



# Industrial High Temperature Heat Pumps – Ongoing Research in the USA

Ammi Amarnath<sup>a\*</sup>, Baskar Vairamohan<sup>a</sup>

<sup>a</sup>Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA 94304. USA

## Abstract

According to the U.S. Department of Energy, it is estimated that approximately 35% 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 1500–3000 trillion Btu per year [1.58 – 3.17 EJ]. The development and testing of a novel heat pump funded by the California Energy Commission in the United States is presented in this paper. This work effort is aimed at developing an industrial heat pump that can capture low-grade industrial waste heat (around 70 – 80°C) and transform it into high-temperature useful heat, specifically in the form of steam. The paper also discusses the use of a low Global Warming Potential (GWP) refrigerant (R1233zd (E)) that can provide a temperature lift of at least 40°C, thereby producing steam, with coefficient of performance (COP) greater than 3.4. Industries such as food processing, chemicals, paper and textile industries can make use of this steam.

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## 1. Introduction to Industrial Decarbonization

Addressing climate crisis is in the limelight globally and almost every country in the world is on a path to decarbonize the buildings, transportation and industry. It is imperative that economy-wide decarbonization is the way to achieve carbon goals and meet the targets set forth in the 2015 Paris agreement and the electric power industry is leading the charge. Since 2005, the US reduced its carbon footprint by one gigaton, primarily by switching to cleaner fuels, expanding renewables and driving efficiencies. To get to the next gigaton, we need solutions to integrate and manage more low carbon energy generation: from distributed to utility scale solutions covering wind, solar, hydro and nuclear; to systems that help us optimize their output. According to a recent EPRI analysis, the annual U.S. emissions can be reduced by at least an additional 3 gigaton (Gt) from 2030–2050 (refer to Figure 1), consistent with an 80% drop since 2005, through strategic R&D focused on post- 2030 deployment of innovations for using clean electricity to capture a growing share of final energy markets. As efficient electrification accelerates, technologies for indirectly electrifying challenging end uses will emerge for deep decarbonization of all major energy sectors.

At the same time, electrification of the end use is a primary option for reducing direct emissions outside the electric sector, particularly in transportation but also in buildings and industry. Combining clean electric power and electrification can help bring about cost-effective decarbonization throughout the economy, although reaching economy-wide net-zero targets will likely require additional breakthrough technologies.

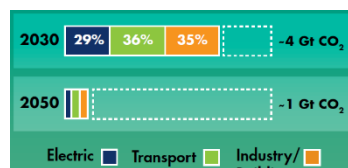


Figure 1 Emissions by US Energy Sector (Source: EPRI)

\* Corresponding author. E-mail address: aamarnath@epri.com

Industrial-scale energy systems integration technologies, such as waste heat recovery and distributed energy generation, can reduce the manufacturing sector’s reliance on the electric grid and increase industrial efficiency. Low-temperature waste heat streams account for the majority of the industrial waste heat inventory. The waste heat inventory in the industrial sector in the United States was analyzed and is estimated to be on the order of 1500–3000 trillion Btu [1.58-3.16 EJ] annually. According to US Department of Energy, process heating account for nearly 70% of the total process energy, accounting for approximately 7500 TBtu [7.91 EJ]. Of this total process heating energy (see Figure 2), only about 5% is direct electricity use and the remaining 95% is contributed by fossil-fuel and steam. Thus, industrial process heating has a very high potential for decarbonization as steam production and fossil-fuel fired processes contribute heavily to the global carbon emissions.

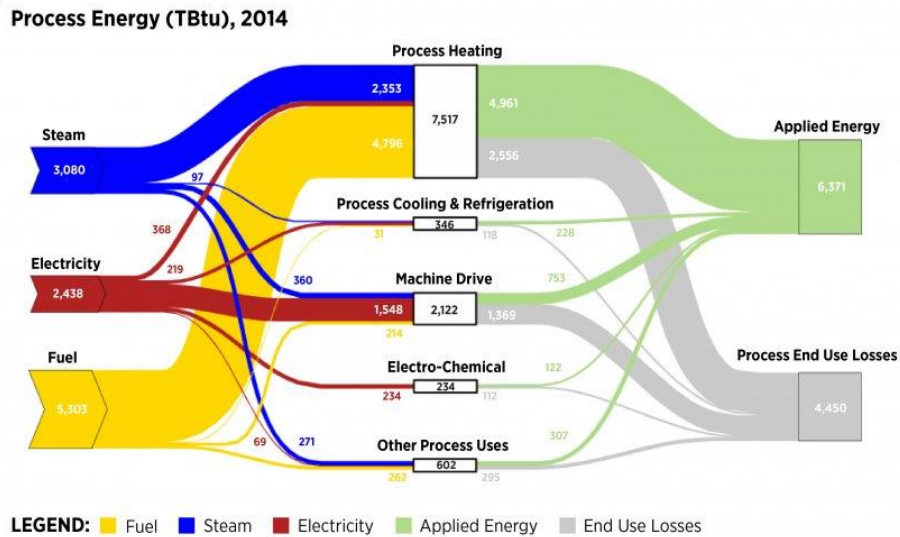


Figure 2 US manufacturing sector energy use and losses by fuel types (Source: US Department of Energy)

Recovering waste heat, though difficult to achieve, could offer a decarbonization solution to the industrial sector. By utilizing wasted heat energy and putting it back to the process reduces the fuel intake which in turn reduces the emissions. Additionally, using heat pump technology – an electric solution – for waste heat recovery reduces the steam and fossil-fuel dependence which effectively lowers the industrial emissions as well.

Waste heat recovery is often utilized in two different ways, (i) generated waste heat from an industrial facility can be captured and re-used by redirecting waste streams for use in other thermal processes, or (ii) the waste heat stream can be converted to electricity.

In this paper, an innovative heat pump technology that is currently in development which can capture the low-grade industrial waste heat (around 70 - 80°C) and transform it into high-temperature useful heat, specifically in the form of steam will be discussed. Unfortunately, heat pumps that are currently available commercially cannot take advantage of high-temperature industrial processes, as currently available heat pumps have an upper-temperature range limit around 94°C.

Currently, the heat pumps that can produce steam are mostly in developmental stages across the world. Low-temperature waste heat streams available abundantly in industries. Typical waste heat sources are at temperatures in the 70-80°C range. The sources of the waste heat in industry typically are chillers, cooling processes, return steam condensate. Most of the industry need for steam is in the range of 115 to 125°C and industries such as food processing, dairy, paper and chemical can make use of this steam. This will provide an immediate high impact heat pump solution to the industries in not only California but also around the world once successfully developed, tested, and verified in the laboratory.

## 2. Market Characteristics

The most dominant existing technology for steam production is gas-fired boilers. Such boilers have significant carbon footprint – the GHG emission factor for gas boilers is about 235.6 g CO<sub>2</sub> equivalent per thermal kWh of heat produced<sup>1</sup>. Some boilers have electric resistance heaters (costly electricity, with COP~1)

that add to carbon emission based on the electric power generation mix. The cost of the electric resistance boilers is in the range of \$30-\$50/kW of heating capacity produced.

The challenge is to bring down the cost of heat pump to be closer to boiler costs. The current projected costs (in literature) are about an order of magnitude higher. This project is exploring the use of existing components with innovative design, in order to be cost effective, as compared to boilers. Details on the bill of materials for low-cost heat pumps are being developed in the project described in Section 5 of this Paper.

Another aspect of this project is to widely transfer knowledge gained. EPRI, through its utility membership consortia, is well qualified to do that. Targeted technology transfer activities are planned to be conducted during the latter part of 2023.

### 3. Other Emerging Heat Pump Technologies and Pilots Around the World

There are several organizations around the world involved in developing high temperature heat pumps some attempts to develop HTHPs. Several heat pumps in the category discussed in this paper from Japan, Norway, France etc. are still in R&D stage and are nearing commercialization status. Some information about the status of technology is given in Table 1 below through the literature survey. This is just a snapshot of example organizations that are developing high temperature heat pumps. Heat pump research is a hot research area and several other organizations in various countries developing breakthrough heat pump technologies as well as refrigerants.

In Japan, Fuji Electric has developed an early commercial heat pump prototype capable of producing steam from waste heat just recently. This heat pump is a smaller capacity (30 kW) exhaust heat recovery type steam generating heat pump system that can produce 120°C saturated steam by means of efficiently recovering hot wastewater of less than 100°C. Details as to the knowledge of refrigerants and other specifications are not available <sup>ii</sup>.

Table 1 Sample of High Temperature Heat Pump research in various countries

Project	Country	Refrigerant	Heat Source (°C)	Heat Sink (°C)	Heating Capacity (kW)
Austrian Institute of Technology, Vienna, Chemours, Bitzer	Austria	R1336mzz(Z)	30 to 100	70 to 160	12
PACO, University of Lyon, EDF	France	R718	70 to 90	120 to 140	300
EDF, Johnson Controls, Alter ECO	France	R245fa	20 to 60	90 to 140	20 to 1,200
Tokyo Electric Power Company, Japan	Japan	R601	40 to 90	95 to 135	150 to 400
Austria: TU GAZ	Austria	R600	50 to 80	80 to 125	20 to 160
The Netherlands: ECN, SmurfitKappa, IBK, Bronswerk.	Netherlands				

### 4. Activities Under IEA Annex 58, Annex 59 and Annex 60

EPRI is a member of United States team that participates in three important international Heat Pump working groups, the IEA Annex 58, Annex 59 and Annex 60. More details about the three working groups are summarized below.

#### 4.1. IEA Annex 58: High Temperature Heat Pump Technologies

This Annex gives an overview of available and close-to-market technologies regarding high-temperature heat pumps. The need for further RD&D developments will be outlined. In order to maximize the impact of high-temperature heat pumps, this Annex also looks at process integration by development of concepts for heat pump-based process heat supply and the implementation of these concepts <sup>iii</sup>.

#### 4.2. IEA Annex 59: Heat Pumps for Drying

The Annex aims to structure and describe the numerous possibilities and advantages of heat pump integration in dryers. Drying processes are widely used in industry and commerce (food industry, paper industry, chemical industry, ceramics industry, laundries etc.) as well as in household applications (white goods, tumble dryers, dishwashers) in various forms and contribute significantly to energy consumption. (10-25% of industrial energy consumption is used for drying processes)<sup>iv</sup>.

#### 4.3. IEA Annex 60: Retrofitting Heat Pump Systems in Large Non-domestic Buildings

The Annex focus on providing straightforward, high-level guidance for building owners and other decision-makers. Retrofitting heat pumps for larger non-domestic buildings is challenging as it contain a variety of complex heating, ventilation and cooling (HVAC) systems. These present different challenges and opportunities. In practice the retrofitting of heat pumps will often be part of more general refurbishment of a building. The scale and extent of anticipated refurbishment will be an important factor in determining which options for heat pump systems are technically or economically feasible. This annex aims to provide evidence of the practical feasibility and satisfactory operation of a range of installed retrofit systems in large non-domestic buildings in a number of countries, together with insights into the thinking that led to the choice of system<sup>v</sup>.

### 5. EPRI Project on High Temperature Heat Pump for Industrial Decarbonization

This section outlines the general operational characteristics of heat pumps, current heat pump research project funded by the California Energy Commission (CEC), and the details of a prototype high temperature industrial waste heat recovery heat pump that is currently being developed under this funding.

#### 5.1. Heat Pump Operation

This section provides a brief overview of the heat pump operating principles as applicable to heat recovery and using it within a process in a manufacturing facility. A heat pump consists of a closed loop containing a refrigerant that is either in the liquid or gaseous phase or both. The refrigerant or the working fluid passes through four main components (see Figure 3), i.e.:

- An evaporator where the refrigerant absorbs heat from the waste heat by evaporating.
- A compressor which increases the enthalpy and pressure of the refrigerant (and therefore its condensation temperature),
- A condenser in which the refrigerant transfers its latent heat to the industrial source by condensing,
- A pressure release valve that adjusts the evaporator supply and transfers the refrigerant from high to low pressure.

Energy is recovered by the successive changes in the states of the refrigerant.

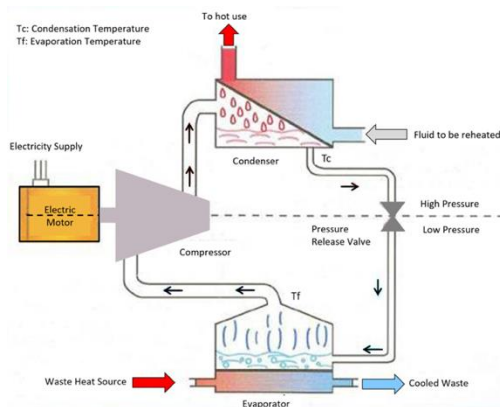


Figure 3 Schematics of a heat pump cycle

#### 5.2. EPRI's CEC Project on Development of Industrial Heat Pump

EPRI has been funded by the CEC to lead this effort to develop an industry wide acceptable decarbonization solution. This high temperature heat pump (HTHP) technology once developed has the potential to meet the industrial steam need of industries such as food processing, chemical, paper and textile industries. Lack of commercial availability of high temperature heat pump technology to convert industrial waste heat to useful heat in the form of low-pressure steam was the motivation behind this project. In this project funded by the CEC<sup>vi</sup>, EPRI is working with a research company called the Creative Thermal Solutions, Inc. (CTS) in the US to develop a high temperature industrial waste heat recovery heat pump that can produce steam. The project

uses an innovative design of building this prototype from commercially available components such as compressors, variable frequency drives, heat exchangers etc. The project requirements are that the developed technology should have a COP of 3.4 or better and provide a temperature lift of at least 40°C. The table, Table 2, below shows the project success criteria that need to be met at the end of the project. This is an ongoing project that was started in 2020 with a planned completion of 2023.

The project innovation lies in two main areas: first, the near-zero GWP and ODP refrigerant that has the characteristics to operate in a sub-critical mode with an ability to exist in two-phases can help to extract low grade waste heat to transform to high temperature useful steam; second, the control system as well as the heat pump design that could deliver the temperature lift of 40°C or more at a coefficient of performance (COP) of at least 3.4. 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 and second, the heat pump will reclaim the waste heat from the industry and utilize it by returning it back to the industrial processes and reduces fossil-fuel consumption and therefore reduces overall emissions associated with the combustion.

Table 2 Performance metric for the industrial high temperature heat pump (HTHP)

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	End-of-Project Performance
Waste Heat Temperature Limits	70 - 80°C	>120 °C	Laboratory Testing	125 °C
Coefficient of Performance (COP)	0.8	3.4	Laboratory Testing	3.6
Estimated Equipment Capital and Installation Costs	\$2540/unit or \$85/kW	\$60,000/unit or \$2000/kW	Market Available Cost	\$45,000/unit or \$1500/kW
Estimated Operation and Maintenance Costs (annual)	\$916	\$215 (based on 3.4 COP)	Market Available Cost	\$203 (based on 3.6 COP)
Other	Size = 3 boiler horsepower (bhp) [equivalent to 29.43kW]	Size = 30kW	Power Measurements in Lab	30kW

5.2.1. Refrigerants

One of the requirements of this project is to create a vapor compression system that will be able to operate between temperatures 70 °C and 135°C. A low GWP refrigerant such as R245fa, R1233zd(E) or R1336mzz(Z) will be utilized as the working fluid. These three refrigerants were selected based on literature studies conducted during the project design and specification stages [1][2][3] & [4]. In addition to creating a higher efficiency and lower emission technology the project team is also committed to choosing a refrigerant that has close to zero GWP and ozone depletion potential (ODP) with additional characteristics of lower toxicity (A1) and no flame propagation (A1) as shown in Figure 4<sup>vii</sup>. The system will operate with one of low GWP refrigerants (working fluids) such as R1233zd(E) or R1336mzz(Z). To take it one notch further, the project team is using R1233zd(E) as a working fluid in the prototype because a) it is a non-flammable fluid, b) it has a GWP of 1 and Ozone Depletion Potential (ODP) of 0, and c) it is a non-toxic fluid. The tests conducted with the breadboard system with the three refrigerants have also shown that the R1233zd(E) has better performance compared to the other two refrigerants.

The following charts (see Figure 5) shows various refrigerants used in various high temperature heat pump research around the world [4] [5] & [6]. Table 3 shows the characteristics of three emerging refrigerants that have been considered for this project – R245fa (as baseline), R1336mzz(Z) and R1233zd(E). The latter two refrigerants are considered promising for industrial applications.

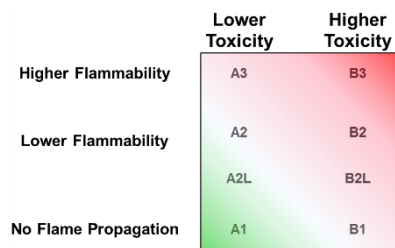


Figure 4 Characteristics of Refrigerants: ASHRAE Safety Designations

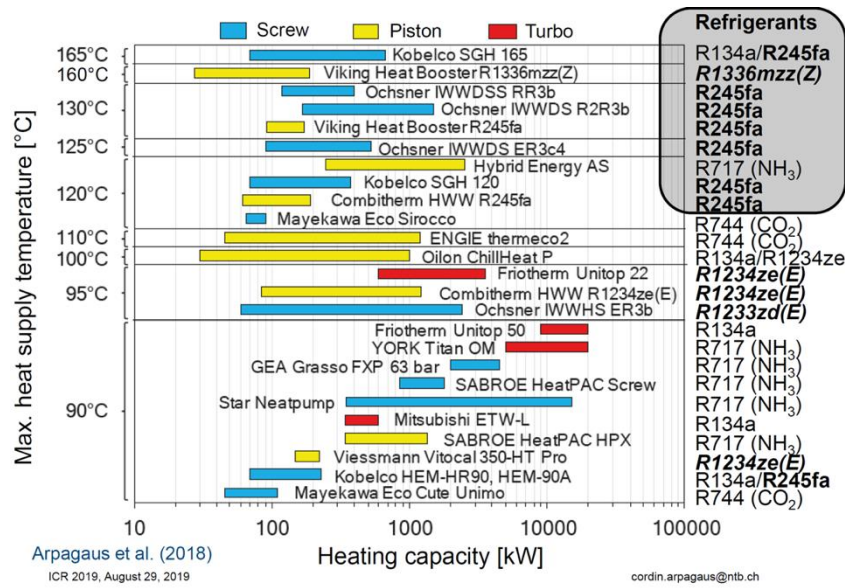


Figure 5 Typical refrigerants used in industrial high temperature heat pumps globally

Table 3 Characteristics of Emerging Refrigerants

Refrigerant	Type	Chemical Description	Heat Sink Temperatures (°C)	Heating Capacity (kW)
R245fa	HFC- Hydrofluorocarbons	Unsaturated organic comprising of hydrogen, fluorine, and carbon Chemical: Fluorine and Propane	120	60 to 370
R1336mzz(Z)	HFO- Hydrofluoroolefins	Unsaturated organic comprising of hydrogen, fluorine, and carbon Chemical: Fluorine and Butene	150	28 to 188
R1233zd(E)	HCFO – Hydrochlorofluoroolefins	Unsaturated organic comprising of hydrogen, chlorine, fluorine, and carbon Chemical: Chlorine, Fluorine, Propene	80 to 150	20 to 200

The preliminary simulation results from the refrigerant testing shows that the required COP could be met.. In summary, when generating 120°C steam from 80°C heat source, both R1233zd(E) and R1336mzz(Z) show a higher COP than R245fa. R1233zd(E) benefits from its larger specific heat of vaporization at 125°C, while R1336mzz(Z) benefits from its smaller specific compression work and they both have significantly lower GWP than R245fa which was used as a baseline. The characteristics of the three refrigerants are shown in Table 4.

Table 4 Thermophysical properties of the refrigerants selected for the HTHP

Refrigerants	MW [g/mol]	T <sub>crit</sub> [°C]	P <sub>crit</sub> [Mpa]	Vaporization Heat [kJ/kg] @ 125 °C	Sat Vapor Density [kg/m <sup>3</sup> ] @ 75 °C	ODP	GWP	ASHRAE Std 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

### 5.2.2. Heat Pump Design

This section presents the simplified, single-stage heat pump design approach taken for this project that meets the performance specifications set forth in the project. The simplified schematic design is presented in Figure 6. below. In the following drawing the refrigerant lines are shown in black while water lines are shown in blue.

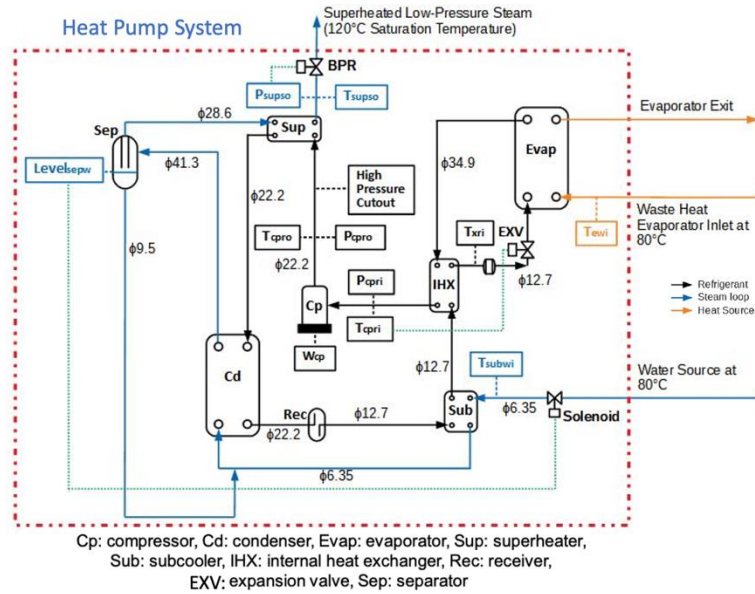


Figure 6 Simplified Schematic Diagram of the Heat Pump System

Compressor  $C_p$  discharges refrigerant to a superheater  $Sup$ . The superheater serves to superheat the steam generated in the condenser  $C_d$ . After the superheater, the refrigerant flows to the condenser  $C_d$  to be condensed. In that process, water on the other side is evaporated. The mixture of steam and water droplets goes to the separator  $Sep$  that sends saturated vapor to the superheater to be additionally heated and effectively prepare for transportation to the user. The condensed refrigerant flows to the high-pressure receiver  $Rec$ . Liquid after the receiver will be subcooled in the subcooler  $Sub$ , heating in that process water that will be later evaporated in the condenser. Recuperative “internal heat exchanger”  $IHX$  improves the performance of the system, taking care of the dry-out in the evaporator, and increases the reliability of the compressor by reducing the chance of sending liquid to the compressor. 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. In this way, we have closed the refrigerant flow loop and explained the flow of water to be evaporated and turned into the superheated steam. The schematics also shows the pipe dimensions in the diagram.

After considering various heat exchanger options, the brazed plate type was chosen because it was by far the most compact and cost-effective option available. Acknowledged potential issues of scaling are to be handled with softened water where possible and periodic chemical cleaning that is conventional and commercially available. Table 5 shows the actual components and the make and model numbers of the parts used in the heat pump design.

Table 5 Components Used in the Heat Pump System

Component Description	Model #
Compressors	Copeland ZB45KCE-TFD (460V-3ph-60Hz)
Superheater	BAODE-BL26C-30D
Condenser	SWEP B45-060
Subcooler	BAODE-BL26C-30D
IHX	GEA-FP5X12L-80
Evaporator	SWEP V45-060
Steam separator	Custom built
Pump for $m_{sepwo}$	Micro pump GJSN27.PVT.G
XV Valve	Sporlan (Parker) SERI-F
Back pressure regulator	Danfoss KVP28 evaporator pressure regulator
Refrigerant receiver	Refrigeration Research 3 liters
Variable Frequency Drive (VFD)	Drivecon N2
Watt Transducer (Compressor Power Measurement)	OSI PC5-015C, 3ph, 380-550V, 0-10A

The heat pump has controls to start and stop the compressor and one water pump. The heat pump is connected to a three-phase 480 V nominal power source at 60 Hz. A variable frequency drive (VFD) has been installed to vary the compressor speed. A 0-20 mA analog control signal must be connected to the drive to control the compressor speed. The speed of the compressor is controlled by adjusting the frequency of the VFD. Full rated compressor speed is achieved when the VFD frequency is set to 60Hz (line frequency of the AC power supply). The frequency of the drive directly correlates to the compressor speed, for example, 60Hz of VFD frequency is 100% of rated compressor speed, while 30Hz of VFD frequency is equal to 50% of the rated compressor speed. Subsequently over speeding of the compressor can be achieved by increasing the frequency to beyond 60 Hz, for example, 90Hz corresponds to 150% of the compressor rated speed.

### 5.2.3. Heat Pump Control System

The key features of the heat pump control system over the existing state-of-the-art technologies that are commercially available today are as follows:

- A new control strategy specifically for new refrigerants in the HTHP applications. Normal control of the expansion valve is based on the superheat exiting the evaporator. Isentropic line (that compressor follows in an idealized way) would enter into the two-phase zone, causing the liquid in the compression volume. To avoid that, the project team is using a novel control based on superheat at the compressor discharge stage.
- Modified compressor. New refrigerants bring several other new challenges. Their specific volume of vapor is significantly higher than in conventional refrigerants so a compressor with a much higher ratio of displacement vs. motor power will be used. Compressor with economized suction or compound type are preferential to maintain simplicity. That is another uniqueness of this approach. The compressor used in the design are commercially available.
- Modified heat exchangers (IHX). Another consequence of specific thermophysical properties (vapor volume) is a need for a special IHXs that will have different channels on the water and refrigerant side. The team would be using a Brazed Plate Heat Exchangers for heat transfer. A Brazed Plate Heat Exchanger (BPHE) offers the highest level of thermal efficiency and durability in a compact, low-cost unit.

### 5.2.4. Configuration of Laboratory Heat Pump System

The heat pump system and the components of the system are depicted in the figure (Figure 7) below.

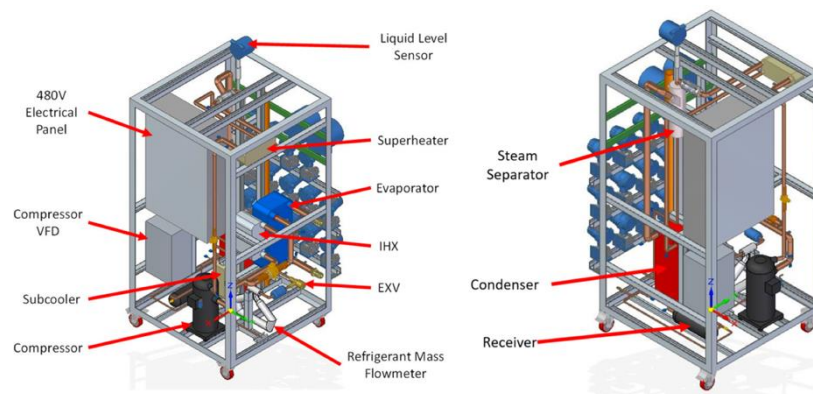


Figure 7 Schematic of a heat recovery heat pump currently being developed in California, USA funded by California Energy Commission (CEC)

Some of the key features of the heat pump design are summarized below:

- Simple single-stage vapor-compression cycle design
- Closed loop refrigerant and closed loop steam system design
- Hermetic sealed compressor to prevent refrigerant leakage
- Emerson (Copeland) scroll compressor is selected and is expected to be a robust and efficient option. The same compressor was used to test all the 3 refrigerants.
- Water conserving design that incorporates a closed loop steam system which returns the steam condensate back to the water reservoir.

The prototype system that is currently being tested at CTS’s facility in Harmony, California is completely instrumented with multiple flow sensors, thermal sensors, steam flow sensors and electrical power meters to monitor and log the data for a thorough and detailed analysis. Multiple iterations have been conducted in the preliminary laboratory testing to ensure the sensitivity of the system load (capacity), input and output temperatures as well as other parameters. The photos in Figure 8 shows the actual prototype system built for this project.



Figure 8 Photos of the Actual HTHP Prototype System

The chart shown in Figure 9 below compares the compressor speed test results for R245fa (green), R1233zd(E) (blue), and R1336mzz(Z) (orange). The data shows that R1233zd(E) achieves the highest overall COP of 4.54 with a VFD set point of 40Hz (2/3<sup>rd</sup> rated compressor speed). The x-axis represents the heating capacity (Qh) of the heat pump and the y-axis represents the COP of the system at various load conditions, which is represented by the frequency set point in the VFD (in Hz).

In the following chart, it can be seen that for the same heating capacity of Qh (= 18.3kW), the COP of R1233zd(E) is 4.8% higher than the COP of R1336mzz(Z). As Qh increases, the percent difference also increases, with the COP of R1233zd(E) being an estimated 13.8% higher at Qh (= 22.4kW). However, the most important comparison is between the three maximum COPs for each refrigerant, as the project’s primary goal is to maximize COP. The maximum COP of R1233zd(E) is 2.2% higher than the maximum COP of R1336mzz(Z), and 10% higher than 245fa’s maximum. Both R245fa and R1336mzz(Z) are within about 10% of the suggested 30kW capacity. Refrigerant R1233zd(E) shows 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% higher than R1336mzz(Z)’s maximum COP of 4.4, and about 10% higher than R245fa’s maximum COP of 4.1.

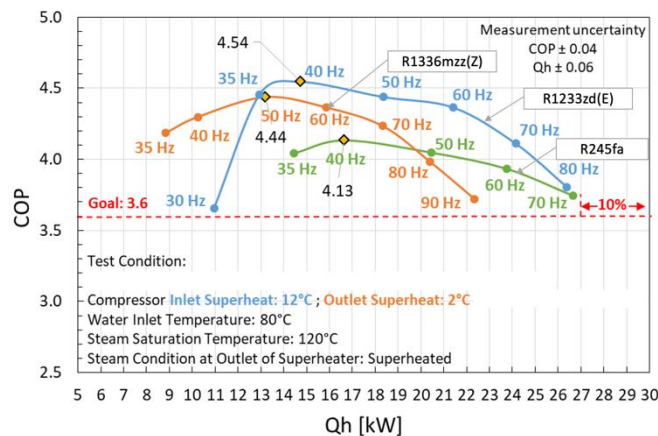


Figure 9 Comparison of COP for a given Qh between R245fa, R1233zd(E) and R1336mzz(Z)

The compressor efficiency of all refrigerants in the VFD set point of 40-70 Hz range are nearly identical, hovering in the 0.65 to 0.7 range. For a given VFD set point of 60 Hz (100% rated compressor speed), the total heating capacity of R1233zd(E) is about 0.89 times R245fa capacity and about 1.35 times of R1336mzz(Z)

capacity. Based on these results as well as other characteristics analyzed per earlier discussion, R1233zd(E) has been chosen as the refrigerant of choice, based on its high capacity, high COP, and lower risk for air to leak into the system.

The heating capacity  $Q_h$  is obtained from three heat exchangers (subcooler, condenser, and superheater) where the refrigerant heats the water source, evaporates it, and then superheats the steam flow. The heat energy supplied to the water is given by Eq.1:

$$Q_h = m_{subw} * [h_{supso} (T_{supso}, P_{supso}) - h_{subwi} (T_{subwi}, P_{subwi})] \tag{Eq.1}$$

Enthalpy  $h_{subwi}$  is found with the temperature  $T_{subwi}$  and  $P_{subwi}$ . Pressure measurement here is not needed because the water is subcooled, and the pressure will not change substantially due to temperature.

Efficiency or Coefficient of Performance (COP) is computed with the Eq.2 given below.

$$COP = Q_h / W_{cp} \tag{Eq.2}$$

where  $W_{cp}$  is the power drawn by the compressor which is measured by a Watt Transducer.

The testing of this system for more than six months has provided consistent, repeatable, and stable results that meet the project goals set forth at the beginning of this project. Table 6, Figures 10 and Figures 11 show the test results from 6 months of heat pump testing. Some of the salient findings from the laboratory tests are given below:

- The COP shows results above the target values of 3.4
- The heating capacity of 25 kW is achieved at compressor speeds around VFD set point of 80 Hz (=1.3 times rated compressor speed)
- Repeatability: The prototype system runs reliably and has shown that repeated test conditions produce similar results
- System has been optimized to achieve an average COP of 3.6 at an average heating capacity of 25kW ( $Q_h$ ) and COP of 4.0 is easily achieved at an average heating capacity of 20kW ( $Q_h$ ).

Table 6 Test results from 6 months of Heat Pump Testing at CTS Laboratory

Refrigerant	VFD Set Point (Hz)	Temp Lift (oC)	Average COP (-)	Average Qh (kW)
R1233zd(E)	60	40	4.0	20
	80	40	3.6	26

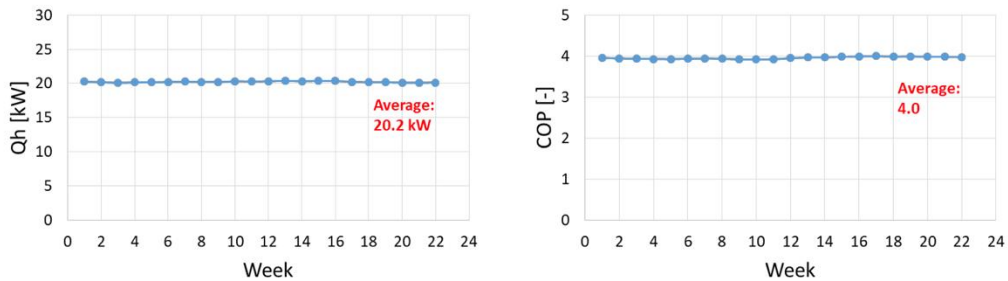


Figure 10 Heating capacity (left) and coefficient of performance (right) of the prototype heat pump system at rated compressor speed (VFD set point = 60 Hz)

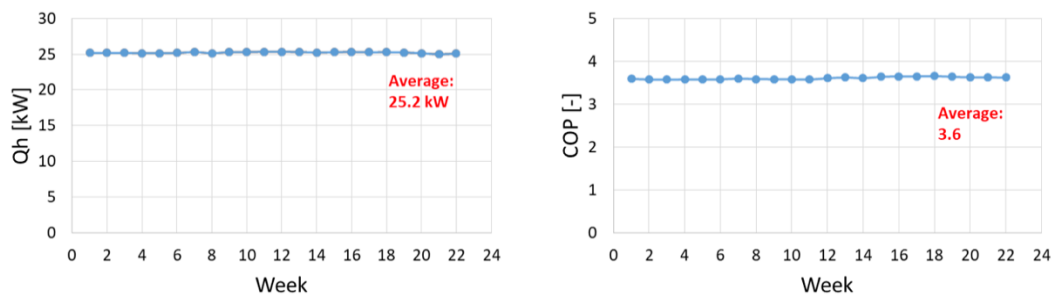


Figure 11 Heating capacity (left) and coefficient of performance (right) of the prototype heat pump system at 1.3 times the rated compressor speed (VFD set point = 80 Hz)

## 6. Summary

This paper provides an overview of an innovative, high temperature, industrial heat recovery heat pump that is currently developed by EPRI under the auspices of the California Energy Commission. This is an ongoing project that has a planned completion timeline of 2023. 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 the industrial customers, firstly it produces useful heat in the form of steam; secondly it lowers the fossil fuel energy use by reusing the otherwise wasted heat energy and thereby reduces emissions due to combustion; and finally, by using clean energy electricity it additionally lowers the emissions and helps in industrial decarbonization. The project will also look into market characteristics and develop pricing of the heat pumps, determine the incentives that electric utilities as well as other governmental agencies can provide to help increase the market adoption. 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. Governments around the world should fund more research to develop high performance refrigerants and innovations in heat pump technology designs that could potentially combat the climate crisis more effectively and efficiently.

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## References

- [1] Arpagaus, Cordin; Bless, Frédéric; Uhlmann, Michael; Büchel, Elias; Frei, Stefan; Schiffmann, Jürg; and Bertsch, Stefan. "High temperature heat pump using HFO and HCFO refrigerants - System design, simulation, and first experimental results" (2018). International Refrigeration and Air Conditioning Conference. Paper 1875. <https://docs.lib.purdue.edu/iracc/1875>
- [2] Jingye Yang, Ziyang Sun, Binbin Yu, Jiangping Chen, Experimental comparison and optimization guidance of R1233zd(E) as a drop-in replacement to R245fa for organic Rankine cycle application, Applied Thermal Engineering 141 (2018) 10–19
- [3] Arpagaus, Cordin; Bless, Frédéric; Uhlmann, Michael; Büchel, Elias; Frei, Stefan; Schiffmann, Jürg; and Bertsch, Stefan, "High temperature heat pump using HFO and HCFO refrigerants - System design, and experimental results" (2019). Manuscript ID: 242, DOI: 10.18462/iir.icr.2019.0242
- [4] Arpagaus, C., Bless, F., Schiffmann, J., Bertsch, S.S., 2017. Review on High Temperature Heat Pumps – Market Overview and Research Status. In: International Workshop on High Temperature Heat Pumps, September 9, 2017, Copenhagen, Denmark. pp. 1–25.
- [5] Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., Bertsch, S.S., 2018b. High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials (Lizenz-/Genehmigungsnummer: 4432121433391). Energy 152, 985–1010.
- [6] Viking Heat Engines, 2018. HeatBooster HBS4: Industrial heat pump for clean energy production up to 160 °C.

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<sup>i</sup> Source: [https://www.researchgate.net/figure/GHG-emission-factors-for-different-boilers-Data-sources-are-GEMIS-495-37-except-for\\_tbl2\\_334164530](https://www.researchgate.net/figure/GHG-emission-factors-for-different-boilers-Data-sources-are-GEMIS-495-37-except-for_tbl2_334164530)

<sup>ii</sup> Source: [https://www.fujielectric.com/company/research\\_development/theme/heatpump.html](https://www.fujielectric.com/company/research_development/theme/heatpump.html)

<sup>iii</sup> Source: <https://heatpumpingtechnologies.org/annex58/>

<sup>iv</sup> Source: <https://heatpumpingtechnologies.org/annex59/>

<sup>v</sup> Source: <https://heatpumpingtechnologies.org/annex60/>

<sup>vi</sup> Source: <https://www.energy.ca.gov/filebrowser/download/280>

<sup>vii</sup> Source: <http://www.epa.gov/ozone/snap/refrigerants/safety.html>