Commercial and Industrial Decarbonization through Waste Heat Recovery

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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. This paper focuses on two technologies that help recover waste heat in Commercial and Industrial facilities. The first technology showcases the development and testing of a novel industrial heat pump funded by the California Energy Commission. This work effort is aimed at developing an industrial heat pump that can capture low-grade industrial waste heat (around 80 °C or 176 °F) and transform it into high-temperature useful heat (steam). Industries such as food processing, chemicals, paper, and textile industries can make use of this steam. The paper also discusses the use of a low Global Warming Potential (GWP) refrigerant that can provide a temperature lift of at least 40° C with a coefficient of performance (COP) of 3.4. The second technology is a waste heat recovery chiller which is applicable in both commercial and industrial sectors. A case study is presented on a waste heat recovery chiller technology that shows how a hospital cut down 500 metric tons of carbon emissions annually while reducing the overall heating energy at the same time. The heat pump and heat recovery chiller are two of many technologies that could help reduce industrial carbon emissions.

Introduction

Addressing the climate crisis is in the limelight globally and almost every country in the world is on a path to decarbonize 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. The electric power industry is leading the charge. Since 2005, the United States (US) reduced its carbon footprint by one gigaton, primarily by switching to cleaner fuels, expanding renewables, and increasing 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 Electric Power Research Institute (EPRI) analysis, the annual US 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. [1] This can be done through strategic research and development 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.[2]

[1] Source: https://www.epri.com/research/products/000000003002019513
[2] Source: https://www.epri.com/research/products/000000003002019513

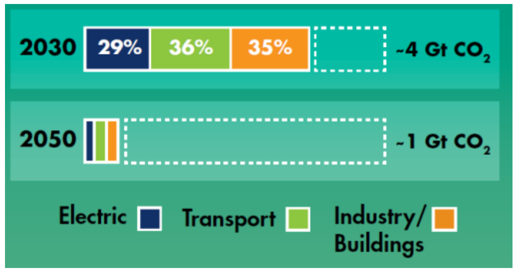

Figure 1. Emissions by US Energy Sector (Source: EPRI)

Electrification of end uses 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 decarbonization throughout the economy, although reaching economy-wide net-zero targets will likely require additional breakthrough technologies.[3]

In the U.S., industrial process heat accounts for about 30% of industrial energy use and greenhouse gas emissions (GHG). Currently this process heating needs are met by fossil-fuel boilers and convection ovens. Deployment of industrial heat pumps in the U.S. chemical, food and paper industries could potentially reduce natural gas use by 293–400 TBtu/year (42–57% of the 704 TBtu/year of process heat energy) and reduce CO_2 emissions by 10–12 million tons/year (Rightor 2022).

Low-temperature waste heat streams account for most of the industrial waste heat inventory. There is an abundance of waste heat at low temperature (70-80 °C) either coming from some cooling devices such as chillers (condensing heat), from open cooling processes, from return condensate from steam applications, etc. The vast majority of industry needs for steam is in the range of 120-130 °C. Industries such as food, paper, chemical, and textiles can make use of this low-pressure steam. The proposed high temperature heat pump will generate low-pressure steam at 120-130 °C. using only electricity, in an energy-efficient way. In this paper, a novel high temperature heat pump capable of capturing waste heat from the industry and converting it into useful heat is presented. Another technology that can help recover waste heat in the industrial facilities (as well as large commercial facilities) is heat recovery chillers. The paper presents the operating principles of the heat recovery chiller and also presents a successful implementation of this technology in a large hospital.

Development of a Waste Heat Recovery Heat Pump

At present, there is a lack of commercially available method to convert industrial waste heat to useful heat in the form of low-pressure steam. EPRI has been involved in the development of a prototype of an industrial high temperature heat pump project funded by the California Energy Commission (CEC) that can produce steam at low pressure. It has the potential to meet the industrial steam need of industries such as food processing, chemical, paper, and textile industries.

The HTHP uses an innovative design utilizing commercially available components such as compressors, variable frequency drives, heat exchangers, etc. The innovation of this HTHP

[3] Source: https://www.epri.com/research/products/000000003002020700

lies in three main areas, namely, refrigerant selection, heat pump design and heat exchanger design.

The innovations used in the heat pump are discussed in detail below:

- Refrigerant Selection: the near-zero global warming potential (GWP) and Ozone depletion potential (ODP) refrigerant that has the characteristics to operate in a sub-critical mode (Figure 2) with an ability to exist in two-phases can help to extract low grade waste heat to transform to high temperature useful steam.

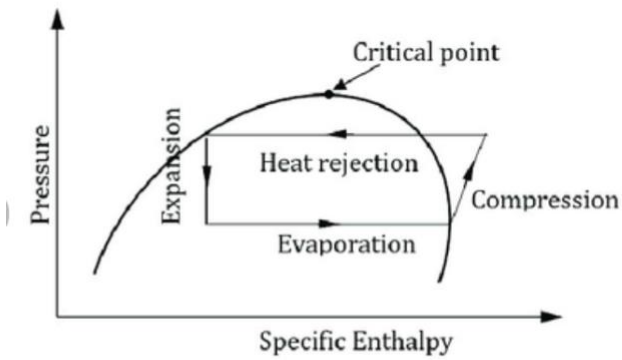

Figure 2 Pressure-Enthalpy diagram showing sub-critical cycle

- Heat Pump Design: 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.
- Heat Exchanger Design: The heat exchanger used in this heat pump is a recuperative heat exchanger type using brazed plate heat exchanger. Plate heat exchangers separate the fluids exchanging heat by the means of plates. They typically consist of two rectangular end members which hold together a number of embossed rectangular plates with holes on the corner for the fluids to pass through. Brazed plate heat exchangers are a category of plate heat exchangers that avoid the possibility of leakage by brazing all the plates together and then welding on the inlet and outlet ports.[4] A Brazed Plate Heat Exchanger (BPHE) offers the highest level of thermal efficiency and durability in a compact, low-cost unit.

Refrigerant Selection

During the development of the HTHP, three refrigerants were considered, namely, R245fa [GWP 845], R1233zd(E) [GWP 1] or R1336mzz(Z) [GWP 2]. These three refrigerants were selected based on literature studies conducted during the project design and specification stage. In addition to creating a higher efficiency and lower emission technology, the team selected refrigerants that are close to zero global warming potential (GWP) and ozone depletion potential (ODP) with additional characteristics of lower toxicity (A1) and no flame propagation (A1) (refer to Figure 3).

[4] Source: https://www.thermopedia.com/content/832/

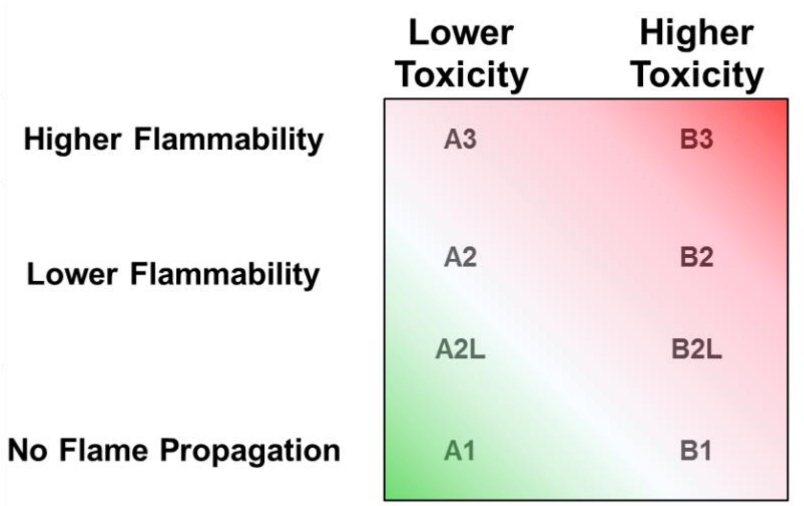

Figure 3. Characteristics of Refrigerants: ASHRAE safety designations.

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 4 below. In the following drawing the refrigerant lines are shown in black while water lines are shown in blue.

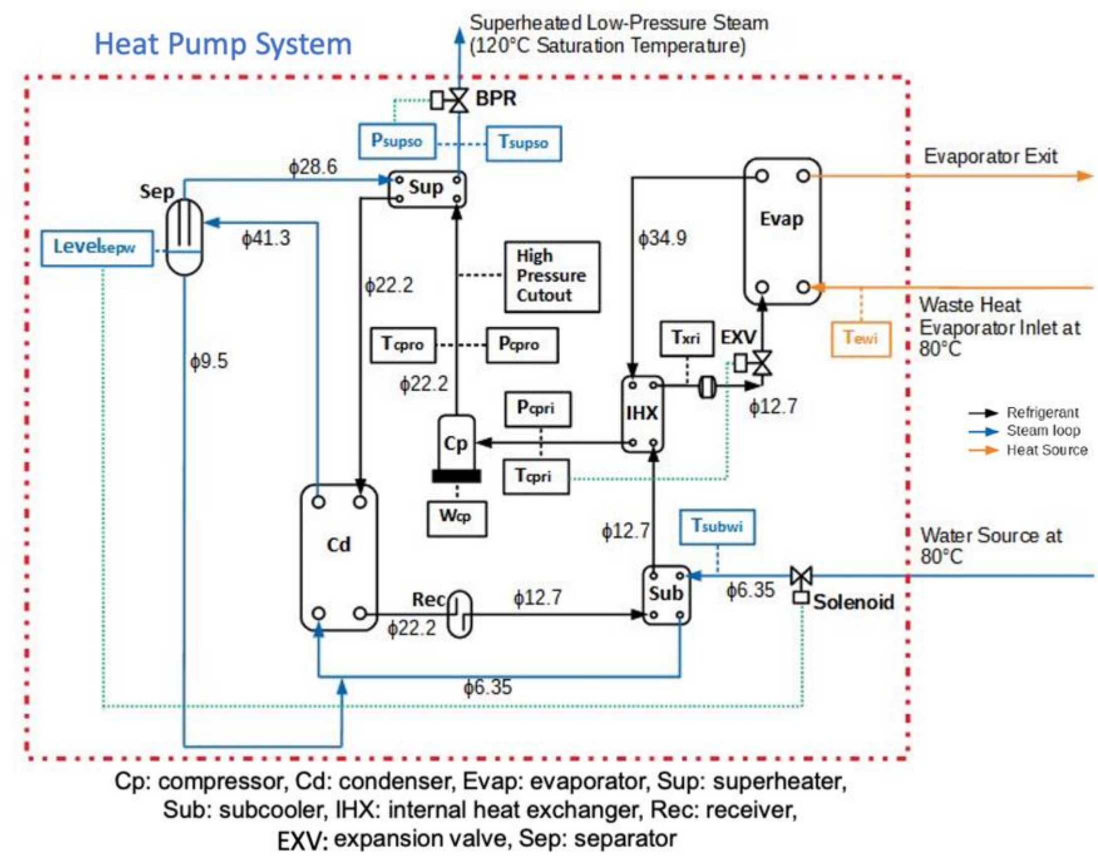

Figure 4. Simplified Schematic Diagram of the Heat Pump System

The sequence of operation in the heat pump are listed below:

1. Compressor **Cp** discharges refrigerant to a superheater **Sup**. The superheater serves to superheat the steam generated in the condenser **Cd**.
2. After the superheater, the refrigerant flows to the condenser **Cd** to be condensed. In that process, water on the other side is evaporated.
3. 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.
4. The condensed refrigerant flows to the high-pressure receiver **Rec**.
5. Liquid after the receiver will be subcooled in the subcooler **Sub**, heating in that process water that will be later evaporated in the condenser.
6. Recuperative 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.
7. 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, the refrigerant flow loop has been closed and the flow of water to be evaporated and turned into the superheated steam is explained. The pipe diameters (in inches) are also shown in the Figure 4 (e.g. ϕ6.35). The final schematics of the HTHP is shown in Figure 5. The low pressure steam does not exceed 15 psi of pressure. Figure 6 shows the final prototype of the assembled HTHP. Some of the other key advantages of this heat pump design are:

1. Simple single-stage vapor-compression cycle design
2. Closed loop refrigerant and closed loop steam system design (open loop steam system design is also possible to achieve with the same setup)
3. Hermetically sealed compressor to prevent refrigerant leakage
4. Emerson (Copeland) scroll compressor is selected and is expected to be a robust and efficient option.

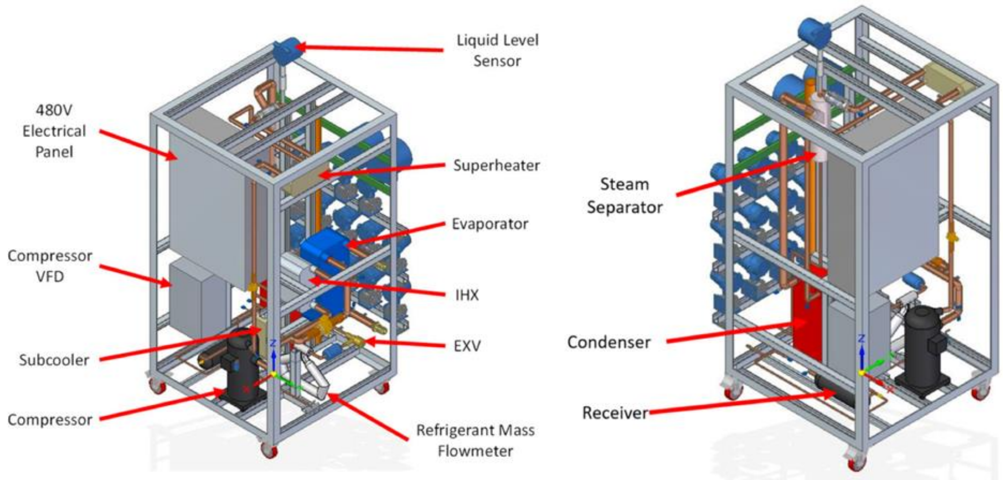

Figure 5. Schematic of the industrial heat recovery heat pump

Figure 6. Final prototype of the HTHP

Heat Pump Test Results

The chart shown in Figure 7 below compares the 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 variable frequency drive (VFD) set point of 40Hz (2/3rd rated compressor speed). The x-axis represents the heating capacity (Qh) (in kW) of the heat pump and the y-axis represents the COP of the heat pump. The curves plotted for each refrigerant represents the COP of the system at various load conditions.

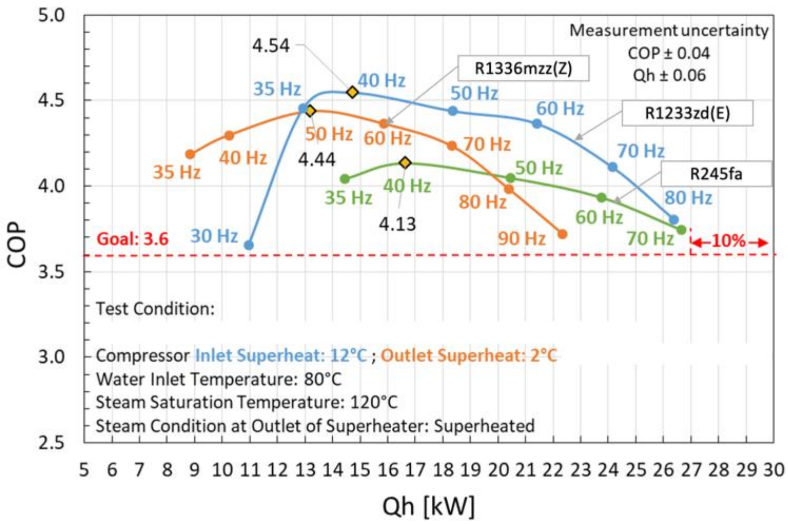

Figure 7. Comparison of COP for a given Qh between R245fa, R1233zd(E) and R1336mzz(Z)

Based on these results, R1233zd(E) has been chosen as the refrigerant for this HTHP, based on its high capacity, high COP, and lower risk for air to leak into the system.

Some of the key findings from the laboratory testing of this HTHP are:

- The COP shows that a higher value of 4.54 COP was achieved at 15kW.
- Repeatability: The HTHP system has produced consistent test results under similar repeated test conditions. The heat pump was tested on an average of 6 to8 hours per day for 5 days a week continuously over a period of six months.
- System has been optimized to achieve an average COP of 3.6 at an average heating capacity of 25kW (Qh) and COP of 4.0 is easily achieved at an average heating capacity of 20kW (Qh).

Key Advantages of the HTHP Design

The advantages of this CEC funded high temperature heat pump (HTHP) design are two-fold. Firstly, the heat pump design offers significant energy efficiency improvements compared to the traditional boilers. Traditional method of producing steam using natural gas or electricity can reach up to a maximum of 100% efficiency, however, the electric high temperature heat pump can reach a coefficient of performance (COP), a measure of heat pump efficiency, of 300% or greater. The HTHP discussed in this paper was able to achieve COP of 3.6 (=efficiency of 360%) 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 it will provide an immediate, high impact, high efficiency decarbonization solution to the industries such as chemical, textile, and food processing. Secondly, 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.

Waste Heat Recovery Chiller

In larger commercial and industrial facilities with central heating, ventilation, and air conditioning (HVAC) systems, heat recovery chillers can simultaneously provide both heating and cooling with excellent efficiency and economy of scale. Unlike the conventional chillers, these heat recovery chillers use the thermal energy from both the evaporator and condenser. Depending on the application, the compressors used in the heat recovery chillers may be reciprocating, screw, or centrifugal units. The heat output extracted from chillers could be used for space heating, for air reheating in the dehumidification process, r domestic water heating, or process water heating. Heat recovery chillers are normally sized to meet the heating needs.

Over the last several years, heat recovery has become a primary area of focus for many building owners and operators. Due to the new American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 90.1-2010, new construction and major renovations require a minimum of waste heat recovery that must be incorporated in the design. Major markets for heat recovery chillers include hospitals, large hotels/office buildings, food processing plants, schools and dormitories, and industrial plants. Heat recovery chillers complement existing chiller/boiler systems as opposed to completely replacing the existing chiller or boiler. The heat recovery technology presented in this paper is a water-to-water heat recovery chiller that could be integrated into an existing boiler/chiller system. Figure 8 shows an example of a 250-ton heat recovery chiller installation at a commercial building.

Figure 8. Example of a 250-ton heat recovery chiller used for facility hot water and HVAC applications (Source: Alabama Power)

Technology Operation

A heat recovery chiller is a specialized type of chiller that not only provides cooling but also recovers and utilizes waste heat generated during the cooling process. It offers additional benefits compared to a standard chiller by maximizing energy efficiency and providing simultaneous cooling and heating capabilities. Here's the simplified steps explaining how a heat recovery chiller works and its advantages:

1. Cooling Mode: In cooling mode, the heat recovery chiller operates similarly to a conventional chiller. It extracts heat from the process fluid or air using a refrigeration cycle. The chiller's evaporator absorbs heat from the cooling load, and the refrigerant carries this heat to the condenser for rejection.

2. Heat Recovery: In a heat recovery chiller, the waste heat from the chiller's condenser is not discarded but captured and utilized. Instead of dissipating the heat into the environment, the heat recovery chiller redirects the waste heat to other applications.

3. Heating Mode: The captured waste heat can be used for various heating purposes. The heat recovery chiller typically incorporates a heat exchanger to transfer the recovered heat to a separate heating system. This heat can be utilized for space heating, domestic hot water production, or other thermal applications.

4. Simultaneous Cooling and Heating: One of the significant advantages of a heat recovery chiller is its ability to provide simultaneous cooling and heating. While it delivers chilled water for cooling needs, it can also utilize the recovered heat to meet the building's heating requirements. This reduces the need for separate cooling and heating systems, resulting in energy savings, cost reduction, and space optimization.

5. Increased Energy Efficiency: By capturing and utilizing waste heat, a heat recovery chiller significantly improves overall energy efficiency. The recovered heat supplements or replaces the energy that would otherwise be required from separate heating systems. This reduces the reliance on primary heating sources, such as boilers or electric heaters, resulting in energy savings and lower utility bills.

A simple schematic of the heat recovery chiller is shown in Figure 9, showing in winter months, the heat recovered from the chilled water is applied to space heating. However, in summer months, the heat recovered from the chilled water is used with the domestic hot water loop. This arrangement ensures that the heat recovery chiller is utilized year-round for both space heating and water heating. In this schematic, under typical operation the condenser water in a chiller system is warm (say around 55 °C) and gets cooled to (say 45 °C) after passing through the cooling tower where the heat is rejected to the atmosphere. The schematics allows the heat recovery chiller to unload the normal chiller by extracting the heat from the warm water so the temperature difference between inlet and outlet for the normal chiller is minimized so it does not have to work harder, and it does not have to cool the water down to 45 ^{o}F.

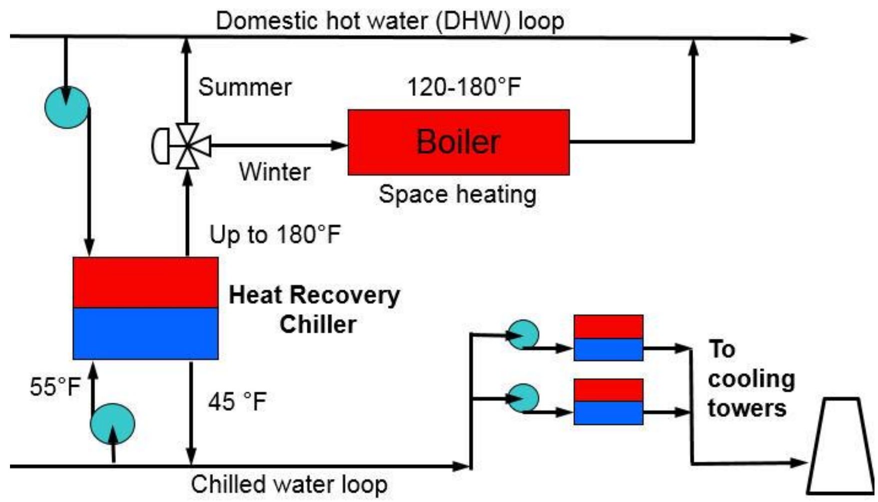

Figure 9. Simple schematic of a heat recovery chiller connected to an existing chilled water and hot water system

The heat recovery chiller finds application in many commercial, institutional, and industrial building types. An ideal application is one where there is year-round simultaneous heating and cooling needs. Examples include hospitals, universities, schools, dormitories, military bases, high-rise commercial buildings, large hotels/convention centers, and casinos (see Figure 10).

Figure 10 Typical applications for heat recovery chillers (Source: EPRI)

Case Study: Waste Heat Recovery Chiller

The following sections present a successful implementation of a heat recovery chiller at a hospital located in Mobile, Alabama. This was implemented through Alabama Power.[5]

Challenge

The University of South Alabama (USA) Medical Center in Mobile, Alabama, the region's only designated Level I trauma center, sought to reduce overall energy expense in order to serve their patients more cost-effectively. The USA Medical Center began a three-part facility upgrade in 2012. In addition to lighting and direct digital control upgrades, the most substantial upgrade involved a retrofit of its hot water heating system, which is the subject of this case study.

Old Way

The center's old hot water heating system relied on two gas-fired hot water boilers installed in the early 1960s. The system's age, together with wear and tear, reduced efficiency to less than 50%.

New Way

The solution was to recover and capture low-temperature heat otherwise rejected from evaporated cooling tower water to produce higher-temperature (120-180 ^oF) hot water from the heat recovery chiller and eliminate the boiler usage which was providing hot water (at 120 ^oF) earlier. USA Medical Center replaced its gas boilers with a 350 ton Multistack modular heat recovery chiller heat pump and energy management system comprised of five 70-ton, dual-compressor stage modules. At the time, a maximum of 200 tons was needed from the new system. It was sized at 350 tons based on historical heating and cooling demands that have been lowered through energy efficiency measures but also allowed for future increase in demands.

The project was funded in part by a U.S. Department of Energy grant awarded in conjunction with the Alabama Department of Economic and Community Affairs Energy Division.

Results

The new system produces 170 °F water, supplementing and thereby offsetting much of the load on the vintage gas boiler water heater system. Before this installation, the gas boiler was producing hot water in the 120 ^oF for the hospitals hot water use.

During the system's first year of operation, Alabama Power and its affiliate, Southern Company, collected and analyzed data, which demonstrated the effectiveness of the heat recovery chiller system. The operating power of the heat recovery chiller ranged from 40 kW to 120 kW (averaging 75 kW) with its condenser at 134 °F (~57 °C) on average, contributing close to 800,000 Btu/hr. to hot water needs. Heating coefficient of performance (COP) averaged 3.3. The heat recovery chiller operated at a minimum load of 25% in the summer but close to 90% in the coldest period (January). It was estimated that the system would eliminate 1,114,660 lbs or approx. 500 metric tons of carbon-dioxide emissions annually.

The vintage gas boiler has been used only once since the system was installed, when outside ambient air temperature dipped below 20 °F and the hospital needed the additional gas-

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[5] Source: https://www.epri.com/research/products/000000003002014679

fired boost. Supplemental package boilers, which could be gas-fired or electric, could be used as a back-up solution to boost the heat recovery hot water from the 170°F (~77 °C) range up to and over 190 °F (~88 °C) for some selective and localized applications within the hospital use, such as for sterilization of surgical instruments.

Key Takeaway

During the first year of operation of the heat recovery chiller, the USA Medical Center saved nearly $300,000 in natural gas costs. The efficiency of the system went up from ~50% from boiler use to a COP of 3.3 (or 330% efficiency) with the heat recovery chiller. Based on the first year's heating season compared to the previous year, the overall return on investment for the heat recovery chiller project was estimated at 1.2 years with grants and estimated to be around 3 years without any grants. The hospital reinvested its savings into patient care, allowing them to hire and retain additional employees to serve patients more efficiently.

Summary and Conclusion

This paper provides an overview of two technologies that take advantage of heat recovery. First is 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. 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 the industrial customers It produces useful heat in the form of steam, and it lowers the 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.

The second technology discussed in this paper is a heat recovery chiller. This technology has the ability to recover waste heat from commercial and industrial installations and this was illustrated through a successful case study presented in the paper.

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.

References

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