	6.1 (42.9)	73.7 (164.7)	125.0 (257.0)	3.5	3.6 (4.8)	0.69	15.9 (21.3)	4.36
	50	**120.0 (248.0)**	**80.0 (176.0)**	**126.5 (259.6)**	**105.1 (0.23)**	**5.2 (0.011)**	**15.1 (59.1)**	**1.9 (35.4)**	**6.1 (42.9)**	**73.4 (164.1)**	**124.8 (256.6)**	**3.5**	**3.0 (4.0)**	**0.70**	**13.2 (17.7)**	**4.44**
	40	120.0 (248.0)	80.2 (176.3)	126.6 (259.8)	81.1 (0.17)	4.0 (0.008)	16.3 (61.3)	2.1 (35.7)	6.2 (43.1)	72.4 (162.3)	124.6 (256.3)	3.5	2.4 (3.2)	0.69	10.2 (13.7)	4.30
	35	120.0 (248.0)	80.1 (176.1)	126.6 (259.8)	70.3 (0.15)	3.5 (0.007)	15.8 (60.4)	2.0 (35.6)	5.9 (42.6)	73.3 (163.9)	124.5 (256.1)	3.4	2.1 (2.8)	0.65	8.8 (11.8)	4.19

Source: Testing performed at CTS4CA laboratory.

Calculation of Balances

The following section provides an overview of the calculation of the various key metrics.

Heating capacity (Q_h)

The heating capacity was obtained from three heat exchangers (subcooler, condenser, and superheater) where the refrigerant heats water, evaporates it, and superheats the steam flow. That heat taken from the refrigerant is as follows.

Refrigerant side heating capacity (Q_{hr})

$$Q_{hr} = m_r*[h_{supri} (T_{supri}, P_{supri}) – h_{subro} (T_{subro}, P_{subro})]$$

On the other side, that heat ends up in the water flow:

Water side heating capacity (Q_{hw})

$$Q_{hw} = m_{subw}*[h_{supso} (T_{supso}, P_{supso}) – h_{subwi} (T_{subwi}, P_{subwi})] + Q_{env}$$

$Q_{env\ is}$ heat exchanged with the environment. Part of it can be measured, and part is just estimated or ignored, Q_{est}.

$$Q_{env} = m_{sepwo}* C_{pw} * (T_{supsi} – T_{sepwo}) + Q_{est}$$

In principle, $Q_{hr} = Q_{hw}$, but there will always be some difference due to measurement imperfectness and potential losses to the environment. That difference should be small and typically within 3–5 percent. Since it is unknown which balance is correct, the heating capacity of the system is defined as an arithmetic average of the two:

$$Q_h = (Q_{hr} + Q_{hw})/2$$

The error between refrigerant and water balances can be presented as:

$$\varepsilon_{Qh} = (Q_{hr} - Q_h) / Q_{hr}$$

or as a deviation from the average value.

Cooling capacity (Q c)

As on the hot side, the cooling capacity on the refrigerant and the water side (in the evaporator) is determined on each side independently.

Refrigerant side (evaporator) cooling capacity (Q er)

Q er = mr*[hero (Tero, Pero)- heri (Teri, Peri)] = mr*[hcpri (Tcpri, Pcpri)- hsubro (Tsubro, Psubro)]

On the other side, there is water side cooling capacity (Q cw)

Q cw = mew*[hewi - hewo] = mew*Cpw * [Tewi - Tewo]

In principle, Q er = Q cw, but there will always be some difference due to measurement imperfectness and potential losses to the environment. That difference should be small and

typically within 3–5 percent. Since it is unknown which balance is correct, the cooling capacity of the system is defined as an arithmetic average of the two:

$Q_c = (Q_{er} + Q_{cw})/2$

The error between the refrigerant and water-cooling balances can be presented as:

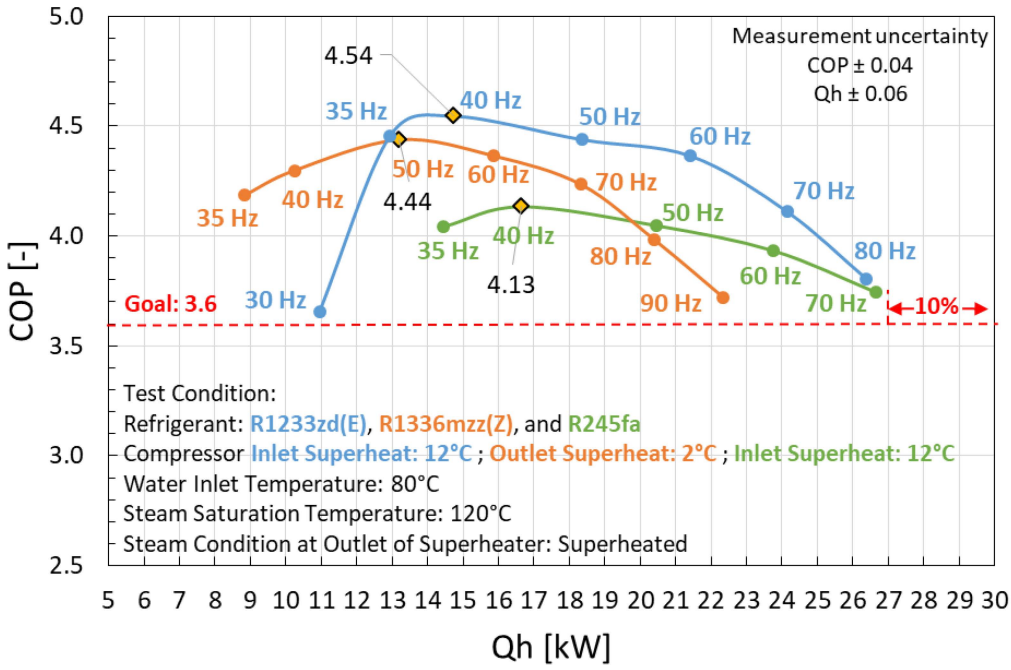
$\varepsilon Q_c = (Q_{er} - Q_c) / Q_{er}$

Results

Effect of Relative Compressor Size

Figure 8 compares the compressor speed test results for R245fa (green), R1233zd(E) (blue), and R1336mzz(Z) (orange). The data shows that R1233zd(E) achieved the highest overall COP of 4.54 with a compressor speed of 40Hz. For the same heating capacity of Q_h = 18.3kW (24.5 HP), the COP of R1233zd(E) was 4.8 percent higher than the COP of R1336mzz(Z). As Q_h increased, the percent difference also increased, with the COP of R1233zd(E) being an estimated 13.8 percent higher at Q_h = 22.4kW (30 HP). However, the most important comparison is between the three maximum COPs for each refrigerant, as the project's primary goal was to maximize COP. The maximum COP of R1233zd(E) is 2.2 percent higher than the maximum COP of R1336mzz(Z), and 10 percent higher than 245fa's maximum. The key parameter and performance values for each test point in Figure 8 are found in Table 11, with the highest COP value conditions highlighted for each refrigerant. Both R245fa and R1336mzz(Z) are within about 10 percent of the suggested 30kW (40.2 HP) capacity.

Figure 8: Comparison of COP for a Given Q_h Between R245fa, R1233zd(E), and R1336mzz(Z)

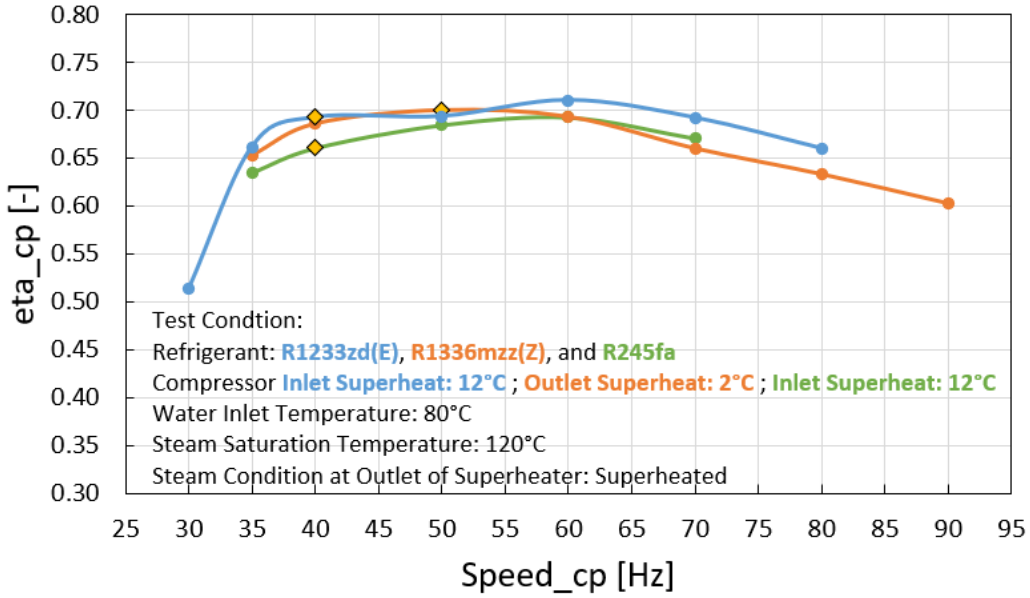


A graph showing the variation of COP against heating capacity for various compressor speeds

Source: Prepared by CTS4CA.

In Figure 9, compressor efficiencies are shown as a function of compressor speed. The compressor shows good efficiency for both refrigerants in the range of 40–60 Hz with a value of around 0.7. When increasing the compressor speed past 60 Hz, R1233zd(E) starts to show better compressor efficiency values than does R1336mzz(Z).

Figure 9: Comparison of Compressor Efficiency for a Given Speed Between R245fa, R1233zd(E), and R1336mzz(Z)

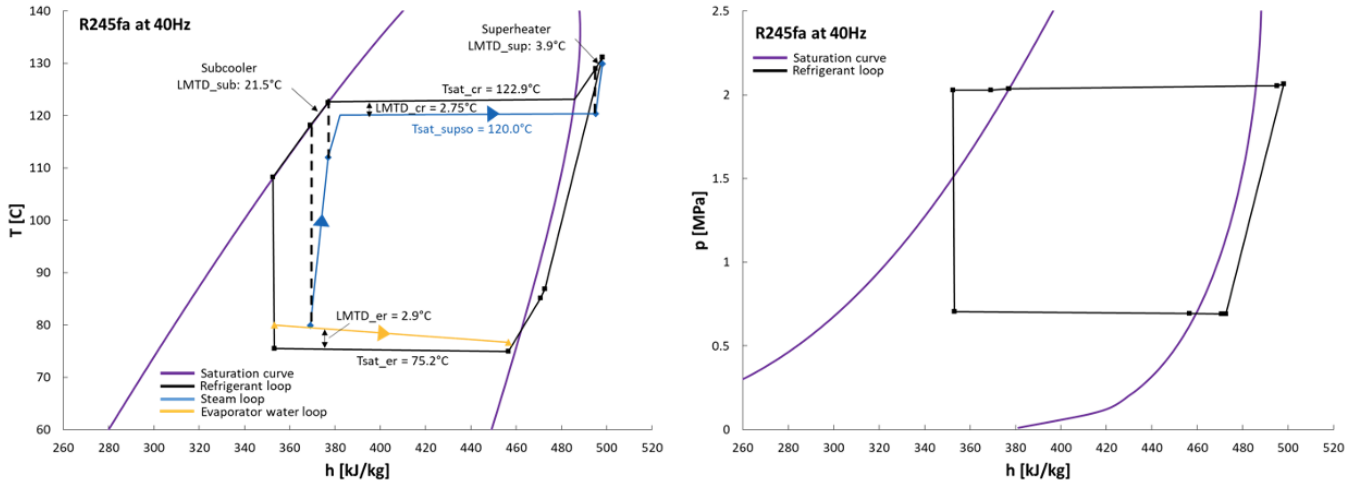


A graph showing the variation of compressor efficiency against compressor speed

Source: Prepared by CTS4CA.

Figure 10, Figure 11, and Figure 12 show the T-h and P-h diagrams for the optimal conditions for each refrigerant (R245fa at 40Hz, R1233zd(E) at 40 Hz and R1336mzz(Z) at 50 Hz). The T-h diagrams have the temperature profiles of the steam loop and evaporator loop overlayed, to give more information about the performance of the system's heat exchangers. The small logarithmic mean temperature difference (LMTD) values of the evaporator and condenser show that both heat exchangers have sufficient surface area for excellent heat transfer, contributing to the high COP values.

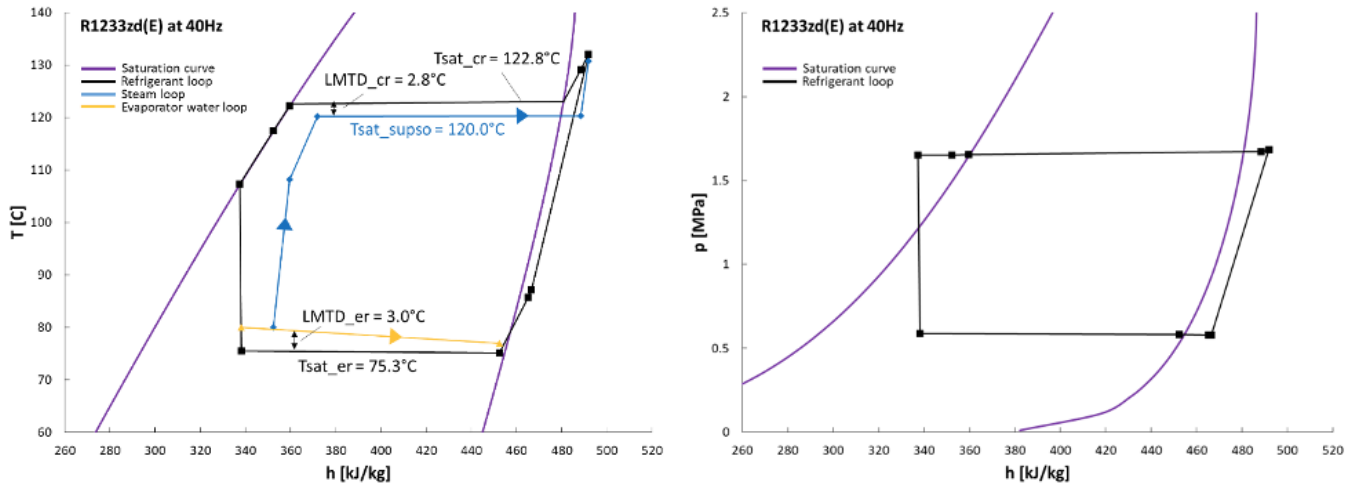
Figure 10: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R245fa



Temperature-enthalpy and pressure-enthalpy diagrams of R-245fa refrigerant showing optimal conditions of operation

Source: Simulations performed by CTS4CA

Figure 11: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R1233zd(E)

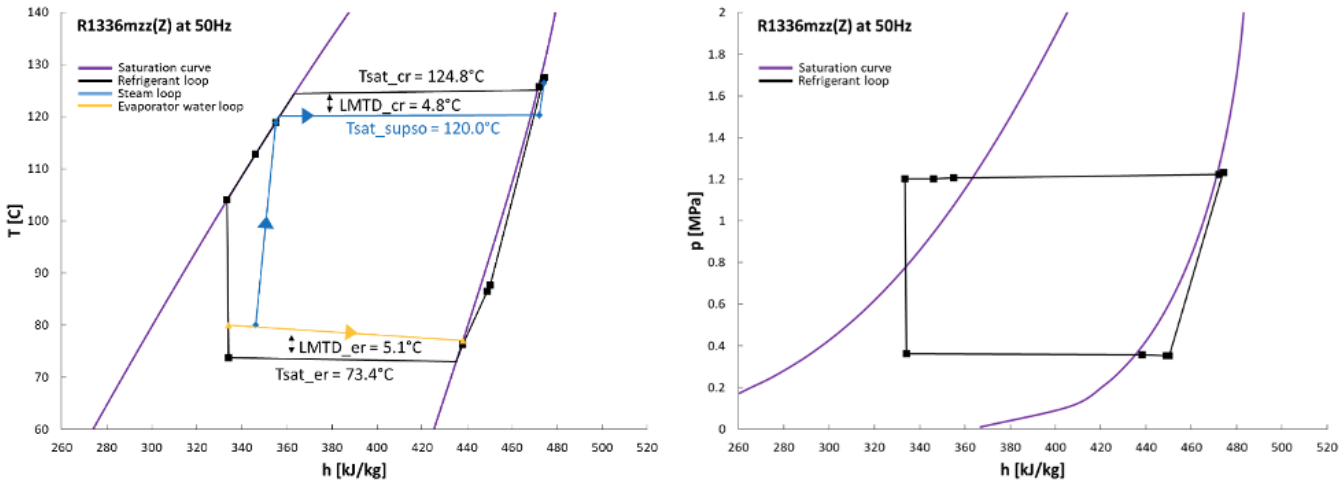


Temperature-enthalpy[2] and pressure-enthalpy diagrams of R-1233zd(E) refrigerant showing optimal conditions of operation

Source: Simulations performed by CTS4CA

[2] Enthalpy is the measurement of energy in a thermodynamic system.

Figure 12: T-h (Left) and P-h (Right) Diagrams of the Optimal Condition for R1336mzz(Z)



Temperature-enthalpy and pressure-enthalpy diagrams of R-1336mzz(Z) refrigerant showing optimal conditions of operation

Source: Simulations performed by CTS4CA

Effect of Water Source Temperatures for Various Steam Conditions

Chart **a1** in Figure 13 shows the normalized COP values as a function of the saturated steam temperature for various water source temperatures. The COP values are in reference to the target condition of 248°F (120°C) saturated steam with a water source temperature of 176°F (80°C). Different-colored lines represent different water source temperatures, while the triangle markers represent test conditions taken with 248°F (120°C) saturated steam. All points were taken with a compressor speed of 40Hz, as this is the speed where the maximum COP occurs for the heat pump system with R245fa. With these results, an overall performance map has been created for a wide variety of conditions, giving insight into how the performance of the heat pump system is affected by the source and sink conditions.

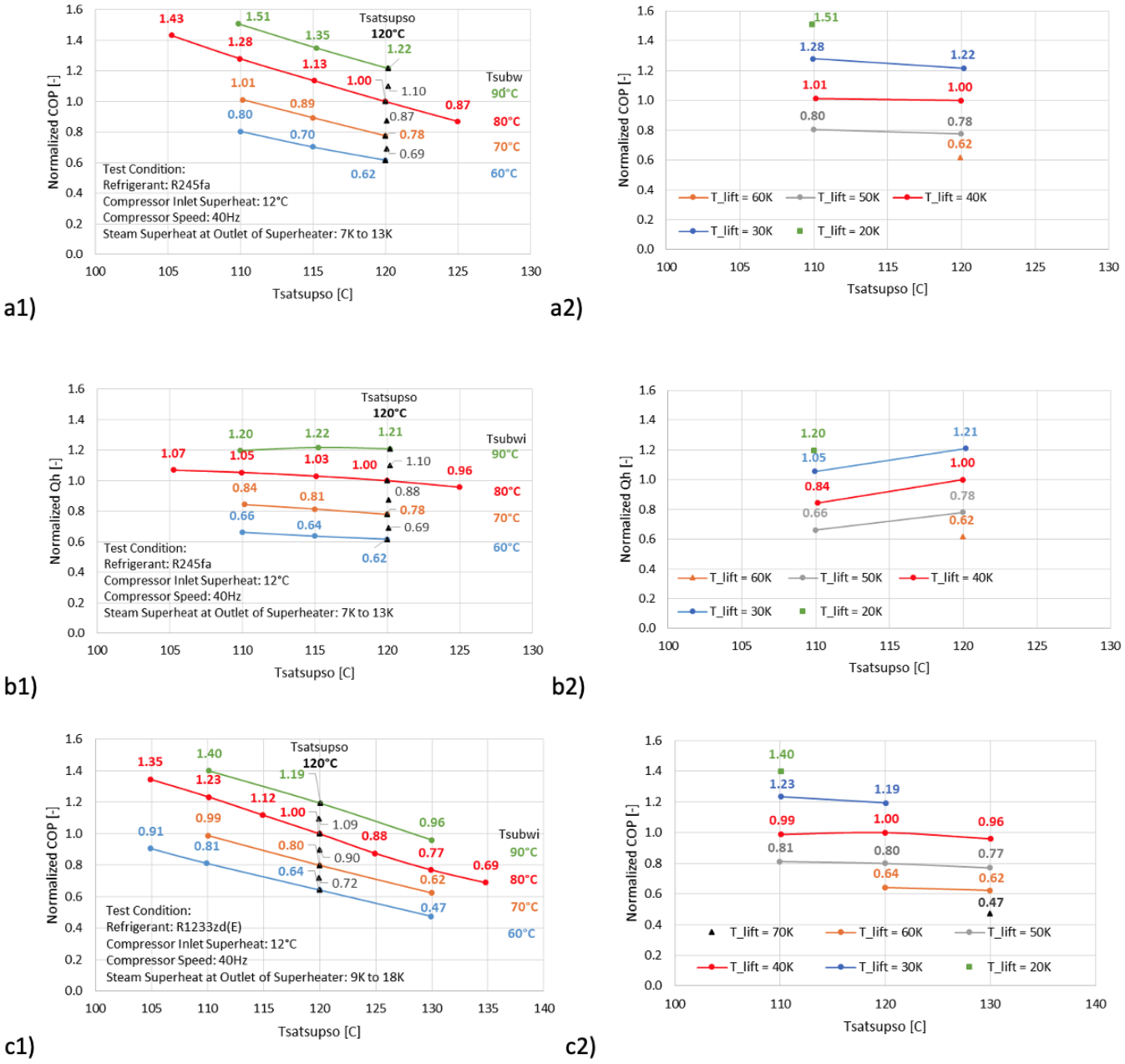
Chart **a2** takes multiple data points from chart **a1** and presents them in a slightly different manner. It shows the normalized COP values as a function of the saturated steam temperature for various temperature lifts. Different-colored lines and markers represent different temperature lifts. It is shown that the COP of the system is directly correlated with the temperature lift and that, for every 1.8°F (1°C) change in the lift, the COP will change by approximately 2 percent.

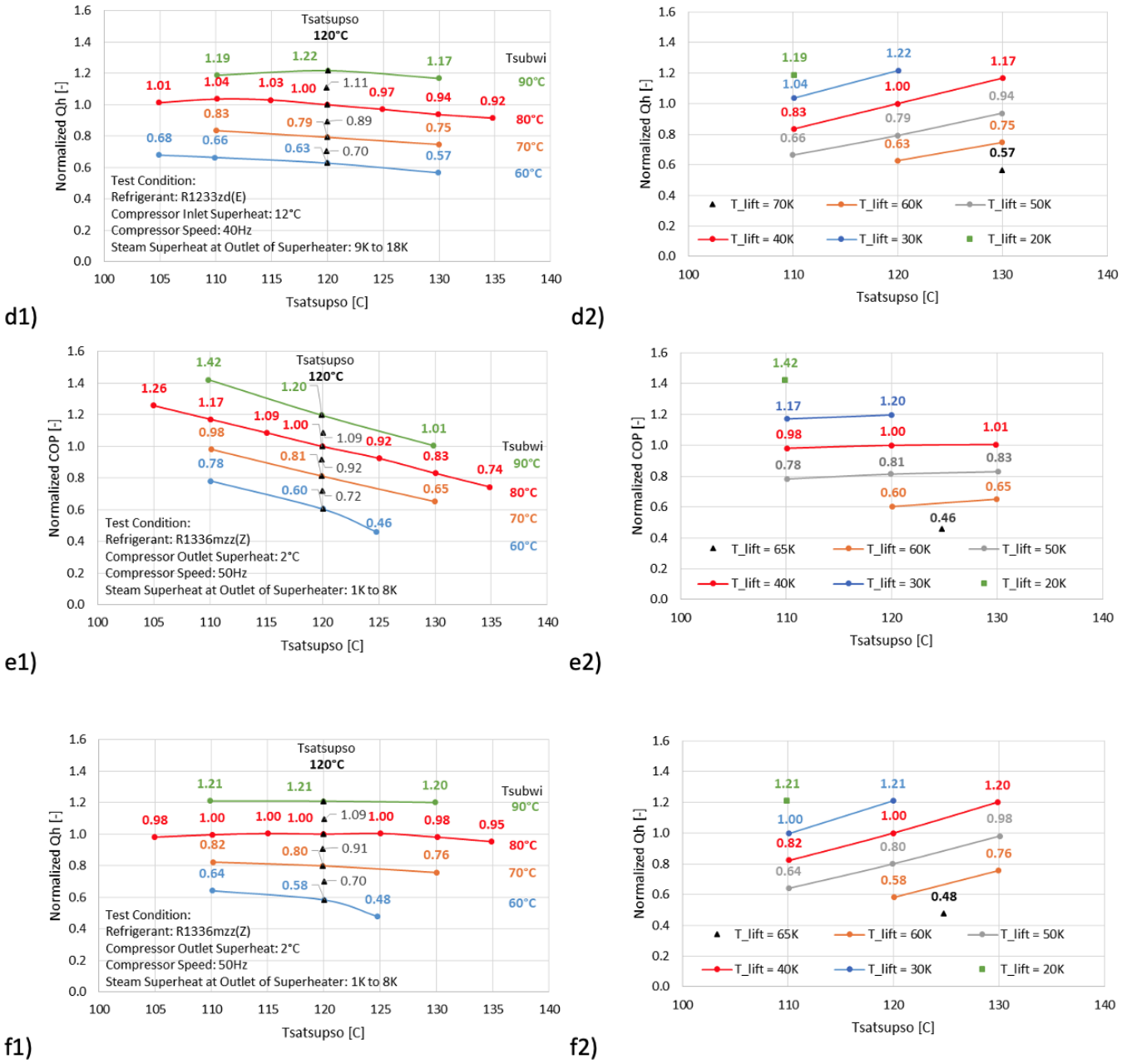
Charts **b1** and **b2** are similar to charts **a1** and **a2**; the only difference is that they show the sensitivity of heating capacity instead of efficiency. Chart **b1** shows that the heating capacity is directly correlated with the water source temperature and that, for every 1.8°F (1°C) change in the temperature, the Q_h will change approximately 2 percent.

Chart sets **c1/c2, d1/d2, e1/e2,** and **f1/f2** show results with R1233zde and R1336mzz(Z) and with a compressor speed of 40Hz and 50Hz, respectively, as this is the speed where the maximum COP occurs for the heat pump system with each refrigerant. Similar trends are

observed, giving confidence in the characterization of the heat pump system, independent of refrigerant type.

Figure 13: Sensitivities of System Performance Based on Delivered Steam Conditions





Normalized heating capacities and normalized COPs plotted against saturated steam temperatures for different water source temperatures

Source: Prepared by CTS4CA.

Conclusion

The project goal was to specify, develop, and test an HTHP system with a low-GWP refrigerant that would recover waste heat at 176°F (80˚C) to produce low-pressure steam at 248°F (120˚C) with a COP of 3.4 or above. The results showed that the specifications are achievable and exceed the efficiency targets by reaching COP of 4.1, 4.4, and 4.5 instead of 3.4, through careful selection of refrigerant and proper optimization. This is a significant achievement. The

final breadboard testing results showed that the target capacity is achievable within the acceptable tolerance at the COP of close to 3.4 and above.

Refrigerant R1233zd(E) showed a bit better performance than R1336mzz(Z) in drop-in replacement mode. R1233zd(E) benefits from its larger specific vaporization heat, while R1336mzz(Z) benefits from its smaller specific compression work. R1233zd(E) leads to the highest COP of 4.5, which is 2.2 percent higher than R1336mzz(Z)'s maximum COP of 4.4, and about 10 percent higher than R245fa's maximum COP of 4.1. The compressor efficiency of all refrigerants in the 40–70 Hz range is nearly identical, hovering in the 0.65 to 0.7 range. For a given compressor speed of 60 Hz, the total heating capacity of R1233zd(E) is about 89 percent of R245fa capacity but about 1.35 times R1336mzz(Z) capacity. Performance maps for each refrigerant have been created that characterize the HTHP system over a wide range of water sources and saturated steam temperatures. R1233zd(E) was chosen as the refrigerant of choice based on these results, that is, based on its high capacity, high COP, and lower risk of air leaking into the system.

CHAPTER 4:
Prototype Development and Testing

A prototype is an engineering-scale model that can be tested in a relevant laboratory environment. Prototype testing represents a significant step up in the technology's demonstrated readiness. For the current heat pump equipment, the prototype was built by assembling the breadboard components into an enclosed system that can perform in the same functional form as expected in a fully operational system.

Design of the Prototype

While the breadboard system testing results showed great performance, the following modifications were deemed necessary to transform the breadboard into a prototype system and were hence performed.

- Elimination of water cart
    - The water cart in the breadboard system served to provide flow and measurement of saturated liquid water taken from the separator and sent to the condenser. Experimental testing of the breadboard system showed that the recirculation of saturated water from the separator had little effect on the performance of the system and that gravity was sufficient in creating the recirculation flow. Because of this, the water cart was deemed unnecessary for the prototype and was eliminated. The separator, however, was left intact, as it served to provide saturated water vapor to the superheater. The recirculation also remained intact, as the measurement of the liquid level in the separator was used to create steady-state conditions by controlling the steam flow rate.
- Elimination of unnecessary instrumentation
    - The experimental testing of the breadboard system required many points of measurement on the refrigerant and water sides to accurately characterize and understand the system performance. When applied in the field, the heat pump would have only the instrumentation needed to produce the required output (superheated steam). This means only minimal points of measurement on the refrigerant and water lines. Additional instrumentation was eliminated while assembling the prototype.
- Updated performance calculations
    - The performance calculations (capacity and efficiency) for the prototype system were updated so that it can be derived only from the steam side of the system.
- Automatic control package
    - For the prototype heat pump to serve as a stand-alone unit, automatic controls were required. Tests performed in the breadboard system were controlled manually; however, automatic controls for the prototype were designed to

reduce testing time and ensure accuracy in reaching steady conditions. Optimization and tuning are needed for the proportional--integral – derivative (PID) controller to be able to control the system during startup, maintain steady state, and respond accordingly to changes in the required condition.

- Enclosure for heat pump
    - An insulating enclosure was added to mimic the design of a commercial product. The enclosure would also boost the performance of the system by reducing heat lost to the environment.

Figure 14, Figure 15, and Figure 16 show the photos of the assembled prototype of the heat pump.

Figure 14: Installation of Heat Pump Enclosure on the Electrical Panel Side of the Prototype System



Source: Image captured at CTS4CA laboratory test site by EPRI

Figure 15: Installation of an Electrical Panel on a New Enclosure of the Prototype System



Source: Image captured at CTS4CA laboratory test site by EPRI

Figure 16: Heat Pump Prototype With Enclosure



Source: Image captured at CTS4CA laboratory test site by EPRI

Test Methodology of the Prototype

The purpose of the prototype system testing was to demonstrate the prototype system performance with the chosen refrigerant R1233zd(E) and to run the system for at least six months for eight hours a day, simulating a single-shift operation in an industrial plant. The COP target was greater or equal to 3.4 (target end of performance, COP = 3.6) when testing with a water source temperature of 176°F (80°C) and providing a 104°F (40°C) temperature lift, resulting in low-pressure steam at 248°F (120°C), per the specifications provided in the CEC agreement for this project.

Figure 17 shows the schematic diagram of the components in the prototype heat pump. A back pressure regulator (BPR) valve set the steam saturation temperature to the required value of 248°F (120°C). The steam superheat was provided by the plate heat exchanger (Sup). The solenoid valve controlled the inlet water source to be evaporated. When steady state was achieved, the system operated and recorded data via the data logger throughout the day. At the end of the work period, the data was saved and stored in an Excel file. Mean values in time were taken from this data and were used for further analysis. Among other variables, the analysis provided the $COP_h = Q_h / W_{cp}$ (COP in heating) for each test, where Q_h

is the heating capacity derived from the water side, while W_{cp} is the measured compressor power.

Heating capacity (Q_h)

The heating capacity was obtained from three heat exchangers (subcooler, condenser, and superheater), where the refrigerant heats the water source, evaporates it, and then superheats the steam flow. That heat supplied to the water is:

$$Q_h = m_{subw}*[h_{supso} (T_{supso}, P_{supso}) – h_{subwi} (T_{subwi}, P_{subwi})]$$

Efficiency or COP_h

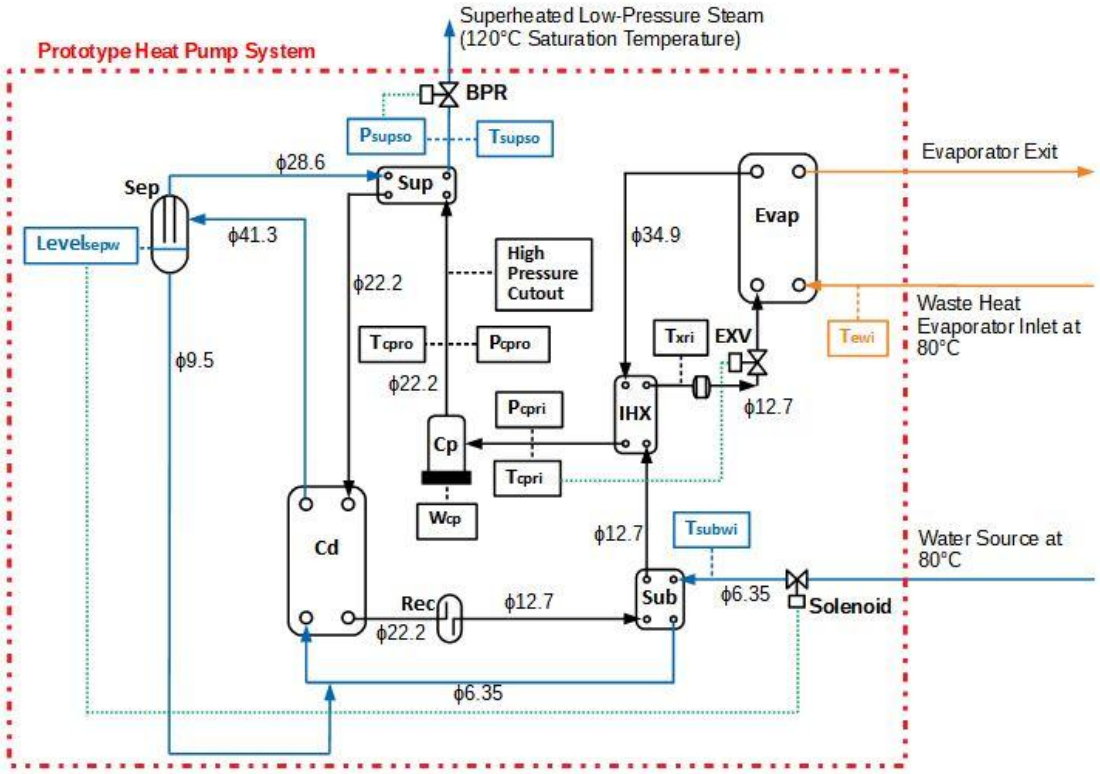
$$COP_h = Q_h / W_{cp}$$

In addition to data required to meet the specifications in the CEC agreement, the performance (COP_h and Q_h) of the system operating with R1233zd(E) at a compressor speed of 60 Hz resulted in the following data/information being obtained.

1. The performance (COP_h) of the system operating at a speed of 80 Hz (high Q_h)
2. The reliability of the prototype system running over a six-month period.

The data was collected at various compressor speeds to monitor the COP_h at different load conditions as well as COP_h variations over the entire eight-hour period per day (single-shift operation).

Figure 17: Schematic Diagram of the Prototype System

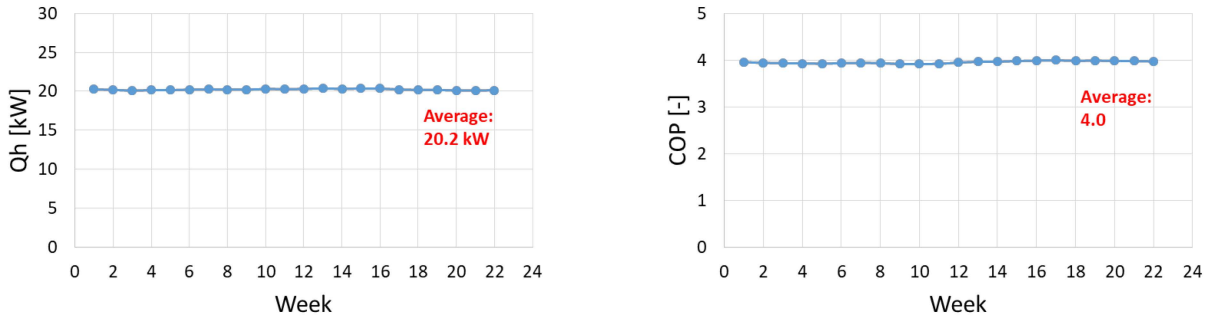


Source: Prepared by CTS4CA.

Data Analysis

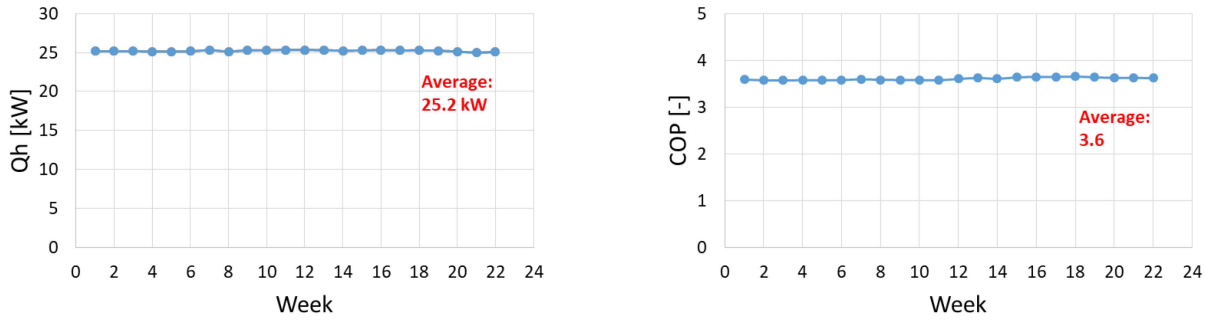
Figure 18 and Figure 19 show the average heating capacity and COP for each week of testing over the six-month testing period (24 weeks) for two different compressor speeds. The value in red is the average of all 24 weeks. The prototype system was tested at a compressor speed of 60 Hz for two reasons: better system reliability compared to higher than nominal speeds such as 80 Hz and for higher COP values. The overall average heating capacity at 60 Hz was 20.2 kW (27.1 HP), with the overall average COP being 4. To maximize the heating capacity, the compressor was overclocked to a speed of 80 Hz. Limited tests were run at this higher speed as a precaution to the high compressor discharge temperatures. The overall average heating capacity at 80 Hz was 25.2 kW (33.8 HP), with the overall average COP being 3.6. The reliability of the prototype system was another important performance criterion. These figures show that, over the six-month testing period, both Q_h and COP remained steady, with little variation in value. Both Q_h and COP for both compressor speeds varied by 1 percent or less from the average.

Figure 18: Heating Capacity (Left) and COP (Right) of Prototype System at 60 Hz Compressor Speed



Source: Prepared by CTS4CA.

Figure 19: Heating Capacity (Left) and COP (Right) of Prototype System at 80 Hz Compressor Speed



Source: Prepared by CTS4CA.

M&V of the Data Analysis

The measurement data collected in prototype testing at the CTS4CA site was subsequently validated by EPRI to verify the heating capacity and COP of the system. To accomplish this

M&V process, the data collected by CTS4CA was first checked for steady-state operation, and the average temperatures and pressures of the refrigerant and steam were independently calculated at steady state. Then, using the equations shown in Chapter 3, the section titled "Data Collection and Analysis," the heating capacity and COP were calculated and matched against the corresponding results reported by CTS4CA.

The refrigerant and steam enthalpies were calculated based on state point data using pressure-enthalpy (P-h) charts. A P-h chart, also known as a P-h diagram, is a chart that shows the relationship between pressure and enthalpy for a refrigerant in a refrigeration system.

The M&V results are shown in Table 12, Table 13, and Table 14. The key observations from the M&V were:

- The HTHP breadboard-prototype system greatly exceeded the required COP of 3.4 in all test conditions for the application of generating 248°F (120°C) steam from a 176°F (80°C) heat source.
- The M&V revealed a nearly exact match with the capacity, input work, and COP of the system calculated between CTS4CA and EPRI.

Table 12: M&V of Heating Capacity of the Prototype Heat Pump

	M&V of Capacity (Output)									
	Inlet Measurements		Outlet Measurements		Enthalpies		Mass Flow	Water Side Heating Capacity (kW)		Difference Between EPRI and CTS4CA Results
	Tsupso (K)[3]	Psupso (kPa)	Tsubwi (K)	Q	hsupso (kJ/kg)	hsubwi (kJ/kg)	msubw (kg/s)	EPRI's M&V	CTS4CA's Value	
13-Sep	406.90	198.143	353.16	0.000	2735.38	335.05	0.008	20.37	20.34	0%
14-Sep	406.91	198.252	353.13	0.000	2735.39	334.93	0.008	20.30	20.22	0%
15-Sep	409.49	199.010	353.16	0.000	2740.75	335.05	0.011	25.33	25.35	0%
20-Sep	406.58	199.433	353.15	0.000	2734.58	335.01	0.008	20.32	20.27	0%
21-Sep	406.22	198.607	353.16	0.000	2733.90	335.05	0.008	20.27	20.29	0%
22-Sep	408.99	199.657	353.15	0.000	2739.64	335.01	0.011	25.33	25.33	0%
23-Sep	406.36	198.767	353.18	0.000	2734.18	335.14	0.008	20.38	20.37	0%
26-Sep	406.30	197.783	353.17	0.000	2734.15	335.10	0.008	20.30	20.26	0%
27-Sep	406.22	198.206	353.16	0.000	2733.94	335.05	0.008	20.32	20.29	0%
28-Sep	406.37	198.151	353.15	0.000	2734.26	335.01	0.008	20.33	20.28	0%

Source: Prototype Testing M&V by EPRI

Table 13: M&V of Compressor Input Work of the Prototype Heat Pump

	M&V of Compressor Work (Input)									
	Inlet Measurements		Outlet Measurements		R1233 zd(E) Enthalpies		Mass Flow	Compressor Work (Power) kW		Difference Between EPRI and CTS4CA Results
	Tcpri (K)	Pcpri (kPa)	Tcpro (K)	Pcpro (kPa)	hcpri	hcpro (kJ/kg)	mr (kg/s)	EPRI's M&V	CTS4CA's Value	
13-Sep	357.23	539.468	407.50	1744.506	470.99	492.97	0.24	5.21	5.19	0%
14-Sep	357.26	539.966	407.56	1744.830	471.01	493.03	0.24	5.22	5.19	-1%
15-Sep	355.14	511.249	410.06	1782.267	469.85	494.97	0.28	7.03	7.08	1%

[3] Key: K = kelvin, kPa= kilopascal, kJ/kg = kilojoules per kilogram, kg/s = kilograms per second.

	M&V of Compressor Work (Input)									
20-Sep	357.05	536.847	407.22	1740.661	470.90	492.74	0.24	5.24	5.16	-2%
21-Sep	356.90	534.974	406.85	1730.045	470.81	492.58	0.24	5.16	5.14	0%
22-Sep	354.85	507.401	409.52	1769.292	469.70	494.66	0.28	6.99	7.02	0%
23-Sep	356.96	535.738	406.88	1729.349	470.85	492.63	0.24	5.16	5.14	0%
26-Sep	356.97	535.866	406.87	1728.232	470.85	492.64	0.24	5.16	5.14	-1%
27-Sep	356.89	534.894	406.84	1725.709	470.80	492.67	0.24	5.25	5.13	-2%
28-Sep	357.01	536.461	406.93	1729.012	470.87	492.69	0.24	5.17	5.14	-1%

Source: Prototype testing M&V by EPRI (Prepared on 10/6/22)

Table 14: M&V of COP of the Prototype Heat Pump

	M&V of COP Calculations ------>	EPRI M&V COP	CTS4CA COP	Difference
13-Sep		3.91	3.91	0%
14-Sep		3.89	3.89	0%
15-Sep		3.60	3.57	-1%
20-Sep		3.88	3.94	2%
21-Sep		3.93	3.94	0%
22-Sep		3.62	3.60	-1%
23-Sep		3.95	3.96	0%
26-Sep		3.93	3.94	0%
27-Sep		3.87	3.95	2%
28-Sep		3.93	3.95	0%

Source: Prototype testing M&V by EPRI

Conclusion

The results from the laboratory testing of the prototype showed that, with the newer and emerging refrigerants, efficient compressors, and innovative control designs, a higher COP heat pump (COP 3.6) that can effectively recover waste heat from the industrial processes is achievable. The industrial waste heat recovery heat pumps offer multiple benefits to industrial customers. They produce useful heat in the form of steam and they lower fossil fuel energy use by reusing the otherwise wasted heat energy, thereby reducing combustion emissions. And, finally, if clean energy sources are used, it helps in industrial decarbonization. Having achieved successful results in laboratory testing, a recommended next step beyond this project, to advance the technology readiness level of this technology, is to validate the test results in an industrial setting. In other words, the focus ought to shift toward real-world validation through field trials, where the technology will be deployed in diverse operational scenarios to gather comprehensive performance data and ensure its reliability and efficiency in practical applications. Concurrently, optimization efforts should be intensified, leveraging the insights gained from the lab tests to fine-tune the system's design and control algorithms.

CHAPTER 5:
Evaluation of Project Benefits

Technology Potential Benefit

HTHPs have significant potential to electrify process heat applications in a variety of industries and to reduce the energy and CO_2 emissions across these sectors. Following are descriptions of some of the potential technology benefits.

Lower Cost

Heat pumps extract heat from the ambient environment and transfer it to a fluid stream, unlike fossil-fuel-fired boilers that create heat by burning the fuel. HTHPs, therefore, provide energy savings over conventional boiler systems where heat is generated through fuel combustion. Moving heat is more efficient than creating heat, hence the COP for a heat pump is greater than 1. Compared to the traditional boilers used for steam generation, the cost savings across three industries where the HTHP has broader application (food, chemicals, and paper) is estimated to be around $56 million per year. Such savings provide value to California investor-owned utility ratepayers. The cost savings are calculated as follows.

The industrial steam use from the three industries is estimated to be about 359 million therms of natural gas consumption; this is approximately equal to (~) 11 percent of natural gas use in the California industries for process heating and steam, based on 3,376 million therms of natural gas used annually in the industrial sectors to generate process heating or used in boilers to generate steam or hot water for industrial processes. This represents the total technical potential to be addressed by HTHP technology. This potential market size is a conservative estimate, as it does not include contributions from industries such as textiles, wood products, or plastics, where the technology could also be used. The annual energy equivalent used for steam generation across the initial three industries, if HTHP is used, with the COP of 3.4 and the boiler efficiency of 80 percent, is 2,334 gigawatt-hours (GWh) per year (approximately equal to 80 million therms per year, where 1 million therms equals 29.30 GWh). Assuming a natural gas price of $0.92 per therm and an electricity price of $0.1175 per kWh for industrial customers, the annual energy cost for steam production with conventional boilers for the three industries is $330,280,000 per year (based on usage of 359 million therms per year). The equivalent annual electric energy usage with HTHP is $274,245,000 per year (based on 2,334 GWh per year). This results in a total cost savings of $56,035,020 per year across the three industries for the state of California.

Lower Maintenance

HTHPs are designed to be efficient and reliable, often incorporating advanced technologies. The mechanical components in industrial heat pumps are less complex compared to those of conventional boilers, which are often prone to wear and tear. In addition, heat pumps typically have fewer moving parts compared to combustion-based heating systems. The combustion-based heating systems often require additional equipment for air supply, flue gas handling, and safety controls, which adds more moving parts. Heat pumps avoid all those additional

parts. This reduces the potential points of failure and decreases maintenance needs. Combustion-related maintenance such as cleaning, servicing, and exhaust management is not required for heat pumps.

Economic Development

HTHPs can help businesses save money on their energy bills by using waste heat or other low-grade heat sources. This can lead to significant cost savings, especially in industries that are energy intensive. Assuming full market penetration, HTHPs can potentially provide energy cost savings of $56 million per year in California that would flow into the economy. The adoption of HTHPs requires the development of supporting infrastructure, such as advanced heat exchange systems, which can stimulate economic growth. Commercialization of HTHPs can create jobs in manufacturing, installation, and maintenance. This can help to boost the economy and create a more sustainable future.

Environmental Benefits

HTHPs contribute to GHG emissions reduction by using waste heat or other low-grade heat sources. The GHG emissions reduction can be quantified by using the standard natural gas emissions rate of 0.00531 $MTCO_2e$ per therm and using a California statewide electricity grid emissions rate of 0.2278 $MTCO_2e$ per megawatt-hour (MWh). Based on 359 million therms of annual boiler energy usage, the equivalent electric energy usage from the HTHP with a COP of 3.6 is 2334 GWh per year. For the selected three industries, the annual GHG emissions from boiler usage for steam production is 1,906,290 $MTCO_2e$. The equivalent HTHP GHG emissions are just 531,903 $MTCO_2e$ annually. Therefore, the resulting emissions savings, comparing electric HTHP to natural gas boilers, is 1,374,387 $MTCO_2e$/ year. This is a conservative value, and it will go up when the electric sector incorporates more renewables in the later years. This can significantly improve air quality for California ratepayers. In addition, businesses can be made more sustainable by using renewable energy sources, such as solar or wind energy, to power the HTHPs. This can help to reduce reliance on fossil fuels and lessen their environmental impact.

Energy Efficiency

HTHPs are 360 percent more efficient in producing low-pressure steam than the baseline gas boiler technology, and they very efficiently extract low-grade waste heat from industrial facilities. This lowers the overall energy dependence and results in conservative energy savings of about 351 million therms (37 petajoule) per year for the food, paper, and chemicals industries, thus improving energy security.

CHAPTER 6:
Technology/Knowledge Transfer Activities

Market Characterization

Total Addressable Market

Industry accounts for at least 25 percent of the U.S. energy use and energy-related CO_2 emissions. In today's market, 17.6 percent of total site industrial energy and less than 5 percent of process heating energy in industrial settings comes from electricity. The majority of U.S. industrial energy usage is in the form of fossil fuels, predominantly natural gas. With these figures, over 80 percent of total site energy and 95 percent of process heating energy settings have yet to be electrified. Industrial heat pumps are a key aspect of industrial electrification solutions.

Research by the American Council for an Energy Efficient Economy (ACEEE) has shown that moderate industrial heat pump (IHP) deployment in the industrial sectors with high process-heating demands could save up to 32 percent net energy use and associated CO_2 emissions per year in the U.S. More specifically, IHP deployment has the potential to reduce process heat energy by ~42–57 percent while reducing CO_2 emissions by 9.7–12.6 million $MTCO_2e$ per year, which equates to emissions from 2.1–2.7 million passenger cars per year. When considering lower emissions factors for grid-produced electricity by 2050, this CO_2e savings potential increases to 13.4–18.2 million $MTCO_2e$/year.

Path to Commercialization

Currently, there are relatively few HTHPs available in the U.S. market, although foreign manufacturers are starting to offer their products domestically. There are two known industrial heat pump manufacturers located in the U.S., namely Carrier and Emerson Electric. Unfortunately, the Carrier IHP offerings do not exceed heating capabilities within the 248°F (120°C) range. The Emerson offerings appear to produce hot water up to 194°F (90°C). Advancement in IHP technology domestically is needed to commercialize IHPs across various industries; output temperatures of 320°F (160°C) cover about 44 percent of industrial process heat needs, and output temperatures of 392°F (200°C) cover about 55 percent of process heat needs.

In addition to product availability, the economics of IHPs needs to improve for widespread adoption and commercialization to occur. The electricity-to-natural-gas price ratio, often referred to as the "spark gap," is critical to the economics of IHPs. Many U.S. states that produce fossil fuels and/or have little renewable electricity generating capacity typically have high ratios. In the cases where the cost ratio is above 4, it may not be economical to implement IHPs. They can, however, have simple economic payback under two years in states where the price of electricity is advantaged over that of natural gas. However, additional barriers, including implementation capital costs, integration, and maintenance considerations, remain.

Market Barriers

Product Availability and Economics

As mentioned above, domestic product availability and economics are barriers to IHP commercialization in the U.S. More specifically, IHPs compete with other technologies in the process heating space, which includes electric boilers, renewable fuels for boilers, combined heat and power, and solar thermal technologies, alongside traditional fossil-fuel-fired boilers. The most readily available heat pumps have delivery temperatures limited to less than 212°F (100˚C). This limits the number of applications that can be served in the current market, since many processes need higher-temperature heat. There is a limited selection of refrigerants that can operate at high temperature ranges and have a low GWP.

Most IHPs are engineered specifically for their application. This elevates the price and increases the difficulty in selection and implementation. Potential implementation site stakeholders prefer "plug and play" technologies, such as a boiler replacement, compared to these highly customized engineered solutions. In addition to the logistical challenges of implementing a highly customized solution like IHPs compared to a traditional technology (boiler), the economics are a barrier to overcome. IHP prices range widely, from ~$110 per kW to $2200 per kW ($32–$645 kilo British thermal units per hour [kBtu/hr]). Economics will improve as competitors enter the U.S. marketplace.

Overcoming Safety Concerns

IHPs use a variety of refrigerants, many of which are flammable, are being phased out, or are at risk of being phased out. As such, potential customers may be wary of buying systems for plant safety and longevity. This risk highlights the importance of using natural refrigerants, like R-704, R-744, R-718, and R-717, which have lower GWPs than conventional refrigerants and have very low or nonexistent flammability.

Compressor overspeed operation is an additional area of safety concern for IHP applications. In Chapter 4, the team described the goal of a 30-kW (40.2-HP) heating capacity. The maximum that was achieved when operating at 60 Hz was 20.2 kW (27.1 HP). The team was able to overspeed the compressor in the test environment to 80 Hz to achieve a 25.2-kW (33.8-HP) heating capacity. There may be a danger of compressor failure if an IHP is operated in an overspeed condition in an industrial application for an extended duration.

Well-Documented Performance History

When considering implementing a perceived new or novel technology, industrial stakeholders and decision makers often want to see sample product installations to feel more comfortable about adopting a novel technology that differs from "business as usual." In the U.S., IHP adoption and market penetration lag those of the global marketplace. Most installations are in Japan and Europe, and many of these international manufacturers do not sell their products in the U.S., making demonstrating an existing installation to potential adopters challenging.

Proper implementation of IHPs is more complicated than the implementation of traditional process heating technologies. Implementation usually requires extensive process analysis, like pinch analysis, which may not be familiar to many engineers. (Note: Pinch analysis involves

the development of "composite curves" for heating and cooling, which represent the overall thermal energy demand and availability profiles for the process as a whole. When the two curves are drawn on a temperature-enthalpy graph, they reveal the location of the process pinch, i.e., the point of closest temperature approach, and the minimum thermodynamic heating and cooling requirements.) Heat storage is also important for the implementation of IHPs in nonsynchronized processes. Many industrial processes do not have simultaneous low-temperature waste heat source operation with high temperature process needs. Storing waste heat as a thermal reservoir in tanks can increase the potential viability of IHPs in processes. However, thermal storage is heavy, space intensive, and a potential new element of industrial process that a manufacturer/site may not be familiar with. Additionally, most large-scale IHPs are not modular; they require additional construction in the field.

Domestic field demonstration of various IHP types in a variety of industrial applications is crucial to lowering market barriers for IHP adoption in the U.S. Implementation today depends on good cooperation and education among utilities, manufacturers, engineers, and end-users. These demonstrations would benefit from common field test procedures and third-party verification and communication.

Sales and Service Support

In addition to available field demonstrations domestically, additional sales and service support are required to further market adoption of IHPs in the U.S. Once a customer has decided to consider a new technology implementation within their facilities, a question that is often posed surrounds available domestic sales and service support. Industrial stakeholders want to ensure that their product will be readily supported throughout its lifetime. The recent acceleration of IHPs in Australia, Europe, and New Zealand has underlined the importance of domestic field-level support development. The drivers for establishing domestic chain capabilities include reliable local IHP service, trained and experienced process engineers to work on end-use integrations, and expertise to design new process implementations.

A process heat system with an IHP has more moving parts than a boiler system. Not only does new site implementation require sales and service support, but it also requires training for the maintenance staff and facilities professionals to ensure a successful implementation and operation of the product.

Technology Transfer Conduits

Developing a new industrial HTHP involves a complex process that requires effective technology transfer conduits. Technology transfer refers to the movement of knowledge, expertise, and intellectual property from one entity or domain to another. In this context, it involves transferring knowledge from research and development to the industrial setting for the production and commercialization of the heat pump product. There are several research organizations worldwide focused on IHP technologies. A summary of research organizations, along with the publications and the key meetings that were conducted, is presented in Table 15.

Table 15: Conferences, Meetings, and Other Events Where Project Information Was Showcased

Marketing Chanel	Organization/Trade Association/Professional Association	Key Meetings	Key Publications
National and International Research Organization	International Energy Agency (IEA)	Heat Pump Conference (HPC 2023)	• The role of utilities and federal/state governments in increasing heat pump deployments in the USA • Industrial High-Temperature Heat Pumps – Ongoing Research in the USA Link: https://heatpumpingtechnologies.org/publications/14th-iea-heat-pump-conference-2023-hpc2023-conference-proceedings-full-papers/
	Danish High-Temperature Symposium (SINTEF, DTU Mechanical Engineering, and Danish Technological Institute)	High-Temperature HP Symposium	
	New Energy and Industrial Technology Development Organization (NEDO, Japan)	In-person meeting	Discuss Industrial Heat Pumps with NEDO in Japan
Non-governmental Organizations	American Council for an Energy Efficient Economy (ACEEE)	2023 Summer Study on Energy Efficiency in Industry	Commercial and Industrial Decarbonization through Waste Heat Recovery
		Industrial Heat Pump Workshop	Industrial Heat Pumps Workshop focused on demonstrations, market transformation initiatives, and available funding to accelerate domestic manufacturing of IHP, market technical support, and plant implementation. The workshop also included a presentation on the global IHP experience from international experts. (July 11, 2023)
State Government	ETCC, CA (Emerging Technologies Coordinating Council)	ET Summit 2021	Development of an Advanced High-Temperature Heat Pump Link: https://www.etcc-ca.com/summits/2021/program/nov17
International Organizations	International Energy Agency (IEA) Annex	Annex 58: High-Temperature Heat Pumps	This Annex gives an overview of available technologies and close-to-market technologies regarding HTHPs. Link: https://heatpumpingtechnologies.org/annex58/

Marketing Chanel	Organization/Trade Association/Professional Association	Key Meetings	Key Publications
		Annex 59: Heat Pumps for Drying	The Annex aims to structure and describe the numerous possibilities and advantages of heat pump integration in dryers. Link: https://heatpumpingtechnologies.org/annex59/
		Annex 60: Retro-fitting Heat Pump Systems in Large Non-domestic Buildings	The Annex focuses on providing straightforward, high-level guidance for building owners and other decision-makers. Link: https://heatpumpingtechnologies.org/annex60/
Utilities	EPRI	8th EPRI Heat Pump Symposium (2023)	The role and application of heat pumps in efficient electrification and load management. The latest and greatest on industrial heat pumps. (April 19–20, 2023)
		Industrial Heat Pump Supplemental Project	Industrial Heat Pumps for Electrification and Energy Efficiency. This project seeks to evaluate market-transforming heat pump technology for industrial process heating, which mostly relies on fossil fuel or low-grade electric heating today. This will be accomplished by characterizing the state-of-the-art for "industrial heat pumps" through a technical and application product review, as well as a thorough analysis of energy savings, cost benefits, and electrification, and GHG reduction potential. Additionally, the project seeks to demonstrate, measure, and verify energy savings impacts for an industrial heat pump through equipment testing in the laboratory, and, though a future phase, at industrial customer sites. Link: https://www.epri.com/research/products/000000003002025533
Manufacturers	Mayekawa GEA Olvondo	EPRI communications	Discussions on developments in Industrial HTHP technologies and commercialization

Source: EPRI

In addition to the marketing channels listed in Table 15, EPRI has been working with 50001 Strategies to advance U.S. installations of IHPs through the development of a U.S.-specific IHP manufacturer database, conducting interviews with IHP manufacturers and documenting key processes in the food and beverage industry that are well suited for IHP applications. EPRI is also working with Alternative Energy Systems Consulting, Inc. (AESC) in its efforts to document the IHP marketplace in California.

Retailers

Effectively marketing the industrial HTHP through a retailer network requires a well-coordinated strategy that highlights the product's unique selling points and benefits. First, conduct market research to identify potential retailers who cater to industries where the heat pump can offer substantial advantages. Provide comprehensive product training to retailers, educating them about the technology, its applications, and the value it brings to their customers. Create marketing collaterals, such as brochures and demonstration videos, showcasing the heat pump's efficiency and cost-effectiveness. Offer or identify attractive incentives to retailers for promoting and selling the product, such as sales commissions or volume-based discounts. Additionally, collaborate with retailers to organize product demonstrations and customer awareness events to generate interest and demand. Retailers can also establish partnerships with local governments, utilities, and environmental organizations to promote the adoption of HTHP technology as part of sustainability initiatives. Continuous communication and feedback loops between retailers and customers as well as between retailers and manufacturers will ensure a smooth sales process and foster a strong, mutually beneficial partnership to drive successful market penetration.

Government

State government organizations such as the CEC and the California Air Resources Board represent additional conduits for sharing information. California has announced a net carbon neutrality goal by 2045 (Mahone et al. 2020), and achieving these economy-wide decarbonization targets requires a reduction in GHG emissions from industries. The CEC and the California Air Resources Board should work together to incentivize increased electrification of industrial energy use using HTHP technology. For example, the California Air Resources Board and the CEC put on several events each year that represent opportunities to share information on HTHP technology.

Codes and Standards

Informing codes and standards about the new industrial HTHP development is crucial to ensure compliance with safety, environmental, and performance regulations. The project team identified relevant regulatory bodies, industry associations, and standards organizations that can use this report to understand the innovative aspects of this heat pump technology and provide their feedback. Standards organizations related to IHPs, such as ASHRAE, International Electrotechnical Commission, International Organization for Standardization (ISO), European Committee for Standardization, Japanese Industrial Standards, Canadian Standards Association, British Standards Institution, Deutsches Institut für Normung, and National Standards Authority of Ireland, play a vital role in establishing guidelines and safety

protocols for the development, manufacturing, and installation of these technologies. They ensure product quality, energy efficiency, and environmental sustainability while promoting international cooperation and innovation in the industry. Collaborating with these entities will help facilitate the integration of the new technology into industrial processes, promote wider adoption, and pave the way for a more sustainable and efficient industrial heating solution. By using the performance data and test results, codes and standards for HTHPs can be established.

Utilities

Sharing a poster and/or presenting at the Electric Program Investment Charge (EPIC) Symposium as well as at the Emerging Technologies Coordinating Council (ETCC) Summit is helpful for messaging. Keeping energy efficiency managers up to date on the technology details and adoption could further encourage rollout. EPRI Utility Advisor Council meetings have strong ties to the utility sector and can assist in disseminating information on the topic to important utility stakeholders. EPRI has conducted knowledge transfer on HTHPs with the utility sector through the heat pump working council meetings.

In addition to the above, EPRI has engaged with electric utilities in organizing industrial HTHP symposiums and supplemental projects to raise funds from the utilities to conduct small-scale pilot demonstrations. In April 2023, EPRI hosted an HTHP symposium that was very well attended by various stakeholders. The goal of this symposium was to provide a forum for open dialogue between utility representatives, manufacturers, government agencies, research organizations, and key stakeholders interested in developing electrification and load management solutions through heat pump technologies that help utility members reach their efficiency, customer satisfaction, and decarbonization goals.

Technology Transfer

Some of the key technology transfer activities and products focused on industrial HTHPs are described in detail in this section.

Fact Sheet

The fact sheet is a two-page summary document that was prepared and submitted to the CEC as a project deliverable, consisting of the following information.

- A Description of the Situation
    - Describe the problem and the current technology being used.
- The Technology
    - Describe the technology, what it looks like, how it works, and how this differs from current practice. Provide a schematic or photo of the technology.
- Advantages and Opportunities
    - Clearly outline the advantages of the new or improved technology and situations where it can best be applied.

- Applications
    - Provide examples of effective applications with initial cost and operating cost.
- Sources of Information
    - Provide authoritative references, opportunities to obtain additional information, and technical assistance in implementing the new or improved technology.
- Other Issues
    - Present information on ancillary issues, applicable codes and standards, health, and human performance improvement, and items not covered in the main body of the fact sheet.

Industry Conferences and Journals

Table 16 highlights specific conferences that are of particular interest to HTHP technology transfer efforts. Some of these events are already complete as indicated in the Notes column. Others are important venues for the project team to share the project knowledge with the key research organizations and HP equipment manufacturers beyond the life of this project. A technical paper in a journal or a technical magazine could also help reach out to the key stakeholders.

Table 16: Heat Pump Conferences for Technology Transfer Efforts

Domestic or International	Organization/ Conference	Location	Notes
U.S. Conferences	IEA Heat Pump Conference (https://heatpumpingtechnologies.org/publications/14th-iea-heat-pump-conference-2023-hpc2023-conference-proceedings-full-papers/)	Chicago, IL	Presented
	EPRI Electrification Conference, dedicated track on industrial electrification and IHP (2024)	Savannah, Georgia, North Carolina	Sessions are in place for Industrial HTHP
International Conferences	ASHRAE Annual Conference	Toronto, Canada/Virtual	Considered for paper presentation
	European Heat Pump Association Power Summit (https://powersummit2022.eurelectric.org/event-sponsors/ehpa/)	Brussels, Belgium	Planned for future
	European Heat Pump Summit (https://www.hp-summit.de/en)	Nuremberg, Germany	Planned for future

Domestic or International	Organization/ Conference	Location	Notes
	High-Temperature Heat Pump Symposium (https://hthp-symposium.org/)	Copenhagen, Denmark	Abstract planned for submittal in 2024
	IIR-Gustav Lorentzen Conference on Natural Refrigerants (https://iifiir.org/en/events/15th-iir-gustav-lorentzen-conference-on-natural-refrigerants)	Trondheim, Norway	Planned for future

Source: EPRI

The leading applications for HTHPs include food and beverage processing, pulp and paper, and chemical industries. These industries are a good fit because they are leading consumers of natural gas and steam temperature needs in the range of 120oC, as provided by the EPRI-CTS demonstration. Other industries such as Oil & Gas and Petroleum Extraction consume a significant volume of natural gas but require steam at much higher temperatures and are not likely to be the first adopters of new heat pumps. Food and beverage processing is likely one of the best entry points to gain traction in the California HTHP market. The food and beverage processing market for heat pumps is large and the required temperature range is appropriate for the system under development. EPRI is currently engaged in a parallel effort to document and quantify specific food and beverage processes that are good candidates for IHP adoption. This effort includes documenting commercially available IHPs in the U.S. in a database, along with manufacturer interviews. This database, documentation, and quantification of food and beverage processes, and manufacturer interviews will aid in advancing the adoption of IHPs in the U.S.

Table 17 highlights specific conferences and the associated near- to mid-term dates that are of particular interest to HTHP technology adoption by industry.

Table 17: Industries and Their Associated Conferences That Could Benefit From HTHP Technologies

Industry	Organization/Conference	Location
Beverage	LRQA Sustainable Food and Drink Conference (https://www.lrqa.com/en-gb/events/sustainable-food-drink-conference/)	London, UK
	Food and Beverage Environmental Conference (https://fbeconf.com/)	Ashville, NC
	Future Drinks Expo	San Francisco, CA
Boiler	ABMA Boiler Technology Conference and Expo (https://abmaboilerexpo.com/boiler2022-recap)	Dallas, TX

Industry	Organization/Conference	Location
	Council of Industrial Boiler Owners (CIBO) Boiler Operations	Virtual
	European Conference on Industrial Furnaces and Boilers	Algarve, Portugal
Chemical	ACS Spring Bonding Through Chemistry (https://www.acs.org/meetings/acs-meetings.html)	San Diego, CA
	Green Chemistry and Engineering Conference (https://www.gcande.org/)	Reston, VA
Dairy	California Dairy Sustainability Conference (https://www.cadairysummit.com/)	Virtual
	IDFA DairyTech Conference	Austin, TX
	Golden State Dairy Management Conference (https://ucanr.edu/sites/CAdairyconference/)	Modesto, CA
Food Processing	Expo Food Processing (https://www.foodprocessingexpo.org/index.cfm)	Sacramento, CA
	Food Northwest Processing and Packaging Expo (https://web.cvent.com/event/eb5a2d64-baba-46dd-8d6a-9bb7d1564b12/summary)	Portland, OR
	Food, Packaging, and Sustainability Summit	Clemson, SC
Pulp and Paper	International Pulp Week (https://internationalpulpweek.com/)	Vancouver, BC
	TAPPI PEERS (https://tappipeers.org/)	Providence, RI
	TAPPI Sustainable Conference	Virtual
Wine	Green Wine Future 2022 International Conference (https://wineindustryadvisor.com/2021/11/15/green-wine-future-2022-international-conference)	Miami, FL
	Sustainable Ag Expo (https://www.sustainableagexpo.org/)	San Luis Obispo, CA

Source: EPRI

Industry-related journals and other publication venues for sharing information on HTHP benefits are listed below.

- ABMA Publications (https://www.abma.com/abma-publications) to track the latest performances of industrial boiler technology
- Annual Review of Food Science and Technology (https://www.annualreviews.org/content/journals/food)
- Beverage Industry Magazine (https://www.bevindustry.com/publications/3-beverage-industry-magazine)

- California Dairy Magazine (https://californiadairymagazine.com/)
- Chemical Industry Journal (https://www.chemicalindustryjournal.co.uk/)
- Journal of Food Processing and Preservation (https://ifst.onlinelibrary.wiley.com/journal/17454549)
- Nordic Pulp & Paper Research Journal (https://www.degruyter.com/journal/key/npprj/html?lang=en)
- Wine Business Journal (https://wbj.scholasticahq.com/)

Journals and other publication venues for technical papers on HTHPs are listed below.

- *Energy Conversion and Management*
- *Applied Thermal Engineering*
- *International Journal of Refrigeration*
- *EPRI Journal*
- *Electrification Magazine*
- *Heat Pumping Technologies Magazine* by IEA

EPRI Activities

EPRI has conducted regular meetings with key market participants to transfer the information developed in this project.

Meetings included EPRI advisory meetings and webcasts with influential utility members that are used to shape EPRI research, develop demonstration and marketing opportunities for technologies, and provide a conduit for the advisors to impart information to colleagues at their "home" utilities. Advisory meetings are held twice a year (spring and fall), usually in February and September.

The EPRI Heat Pump Symposium is held annually as a forum for utility company members, manufacturers, researchers (EPRI and others), industry stakeholders, and government agencies to discuss changes in the industry and actions that need to be taken. As mentioned earlier, learnings from this industrial HTHP project were presented at this symposium.

EPRI Electrification Conference (2024) will explore the critical issues, benefits, and opportunities of electrification. Session tracks would include industrial electric technologies and as such afford an excellent opportunity to transfer technology information to target audiences. Conference attendees typically include utilities, industry, government, and academic leaders. This conference will occur after the end of this project.

Utility Incentive Programs and Applicable Codes and Standards

This section briefly describes some of the utility incentive programs in California that are applicable to industrial HTHPs. The section also outlines some of the codes and standards from different entities that are relevant to HTHPs.

Utility Incentive Programs

When compared to boilers, HTHPs require a larger upfront capital cost that is balanced by the significantly higher COP of the HTHP and reduced operational costs. HTHP early adopters will need properly sized financial incentives to help overcome the entrenched market inertia of boilers. Major California utilities Pacific Gas and Electric Company (PG&E), SCE, and San Diego Gas & Electric Company (SDG&E) provide incentives to industrial customers for the deployment of energy-efficient equipment in their facilities. Industrial customers can take advantage of these incentives to replace boilers with more efficient HTHPs.

- PG&E offers an Energy Efficiency Financing Program where industrial customers can get zero-percent-interest loans up to $4,000,000 for upgrading to energy-efficient equipment (Pacific Gas & Electric Company 2026). The utility also offers cash incentives for heavy-industry customers (Pacific Gas and Electric Company. n.d.).
- SCE offers third-party energy efficiency programs through which industrial customers can obtain financial incentives such as rebates and low-interest financing options to upgrade to energy-efficient equipment (Southern California Edison Company 2026).
- SDG&E offers industrial customers incentive payments for energy-efficiency projects involving the installation of new, high-efficiency equipment or systems. Incentives through this program are paid based on the number of kilowatt hours or therms saved resulting from the installation of the new equipment or system (San Diego Gas & Electric Company 2018).

Applicable Codes and Standards

Codes and standards for industrial HTHPs used in process heating applications may vary by region and the specific industry. The codes and standards that apply to HTHPs are summarized below.

- ASHRAE: The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) publishes standards related to heating, ventilation, and air conditioning. ASHRAE Standard 90.1 covers the rating and performance of heat pumps, while ASHRAE Standards 15 and 34 provide safety guidelines for refrigerants.
- ISO Standards: The ISO has several standards related to heat pumps and refrigeration systems. ISO 15042:2017 and ISO 13256-1:2021 provide guidelines for the evaluation of the performance of heat pumps for industrial applications.
- EN Standards: In Europe, the European Committee for Standardization and the European Committee for Electrotechnical Standardization publish standards for heat pumps and refrigeration equipment. EN 14511 is an example of a standard for air-to-air heat pumps used in industrial processes.

It is essential to work closely with qualified engineers, industrial process experts, and professionals who are knowledgeable about HTHP technology as well as the installation process specific to the industry. Complying with the standards ensures the safety, performance, and efficiency of the systems.

CHAPTER 7:
Production Readiness Plan

This chapter describes the production readiness plan of the HTHP designed in this project. The plan includes a discussion of the features and components of HTHPs, along with parameters that influence their design and operation. In this way, an overview of the production is established. The production requirements needed to install an HTHP solution are also discussed in detail. Finally, estimates of the prices of HTHPs are discussed, and the challenges involved in getting to scale are briefly indicated.

System Features

The main benefit of HTHPs is the fact that they can deliver heat at better efficiency than, for example, electrical boilers due to the unique layout of the HTHPs with a compressor, a condenser, and an evaporator. The efficiency of HTHPs is determined by the COP and is the ratio between energy output (thermal) and energy input (electrical). The COP for HTHPs will typically be between 2 and 4. HTHPs can be classified into open cycle and closed cycle heat pumps. In open cycle heat pumps, there is close integration between the heat pump cycle and industrial processes, enabling higher efficiencies. However, open cycles may become challenging for process handling because the boundaries between the process and the heat pump are close and highly impact each other. This requires highly integrated solutions, advanced controls, and a sophisticated design, often resulting in comprehensive and conservative solutions and, ultimately, in higher investment costs. Therefore, many HTHPs available commercially are closed cycle heat pumps.

Several features influence the performance of the HTHPs; the most important ones are listed below.

Boundary Conditions

The main influence on the performance of the HTHPs is the boundary conditions for the heat pump. This is typically defined by the available temperatures and capacities for the heat source and the demanded temperature and capacity for the heat sink. A typical limit of the HTHPs is the fact that the increase of temperature from the heat source to the heat sink strongly influences the efficiency of the heat pump — a larger temperature increase will result in a lower efficiency. Also, if a phase change is required for the heat sink, the efficiency will decrease due to a lower temperature glide for the heat sink. The HTHP developed under this project has a system design that delivers a temperature lift of 40°C (104°F) or more.

Refrigerant

The refrigerants used for HTHPs depend strongly on the application of the HTHPs. This is because each refrigerant has a different characteristic, making some refrigerants good for lower temperatures and other refrigerants more suitable for high temperatures. In addition to this, some refrigerants are used for applications with a high temperature glide and other refrigerants are used for applications with a low temperature glide, for example, evaporation. This also means that some HTHPs are made of systems using two or more refrigerants, either

as mixtures or as multiple stage-systems, making the HTHPs more complex and therefore more expensive. The team's HTHP used R-1233zd(e) as the refrigerant, which has a GWP of 1.

Compressors

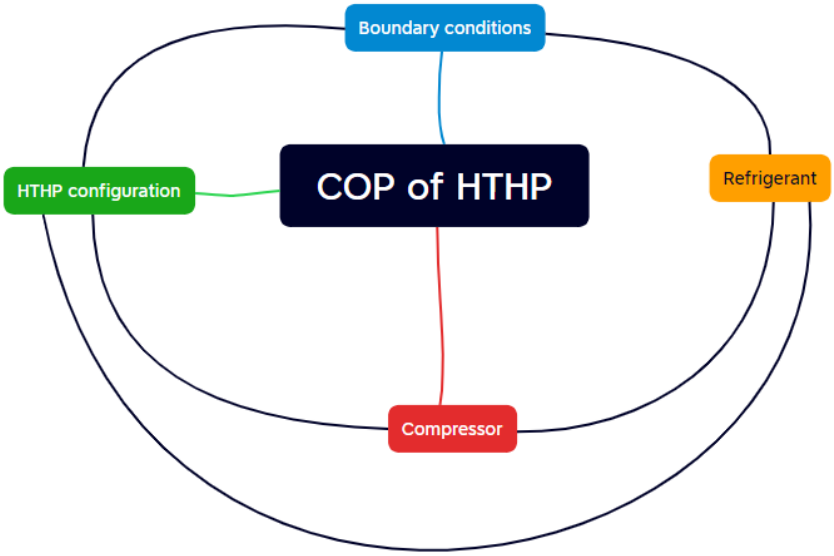
The compressor is the main part of HTHPs, and there are several compressor technologies for different applications. The choice of compressor technology is typically dependent on the choice of refrigerant for the HTHPs. Also, the technology will depend on the boundary conditions, meaning that one technology typically will be used for one combination of refrigerant and temperature lift, whereas another compressor technology may be better for a different application. In this HTHP, the compressor with hermetic construction was used, providing the possibility for a minimal refrigerant leak and fully automated operation. Besides, the hermetic design retains the heat of the motor in the system, increasing efficiency, assuming the motor is capable of operating at given temperatures. The Emerson (Copeland) scroll compressor was selected and is expected to be a robust and efficient option when it is developed on a production scale.

Heat Pump Configuration

Many different heat pump configurations are applicable for different purposes. The simplest configuration is the one-stage HTHP (as used in the team's HTHP), consisting of an evaporator, one compressor, a condenser, and an expansion valve. This configuration is typically for lower temperature lifts and results in a lower capital expenditure (CAPEX) due to the few parts in the system. Typically, it can be an advantage to divide the system into two or more steps consisting of either the same refrigerant or different refrigerants, resulting in a higher CAPEX but typically higher temperature lifts and better efficiency of the system. This is because each compressor will have lower pressure ratios and more optimized compression stages for each refrigerant used. Hence, other HTHP systems can consist of two or more stages.

Figure 20 shows the influence that each parameter has on the system and the final COP of the HTHP. Typically, one would start looking at the boundary conditions and determine a suitable refrigerant and system configuration that can handle the temperature and capacity characteristics of the boundary conditions. Based on this information, a suitable compressor would be chosen, resulting in a final COP of the system based on the HTHP configuration, the boundary conditions, and the chosen compressor.

Figure 20: The Influence of Each Key Component in an HTHP



The influence of each key component of the HTHP on its COP

Source: Prepared by the Danish Technological Institute for EPRI.

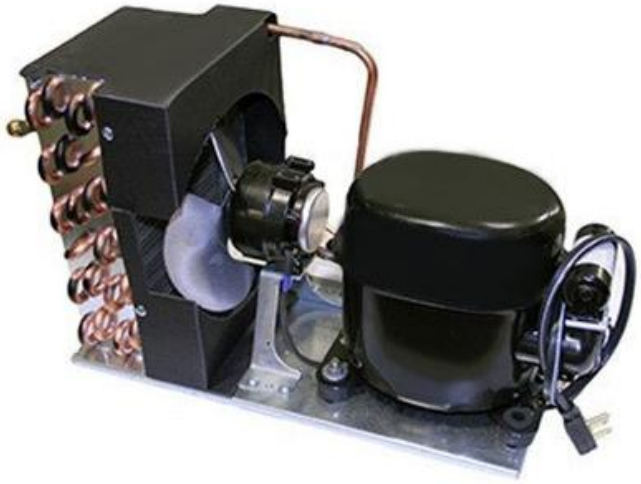
Production Requirements

The key components of the HTHPs are stated in the following section, with the most important production requirements described for each of the key components. This includes the typical challenges for each of the components regarding stability and performance.

Condensers

The condensers may be used as general condensers or as gas coolers, depending on the refrigerant and temperatures needed on the secondary side. It is important to make sure that the condensers are large enough to transfer the capacity needed from the system to the secondary side. If the condenser is too small, a larger temperature difference between the secondary side (sink) and the HTHP will occur, resulting in a too-low heat sink temperature or a higher pressure resulting in a lower COP. A gas cooler is used for specific refrigerants where the pressure on the high-pressure side is so high that a liquid state is not possible for the refrigerant. By using a gas cooler, the volume flow of the fluid will be higher (due to heat capacity), resulting in a larger heat exchanger. Figure 21 shows a condenser unit used in an HTHP.

Figure 21: Condenser Unit of an HTHP With the Compressor



A commercially sold condensing unit package

Source: True 950663 Condensing Unit - 115V, ITEM NUMBER: 200950663; image obtained from the web.

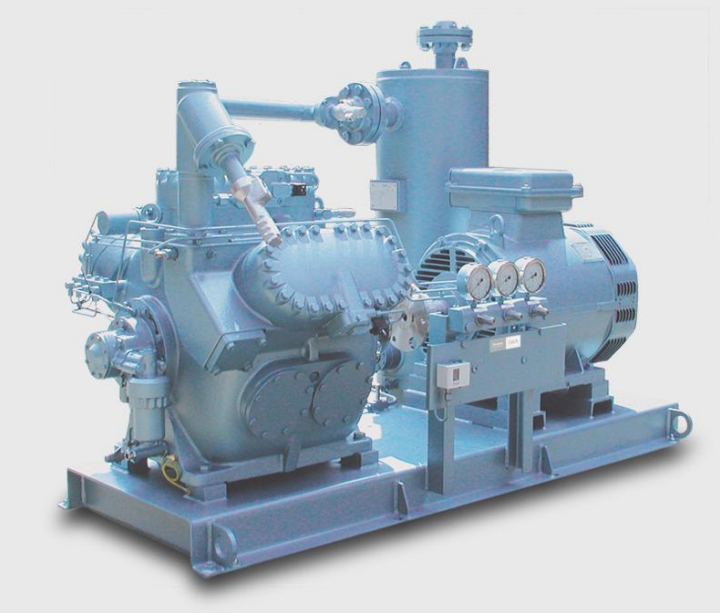
Evaporators

The evaporator is transferring energy from the heat source to the HTHP system and hence needs to be large enough to ensure proper heat energy transfer from the heat source. Again, if the evaporator is too small, the transferred energy between the heat source and the HTHP will not be sufficient, resulting in a smaller heat pump capacity. For refrigerants with very low pressure at low temperatures (for example, water), pressure loss is also an important factor in the evaporators, as even a small pressure loss can have a significant impact on the system. Therefore, the tubes in the evaporator need to be large enough to avoid a pressure loss that is higher than desired.

Compressors

The compressor is the main part of the HTHP and has the main influence on the choice of refrigerant. The compressor is typically the first component that is chosen for the HTHP. The compressor needs to be able to handle the calculated volume flow of the system to make sure the HTHP has the desired capacity. Along with this, the isentropic efficiency (efficiency of a thermodynamic process occurring in a theoretically perfect, reversible adiabatic manner) has great importance on the overall COP. Figure 22 shows a typical compressor.

Figure 22: Reciprocating Compressor



A commercially sold compressor unit

Source: GEA GRASSO 5HP SERIES PACKAGES; image obtained from the web. Link: https://www.gea.com/en/products/packaged-compressors/packaged-reciprocating-unit/packaged-reciprocating-unit-5hp/

Expansion Valve

The expansion valve ensures a pressure change from the high-pressure side to the low-pressure side of the HTHP and needs to be chosen after deciding the temperatures and pressures in the system to make sure it fits the desired system. Figure 23 shows an expansion valve used for the vapor compression cycle of the HTHP.

Figure 23: Expansion Valve



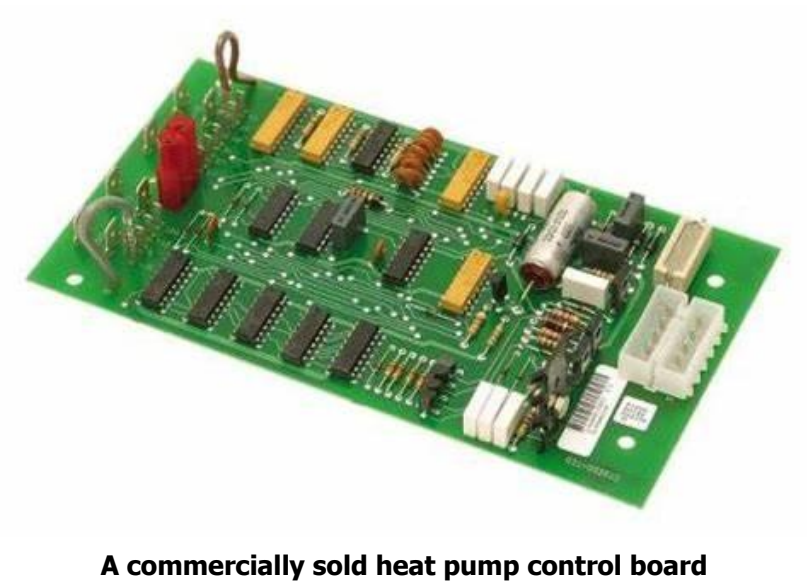
A commercially sold expansion valve

Source: Lennox thermal expansion valve kit; image obtained from the web.

Configurations and Control System

The configuration of the HTHPs is typically where the error is made regarding HTHPs. The configuration of the system has a large impact on the efficiency of the HTHP and must be decided after analyzing the boundary conditions of the system. This means that a configuration must fit the purpose of the HTHP and is typically dependent on a variety of factors, such as choice of compressor and refrigerant as well as economic factors such as lifetime and importance of CAPEX versus operating expenses. Figure 24 shows a typical control board.

Figure 24: Control Board for the Heat Pump Unit



A commercially sold heat pump control board

Source: York-031-00251-700 heat pump control board; image obtained from the web.

Estimated Cost of Production

The key components of the HTHPs are stated in the following section, with the most important production requirements described for each of the key components. This includes the typical challenges for each of the components regarding stability and performance.

A lot of different aspects affect the design of the heat pump, which also applies to the cost of production. The temperature of the heat supply, the mean temperature lift, and the refrigerant used would all influence the cost of production. The cost of production is difficult to obtain from U.S. manufacturers due to the limited installations of HTHPs in the country. However, the production cost is reported in IEA Heat Pumping Technologies (HPT) Annex 58.[4] These are based on different technologies but mostly compressors. The compressors could be divided into the following three categories.

- Compressors from the process industry: These are typical application-specific designs with relatively high capacities and compressors already available in the industry, which

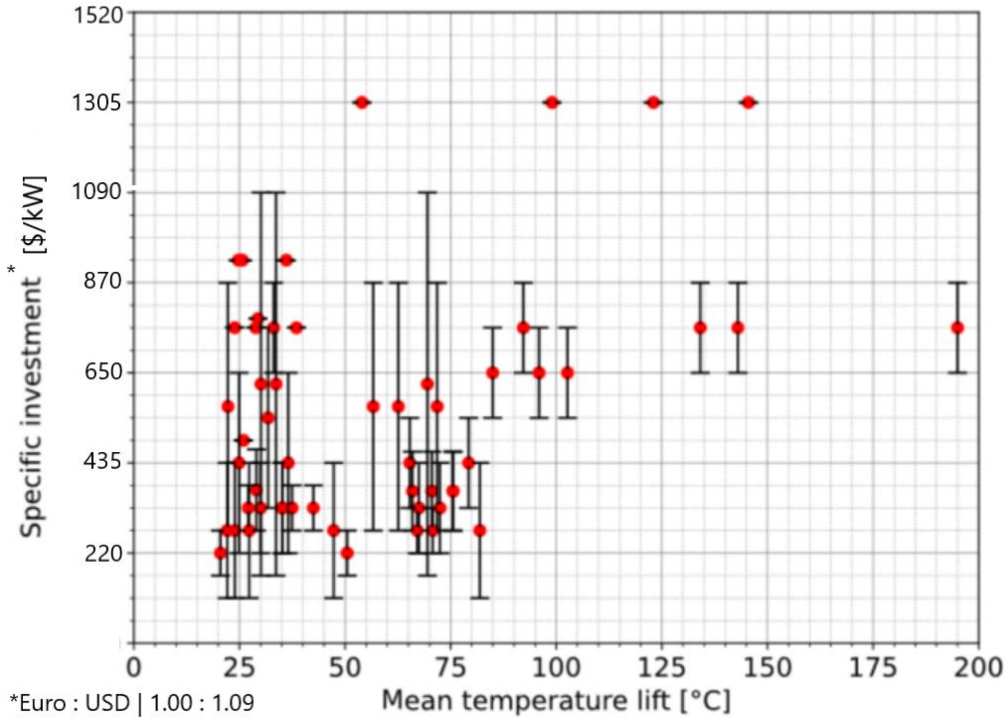
[4] Annex 58 – https://heatpumpingtechnologies.org/annex58/

also can be used in connection with a heat pump system. These compressors have a large potential in large-scale applications and relatively low maintenance costs.

- Modified refrigeration compressors: These include standard compressors based on cost-effective, proven technology that have continuously been modified to operate at higher temperatures. Typical compressors have lower capacities than compressors from the process industry.
- Novel and adapted compressor technologies: These include compressor technologies based on (and strongly adapted to) equipment from automobiles (for example, turbo compressors with a high potential for mass production), pumps, Stirling engines, and so on.

The production price may therefore vary in a wide range in the IEA Annex 58 data. The Annex has generated the data shown in Figure 25 and Figure 26 on the specific investment cost dependency based on the mean temperature lift supply temperature. It is seen in the range of $200–$1,090 per kW ($59–$319 kBtu per hr). Values were originally reported in €euros per kW in the IEA Annex data, but these have been converted to reflect equivalent production costs in U.S. currency. It can be seen that there is a wide range of prices, but the cost would generally be lower with a lower mean temperature lift and lower supply temperature. There is one case with high supply temperature and low cost.

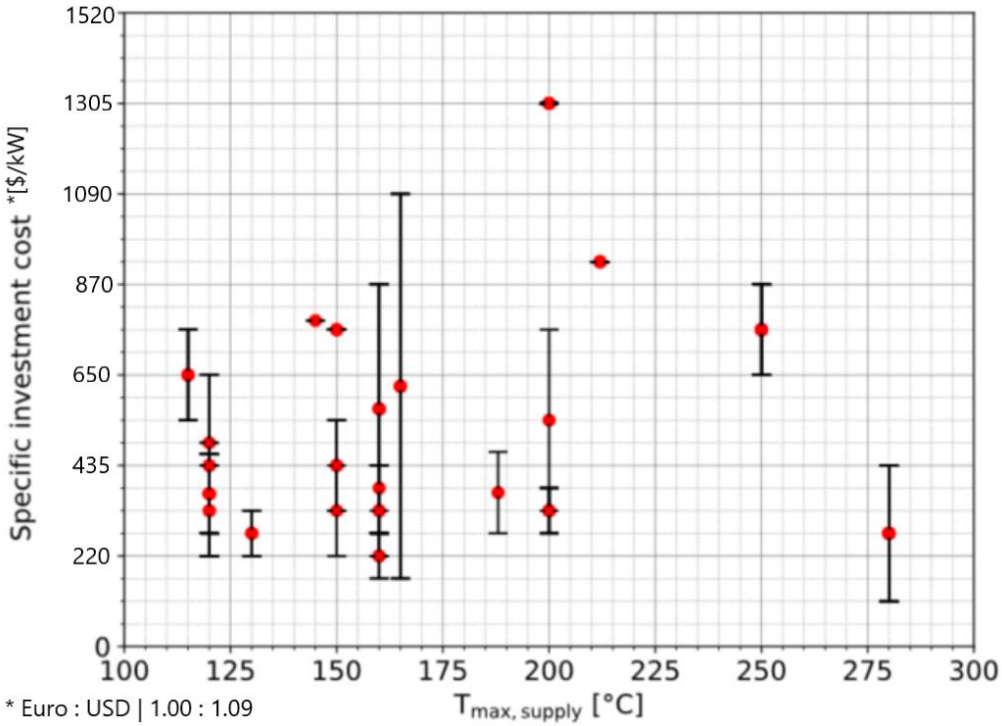
Figure 25: The Cost per Kilowatt Based on the Mean Temperature Lift



The cost of various commercially sold HTHPs per kW as a function of mean temperature lift

Source: IEA Annex 58 (https://heatpumpingtechnologies.org/annex58/)

Figure 26: The Cost per Kilowatt Based on Supply Temperature



The cost of various commercially sold HTHPs per kW as a function of maximum supply temperature

Source: IEA Annex 58 (https://heatpumpingtechnologies.org/annex58/)

Expected Investment Needed to Launch a Commercial Product

Before achieving commercial production, the steps described in the previous sections must be taken. The choices for which type of technology, the types of features, the degree to which components will be developed, and which technology will be adopted from other suppliers are the decisions that must be made. Therefore, it is hard to estimate the exact costs of investment.

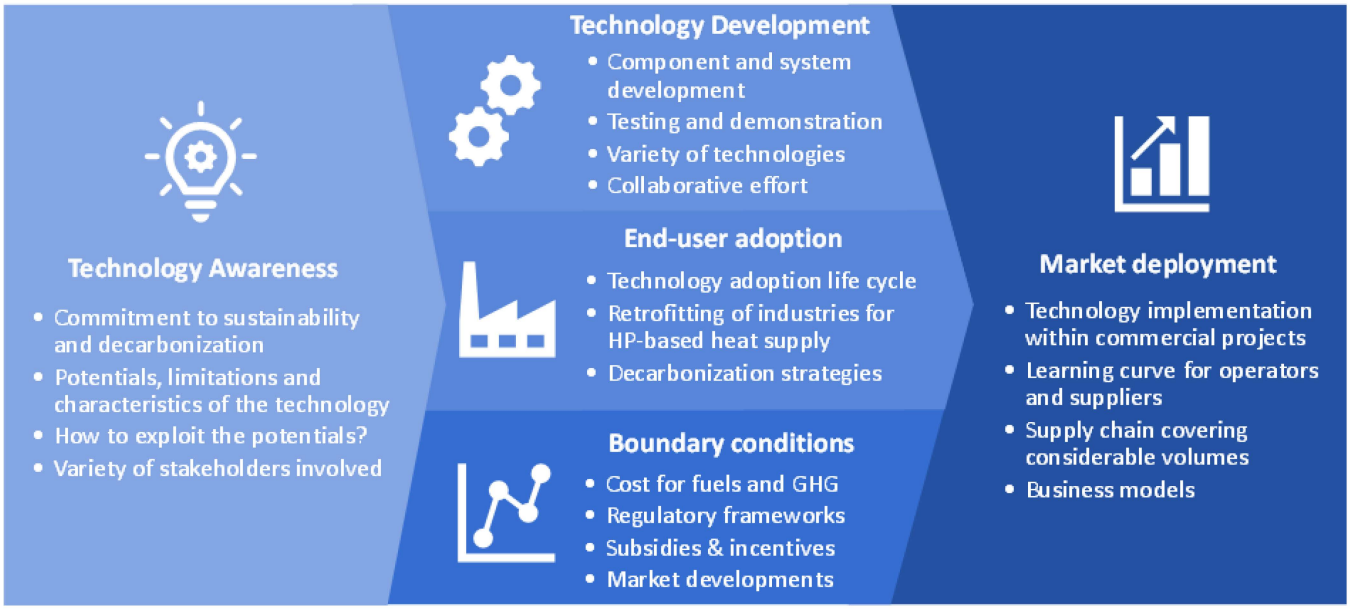
It can also be said that, when launching a commercial product, the investment level is dependent on the specific industry or application and the local market conditions. For instance, costs may vary based on labor costs, availability of resources, and local demand for heat pump technology. Due to this variety of factors that influence the investment decision for IHP manufacturers, conducting a detailed feasibility study and financial analysis to determine the specific investment requirements is recommended. Consulting with experts in the field, such as engineers, energy consultants, and financial analysts, can provide valuable insights into the potential costs and benefits of taking the research and development on an IHP to the product commercialization level.

Getting to Scale

EPRI is planning to work with heat pump manufacturers to take the success of this project forward so that the product can be commercialized and built at scale. Customer awareness and education must be considered in expanding the HTHP technology and getting it to scale in

California and the rest of the U.S. The scaling up of the heat pump is dependent on technological development, but it is also dependent on the readiness of the end-users to adapt the technology. Industrial end-users will only prepare for implementing HTHPs when they are aware of the technology. Technology suppliers will, on the other hand, only invest in the development of new technologies when they see a clear and direct market potential. This is illustrated in Figure 27.

Figure 27: Schematic Overview of the Aspects Impacting Technology Development Toward Market Deployment

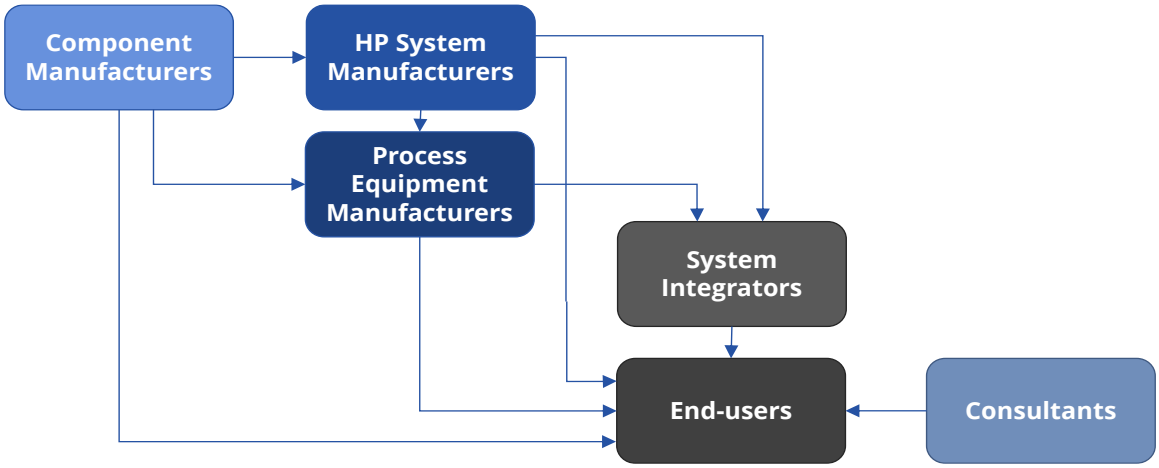


The factors that link HTHP technology development to market deployment

Source: IEA Annex 58 (https://heatpumpingtechnologies.org/annex58/)

For the end-user to get an HTHP, several ways could lead to a solution. They may hire a consultant to buy and fit the heat pump, but there could be a variety of solutions ranging from the end-user buying components to buying plug-in solutions. The cost of a solution will then depend on the chosen way. See Figure 28.

Figure 28: Illustration of the Ways for End-Users to Put Together Their Energy Supply



Various players involved between HTHP manufacturers and end-users

Source: Prepared by the Danish Technological Institute for EPRI.

Conclusion

This production readiness plan covers various aspects of the industrial HTHP, such as the system features, production requirements, cost of production, and steps needed to get to scale. The information can be used by manufacturers as a guideline to launch the production of this HTHP at scale. Given that a majority of HTHPs are currently manufactured outside the U.S. today (in Europe and Japan, for example), it is also important to rely on the expertise and best practices followed by non-U.S. manufacturers in launching and commercializing their products.

CHAPTER 8:
Concluding Remarks

This project's final report provides an overview of an innovative, high-temperature, industrial heat recovery heat pump that is currently being developed by EPRI with CEC funding (Agreement EPC-19-024). Results from the prototype laboratory testing show that, with the newer and emerging refrigerants, efficient compressors, and innovative control designs, a higher-COP heat pump that can effectively recover waste heat from the industrial processes is achievable.

The industrial waste heat recovery heat pumps offer multiple benefits to industrial customers: firstly, they produce useful heat in the form of steam; secondly, they lower fossil fuel energy use by reusing the otherwise wasted heat energy and thereby reducing emissions due to combustion; and, finally, by using clean energy electricity, they also lower the emissions and help in industrial decarbonization. The project confirmed the energy efficiency benefits by using the electric-powered HTHP through laboratory testing, as outlined in Chapter 4. The project also investigated market characteristics and developed commercialization strategies for IHPs. It further investigated the opportunities for wide market adoption through incentives from electric utilities and governmental agencies.

In summary, even though there is no one "silver bullet" solution to decarbonize the world, heat pumps offer a great pathway for industries to achieve their carbon reduction targets. More research funding from government agencies, electric utilities, and other stakeholders around the world would go a long way in developing further innovations in heat pump technology designs that could potentially combat the climate crisis more effectively and efficiently.

List of Terms/Glossary

Term	Definition
ACEEE	American Council for an Energy Efficient Economy
AESC	Alternative Energy Systems Consulting, Inc.
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTU	British thermal unit
CAPEX	capital expenses
CEC	California Energy Commission
COP	coefficient of performance
CRIEPI	Central Research Institute of Electric Power Industry
CTS	Creative Thermal Solutions
CTS4CA	Creative Thermal Solutions for California
EDF	Électricité de France
EHPA	European Heat Pump Association
EPA	Environmental Protection Agency
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
exajoule	1 exajoule = 10^{18} joules)
GHG	greenhouse gas
GWh	gigawatt-hours
GWP	global warming potential
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HP	horsepower
HTHP	high-temperature heat pump
IEA	International Energy Agency
IHP	industrial heat pump
ISO	International Organization for Standardization
kBtu/hr	kilo BTU per hour
kW	kilowatt
kWh	kilowatt-hour
LMTD	log mean temperature difference
M&V	measurement and verification

Term	Definition
$MTCO_2e$	metric tons of carbon dioxide equivalent
MWh	megawatt-hour
ODP	ozone depletion potential
PG&E	Pacific Gas and Electric Company
PID	proportional-integral-derivative (controller)
P-h	pressure-enthalpy
petajoule	1 petajoule = 10^{15} joules
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric Company
T-h	temperature-enthalpy
TRL	technology readiness level
VFD	variable frequency drive
Symbols	
DP	pressure differential
I	current
P	pressure
m	mass flow rate
T	temperature
W	work
Subscripts	
atm	atmospheric
c	cooling
cp	compressor
cpri	refrigerant at compressor inlet
cpro	refrigerant at compressor outlet
cri	refrigerant at compressor inlet
cw	cooling water
cwo	cooling water outlet
env	environmental
er	refrigerant side at the evaporator
eri	refrigerant inlet at evaporator
ero	refrigerant outlet at evaporator
est	estimated

Term	Definition
ew	entering water
h	enthalpy (also, h = heating when subscripted with Q)
hr	using refrigerant side enthalpy
hw	using water side enthalpy
ihx	internal heat exchanger
R	refrigerant
recr	receiver
sepwo	water outlet at separator
subr	of the refrigerant at subcooler
subro	refrigerant outlet at subcooler
supsi	inlet saturation at superheater
subw	of the water at subcooler
supr	of the refrigerant at superheater
supri	refrigerant inlet at superheater
supw	of the water at superheater
pw	work (when used as subscript with C, compressor work)

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APPENDIX A: List of Input, Output, and Instrumentation Used in Prototype Testing

November 2026 | CEC-500-2026-032

Appendix A:
List of Input, Output, and Instrumentation Used in Prototype Testing

Input, Output, and Other Key Parameters

Table A-1: Input Parameters

Input	Input Name	Range	Description
Water source temperature	T_{subwi}	80°C	Water temperature at inlet of subcooler
Waste heat evaporator inlet temperature	T_{ewi}	80°C	Water temperature at inlet of evaporator
Low-pressure steam saturation temperature	$T_{satsupso}$	120°C	Saturation temperature of superheated steam at exit of superheater
Compressor speed	N/A	60-80 Hz	Speed of compressor in Hz

Source: Prepared by CTS4CA.

Table A-2: Output Parameters

Output	Output Name	Range	Description
Heating capacity	Q_h	20-27 kW	Amount of heat taken from high side heat exchangers and put into the steam loop
Coefficient of performance	COP	3.4	Energy efficiency of heat pump system

Source: Prepared by CTS4CA.

Table A-3: Other Key Measurement Parameters

Key Parameters	Parameter Name	Description
Compressor inlet superheat	SH_{cpri}	Amount of superheat (°C) at compressor suction
Steam separator water level	$level_{sepw}$	Saturated liquid level in the steam separator in inches
Steam superheat	SH_{supso}	Amount of superheat (°C) at exit of superheater
Compressor work	W_{cp}	Power input to the compressor in kW

Source: Prepared by CTS4CA.

List of Instruments

Table A-4: Pressure Transducers

Name	Range	Model	Uncertainty
P_{atm}	30 to 110 kPa	BMP280+Arduino DUE R3 Board	±0.1 kPa
P_{cpri}	0 to 1400 kPa	Rosemount 1151GP8	±0.25% span
P_{supso}	0 to 400 kPa	Rosemount 1151AP6	±0.25% span
P_{cpro}	0 to 5500 kPa	Rosemount 3051TG4A	±0.04% span

Source: Prepared by CTS4CA.

Table A-5: Thermocouples

Name	Range	Model	Accuracy
T_{cpri}	20 to 130 °C	Omega T type, 0.062" OD, 6" L	±0.1 °C (after CTS calibration)
T_{cpro}	20 to 130 °C	Omega T type, 0.062" OD, 6" L	±0.1 °C (after CTS calibration)
T_{xri}	20 to 130 °C	Omega T type, 0.062" OD, 6" L	±0.1 °C (after CTS calibration)
T_{supso}	20 to 130 °C	Omega T type, 0.062” OD, 6” L	±0.1 °C (after CTS calibration)
T_{subwi}	20 to 130 °C	Omega T type, 0.062” OD, 6” L	±0.1 °C (after CTS calibration)
T_{ewi}	20 to 130 °C	Omega T type, 0.062” OD, 6” L	±0.1 °C (after CTS calibration)

Source: Prepared by CTS4CA.

Table A-6: Watt Transducer

Name	Range	Model	Accuracy
Wc_p	0 to 8 kW	OSI PC5-015C, 3ph, 380-550V, 0-10A	±0.5% span

Source: Prepared by CTS4CA.

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APPENDIX B: Details of the HTHP Market

November 2026 | CEC-500-2026-032

Appendix B:
Details of the HTHP Market

Overview of Market Size

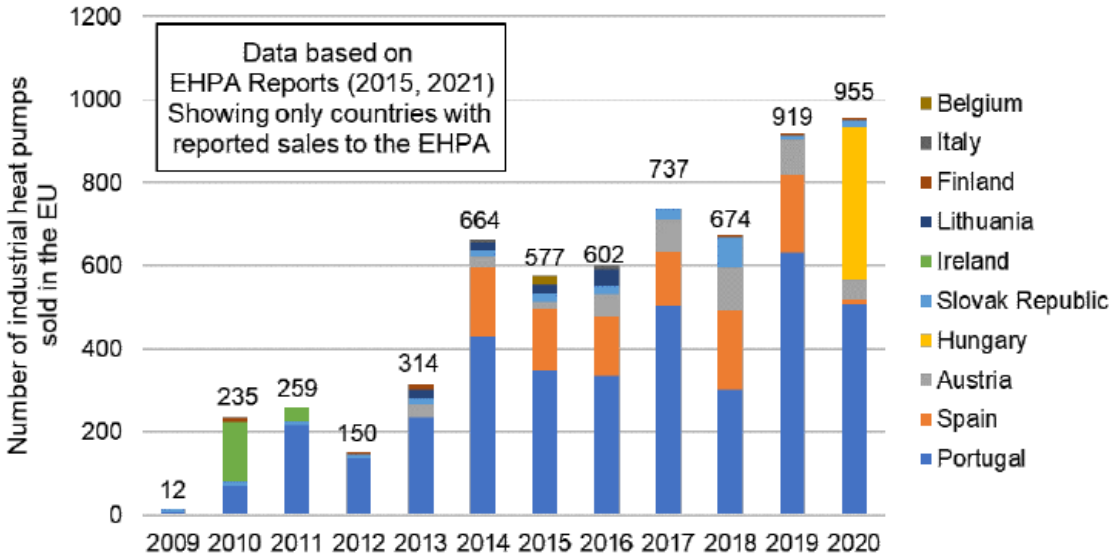
Presently, IHPs account for $0.6–1 billion of the world market. There are more than 20 manufacturers who have IHP offerings. They are primarily located in Europe and Asia, while some companies have a U.S. presence.

Example processes where heat pumps are employed today include simultaneous heating and cooling in the food industry, machinery, mechanical vapor recompression in concentration, distillation, drying, and reducing boiler load by recovering waste heat and so on.

European Union has the highest number of IHP installations. Belgium, Italy, Finland, Lithuania, Ireland, Slovak Republic, Hungary, Austria, Spain, and Portugal are some of the countries where there is a notable presence of installations of IHPs in the European Union (EU).

Figure B-1 below indicates that there were close to 1,000 IHP installations in the EU. Nearly 50 percent of the EU heat pump installations are less than 3 megawatts (MW) in capacity, and only 20 percent of them are more than 10-MW capacity.

Figure B-1: Current Installations of Industrial Heat Pumps in the European Union



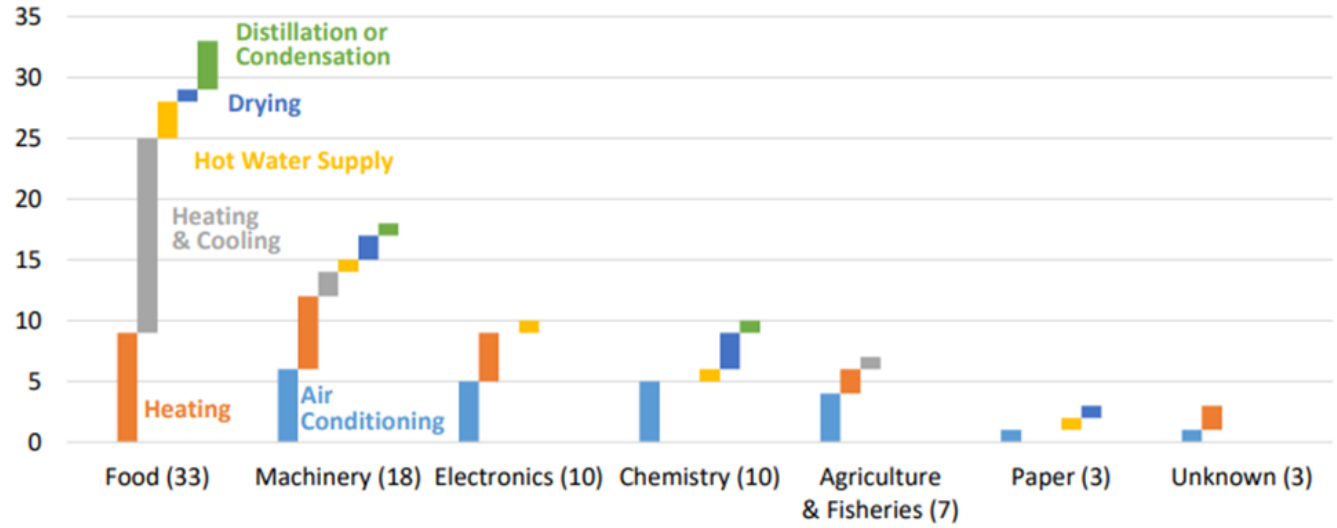
The current installations of IHPs in the European Union

Source: Data based on European Heat Pump Association (EHPA) Reports (2015, 2021). Only countries with reported sales to EHPA are shown.

The other main IHP market is in Japan. Today there are installations in Japan that provide ~200-MW heating capacity cumulatively. There are several installations in the hundreds of kW class (Note that 700kW ≃ 1 ton/h steam boiler). The main industrial applications for which the heat pump is installed in Japan are in the food industry (33 installations in various processes), machinery (18 installations), electronics (10 installations), chemical industry (10 installations),

agriculture and fisheries (7 installations, for example, air conditioners (AC)for greenhouses). The paper industry has large potential but limited application today, with only three known installations. (See Figure B-2 below for details).

Figure B-2: Current Installations of IHPs in Japan



The current installations of IHPs in Japan

Source: T. Kaida, Central Research Institute of Electric Power Industry (CRIEPI) "Industrial Heat Pump Applications in Japan" Chillventa Congress (2018)

Commercial Heat Pump Models Available in the Market Today, by Heating Capacity and Temperature Range

Most commercially available HTHPs typically provide a temperature range of 80–110°C and hot water output. However, certain suppliers, majorly centered around Europe, have managed to achieve higher temperatures, reaching up to 200°C. The EPRI-CTS demonstration is one of the few projects in the U.S. that developed and demonstrated an HTHP providing low-pressure steam with a temperature >120°C. Table B-1 gives an overview of HTHP models with different TRLs developed by manufacturers around the world.

Many heat pump manufacturers could ramp up production of IHPs in the U.S.A. Original equipment manufacturers (OEMs) who have a U.S. presence for heat pumps, in general, could be more promising candidates to target for the adoption of IHPs in the U.S. As of 2022, a partial list of these OEMs includes Carrier, Emerson Electric, Danfoss, GEA Group, Johnson Controls, Mayekawa, Mitsubishi Heavy, Oilon, Robert Bosch, Thermax Limited, Trane Technologies, and Viessmann Group. Except for the first two companies listed above, other OEMs are non-U.S. companies with U.S.-based facilities.

There are a few promising ventures in the HTHP space in the U.S. such as AtmosZero, SkyVen Technologies, and Thar. AtmosZero has piloted a 650-kW system capable of delivering 165°C. Skyven Technologies has developed industrial heat pumps capable of producing 200°C. Thar Heat Pumps, a subsidiary of Thar Energy, has designed heat pumps with CO_2 as refrigerant and capable of producing steam at 200°C.

NEDO: The New Energy and Industrial Technology Development Organization (NEDO) in Japan has been actively involved in promoting HTHP research activities. NEDO recognizes the significance of advancing energy-efficient technologies to tackle environmental challenges. To this end, it has been supporting various research projects focused on developing and deploying HTHPs in industrial applications. NEDO's initiatives encompass collaborative efforts with industry partners and research institutions to enhance heat pump performance, optimize system designs, and identify potential areas of application in diverse industrial processes. By fostering innovation and conducting practical demonstrations, NEDO aims to validate the viability of HTHPs and their positive impact on energy savings and GHG reduction. As Japan continues to emphasize sustainability and energy conservation, NEDO's dedicated efforts in HTHP research play a pivotal role in driving Japan's transition toward a more environmentally friendly and technologically advanced industrial landscape.

Denmark: Denmark has been at the forefront of HTHP research, demonstrating a strong commitment to sustainable energy solutions. With a focus on reducing carbon emissions and promoting energy efficiency, Danish research institutions and industry partners have collaborated extensively to advance heat pump technologies tailored to high-temperature applications. Key players like the Danish Technology Institute, SINTEF, and so on have ongoing research efforts that identified significant advancements in system design, refrigerants, and thermal performance, enabling the use of waste heat from various industrial processes, district heating systems, and even geothermal sources. Denmark's extensive experience with district heating networks has provided a unique testing ground for HTHPs, showcasing their potential to enhance the integration of renewable energy sources and support the country's transition to a low-carbon future.

Austria: Austria has a goal of climate neutrality by 2050 at the latest, without the use of nuclear energy. A climate action study completed in 2019 illustrates that Austrian industry can be theoretically supplied with exclusively renewable energy. The study also identifies HTHPs for steam generation and supplying drying processes. The number of IHPs in Austria has increased steadily since 2012 and is expected to continue to increase at least through 2030.

Below is a list of commercially available HTHPs with TRL 8–9, and capable of delivering temperatures above 120°C.

MAN Energy Solution & TurboDen: These heat pumps are built using large turbo-compressors and may use different refrigerants such as HFOs, hydrocarbons, and steam The official capacity of MAN is 10–50 MW, and for Turboden is 3 – 30 MW. Actual capacities could vary based on the choice of refrigerant, source, and sink temperatures, and these units are generally custom-designed. Steam temperature can go as high as 150°C in both cases.

Piller & Epcon: These heat pumps are used in multistage applications and use centrifugal blowers (or low-pressure ratio centrifugal compressors), to compress steam as a medium. The capacity for Piller is 1–70 MW and for Epcon is 0.5–30 MW. Standardized blowers are connected in series to obtain the desired result. Steam temperatures up to 212°C (Piller) and 150°C (Epcon) are produced using these heat pumps.

Spilling: These are piston compressor-based heat pumps. Typically, the incoming steam has a temperature higher than 100°C and is lifted by the compressor up to a maximum of 280°C. The source energy for this heat pump must be available at 100°C or higher, or the steam must be generated by a separate low-stage heat pump. The official capacity is 1–15 MW, depending on sink and source temperatures.

Olvondo: This heat pump is a Stirling cycle unit with helium as the refrigerant. The heat pump can deliver steam at up to 200°C and has a heating capacity of 500 kW.

Kobelco: There are two heat pump models available from Kobelco:

- A twin-screw compressor taking low-pressure steam (0.5 to 1 bar) and compressing it to up to 175°C with a heating capacity of 0.8 MW.
- A two-stage system using a mixture of refrigerants, R245fa and 134a in the low stage, supplying heat to a steam generator. The steam is compressed further by a screw compressor up to 175°C. The heating capacity is 0.4 MW.

Qpinch: This heat pump is a chemical adsorption heat transformer capable of producing 230°C supply temperatures in capacities above 2.0 MW.

Table B-1: Overview of HTHP Products Available Worldwide[5]

HTHP Supplier	Compressor Type	Working Fluid (Refrigerant)	Max. Capacity (MW)	Max. Supply Temp [deg(C)]	TRL
Spilling (DE)	Piston	R718	15	280	9
Enerin (NO)	Piston	R704	10	250	6
Piller (DE)	Turbo	R718	70	212	8 to 9
Olvondo (NO)	Piston (double acting)	R704	5	200	9
Turboden (IT)	Turbo	Application specific	30	200	7 to 9
ToCircle (NO)	Rotary vane	R717+R718	5	188	6 to 7
Kobelco (JP)	Twin-screw	R245fa/R134a + R718	0.4	175	9
SRM (SE)	Screw	R718	3	165	5
SPH (DE)	Piston	HFOs	5	165	7 to 8
Heaten (NO)	Reciprocating	HFOs	6	165	7 to 9
Weel & Sandvig (DK)	Turbo	R718	5	160	4 to 9
Siemens Energy (DE)	Turbo	R1233zd(E)/R1234ze(E)	70	160	9
ECOP (AT)	Rotational Heat Pump	ecop fluid 1	0.7	150	6 to 7
Rank (ES)	Screw	R245fa, R1336mzz(Z), R1233zd	2	150	7
Epcon (NO)	Centrifugal fans, blowers	R718	30	150	9
MAN Energy Solutions (CH)	Turbo with expander	R744	50	150	7 to 8
Mitsubishi Heavy Industries	Two-stage centrifugal	R134a	0.6	130	9
Fuji Electric (JP)	Reciprocating	R245fa	0.03	120	9
Emerson (US)	Scroll and EVI scroll	R245fa, R410a, R718	0.03	120	6
Mayekawa (JP)	Reciprocating	R744	0.1	120	8 to 9
Fenagy (DK)	Reciprocating	R744	1.8	120	5 to 6
Johnson Controls (DK)	Reciprocating	R717+R600(cascade)	5	120	7 to 8

Source: Arpagaus et al. "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials." Energy 152 (2018).

[5] AT-Austria, CH-Switzerland, DE-Germany, DK-Denmark, ES-Spain, IT- Italy, JP-Japan, NO-Norway, SE-Sweden, US-United States of America

California ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX C: Supplemental Technology Transfer Content

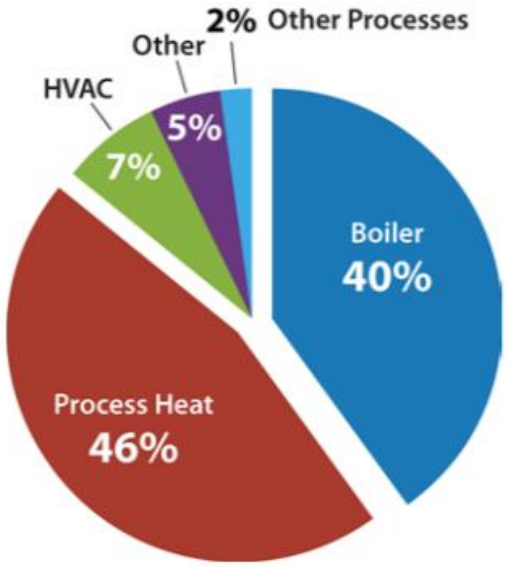
November 2026 | CEC-500-2026-032

Appendix C:
Supplemental Technology Transfer Content

Applicability of HTHPs for California[1]

In 2020, California ranked third in the country for its natural gas use by industrial customers (726 Billion Cu Ft in 2020, which is about 35 percent of the total statewide natural gas consumption of 2075 Billion Cu Ft).[2] The majority of the natural gas is used to generate direct process heating or used in boilers to generate steam or hot water for industrial processes (see Figure C-1). Oil & gas, food processing, petroleum, paper, and stone/clay/glass industries are the major consumers of natural gas in California (see Figure C-2).

Figure C-1: Industrial Natural Gas End-Use for California



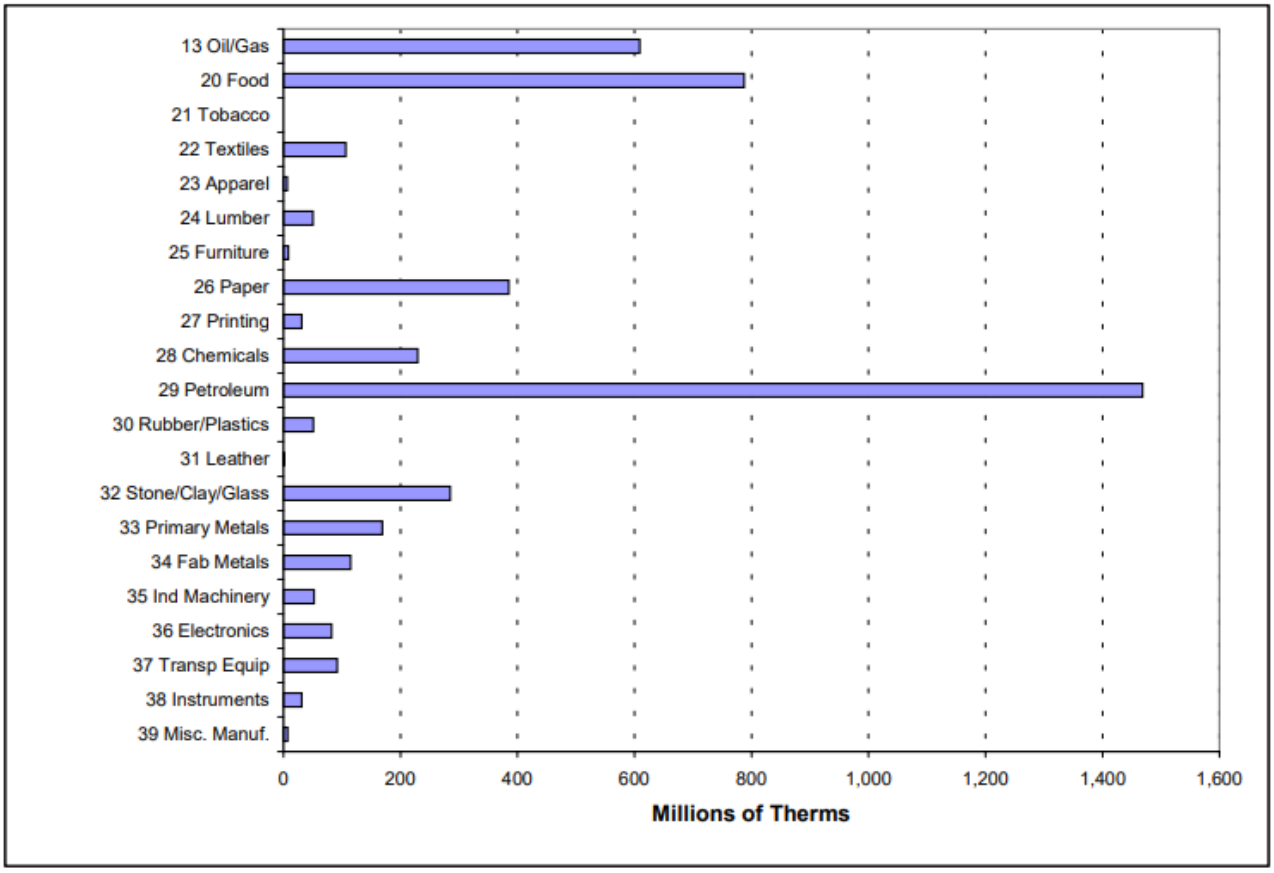
End-use applications of natural gas as a fuel in California

Source: XENERGY Inc. "California Industrial Energy Efficiency Market Characterization Study."

[1] The information contained in this appendix has been prepared with the support of Electricite de France (EDF).

[2] https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_use_ng.html&sid=US&sid=CA

Figure C-2: Industrial Natural Gas Consumption in California (by 2-Digit Standard Industry Classification (SIC) Grouping)



Industrial applications for consumption of natural gas in California

Source: XENERGY Inc. "California Industrial Energy Efficiency Market Characterization Study."

California's food processing and paper industries are ideal targets for using the HTHP technology and could be the first industries in the state to adopt HTHP. This is because they have the steam temperature requirements in the range of 120–140˚C (see Table C-1), which happens to be the temperature range aimed at with this project (> 120 0C).

Table C-1: Industrial Sectors with the Greatest Steam Use and Steam Temperature Distribution

	Steam Energy	Temperature	Distribution (%)		
Temperature Range (ºC)	Food (311)	Paper (322)	Petroleum and Coal (324)	Chemical (325)	Primary Metals (331)
>260	-	-	-	22	38
240-260	-	-	-	9	
220-240	-	-	-	-	

	Steam Energy	Temperature	Distribution (%)		
200-220	2	-	100	-	
180-200	6	-	-	9	
160-180	8	14	-	32	62
140-160	-	22	-	5	
120-140	11	64	-	23	
100-120	16	-	-	-	
80-100	16	-	-	-	
60-80	20	-	-	-	
40-60	21	-	-	-	
All Temps	100%	100%	100%	100%	100%
< 260	100%	100%	100%	78%	62%

Source: Table 7 of "Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States", NREL Report 2015.

The State-of-the-Art of the IHP Technology and Ranges of Temperatures Achieved by Demonstration Projects Around the World

The usefulness of the HP technology to industrial customers depends on the range of the output temperatures achieved. At present, most commercially available HP offerings are limited to 80˚C–110˚C and provide hot water output. However, industrial customers need steam output of 120˚C or higher. Achieving industrial steam generation of 120˚C or higher is where most of the researchers around the world are currently working. Table C-2 below shows the mapping of the leading HTHP demonstration projects around the world, mainly in Europe and Japan. There are several projects generating steam and demonstrating in the field settings at >120˚C and a few projects aiming to achieve very high temperatures of 160–2000C for steam production. These HTHPs are at varying levels of technology maturity with many of the heat pumps still at the laboratory demonstration stage and some installed in the field. An estimated TRL is also included in Table C-2, but in some cases, the estimate might not be correct because organizations are intentionally not sharing product development details with the public at this time.

Table C-2: State-of-the-Art for the Industrial HTHP Technology Around the World

Project/Org	Location	Max Temp	Low-GWP Refrigerant	Target COP	Size	Estimated Maturity
Combitherm	Germany	120ºC	R245fa	3.4	252 kW	TRL 7
DryFiciency	Austria	160ºC	R1336mzz-Z	3.0	300 kW	Field install – TRL 6

Project/Org	Location	Max Temp	Low-GWP Refrigerant	Target COP	Size	Estimated Maturity
EPRI CTS Demo	**California**	**120ºC**	**R1233zd (to be finalized)**	**3.6**	**30 kW**	**Lab demo – TRL 3**
Free2Heat SINTEF	Norway	180ºC	R718 (water)	3.1	60 MW	Lab demo – TRL 4
HighEFFLab SINTEF	Norway	115ºC	"Natural refrigerant"	2.5	300 kW	Field install Dairy – TRL 7
Hybrid Energy	Norway	120ºC	R717/R718	4.3	1.3 MW	TRL 8
Kobelco	Japan	165ºC	R134a and R245fa	2.5	660 kW	TRL 4
Mayekawa	Japan	120ºC	R744 (CO_2)	3.1	120 KW	TRL 8
Mitsubishi Heavy Industries	Japan	200ºC	Proprietary	3.5	600 kW	Lab demo, 2022 goal – TRL 5
Ochsner	Austria	130ºC	OKO1	2.0 at the highest temp	1.6 kW	TRL 7
PACO EDF Research and Development	France	130ºC	R718 (water)	>5.0	600 kW	Field install district heating by Luminus – TRL 7
Siemens Energy	Germany	150ºC	Proprietary	"High COP"	70 MW	TRL 5
Sustainable Process Heat	Germany	160ºC	HFOs with GWP < 10 or natural hydrocarbons	2.0	1 MW	TRL 7
Thermea	Netherlands	130ºC	R744 (CO_2)	6.3	4 MW	Lab demo – TRL 4

Source: Arpagaus et al. "High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials." Energy 152 (2018)

Understanding The Potential Market Barriers to HTHP Manufacturing and Adoption

Lack of Commercial HTHP Product Availability and Awareness

In the US, there are almost no industrial HTHPs commercially available on the market that can produce low-pressure steam for ranges >120˚C although during this project, certain manufacturers have come forward to demonstrate this ability. Europe and Japan are currently leading the way with HTHP research and early implementations at increasingly higher temperatures. When compared to natural gas boilers, HTHPs are lower cost, enable greater flexibility, reduce environmental impacts, and increase safety in addition to providing numerous other benefits.

Being a new technology, that is currently tested in a laboratory setting, there is an obvious lack of product awareness. Currently, nearly all the HTHP options are from international vendors, many of which have limited market share in the U.S. The absence of domestic HTHP products raises the barrier to adopting HTHP technology, reducing awareness and in turn inhibiting the adoption of available HTHP options. Overall, this recursive loop has made the U.S. lag in HTHP adoption. The goal of this EPRI-led project is to break this cycle by introducing a U.S.-designed and built HTHP to the domestic market. A mix of HTHP advanced research and development, as well as government incentives and outreach, have helped make Europe and Japan leaders in the field. The outcomes of this CEC project can be taken forward to replicate the same within the U.S. market.

Slow Rate of Replacement of Legacy Boiler Systems

On average boilers have an operating life of approximately 20 years. That suggests that five percent of the boilers in service are replaced annually. Assuming no additional boilers were installed in the U.S., it would take 20 years to make the complete transition to HTHPs. Given this timeframe, electrification of steam generation must begin as soon as possible to support energy independence and decarbonization. Encouraging complete annual replacement with HTHPs will require that the economics be favorable when compared to boilers.

Customer Payback Period Expectations for Adopting New Technologies

A key market adoption challenge with the leading HTHP researchers and equipment manufacturers is that the industrial adopters are looking for short HTHP payback periods in the range of two to three years. When compared to boilers, HTHPs require a larger upfront capital cost that is balanced by the significantly higher COP of the HTHP and reduced operational costs.[3] HTHP early adopters will need properly sized financial incentives to help overcome the entrenched market inertia of boilers. Moreover, HTHPs will need to be better in nearly every way to justify customers taking the risk of moving to a newer technology. For some customers, local service and maintenance can also be a cause for concern. As HTHP technology matures, prices will naturally come down and support will improve enabling them to compete without government incentives.

[3] This is somewhat analogous to Electric Vehicles (EVs) versus gasoline automobiles. EVs have a higher purchase price, but a lower operating cost, which in the long run lowers the total cost of ownership.

This CEC project accelerates the process of developing high-efficiency/COP steam generation within the U.S. while providing a case study that helps build customer confidence in heat pumps. The publicly available documented field demonstration and performance history will clarify the long-term reliability and economics of HTHPs. With time the electricity grid will get cleaner, HTHPs will have greater GHG reduction benefits, and a higher temperature range will help additional industries in California achieve their environmental goals.