

Industrial Heat Pumps – Chemical/Petrochemical Industry

Introduction

Results from a 2009 study conducted by the Electric Power Research Institute (EPRI) indicate that the potential for saving energy and reducing CO₂ emissions by expanding end-use applications of electricity is significant.¹ As the study showed, converting existing and anticipated residential, commercial, and industrial equipment and processes from traditional fossil-fueled technologies to more efficient electric technologies can result in annual energy savings in 2030 of 5.32 quadrillion BTUs per year and CO₂ reductions of 320 million metric tons per year. Another recently completed report identified promising research and development opportunities for electric technologies in industrial applications.² These reports have identified several potentially beneficial electric technologies that have very low market penetration in the industrial sector and may be good candidates for demonstration projects.

The use of heat pumps to recover waste heat in industrial applications represents one of these opportunities. This paper highlights the advantages of this electric technology over conventional fossil-fueled technologies used in the industrial sector. Specific emphasis is on estimating the potential for industrial heat pumps, in general, and heat recovery heat pumps, in particular, to save energy and reduce CO₂ emissions.

This paper begins with an overview of common industrial heat pump technologies, followed by a description of typical industrial heat pump applications. From the various types of industrial heat pumps and applications, the paper focuses on the benefits that one specific heat pump technology and application brings to a typical plant that uses the technology. The technology is an open-cycle Mechanical Vapor Recompression (MVR) heat pump and the application is separation of propylene and propane in a distillation column at a chemical plant. The paper concludes with an estimation of the regional and national potential for saving energy and reducing CO₂ emissions by expanding applications of heat pumps in the chemical/petrochemical industry.

Technology Description

Heat pumps are systems that operate in a cyclic manner. They absorb heat at low temperature from an energy source, apply external energy, and deliver heat to a higher temperature load, as illustrated in Figure 1. The external energy is usually supplied by an electric motor, but can also come from a thermal energy source. This study focuses on electric-driven heat pumps.

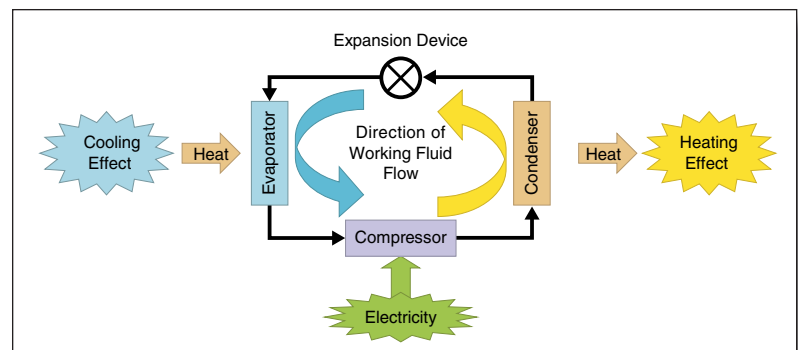


Figure 1: Operation of Closed-Cycle Mechanical Heat Pump

There are four common types of industrial heat pumps:

- **Closed-cycle mechanical heat pumps** use mechanical compression of refrigerant. They are used for lumber drying, space heating, and heating water and process liquids (Figure 1).
- **Open-cycle mechanical vapor recompression (MVR) heat pumps** use mechanical compression to increase the pressure of waste vapor. They are used in evaporation and distillation processes commonly found in the petroleum, chemical and petrochemical, pulp, and food and beverage industries (Figure 2).
- **Open-cycle thermo compression heat pumps** use high-pressure steam to increase the pressure of waste vapor. They are used in evaporators and flash-steam recovery systems, such as paper dryers.
- **Closed-cycle absorption heat pumps** use a two-component working fluid and

1. *The Potential to Reduce CO₂ Emissions by Expanding End-Use Applications of Electricity*, EPRI, Palo Alto, CA: 2009. 1018871.

2. *Program on Technology Innovation: Industrial Electrotechnology Development Opportunities*, EPRI, Palo Alto, CA: 2009. 1019416.

the principles of boiling-point elevation and heat of absorption. They can deliver a much higher temperature rise than the other heat pumps and have the ability to provide simultaneous cooling and heating. They are typically used in chilling applications.

In a closed-cycle heat pump, the working fluid circulates through the heat exchangers (evaporator and condenser). In an open-cycle heat pump, the process steam itself (e.g., low-pressure discharge steam) is compressed to provide a higher temperature heat source to the process, thereby eliminating the need for one or both heat exchangers as illustrated in Figure 2. It is generally more cost-effective to select an open-cycle heat pump, as it has both a higher coefficient of performance (COP) and a lower capital cost relative to a closed-cycle heat pump. The COP of the heat pump cycle is the simple ratio of heat delivered to work required. The maximum theoretical COP for an ideal heat pump is calculated by:

$$COP_{HP} = Q_H / Q_{net} = Q_H / W_{net} = 1 / (1 - T_L / T_H)$$

Where T_L = temperature of energy source

T_H = temperature of energy load

Heat pump technology is relatively mature and established, but the penetration of heat pumps in the U.S. industrial sector is still low. Indeed, a mere 14% of U.S. manufacturing plants currently employ waste heat recovery techniques to recover heat and/or to produce steam, and less than 5% of U.S. manufacturing plants utilize heat pump systems, specifically.³ It is estimated waste heat losses such as hot exhaust gases, air streams, and/or liquids that leave the boundaries of industrial plants and enter the environment account for 13% to 18% of U.S. industrial energy use.⁴ Although all waste heat cannot be recovered economically, a gross estimate is that economical waste heat recovery could save 9% of total energy consumed in the U.S. industrial sector by substituting the recovered energy for purchased energy.⁵ For reference, the U.S. manufacturing industry used 22,266 trillion Btu of

energy in 2002.⁶ Consequently, there is tremendous potential for waste heat recovery and heat recovery heat pump applications in U.S. industry.

Heat pumps are extremely beneficial in recovering low temperature waste heat. It is ordinarily not practical to extract work from waste heat sources in the low temperature range and many applications of low temperature waste heat are limited to using the waste heat for preheating liquids or gases by means of heat exchangers. Under many circumstances, however, heat pumps enable the economic use of low temperature waste heat in industrial applications requiring higher temperature heat. Examples of industrial waste heat sources in the low-temperature range include process steam condensate (~130-170°F) and cooling water from various industrial machines, furnaces, internal combustion engines, and hot-processed liquids and solids (~90-450°F).⁷

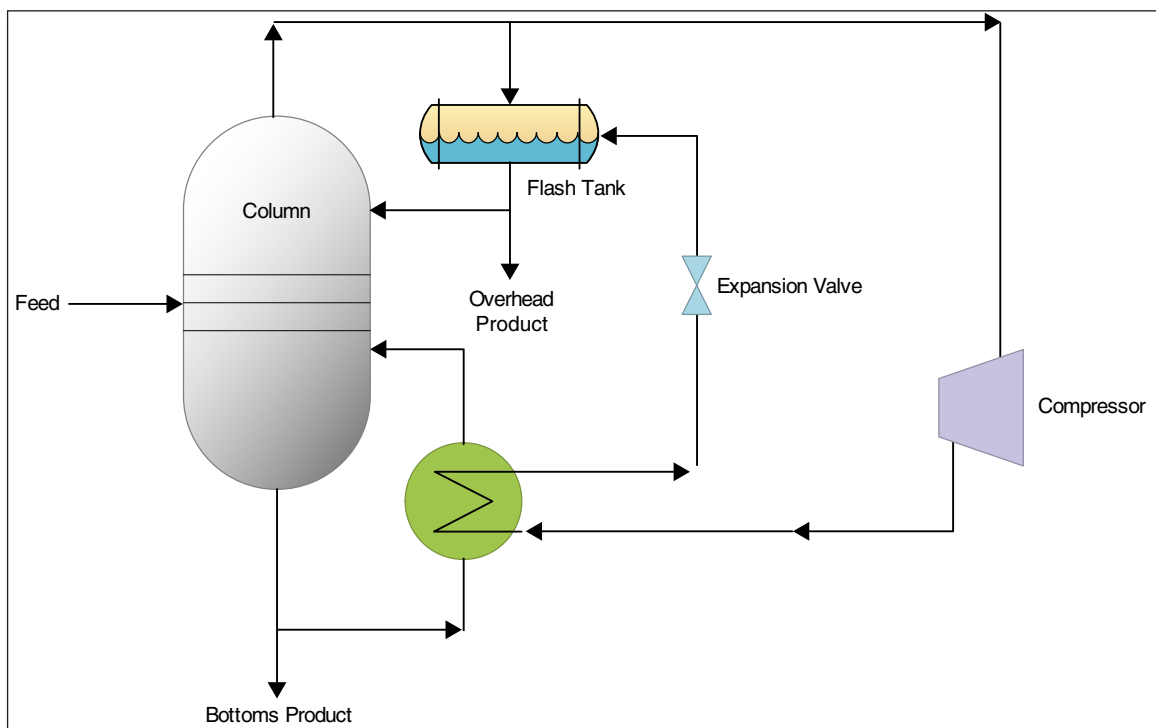


Figure 2: Open-Cycle Mechanical Vapor Recompression (MVR) Heat Pump in Distillation Column

3. *Manufacturing Energy Consumption Survey*, Energy Information Administration, U.S. Department of Energy, Washington, DC: 2002.
 4. *Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing and Mining*, prepared for the U.S. Department of Energy Industrial Technologies Program, prepared by Energetics, Inc. and E3M, Inc.: December 2004.
 5. *Ibid.*
 6. *Manufacturing Energy Consumption Survey*, Energy Information Administration, U.S. Department of Energy, Washington, DC: 2002.
 7. Global Energy Partners, *Industrial Heat Pumps for Waste Heat Recovery*, Tech Review, 2007.

Industrial Applications

There are numerous industrial applications of heat pumps. Industrial heat pumps are predominately used by the lumber, petroleum refining, chemical and petrochemical, pulp and paper, and food and dairy industries, as illustrated in Table 1. Common industrial processes benefiting from heat pumps include drying, evaporation, and distillation. Heat pumps are also employed across most industrial sectors for water heating and space conditioning, similar to how heat pumps are used in residential and commercial buildings. Additionally, the application of absorption heat pumps for chilling is emerging.

The use of closed-cycle heat pumps for drying of leather, foodstuff, and paper is a relatively popular application but these tend to be small-scale applications. Other closed-cycle applications are generally of a larger scale, but they are typically low energy-intensive applications, such as heating process water or process fluids and heating water for cleaning purposes.

In contrast, evaporation and distillation applications are highly energy-intensive and often involve large-scale systems. Distillation and evaporation lend themselves extremely well to open-cycle mechanical vapor recompression (MVR) heat pumps. In the evaporation process, MVR heat

pumps are mainly used for water-based solutions where the vapor produced by the evaporation of liquor is compressed and used to drive the evaporator. The distillation process is a physical separation process that involves the separation of mixtures based on differences in their volatilities. It is an extremely energy-intensive process found in numerous industries, including food and beverage, chemical and petrochemical, oil production, and refineries. For example, distillation separation of propylene and propane is extensively used by the chemical industry to produce propylene, a key material in the production of many chemical products.

Industry	Drying	Evaporation	Distillation	Water Heating	Space Conditioning	Chilling
Food Processing	Drying of food products, including fish, fruits, and grains.	Evaporation of food products, including starch and sugar.	Distillation of liquors.			Chilling of food products.
Beverage Manufacturing		Evaporation of water to produce powdered beverages (e.g., skim milk powder) and fruit juice concentrations.	Distillation of liquors, including alcohol.			
Leather	Processing and drying of leather.					
Lumber	Drying of lumber.					
Paper and Paper	Drying of paper.	Pre-concentration of black liquor.				
Chemical	Drying of fine chemicals.	Evaporation of liquor, including chlor-alkali evaporation and alcohol fermentation.	Distillation of liquors, including propane-propylene splitting. Purification of specialty chemicals.			
Petroleum Refining			Distillation of liquors, isobutene-normal butane splitting and isopentane-normal pentane splitting.			
All Industrial Sectors		Treatment of wastewater.	Recovery of solvents (distill for reuse).	Heating of process water and/or domestic water.	Space conditioning (heating, cooling, dehumidification) of buildings.	Chilling of refrigerants.

Table 1: Examples of Industrial Heat Pump Applications.

Sources: Heat Pump Network, http://www.heatpumpnet.org.uk/publications_intro.asp#Publications%20on%20Industrial%20Applications; EPRI, *Industrial Heat Pumps, TechCommentary*, Vol. 1, No. 4, 1988.

Typically, the distillation separation of propylene and propane (in a PP-splitter column) relies on a reboiler and a water-cooled condenser. The reboiler is heated by low-pressure steam and the overhead vapors are cooled with cooling water. A significant amount of fossil fuel (typically natural gas, oil, or coal) is required for the production of steam. The temperature difference between the top and bottoms of the distillation column is typically 80°F or less which makes them prime candidates for heat recovery heat pump applications. Heat pump applications are

restricted to columns that separate components with similar boiling points and, therefore, have a low temperature difference across the column. Though industrial distillation processes can benefit from both open- or closed-cycle heat pumps, open-cycle heat pumps are especially beneficial because they allow for the recovery of waste heat from vapor within the distillation columns. Indeed, MVR heat pumps can recover the energy in the overhead vapors from the column by compressing the vapor and then using it to reboil

the column, as illustrated in Figure 2. This results in a higher COP and, thus, much higher energy savings and CO₂ reductions. For example, a COP of 8 for heating the column (and a COP of 1.5 if the resulting cooling energy from the heat pump were to be used on-site) has been obtained in a PP splitter column in the Netherlands that uses an MVR heat pump.⁸ While new construction applications result in higher economic benefits, many retrofit applications can result in paybacks of 1 to 3 years.

8. Heat Pump Center, *Mechanical Vapour Recompression Case Study*, Pernis, the Netherlands, www.heatpumpcentre.org/Publications/case_pernis.asp.

Benefits for a Typical Industrial Plant

Because of the many advantages of open-cycle heat pumps, a detailed analyses of the benefits associated with the use of an MVR heat pump in a chemical plant has been conducted. The MVR heat pump is used in a distillation column to separate propylene and propane and displaces steam generated by a natural gas boiler.⁹ The primary plant-level benefits associated with this heat recovery heat pump application are summarized in Figure 3 and are described in more detail below.

The main benefits associated with this type of industrial heat pump application include significant energy savings, considerable reductions in CO₂ emissions, and improved product quality and production yields.

- **Energy savings:** Because heat recovery heat pumps rely on waste heat for operation, they are extremely efficient. It is not uncommon for heat pumps to reduce on-site energy use by as much as 90%. For the given application, the net plant-level energy savings are 1,652,000 MMBtu per year (91%).
- **Reduction in CO₂ emissions:** Due to their high efficiency, heat recovery heat pumps generally provide large reductions in net overall CO₂ emissions when used as replacements for fossil-fueled technologies. The level of CO₂ reduction depends on where the electricity used to power the heat pump is generated since the generation mix of purchased electricity varies across the U.S. For example, the electricity generation mix in the Midwest is about 65% more carbon-intensive than the generation mix in the Northeast. For the given

application, the potential reduction in CO₂ emissions ranges from 62,500 to 76,100 metric tons per year with the current generation mix in each region (see Figure 3). With a 20% reduction in the carbon-intensity of the generation mix in each region, the range of potential CO₂ reductions increases to 69,400 to 80,200 metric tons per year.

- **Improved product quality:** Heat pumps can typically improve product quality and yield in most industrial processes. Because the propylene-propane splitter column can operate independently of a cooling fluid when an MVR heat pump is used, the column pressure can be reduced. The reduced pressure results in an improved split between propylene and propane and an increase in the polymer grade propylene purity. For example, a case study in the Netherlands showed the polymer grade propylene purity increased from 90 to 99.5 weight percent in a propylene-propane distillation column that replaced the reboiler and water-cooled condenser with a MVR heat pump.¹⁰

- **Reduced cooling water requirements:** Because heat pumps are also capable of providing useful cooling energy, the cooling water requirements can often be reduced in this type of application. Reducing cooling water requirements is an important consideration when cooling water supply and water treatment costs are high. In the Netherlands case study, surface water requirements for cooling were considerably reduced.¹¹

- **Less thermal pollution:** Because heat pumps recover waste heat that otherwise would be released to the surroundings, they reduce the thermal pollution associated with the hot waste streams.

- **Increased capacity:** The use of heat pumps can overcome limitations in industrial heating and cooling systems. For example, the use of a heat pump in the current application can avoid the purchase of a steam reboiler and cooling tower. Alternatively, for the same production

Industry	Chemical/petrochemical (NAICS 325)
End-Use	Separation of propylene and propane in distillation column
Electric Technology	50.2 MW open-cycle MVR heat pump, COP = 8
Electricity Requirement	50,400 MWh per year (172,000 MMBtu per year)
Displaced Technology	Natural gas boiler for steam generation, 75% efficient
Natural Gas Savings	1,824,000 MMBtu per year
Net On-Site Energy Savings	1,652,000 MMBtu per year (91% savings)

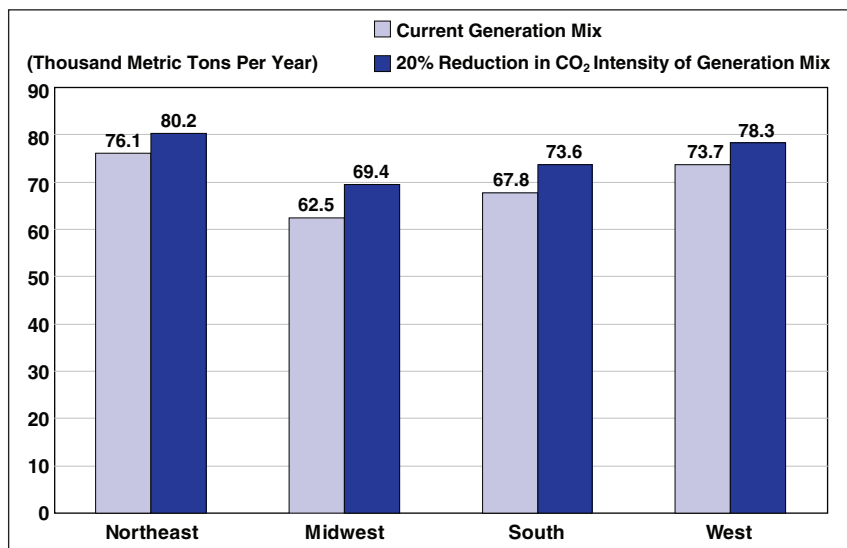


Figure 3: Plant-Level Energy and CO₂ Benefits by Region

9. Heat Pump Center, *Mechanical Vapour Recompression Case Study*, Pernis, the Netherlands, www.hetapumpcentre.org/Publications/case_pernis.asp.

10. Ibid.

11. Ibid.

capacity, a heat pump typically reduces the capacity requirements for energy conversion equipment.

- **Less floor space:** Heat pumps often require less floor space relative to conventional energy supply systems such as boilers and cooling towers. This can be especially beneficial in retrofit applications.

In addition to significant energy savings and CO₂ emission reductions, the use of MVR heat pumps offers many benefits to chemical and other industrial plants. The next section presents the benefits for the U.S. chemical/petrochemical industrial sector as a whole.

National Potential to Save Energy and Reduce CO₂ Emissions

To estimate the potential for energy savings and CO₂ reductions resulting from the expanded use of heat pumps in the chemical/petrochemical industry (NAICS 325), all possible applications of industrial heat pumps to displace steam produced with natural gas boilers and to displace direct-fired natural gas process heating equipment were considered. The plant-level benefits of the specific application presented above were extended to this more general national-level case.

Table 2 summarizes the characteristics of the national-level analysis. Two of the key parameters that affect the results are the energy efficiency ratio and the market share. The energy efficiency ratio is a dimensionless number that represents the quantity of on-site energy required for the electric technology for every unit of energy required to accomplish the same desired output with the displaced fossil-fueled technology. That is, a ratio of 0.152 means that 0.152 units of energy are required by the electric technology for every 1 unit of energy required by the fossil-fueled technology. The market share is an estimate of the degree the electric technology could *technically* penetrate the market for the given end-use.¹²

Figure 4 and Table 3 present the results of the national-level analysis by census region and for the U.S. as a whole. A range of values is provided for each result to reflect variations in the energy efficiency ratios.

Figure 4 shows the potential for *primary* energy savings. The primary energy savings account for losses related to generation, transmission, and distribution of electricity; thus, unlike on-site energy savings, primary energy savings represent an overall energy use picture and are useful as a metric for quantifying the regional/national energy impact of replacing fossil-fueled technologies with electric technologies.

Industry	Chemical/petrochemical (NAICS 325)	
End-Use	Process heating	
Analysis Period	2010-2030	
Electric Technology	Heat pump	
Displaced Technology	Natural gas boiler	Natural gas furnace
Energy Efficiency Ratio	0.076 - 0.152	0.095 - 0.190
Market Share	0.15	0.15

Table 2: Characteristics of National-Level Analysis

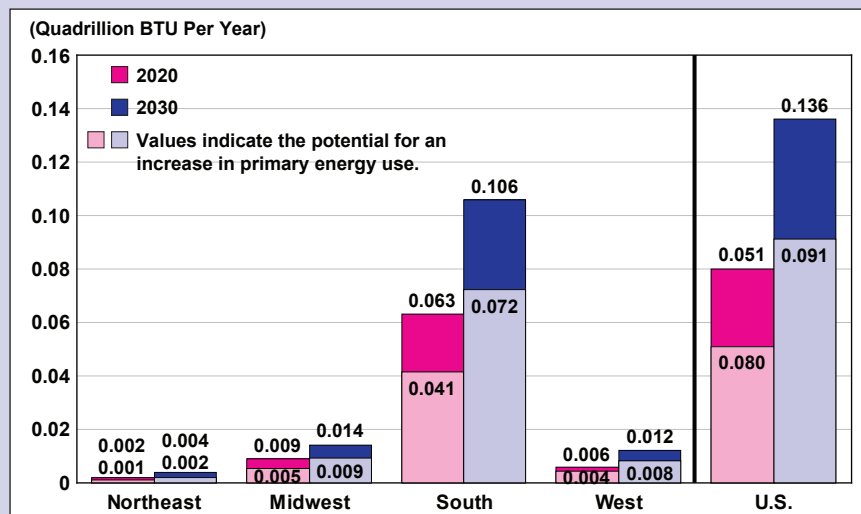


Figure 4: National Potential for Primary Energy Savings

12. Using this approach, the market share would be smaller for an economic or realistic potential.

The results indicate that the national potential for primary energy savings in this application ranges from 0.091 to 0.136 quadrillion Btu per year in 2030. The potential is greatest in the South, followed by the Midwest, West, and then the Northeast.

Table 3 shows the potential for overall reductions in CO₂ emissions. The results indicate that the national potential for CO₂ reductions ranges from 4.33 to 6.99 million metric tons per year in 2030 under the current generation mix. Since significant efforts are underway to reduce the CO₂ intensity of the generation mix, it is useful to evaluate the potential impacts with a greener

generation mix in the future. Assuming a 20% reduction in the CO₂ intensity of the generation mix, the potential for CO₂ emissions reductions rises to a range of 5.40 to 7.52 million metric tons per year. Again, the potential is greatest in the South, followed by the Midwest, West, and then the Northeast.

These estimates imply that heat pumps have an enormous potential to save energy and reduce CO₂ emissions in the chemical/petrochemical industry, particularly in the South. As a result, a heat pump application would make an ideal candidate for a demonstration project. Specifically, demonstrating a heat recovery heat pump

in a distillation application would increase awareness of the benefits of this technology as well as help further its technological advancement.

Region	Overall CO ₂ Reduction (million metric tons per year)			
	Current Generation Mix		20% Reduction in CO ₂ Intensity of Generation Mix	
	2020	2030	2020	2030
Northeast	0.10 - 0.13	0.16 - 0.21	0.11 - 0.13	0.18 - 0.22
Midwest	0.23 - 0.44	0.38 - 0.73	0.31 - 0.48	0.52 - 0.80
South	2.02 - 3.26	3.31 - 5.37	2.51 - 3.51	4.13 - 5.79
West	0.26 - 0.36	0.49 - 0.68	0.30 - 0.39	0.57 - 0.72
U.S.	2.61 - 4.19	4.33 - 6.99	3.24 - 4.50	5.40 - 7.52

Table 3: National Potential for Reductions in CO₂ Emissions