INDUSTRIAL HEAT PUMPS: ELECTRIFYING INDUSTRY'S PROCESS HEAT SUPPLY

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Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Executive Summary

KEY FINDINGS

- Industrial heat pumps (IHPs) can save up to 32% of the source energy for process heat generation. For industrial groups such as food, chemicals, and pulp and paper, our work shows IHPs could save the energy equivalent to powering 1.3 million homes and CO_2 emissions equivalent to that of 2.7 million passenger cars.

- IHPs can have simple economic paybacks under two years in states where the price of electricity is advantaged over that of natural gas. Yet, due to uncertainties about full implementation capital costs, integration, and maintenance, incentives from policy and utilities are essential for accelerating adoption—especially in most states where the electricity/natural gas cost ratio is disadvantaged.

- Field-level demonstrations of various IHP types—in multiple industrial applications—are crucial to lowering hurdles, increasing awareness of IHP benefits, and developing diverse workforce to support installations. Broad support and engagement across industry, utilities, agencies, and technology providers is needed to promptly accelerate demonstrations and the learning they provide.

Industry accounts for more than 25% of the nation's energy use and energy-related carbon dioxide (CO_2) emissions—emissions that must be reduced to achieve national and international climate goals. Among climate stabilization experts, decarbonization, that is, dramatically reducing atmospheric net GHG emissions and decoupling energy and feedstock use from fossil fuels, is a widely accepted goal.

Industry has several pathways to decarbonization, including electrification; today, it gets 17.6% of its total site energy and less than 5% of its process heating energy from electricity. Instead, U.S. industry sources most of its energy from fossil fuels—largely natural gas. This energy includes process heat: The heat that powers manufacturing and accounts for 50% of on-site industrial energy use. There are thousands of industrial operations, and with process heat being cross-cutting, electrifying it using low-carbon sources is a prime opportunity. Here, industrial heat pumps (IHPs) can significantly reduce energy consumption and GHGs while aiding electrification by providing much of the process heat needed in U.S. industry and helping to make dramatic cuts in industrial emissions.

Currently, a few types of IHPs can provide heat up to about 160°C (covering roughly 44% of industrial process heat needs), and products are in development to raise this temperature ceiling to about 200°C (covering roughly 55% of industrial process heat needs). IHPs are not new. They were integrated into U.S. industrial processes to a limited extent as far back as the 1960s and have been referred to as mechanical or thermal vapor recompression (MVR, TVR) units. The arrival of inexpensive natural gas cut into their economic favorability, and adoption stalled. Today, their use is sparse and their capabilities for energy- and GHG-reduction remain largely unknown. Now, the urgency of the climate crisis and advancements in IHP technology (e.g., doubling the maximum temperature to 160°C for several IHP types), make them a key industrial electrification solution.

Increasing corporate interest in both sustainability and GHG reductions are strong arguments for implementing IHPs without delay. And we can do this now with the right incentives and policy levers. The high price of electricity relative to the low price of natural gas is the largest economic obstacle to IHP adoption. Our research shows that IHPs can have paybacks under two years (an attractive marker), especially when the electricity/natural gas price ratio is under 4. In regions of the country where this ratio is over 4, policies can have a key role in addressing this economic gap. Other hurdles include process integration, uncertainties (e.g., service lifetime, maintenance), product availability, and workforce limitations (e.g., lack of experienced and trained process engineers).

Policymakers can address these uncertainties with economic incentives and support for development of a skilled workforce; such efforts will have the added benefit of creating jobs. Expanding pilot and demonstration projects will help convince industrial-sector leaders of IHP viability and benefits over current equipment. IHPs are being aggressively deployed in Europe, Japan, and Australia, and the manufacturers are primarily in the European Union and Japan. There are no suppliers in the United States (above 0.5 megawatts), so global suppliers need to be incentivized to pilot IHPs while a domestic market is still being developed.

Our research shows that moderate deployment of IHPs in industrial groups with high process heating demands, such as pulp and paper, chemicals, and food manufacturing, could save 26–32% of the source energy (or 166–210 trillion Btus net depending on scenario after subtracting electricity use) across multiple unit operations, which is the equivalent energy use/year of 1.1–1.3 million homes. In parallel, IHPs could avoid emissions of 9.7–12.6 million metric tons/year of CO_2, equivalent to emissions from 2.1–2.7 million passenger cars. As the electric supply becomes further decarbonized, the amount of CO_2 avoided could double. The electricity used to run the IHPs (instead of natural gas) would approach 2.1 gigawatts of electricity: the power needed to run several medium sized cities. Expansion of IHP use across the far greater breadth of industry would save even more energy and CO_2 emissions.

Our report goes beyond high-level assessments and describes how and where IHPs could be deployed at the unit operations level (the basic process level where materials are transformed, separated, and dried). The following unit operations in three industrial groups were analyzed.

Paper: pulp mill digester and multi-effect evaporator; non-integrated paper mill pulper

Food: wet corn-milling steepwater and high fructose corn syrup starch conversion; potato-processing hot air dryer

Chemicals: ethyl alcohol for fuel applications from dry mill production, ethylene (above ambient) debutanizer reboiler, and process water stripper reboiler.

This report shows how and where IHPs could deliver energy and GHG savings while delivering multiple nonenergy benefits like cleaner air, improved temperature control, productivity, quality, and waste reduction. The report also describes routes that stakeholders can use to lower hurdles, enable policy, and develop public-private partnerships that accelerate adoption.

Definitions/Acronyms

Acronym	Definition
AMO	Advanced Manufacturing Office
BASF	Badische Anilin und Soda Fabrik, leading chemical manufacturer
Btu	British thermal unit
CapEx	Capital cost
Cwt	Hundred weight
CO_2e	Carbon dioxide equivalent
COP	Coefficient of performance
Cts	cents
DOE	Department of Energy
GHG	Greenhouse gases
GJ	Gigajoule units
GWP	Global warming potential
HA	Heat activated
IHP	Industrial heat pump
kW	Kilowatt
kWh	Kilowatt hour
MMBtus	Millions of British thermal units
MT	Metric ton
MMT	Millions of metric tons
MVC	Mechanical vapor compression
MVR	Mechanical vapor recompression
MW	Megawatt

NYSERDA	New York State Energy Research & Development Authority
PB	Payback
PSIG	Pounds per square inch gauge
RD&D	Research, development, and deployment
TBtus	Trillions of British thermal units
TVR	Thermal vapor recompression
WCM	Wet corn milling

Introduction

Industry accounts for more than 25% of the nation's energy use[1] and energy-related carbon dioxide (CO_2) emissions. Considering the magnitude of its emissions and its role in supplying goods that enable reductions in other sectors, industry is an increasing focus of the societal drive for climate stabilization. U.S. industry's generation and use of process heat, 7,576 trillion Btus/year (EIA 2021a), accounts for 51% of on-site industrial energy use and thus is a prime target for energy and CO_2 emissions reduction.

Among climate stabilization experts, decarbonization[2]—replacing fossil fuels with power from low-carbon sources like wind, solar, and hydropower—is a widely accepted goal. Beneficial electrification (Whitlock, Elliott, and Rightor 2020), where fossil fuel use is replaced with electricity from low-carbon sources, stands out as a key pathway to making step-change reductions in this footprint as the grid is decarbonized. The potential for electrification to transform the footprint of process heat is high, as electricity accounts for only 5% of this heat today, with the balance from fossil fuels.

Industrial heat pumps (IHPs) are a key technology that can be scaled as part of the transformation of industry's process heat generation. IHPs are not new: There was increased IHP commercialization in Europe from 1995–2010 (IEA, Annex 48). IHPs had been integrated into U.S. industrial processes to a limited extent as far back as the 1960s, when they were known as mechanical or thermal vapor recompression (MVR, TVR) units (Gluckman and McMullan 1988), but the production of inexpensive natural gas in the United States reduced their economic advantage and adoption stalled. Today, their use is sparse and their capabilities for energy and GHG reduction are largely unknown. Now, the urgency of the climate crisis and advancements in IHP technology (they can now produce heat 80°C higher than their previous maximum temperature, reaching 160°C for some IHPs), make them a logical solution to cutting industrial GHG emissions.

IHPs can reduce industry's carbon footprint in several ways: 1) electrification of process heat; 2) improved efficiency: current generation IHPs use power more efficiently and can be deployed locally, avoiding lengthy steam distributions systems; and 3) reuse or recovery of waste heat. These approaches are interrelated; they depend on how much of the process heat load is electrified and on the carbon intensity of the electricity; the degree of GHG reduction may vary. Regardless of the source of the waste heat (fossil fuel, biomass, solar, or nuclear) recovering and upgrading waste heat is valuable for many applications. Corporate

[1] Including feedstocks—fossil inputs to material production (i.e., plastics, chemicals)

[2] In this report decarbonization will refer to reducing atmospheric net GHG emissions (in terms of CO_2 equivalents (CO_2e)) attributable to industrial processes.

appetite for sustainable energy and GHG reduction is a strong motivation for upgrading and effectively using process heat, including implementing IHPs, without delay.

The low price of natural gas compared to electricity is currently the largest economic obstacle to IHP adoption. In many cases, however, IHPs have paybacks that are acceptable to industry, especially in regions of the country where the electricity/natural gas price ratio is under 4. Other obstacles include the uncertainty of investing in newer IHPs that are not yet widely adopted, and long equipment lifetimes (>15 years) providing infrequent opportunities for equipment replacement. Policymakers can minimize perceived risk through economic incentives and by supporting the development of a workforce skilled at designing, installing, and servicing IHPs (with the added benefit of creating jobs). Policies have a key role to play in accelerating adoption.

While there have been multiple studies examining the potential for IHPs in some industries, there are no recent studies that examine actual process heating and cooling streams to determine IHP potential; there is a paucity of IHP applications information for specific industries and processes at the energy analysis level.

The research in this report aims to fill this gap by providing information at the unit operations level. This report presents research examining the IHP market; capability fit with industrial needs; economics; electrification potential to reduce energy and GHGs; and enablers to accelerate research, development, and deployment (RD&D) of current and emerging IHP technologies in U.S. industry. The technical nature of this report lays the foundation for gauging where IHPs can most effectively provide process heat in industry and connects to policies that could accelerate adoption.

Background

Multiple drivers are revitalizing interest in addressing the energy and carbon footprint of process heat within the United States, including more aggressive company GHG reduction/sustainability goals, industry consideration of electrification of process heat demand, and nonenergy benefits, such as improved process control, faster temperature adjustments, reduced water consumption for cooling, and local heat generation versus centralized steam systems.

PROCESS HEAT AND THERMAL RANGES OF INTEREST

Industrial subsectors with high levels of process heating demand in the supply (i.e., heat pump sink) temperature range are shown in figure 1. Process heat is used in numerous applications that are common across these industry groups, including (in order of the amount of energy consumed): fluid heating and distillation, drying, metal smelting, and calcing (DOE 2015). The temperature range of 60–200°C is an attractive range for IHPs. Currently, a few types of IHPs can provide heat up to about 160°C (covering roughly 44% of industrial process heat needs), and further developments may raise this temperature ceiling to about 200°C (covering roughly 55% of industrial process heat needs). Where refrigeration is present (e.g., food and some chemical applications), dual heating and cooling service would also be an ideal market entry for IHPs in the United States (EIA 2021a).

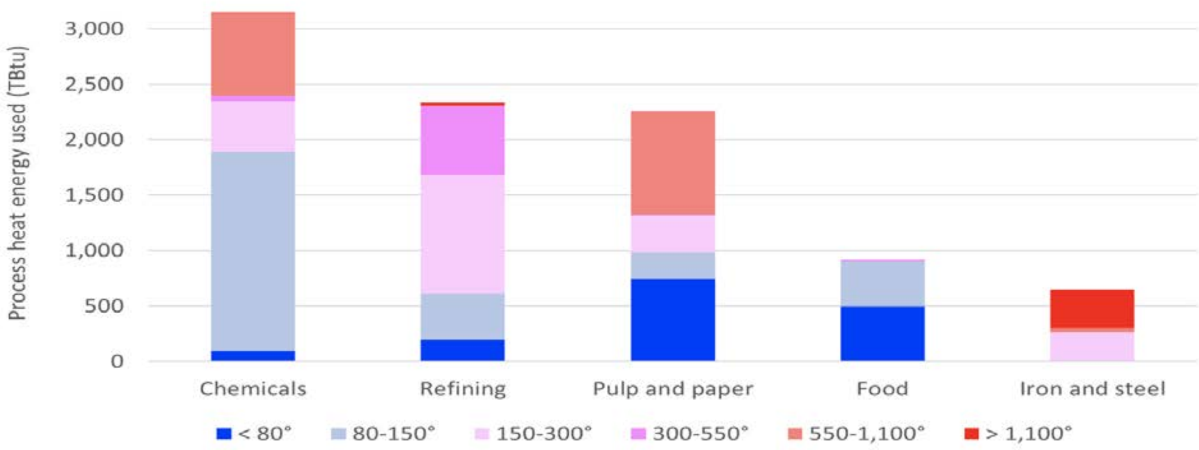


Figure 1. Process heat demand at different temperature (°C) levels in select U.S. Industrial I groups. Data source: McMillan 2019.

Where process cooling and heating are both significant (e.g., breweries, wineries, food processing, some chemical and material processing), dedicated heat recovery chillers (a form of IHP) can offset significant fossil fuel use for steam generation while improving efficiency and reducing costs (Rightor, Whitlock, and Elliott 2020). In addition to replacements for steam generation (Bless et al. 2017; Arpagaus 2020a), IHPs are being considered for drying products and removing water from solids, which accounts for 15–25% of the energy associated with processes (Jakobs 2019). Applications for moisture removal are numerous and include proofing bread dough, manufacturing bricks, purifying chemical products, and drying biosolids.

INDUSTRIAL HEAT PUMPS

At their simplest, heat pumps are devices that move heat from low to high temperature, often using a vapor compression system similar to the heat pump space heating systems used in homes and buildings or in refrigerators. However, industrial heat pumps are more complicated, tailored to meet the diverse needs of industrial processes, and they are usually integrated with one or more such processes.

Prior studies showed that moderate deployment of IHPs in manufacturing could save 2–5% of the total U.S. industrial process heat demand (170–350 trillion Btus/year) and avoid emissions of 12–25 million tons/year of CO_2 by 2010 (IEA 1995). IHPs are used commercially in numerous industrial applications globally, yet adoption of earlier generation IHPs in the United States was limited due to a relatively low upper temperature bound for conventional heat pumps (80°C, primarily due to limitations of refrigerants and other working fluids), the high cost of electricity versus natural gas in some regions of North America, compressor technology limitations, and the lack of field service capabilities.

Mechanical and thermal vapor recompression IHPs (e.g., MVRs, TVRs) can be found in industry. A survey of the industrial use of IHPs in 1988 found 69 closed cycle and 309 open cycle IHPs in use (excluding lumber drying) (Gluckman and McMullan 1988). The closed cycle IHPs were largely used in water/sewer facilities with fewer units in food, chemicals, and dairy. The open cycles were found in dairy, wet corn milling, chemicals, water/sewer, and pulp and paper. The later Annex 21 study found 318 IHPs in use, with the estimated percentage of plants with IHPs ranging from 1–5%, with the exception of corn milling, which had 20% (Annex 21).

An updated survey of IHP use in industry would be advantageous. When we interviewed industry leaders, we heard that scattered MVRs and TVRs are operating in dairy, corn milling, liquor, and pulp and paper applications but their number is relatively low. We did learn that IHPs can be found in equipment provided as a package, such as drying equipment, concentrators, and multi-effect evaporators. Advances in low-environmental-impact refrigerants (McLinden et al. 2014) and other working fluids (oils and other lubricants specially designed for IHP applications) that can operate at higher delivery temperatures (e.g., up to 160°C for electrically driven IHPs) have broadened the range of IHP applications, such as in waste heat recovery and product drying, which can account for 12–25% of energy use (Lauermann et al. 2019).

As the technology has advanced, so has understanding of IHP economics and favorable deployment scenarios (Arpagaus and Bertsch 2020; Arpagaus 2020a; Kosmadakis et al. 2020). Further, new heat activated IHP technologies, driven mostly by waste heat, promise to supply process heat up to 260°C. Also, the potential of more favorable economics (high heat pump lift temperature, e.g., 80 K) compared to electric-driven vapor compression heat pumps could provide even broader applicability (QPinch 2021).

The market and vendor capabilities for IHPs are most well developed in Europe and Japan (Arpagaus et al. 2018), where there are strong economic (relatively high fuel-to-electricity utility rates) and policy incentives (e.g., European carbon price and/or mandated carbon targets), and well-funded public-private R&D partnerships to develop IHP technology (e.g., the Horizon Europe program or Japan New Energy and Industrial Technology Development Organization (NEDO) to decarbonize and electrify process heating demand. IHPs are commercially available today, and there are hundreds of economic applications that have been documented with case studies (IEA Annex 48). A recent study of the IHP potential in Europe highlighted that 80% of the IHPs in industry would be under 5 MW, meaning that the vast majority of IHP applications are within reach of modest commercial systems under this upper scale marker. (Marina et al. 2021). (Here MW refers to the heating capacity or heat pump thermal output and not the electrical power supplied to the heat pump). Recent IHP demonstrations include those at 1–2 MW (Borealis 2021), again showing application of this technology within a reachable range. Also, IHPs were mentioned in BASF's goals of reducing CO_2 25% by 2030 and getting to net zero CO_2 by 2050 (BASF 2021).

TYPES OF INDUSTRIAL HEAT PUMPS

There are multiple types of IHPs. For example, ambient heat pumps can work as stand-alone equipment for relatively low temperature uses such as preheating and heating air and water. Heat activated heat pumps rely on prime heat or waste heat to drive them and are installed near an existing base process where there is excess heat that can be used. IHPs can be open cycle, where the heat pump working fluid is the process stream itself, such as when waste steam is being compressed and returns for process, or closed cycle, where the heat pump has a heat exchange on the heat source and sink side to separate the heat pump working fluid from the environment. A classification of IHPs is provided in figure 2. Six IHP types were considered in this work for optimum fit within any process; they are briefly described below, and more detail is provided in table A2 of Appendix A. These descriptions are illustrative of process types and not meant to be comprehensive.

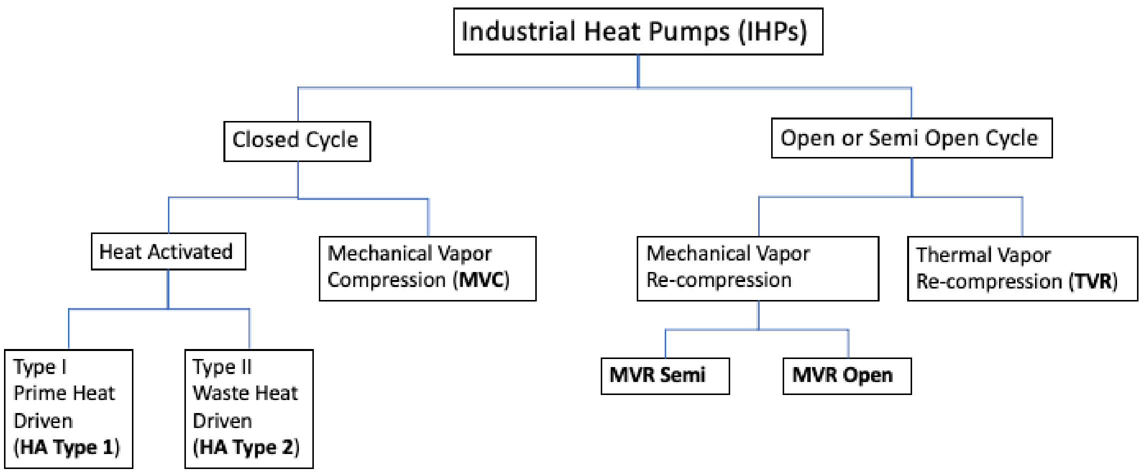


Figure 2. Six different IHP types considered in this study (adapted from Gluckman and McMullan 1988)

The IHPs are introduced below; detailed descriptions can be found in Appendix A. Parameters for the economic estimates, including capital costs and maintenance cost factors, can be found in Appendix B and table B1. The choice of IHP type depends on the application and multiple parameters. For the unit operations examined in this study, insights on IHP types are provided in the "Types and Fit with Applications" section.

1. Mechanical vapor compression (MVC), closed cycle. A completely closed refrigerant loop maintains the working fluid's pressures and temperatures. A heat exchanger is required on both the heat sink (condenser) and heat source (evaporator) sides.
2. Mechanical vapor recompression (MVR Semi), semi-open cycle. This IHP will typically take advantage of recompressing waste low-pressure steam or hydrocarbon vapor that would otherwise be vented or condensed with heat rejected to the ambient air.

3. Mechanical vapor recompression (MVR Open), open cycle. The difference between the semi-open and open cycle is that a heat exchanger is used in the semi-open cycle to keep the waste vapors separate from the process steam or other heat exchange process vapors/liquids. In the open cycle, the (waste) vapors are reinjected directly back into the process without a separate heat exchanger.
4. Thermal vapor recompression (TVR), open cycle. The TVR heat pump is perhaps the most common in industry today. It is the simplest as it has no moving parts, but it is restricted to compressing low-pressure (waste) steam (heat source) to a medium pressure steam header (heat sink) using high-pressure steam (IHP driver). It does not use any electrical energy. Additional information on TVRs and their efficiency can be found in Appendix D.
5. Heat activated Type 1 (HA Type 1), closed cycle. The heat activated (HA) heat pump technology uses various chemical processes, such as absorption, adsorption, or a reversible chemical reaction to transfer the heat from the source to the sink. In these systems the heat pump cycle is predominantly heat activated. However, it does require a small amount of electricity for pumping the working fluids. The Type 1 design requires a supply of prime heat at an elevated temperature well above the heat sink temperature to enable it to lift the waste heat to the intermediate sink temperature.
6. Heat activated Type 2 (HA Type 2), closed cycle. The Type 2 design is a waste-heat-driven heat pump where typically about one unit of heat is lifted to the higher sink temperature and one unit of heat is rejected to the ambient temperature. Type 2 designs require a sufficient temperature difference between the heat source and ambient, relative to the heat sink and source (lift temperature). Additional information on the efficiency assumptions HA IHPs can be found in Appendix D.

Methodology Summary

This section describes why we chose certain industrial groups and unit operations for study. It also explains how we decided on where to place the IHPs in the thermal cascade associated with these processes (e.g., pinch analysis), and it notes the process used to validate parameters, assumptions, and early results. The pinch analyses were crucial to optimize the efficient upgrading of thermal energy while minimizing the energy spend. They provide a starting assessment useful for discussion with experts at the plant level. For this study the pinch analyses also were central to providing outputs for estimation of energy and GHG reduction potential at the unit operations level, as well as simple economic assessments. It should be noted that detailed engineering, thermal, integration, and economic studies would be needed to advance pilot or final implementation.

CHOICE OF MARKET APPLICATIONS

The food, paper, and chemicals industry groups were chosen for study as they have a high proportion of low-moderate process heat in a temperature range (e.g., 60–200°C) that is readily accessible by IHPs. Food unit operations tend to be less highly integrated, and their simplicity was attractive. Food as well as pulp and paper facilities can found throughout the United States, providing good representation for dispersed industries. Chemicals applications, as well as pulp and paper, can have high to moderate levels of process heat integration, representing more complex systems. Evaporation and drying (areas of likely IHP applicability) are common in all of these industrial groups. The industrial groups and unit operations selected for study are summarized in table 1.

The Annex 21 study (IEA 1995) examined 24 top candidate applications. A related study described the IHP impact potential (RCG/Hagler Bailey, Inc. 1995). Research on IHPs in the United States has been largely dormant since these studies, but they provided a good starting point for exploring candidate processes in our study.

It should be noted that the North American Industry Classification System (NAICS) codes are used in this report to reference the portions of industry analyzed. For the NAICS code, the first two numbers designate the sector, the third the subsector, the fourth the industry group, the fifth the industry, and the sixth number the national industry. For some of the entities examined, data could not be assigned to a single NAICS code (e.g., potato processing, ethylene) so data at the industry group level were used as a starting point and assumptions were made based on public industry information that could be found.

Table 1. NAICS codes for industries of interest for this work

Manufacturing sectors	Select subsector	Select industry group	Industry
31	Food (311)	Fruit and vegetables (3114)	Wet corn milling (311221)
32	Pulp and paper (322) Chemicals (325)		Pulp mills (322110) Paper mills (322121) Newsprint (322122) Paperboard mills (322130) Petrochemicals (325110) Ethyl alcohol (325193)

PINCH ANALYSIS

We used pinch analysis to find the optimum location for the IHP in the multiple thermal flows typical of industrial processes. The optimum location where the heat availability (heat sources) is best aligned with the heat demands (heat sinks) is called the "pinch point." Pinch analysis is a structured methodology for minimizing the energy consumption of industrial processes by optimizing process operations including heat recovery systems and energy supply. In the past 40 years, application of this methodology in multiple industrial segments has been able to identify savings in energy (10–35%), water consumption (25–40%), and hydrogen consumption (up to 20%) (NRCan 2003). In production facilities that have been highly optimized for heat integration (e.g., world scale chemical plants), the potential savings may be smaller.

The pinch analysis identified the best cold streams (heat sinks) and hot streams (heat sources) for the heat pump to operate between (source to sink), including the size of the source and sink (MMBtus/ton product) and the temperature range of the source and sink. Careful attention was paid for getting hot or cold streams that were best suited for heat pumping by, for example, minimizing the number of hot or cold streams (one is ideal), evaporating and condensing streams, and lifting the temperature required by the heat pump. Details on the pinch analysis can be found in Appendix G with a more detailed description in the Annex, section 1. An explanation of the IChemE software used for pinch analyses is given in the Annex, section 2. We used data from earlier studies graciously provided by Per-Ake Franck of Chalmers ETA (Sweden) as a starting point for these analyses.[3] Finally, the Annex, sections 3, 4, and 5 document the inputs and assumptions, raw data, and results for all nine unit operations analyzed.

To most effectively apply the IHPs, we screened for the conditions summarized in table 2.

Table 2. Screening criteria for IHP applications.

Parameter	Maximum, with emerging technology	Ideal target today
Process heat sink temperature	< 200°C	< 160°C
Lift temperature	< 100°C	< 40°C
Heat sources and sinks comparable in size (MW)	Multiple condensing or evaporating streams at constant temperature with multiple hot and cold streams with temperature glide	One condensing or evaporating application at constant temperature and the other with hot or cold stream with glide

The ideally placed and integrated IHP would take heat from a heat source around 5°C or more below the pinch point and pump or upgrade the heat to a desired "lift" to the heat sink, around 5°C or more above the pinch point. If done efficiently, heat exchangers could be minimized, particularly above the pinch point. Figure 3 shows an IHP lifting heat by capturing waste heat at T_{source} and delivering heat to the process heat load at T_{sink}. The higher the IHP lift temperature, the greater the IHP capital cost and required IHP driver

[3] Franck, Per-Ake, Chalmers E-Sectionens Teletekniska Avdelnining (ETA), Pinch Analysis of Hot and Cold Stream Data for 140 Industrial Processes, pers. comm., December 2020.

energy and the lower the IHP coefficient of performance (COP); see also Appendix A, table A1 for definitions of COP for the various IHP types.

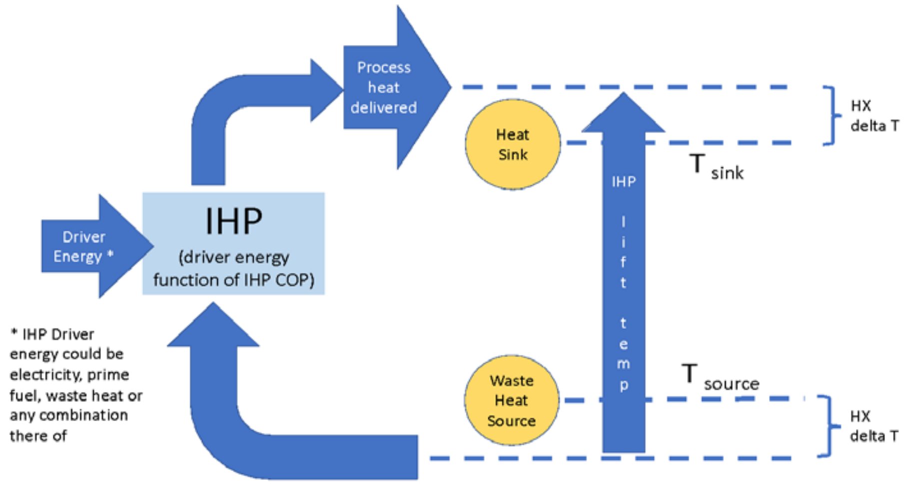


Figure 3. Generic IHP diagram illustrating IHP lift temperature, T_{source} and T_{sink}

Table 3 shows the industrial groups/unit operations analyzed via the pinch methodology and evaluated for the potential economic and technical impacts.

Table 3. Industrial groups and unit operation analyzed

Industrial group	Unit operation	Heat source / sink temperature (°C)	Process heat demand
Paper	Pulp Mill – Digestor	104/130 (economic) 53/127 (technical)	0.2–0.5 MMBtus/ton pulp
	Pulp Mill – Multi-Effect Evaporator	58/78 (economic) 63/102 (technical)	0.3–1.3 MMBtus/ton pulp
	Non-Integrated Paper Mill – Pulper	36/70	0.06–0.07 MMBtus/ton paper
Food	Wet Corn Milling – Steepwater	57/90 (economic) 51/120 (technical)	0.06–0.07 MMBtus/ton corn processed
	Wet Corn Milling – High fructose corn syrup starch conversion	59/91 (economic) 53/97 (technical)	0.02–0.17 MMBtus/ton corn processed
	Potato processing – Hot air dryer	46/70 (economic) 41/110 (technical)	0.4–1.0 MMBtus/ton potatoes processed

Industrial group	Unit operation	Heat source / sink temperature (°C)	Process heat demand
Chemicals	Ethyl Alcohol or Ethanol Fuel, dry mill	78/100	4.5 MMBtus/ton ethanol produced, dry mill
	Ethylene (above ambient) – Debutanizer reboiler	78/101	0.1 MMBtus/ton ethylene produced
	Ethylene (above ambient) – Process water stripper reboiler	77/109	0.02 MMBtus/ton ethylene produced

ECONOMIC AND TECHNICAL POTENTIAL: SCENARIOS

The pinch analysis methodology provided the heat source, sink size (MMBtus/ton product), and temperature level (°C) for the economic analyses, assuming the IHP replaces the process heat supplied by an already installed, conventional process heating system (e.g., boiler steam or fired process heater), as shown in figure 4 (i.e., a retrofit IHP situation, not requiring new boiler or fired heater capital investment). To assess the potential energy savings we assessed both the "economic" and "technical" IHP potential. Figure 5 illustrates these two scenarios.

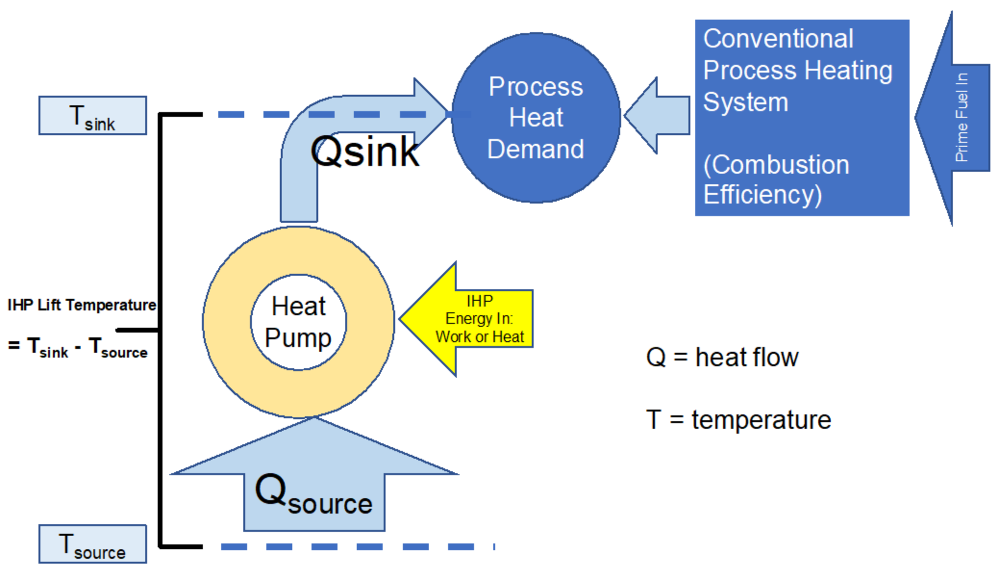


Figure 4. Generic diagram of industrial heat pump alternatively supplying process heat

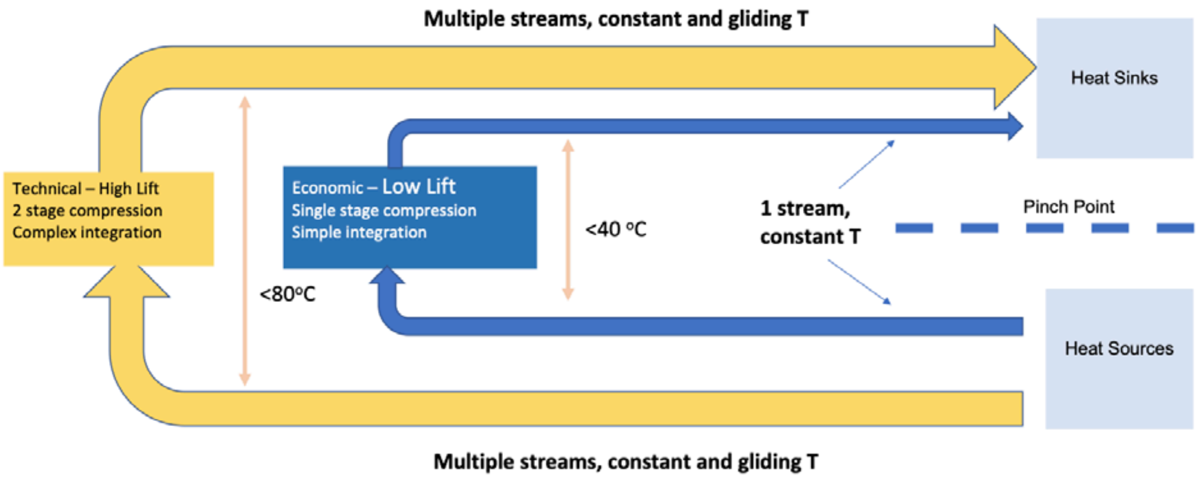


Figure 5. Economic and technical IHP potential energy savings

The economic potential case is simple when using one hot and one cold stream for the heat source and sink, respectively. Also, one constant condensing or evaporating (latent heat) stream was preferred as a heat source and/or sink to keep it to a simple configuration. The simplest cases were when both hot and cold streams were at a constant temperature, but that was not commonly found in all the unit operations. Finally, the IHP lift was limited to less than ~40 K, which is within the capability of a single-staged compression IHP.

Conversely, the technical potential case is much more aggressive in tapping into multiple heat sources and sinks at varying temperatures. Multiple IHPs were possible in this case. We did not limit the hot and cold streams to constant temperature, as they could offer a gliding temperature heat recovery or heat supply situation. The gliding temperature is when the heat source temperature will be reduced to capture the sensible heat and/or the heat sink temperature will be raised by the heat pump. The IHP lift temperature is higher and limited to less than 80°C for this case. Potential technical cases could require extensive engineering process redesign and heat integration changes to capture the estimated energy savings opportunity. Also, the compression heat pump in this case would require two stages of compression.

Note that the energy savings estimates are at two levels, economic and technical. Later in the report when we refer to the technical energy savings potential we mean the cumulative energy savings from both the economic and technical pinch analysis and the IHP energy savings of each level.

In both cases, we adjusted the capital costs of the IHP equipment and the installation costs assumed (more expensive for technical versus economic), see Appendix B, table B1; however, in summary MVR heat pump costs ranged from $250/kW to $500/kW, TVR costs were $150/kW, and the heat activated heat pump costs ranged from $1,000/kW to $1,875/kW. The IHP lift temperature will influence the amount of energy required to run the IHP.

Using the economic or technical cases, six different IHP types were evaluated for their cost effectiveness (simple payback) for the nine unit operations. In some unit operations, a heat pump type was ruled out due to mechanical limitations (e.g., TVR with heat pump lift greater than 20°C). The six selected represent those that are most likely to be installed currently. Figure 6 and table 4 conceptually introduce the six IHP types and show how they are driven with mechanical shaft power, prime heat, or waste heat. Note that Q_{prime} is the thermal energy provided to the heat pump at a temperature higher than the heat sink and $Q_{ambient}$ is the heat rejected from the heat pump at the source temperature to the ambient temperature.

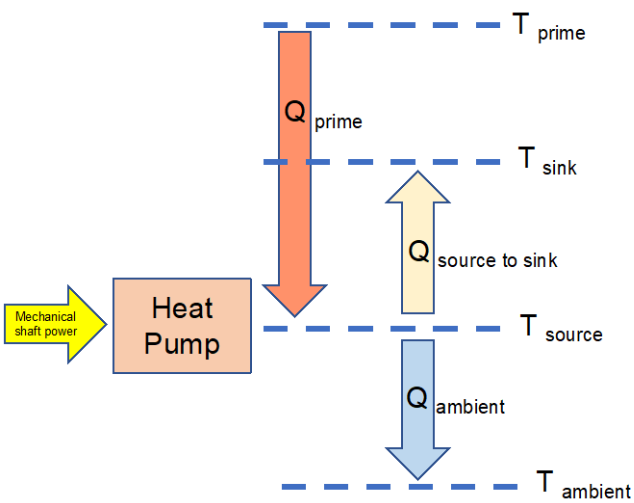


Figure 6. Illustration of how the IHP types are driven, where Q = heat moved between the source and sink

Table 4. Characterization of six IHP types per figure 9

IHP type	Mechanical shaft power energy	Heat exchanger locations	Q_{prime^*}	$Q_{ambient^*}$	Technology readiness level (TRL)
Mechanical vapor compression, closed cycle (MVC)	Large	Sink and source	--	--	9
Mechanical vapor recompression, semi-open cycle (MVR Semi)	Large	Sink or source	--	--	9
Mechanical vapor recompression, open cycle (MVR Open)	Large	--	--	--	9

IHP type	Mechanical shaft power energy	Heat exchanger locations	Q_{prime*}	$Q_{ambient*}$	Technology readiness level (TRL)
Thermal vapor recompression, open cycle (TVR Open)	--	--	Yes	--	9
Heat activated heat pump, Type 1 (HA Type 1)	Small	Sink and source	Yes	--	4–7
Heat activated heat pump, Type 2 (HA Type 2)	Small	Sink and source	--	Yes	4–7

VALIDATION INTERVIEWS

The pinch studies provided an excellent starting point for an initial understanding of where an IHP could be optimally placed in the process, temperatures for the source and sink, lift, and the estimation of process-heat savings. However, as this information was based on process heating and cooling data with limited details of the unit operation type and dates (we were not able to clarify actual process details with the original source), the team sought to validate key assumptions, aspects of practical application, and barriers to adoption with industry experts. Working with industry associations and our networks, we identified subject matter experts who could provide input on the process flow as well as the process heat usage in that industrial group. The key findings from these discussions were incorporated into the analysis to select unit operations that could be more practically modified for heat pump installation. For example, the conversations directed us to certain waste heat sources in ethylene and wet corn milling that were more self-contained (e.g., simpler analysis).

PARAMETERS AND RESULTS

Parameters, pinch analysis summaries, and results for the full range of IHPs examined across all applications/unit operations can be found in the Annex, sections 3–5. A listing of the carbon intensity emission factors used for natural gas and electricity can be found in Appendix C.

Potential Applications of IHP in Example Industries

The potential for IHP adoption in the nine unit operations in selected industrial segments was examined to identify the most efficient, cost-effective, and impactful geographic location for IHPs. We examined IHP application in food manufacturing, using potato processing as an example since it is a simple process and uses a drying process (a common unit operation in industry). For additional unit operations, results are provided below, and additional details can be found in the appendices.

FOOD

The food processing industrial group (NAICS code 311) is among the top five energy-consuming industries in the United States, and ranks fifth in energy use for process heating, using 532 TBtus/year (non-electric, EIA 2021a). The food industry is responsible for just over 3% of the nation's CO_2 emissions with 49 MMT CO_2 (EIA 2021a). Fluid heating, boiling, drying, and other preparation steps are among the top energy users. This industry is well distributed across the United States, with over 36,000 manufacturing plants owned by over 31,000 companies (USDA 2020), and 22 large facilities producing potatoes. There are also a multitude of product subsegments, including meats, beverages, dairy, grains, fruits and vegetables, animal foods, and bakery products. Several food products have similar processing steps where IHPs could be used to supply process heat, including pasteurization, blanching, sterilization, drying, and evaporation (New Zealand EECA 2019).

As a simple example for screening applicability, we chose the potato hot air drying process. In 2020, 279 million cwt (hundred weight or 112 lbs., equal to 15,668 thousand tons) of potatoes were processed (USDA 2021)[4]; the three top producing states were Idaho (32%), Washington (18%), and Wisconsin (7%). The estimate of total process heat utilized across the industry for processing of potatoes is 36.7 TBtus/year (50% of the process heat for fruit and vegetables, EIA 2021a). A portion of the potato process heat is for hot air drying. A summary of the analysis and results for the potato processing can be found in Annex, sections 3 and 5.

Figure 7 shows the generic potato drying process with the IHP applied. The heat pump's heat source is moist, hot air exiting the dryer and the heat sink is the inlet air. The heat pump preheats the dryer inlet air to reduce the steam consumption, and thus reduce the natural gas use for the boiler. In this example, the pinch analysis in the economic potential case found the heat pump lift temperature to be 34 K for a closed cycle MVC IHP.

[4] Hundred weight (cwt) is referenced here as it is the unit of mass equal to 100 pounds used in the field. The translation to more common units is given in the parentheses.

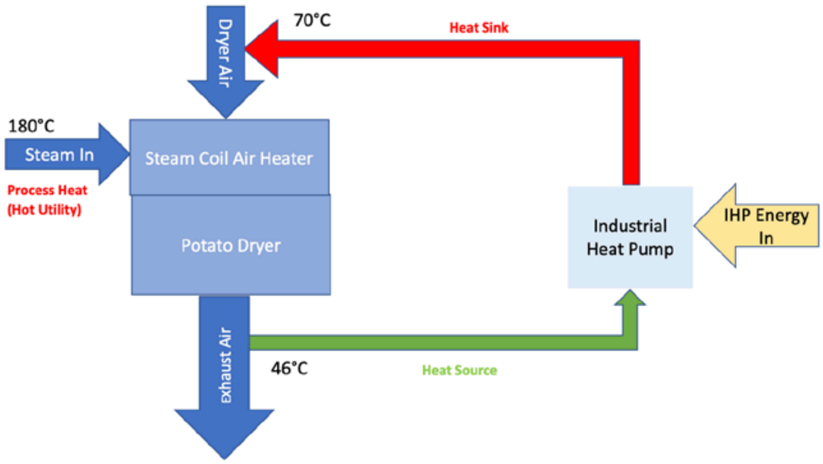


Figure 7. Simple flow sheet for potato drying IHP application

For practical reasons, the closed cycle MVC IHP designs would be the only IHP type considered for this type of food processing application, that is, to isolate the heat pump working fluid from the drying oven's inlet air stream. However, to illustrate comparative economics we show the results for all six IHP types. Analyses for the various heat pump types in figure 8 are for a typical potato processing facility (assuming all potato dryers have IHPs) under the economic potential case.

The results show that all the compression type IHPs (MVC, MVR Semi, MVR Open) save significant natural gas, about 11.4%. This is the case because the moist, hot air is a significant heat source relative to the preheated inlet air (heat sink). There are minor increases in electricity usage for the compression IHP types because the lift temperatures are modest at 24–34 K.

The TVR-Open Cycle results are shown for completeness even though TVRs require low lift temperature (less than 20 K) to operate. The immediate and greatest energy savings opportunity in the potato drying application is capturing the waste heat from the exhaust air of the dryer and using it to heat up the inlet air, thereby offsetting the steam demand (process heat). The TVR could be a fit here provided the temperature lift is within the thermodynamic and design limitations and there is a way to configure it with steam. However, in the potato drying unit operation that was considered in this report, even in the economic potential case, the temperature lift was found to be 24 K (the difference between the dryer air and the exhaust air temperatures). If this application used a steam TVR, it would further increase the temperature lift to probably 34 K, further limiting the TVR application. Hence, TVRs are not included in either of the economic or technical potential cases for potato drying IHP applications in table 5.

The HA Type 1 IHP's natural gas savings are modest (~3%) because it requires steam to operate and the heat pump's savings in preheating the dryer's inlet air are offset by the HA Type 1 IHP steam driver energy requirements. The waste heat driving force for the HA Type 2

IHP (dryer moist hot air temperature minus ambient temperature) is not ideal for waste-heat-driven heat pumps and thus is not applicable to the potato drying process.

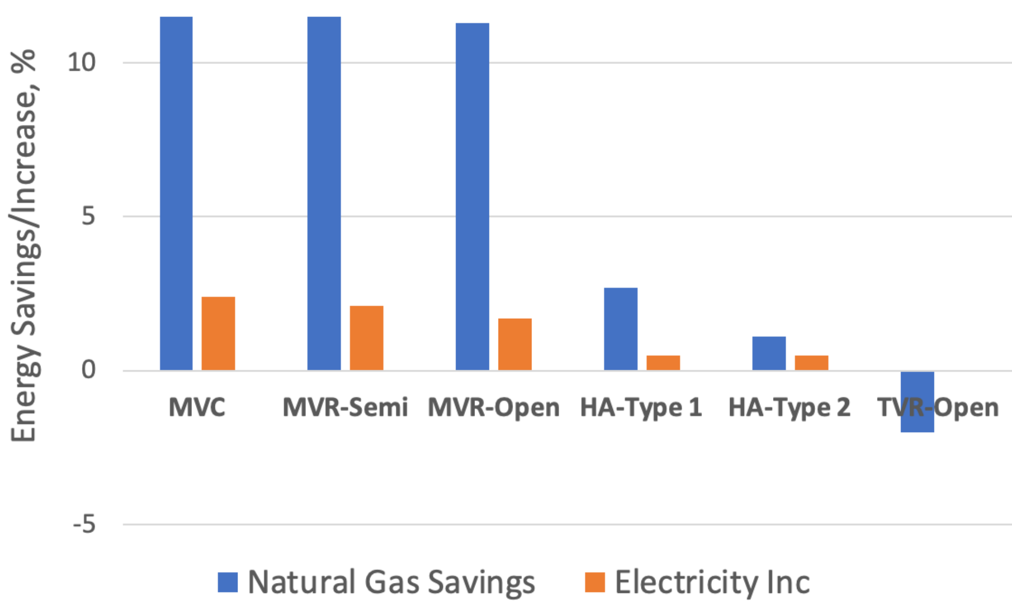


Figure 8. Energy savings for the potato drying IHP types per facility, economic case

An analysis of the CO_2e emissions reductions is shown in figure 9 for the economic and technical potential cases for all potato drying facilities (22 facilities estimated). The IHP lift temperature makes a significant difference as the CO_2 savings for each IHP is influenced by the heat pump electricity requirements relative to the natural gas savings. We assumed carbon emission factors for natural gas and electricity based on current U.S. national grid averages: 0.005 metric tons CO_2e per therm for natural gas and 0.0004 per metric tons CO_2e per kWh for electricity in 2020, decreasing to 0.00025 and 0.0001 in 2035 and 2050, respectively (see Appendix C). The current U.S. electricity grid still has a fairly high carbon emission factor, but as the grid becomes cleaner the technical potential case will show even higher CO_2 reductions.

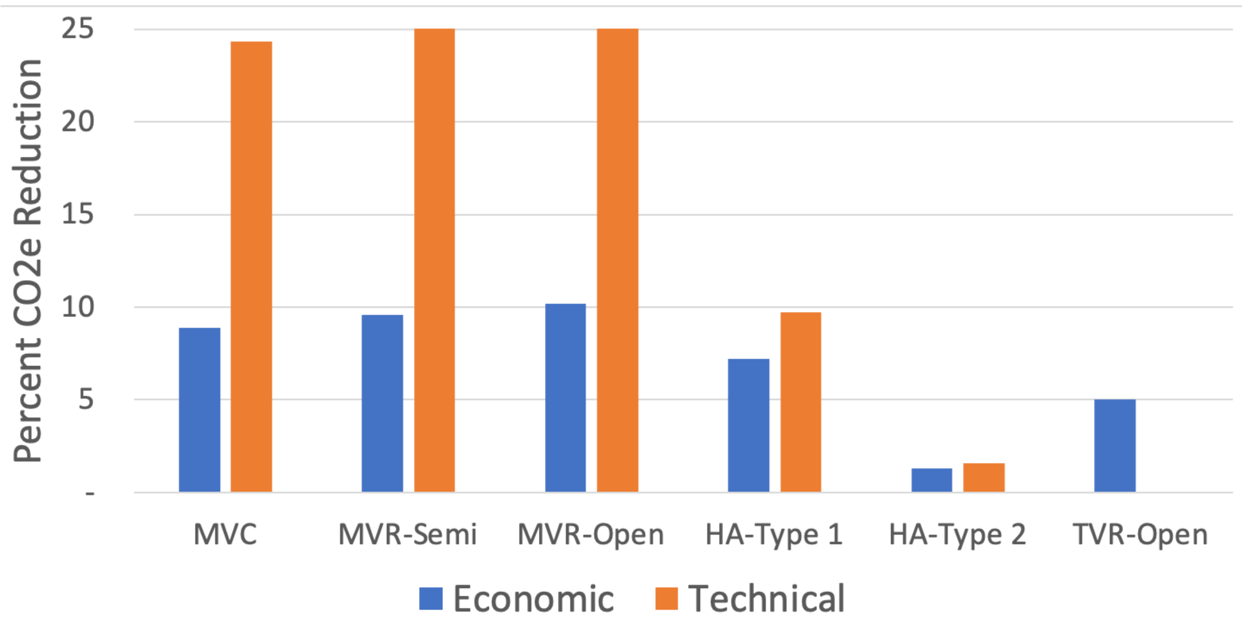


Figure 9. CO_2e reductions, (%) for economic and technical potential case, per potato drying facility

Table 5 shows the relationship of natural gas savings, source energy savings, COP (see note below), and CO_{2e} reductions for the economic and technical potential cases.

Table 5. Summary of parameters for the potato drying economic and technical potential cases

	MVC	MVR Semi	MVR Open	HA Type 1	HA Type 2
IHP lift temp (economic), °C	34	29	24	34	34
IHP lift temp (technical), °C	79	74	69	79	79
Natural gas savings (economic)	11.5	11.5	11.3	2.7	1.1
Natural gas savings (technical), %*	28.9	28.5	27.9	–17.0	0.2
Source energy savings (economic), %*	5.8	6.6	7.3	1.6	1.0
Source energy savings (technical), %*	7.8	8.4	9.2	–20.2	0.2
COP (economic)	5.1	5.9	7.1	2.4	0.1

	MVC	MVR Semi	MVR Open	HA Type 1	HA Type 2
COP (technical)	2.5	2.6	2.8	1.2	0
CO_2e reductions (economic), MMT/year	0.13	0.14	0.15	0.11	0.02
CO_2e reductions (economic), %	8.9	9.6	10.2	7.2	1.3
CO_2e reductions (technical), MMT/year	0.23	0.24	0.25	0.04	0.01
CO_2e reductions (technical), %	15.5	16.0	16.6	2.5	0.3

*** The percentage savings are relative to usage of natural gas or energy per facility for the potato drying unit operation before application of the IHP**

Note:

Source energy represents the total amount of raw fuel that is required for an end use application. It incorporates all generation, transmission, delivery, and production losses.

COP, coefficient of performance, is defined and described in Appendix A (IHP Types) in more detail, but very simply it is:

$COP = Q_{sink} / E_{driver}$

Q_{sink} = amount of heat supplied by the heat pump to the heat sink

E_{driver} = amount of energy input to drive the heat pump; can be electricity, prime or waste heat, or a combination thereof.

While the technical potential case always saves more natural gas than the economic potential case, it does not necessarily reduce CO_{2e} emissions proportionately if the electricity demand goes up due to the higher IHP lift temperature (lowered COP). The compression-type heat pumps show an increase from the economic to technical potential cases since their COPs are still favorable (> 2.5) and they have good overall IHP energy savings, whereas the heat activated Type 1 COP decreases to as low as 1.2 at the higher lift temperature assumed for this study (e.g., 80°K versus < 40°K) and thus there is minimal additional CO_{2e} emissions reduction for the HA Types 1 and 2 going from the economic to the technical potential case.

Simple payback was derived from the estimated energy cost savings and total installed capital cost (see Appendix B). However, capital costs ranged from $250 to $800 per kW for heat delivered for the vapor compression IHP types (MVC, MVR Semi, and MVR Open), $150 per kW for the TVR, and from $1,000 to $1,875 per kW for the HA Types 1 and 2 (table 10).

As an example of one IHP type, a plot of the simple payback for the economic potential case (figure 10) for the MVC IHP shows that at a low natural gas price there is a significant spread in the payback, but as the natural gas price increases, the spread narrows considerably. This is the result of the overall process heat operating savings being composed of the natural gas savings plus the savings attributed to decreased need for pollution control and cooling tower water chemicals—and this cost is more than three times the electricity costs for running the heat pump. That is, with high natural gas costs, the influence of other factors associated with burning natural gas and producing steam has a stronger influence on the payback than the relatively small electricity costs for running the heat pump. When the natural gas price is high, the savings afforded by IHPs brings the payback to well under two years. However, at lower natural gas prices (e.g., $3 per MMBtus or $2.84 per gigajoule (GJ)), the electricity price will have a strong influence on the payback.

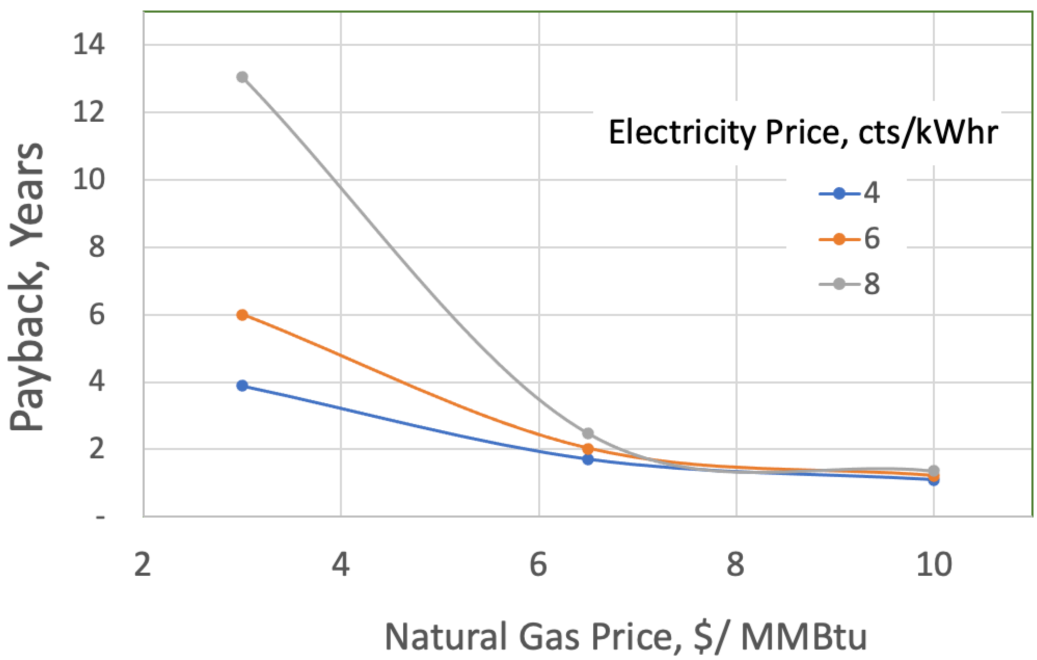


Figure 10. Simple payback for the potato drying application at various electricity prices for the MVC IHP with a capital cost of $250 per kW

The general trends of greater payback sensitivity to the electricity price when the natural gas price is low and relative insensitivity when the natural gas price is high are observed across the IHP types, as shown in figure 11. The paybacks for the compression type IHPs demonstrate payback from 1–8 years across the range of natural gas and electricity prices assumed in the analysis. However, the HA Type 1 has higher paybacks (e.g., >10 years) and requires higher natural gas prices to provide reasonable payback (e.g., less than 6 years). It should be noted that the capital costs assumed for the heat activated heat pumps were from

$1,000 to $1,875 per kW [this work]. However, because heat activated heat pump designs are generally at TRL 7 or lower we can anticipate that with additional RD&D these costs could decrease significantly over time (Scheihing 2021). Likewise, while not plotted on figure 11, note that the paybacks on investment for the technical potential case were under four years for the vapor compression heat pumps when natural gas prices were over $6.5 per MMBtus.

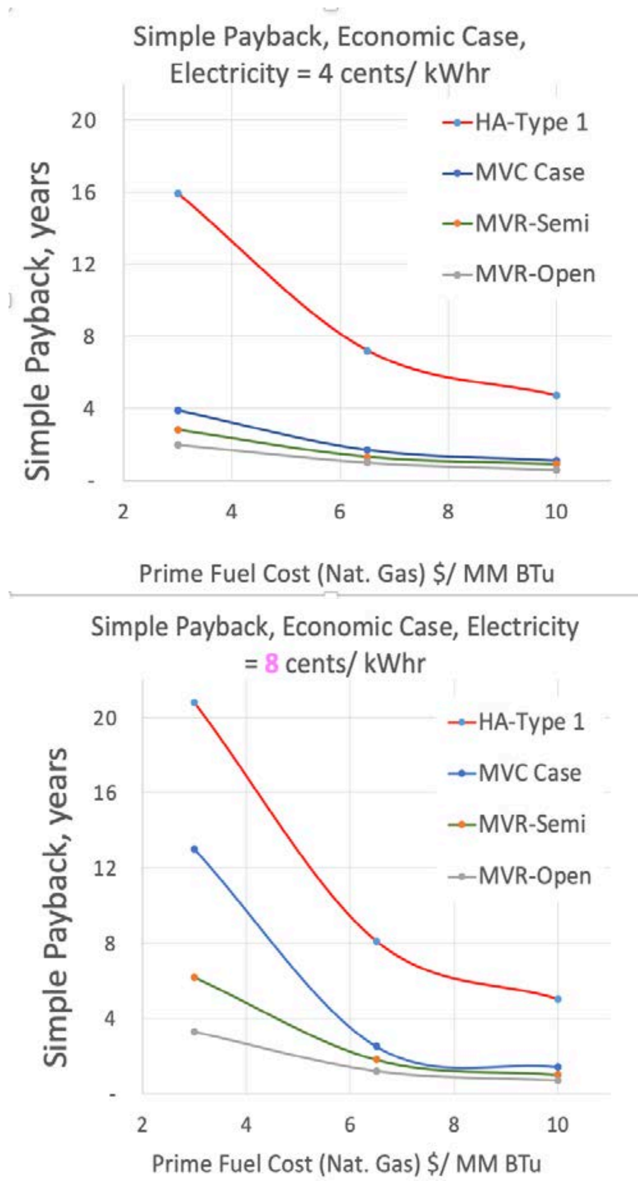


Figure 11. Payback versus natural gas cost for four IHP types at 4 (above) and 8 cents/kWh (below) electricity cost for the potato drying application, assuming capital costs from $250–1,000 per kW for a single facility

IHP SUMMARY ACROSS ALL INDUSTRIAL GROUPS AND UNIT OPERATIONS

Now we shift from describing the results for just the potato process unit operation to the results for IHPs across all industrial groups and unit operations studied (nine unit operations). Table 6 shows the results for all facilities in the nine unit operations for the MVC IHP case, with natural gas prices of $6.50/MMBtus and an electricity price of 6 cents/kWh. This could be considered an upper estimate at 100% market penetration. While this may be a high estimate it should be noted that dual heating and cooling IHP opportunities were not yet included and the benefits of downsizing the process heat load from current steam systems (e.g., oversized boilers, steam losses) were not accounted for.

Table 6. Summary of results across all unit operations for the economic and technical potential case and MVC IHP

		Technical Energy Savings Potential Case						
		Natural Gas Savings	Natural Gas Savings	Electricity Increase	Electricity Increase	Carbon Reduction	Carbon Reduction	Simple Payback
Sector	**Unit Operation**	Tbtu/yr	%	MM kWh/yr	%	MMTCe/yr	%	Years
Food	Potato Drying	15	40.4	962.0	11.2	0.4	24.3	4.5
	Wet Corn Milling(WCM) Steepwater	2	20.4	128.0	5.5	0.1	1.2	3.7
	WCM, High Fructose Corn Syrup	3	75.8	173.0	17.9	0.1	1.9	4.4
Paper	Kraft Mill Digester	38	34.6	2,384.0	9.2	1.0	21.7	4.2
	Kraft Mill Multi Effect Evaporator	86	45.1	4,169.0	9.4	2.6	34.5	3.8
	Non-Integrated Mill Pulper	3	9.3	197.0	2.5	0.1	5.7	2.5
Chemicals	Ethylene Debutanizer	5	18.4	6.0	3.4	0.2	15.1	1.9
	Ethylene Process Water Strip Reboiler	1	9.8	66.0	2.2	0.0	7.0	2.2
	Ethanol Fuel, Ethyl Alcohol, Dry Mill	247	90.0	10,313.0	16.0	8.2	52.0	1.9
Total		400		18,398.0		12.6		

Note: % Electricity Increase is related to Initial Natrual Gas Demand

The total source energy savings across all industrial groups and unit operations are shown in figure 12. This plot shows that the total source energy savings is significantly higher for the technical potential cases than expected, given the assumption of more extensive application of IHPs. Although lower energy savings are shown for the HA types, it is expected that greater use of waste heat in the future will be enabled by heat activated heat pumps since they can lift heat over higher temperatures without penalty of high electricity operational costs. Heat activated systems could also prove to be more flexible in operating over wide turndown ratios within processes and thus increase the energy savings potential as they are further developed and deployed. The MVR Semi and MVR Open IHPs each show higher energy savings improvement over the MVC heat pump, reflecting the fact that not requiring one (semi-open) or two (open) heat exchangers to capture waste heat vapors yields higher heat pump COPs; for example, high pump lift temperatures are lower than for the MVC type. The elimination of heat exchange translates into overall source energy savings.

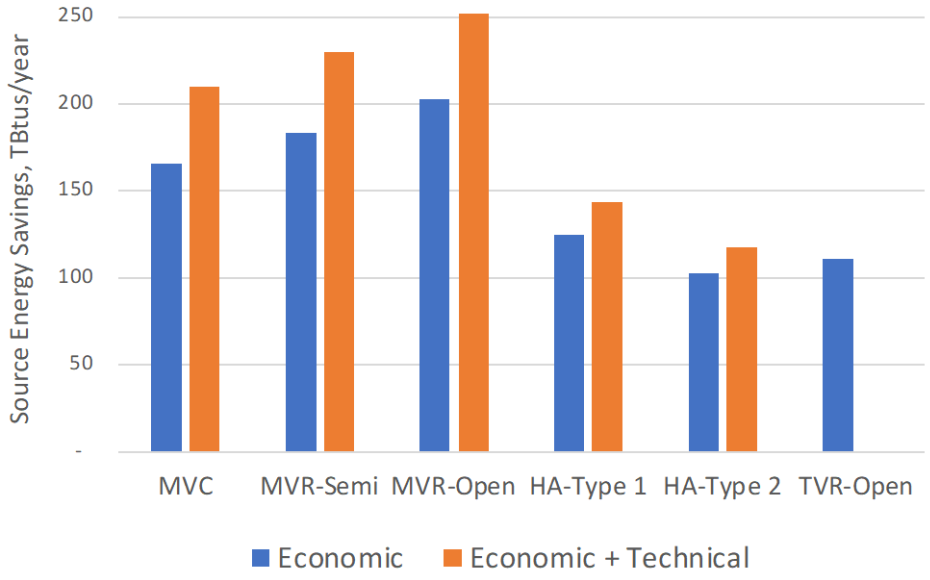


Figure 12. Summary of source energy savings for all nine unit operations combined for the "economic" and "economic + technical"

While the IHPs save natural gas, electricity is required to run the compressors for the MVC, MVR Semi, and MVR Open heat pumps. The heat activated heat pumps (HA Type 1 and HA Type 2) do require less electricity than the MVC, MVR Semi, and MVR Open heat pumps, but their COPs are lower and thus the thermal energy (natural gas) is lower. Figure 13 shows the magnitude of the energy changes for natural gas and electricity usage for all nine industrial groups analyzed. Here the increased electric load is shown to the right of the *y*-axis, and the natural gas decrease is shown to the left. Looking at the MVC, MVR Semi, and MVR Open types, the natural gas savings are similar, but the electricity decreases in this order. For the MVC (closed cycle), electricity is used to compress refrigerant vapors, and there are heat exchangers at both the source and sink so the heat pump lift will be higher, requiring additional electrical energy. The MVR Semi eliminates one heat exchanger and the MVR Open eliminates two heat exchangers, so the lift is lower resulting in somewhat lower electricity needs. The HA types require much lower amounts of electricity since they pump liquids and do not compress vapors, but as mentioned, their lower heating COP, compared to vapor compression heat pumps, yields a lower net energy savings.

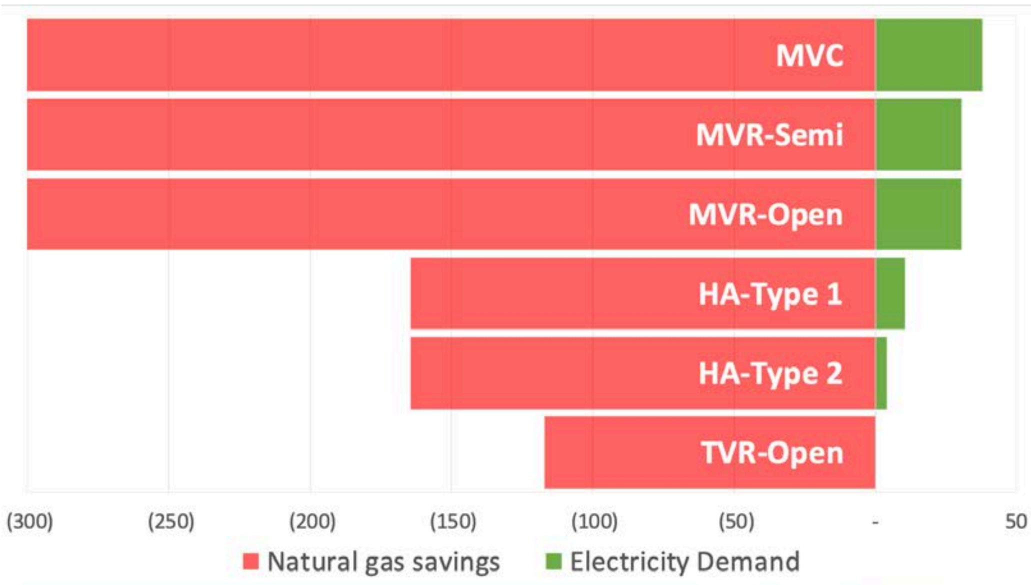


Figure 13. Energy changes across all nine unit operations, economic case, TBtus/year

Figure 14 shows the changes from a carbon perspective, where it is evident that the increase in carbon emissions from electricity (right, green) is significantly less than the reduction in carbon emissions from the decrease in natural gas use (left). Hence, there is an overall net decrease in CO_2e emissions. As the grid incorporates more low-carbon energy and the emissions factors decrease, the carbon emissions footprint for electricity will decrease, so the difference between the electricity and natural gas bars will become larger for the other types as well.

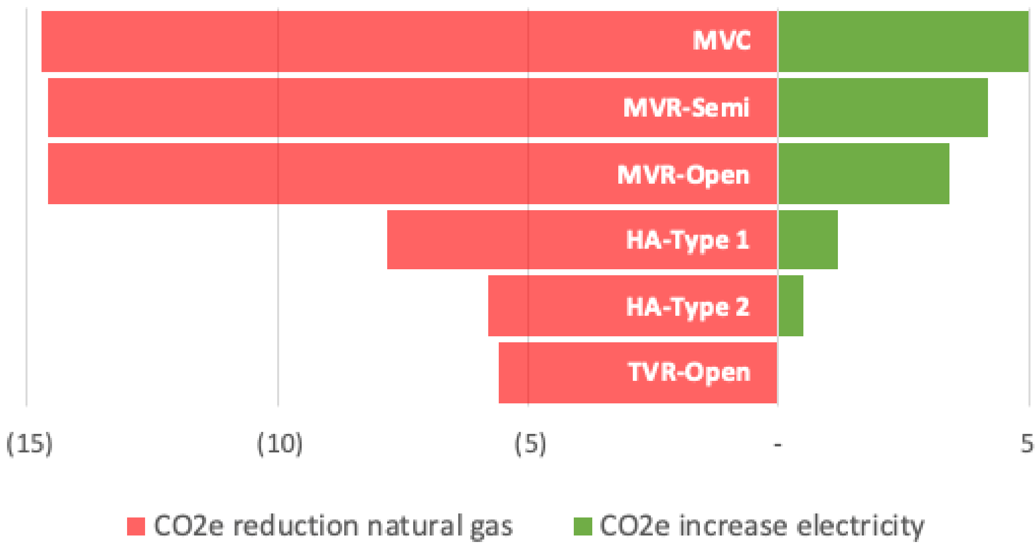


Figure 14. Changes in CO_2e emissions for the IHP types across all unit operations, economic case, in millions of metric tons CO_2e/year

As the grid adds more low-carbon generation, the carbon emissions factors for the grid will decrease (see Appendix C), and the CO_2 reductions delivered by IHPs will increase (as the electricity to run the compressors will have a lower carbon intensity), as shown in figure 15. For simplicity, we assumed a static fuel mix and process heating demand to show that the impact of CO_2 reductions would grow as the electric grid becomes decarbonized. It is possible that the amount of waste heat demand could diminish over time due to structural changes in manufacturing, further process heat integration, and process technology innovations.

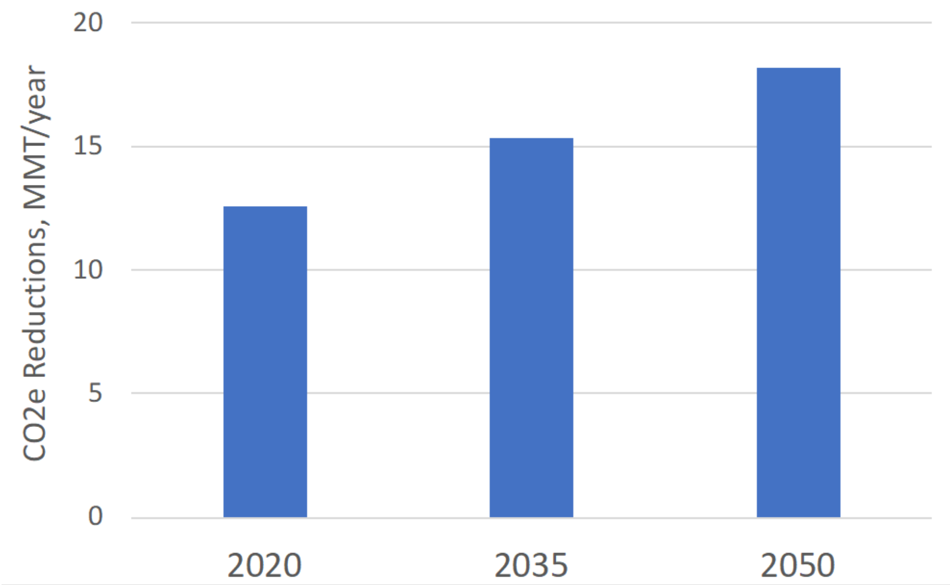


Figure 15. CO_2e reductions across all unit operations for economic + technical potential (paper pulper, ethyl alcohol, ethylene debutanizer, and ethylene process water stripper reboiler contributes at economic potential only; see text). Estimates for 2035 and 2050 use carbon emissions factors for electricity that are reduced due to more low-carbon generation.

For 2020 the amount of CO_2e reduction potential for the unit operations studied ranges from 9.7–12.6 MMT CO_2e /year, which is equivalent to the emissions from 2.1–2.8 million cars/year or the emissions associated with generating power to serve 1.1–1.5 million homes for a year (EPA 2021). With lower emissions factors for grid-produced electricity expected by 2050, the reduction potential would be 13.4–18.2 MMT CO_2e/year.

Contributions for the paper pulper, ethylene (debutanizer and process water stripper reboiler), and ethyl alcohol/ethanol fuel operations added only their economic potential carbon reductions to the total across the nine unit operations; the technical potential case for these unit operations was not possible as the process heat data available were not of sufficient quality and reflective of current processes to provide a credible estimate. Also, a more sophisticated and higher-fidelity level of the pinch analysis tool would be needed to provide a plausible estimate. Further details for the chemicals unit operations are in Appendix F.

The Technology Fit for Applications

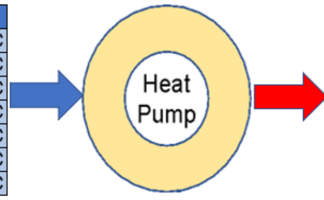
The application of IHPs to upgrade process heat are one of several significant solutions to systematically optimize industrial processes in order to drive them closer to their practical minimum energy performance, and thus, to reduce energy consumption and carbon emissions. At a deeper applications level there are several insights for areas where IHPs could do particularly well in reducing energy and carbon emissions and aiding the transition to low-carbon electricity in industry. The application of IHPs to upgrade process heat can be considered as part of a holistic approach to reducing energy use and carbon emissions. It can be complimentary to a systems efficiency drive that addresses cross-cutting and process-specific opportunities. Studies on energy efficiency opportunities in specific industrial groups are part of that context, for example, studies in pulp and paper (Kramer, Masanet, and Worrell 2008). IHPs could have complementary benefits in the following areas, considering the insights of this work.

Types and fit with applications. The MVC and MVR IHPs would do well in IHP applications below 40 K lift, especially with condensing and evaporating streams for heat sources and sinks. This is because the electricity requirements increase substantially above 40 K lift temperature and the payback on investment becomes much greater than three years. TVRs work best with lift temperature less than 20ºC and for steam only applications. The TVR's lower capital cost and lack of moving parts makes it attractive and durable. Further discussion on the applicability of TVRs can be found in Appendix D.

The HA Types 1 and 2 will be more competitive with the electric-driven vapor compression heat pumps for lift temperatures between 40 K and 80 K. While the heat activated heat pumps currently are estimated to have capital costs two to three times higher than vapor compression heat pumps, they show great potential, can lift heat efficiently up to 100ºC, and should be more able to adjust to changing process conditions without performance degradation. As mentioned previously, because heat activated heat pump designs are generally less mature, we could expect further RD&D to significantly reduce these costs. Additional discussion on the heat activated IHPs can be found in Appendix E.

The food and beverage, chemicals, pulp and paper, and refining industrial groups could be early candidates for applications, as noted in figure 16. These industrial groups have relatively high levels of low-medium grade process heat (< 200ºC, see figure 2), which would be suitable for current and emerging IHP use. Although heat integration and pinch analysis is common for world class chemicals facilities, additional optimization is of interest as the product mix, technology, and new drivers evolve (e.g., carbon emissions constraints). Also, it should be noted that the use of heat integration and pinch analysis is less prevalent for small- and medium-sized manufacturers and light industry (e.g., food and beverage, metal casting, and others). A compilation of current applications for IHPs finds a number of examples of IHPs already being used in these industrial groups around the globe.[5] COPs above 3 are common in these applications and multiple case studies are available (New Zealand EECA 2019).

Sector	Process	Typical Range
Brewing	Hot water, process cooling	5-60° C
Dairy	Hot water, process cooling	5-60° C
Paper	Waste water	30-100° C
Brick	Exhaust air, waste heat	50-90° C
Starch	Exhaust air	50-90° C
Chemical	Waste heat, process cooling	60-120° C
Sugar	Waste heat	60-120° C



Sector	Process	Typical Range
Brewing	Hot water or saturated streams	60-120° C
Dairy	Hot water or saturated streams	80-150° C
Paper	Preheating	80-160° C
Brick	Hot air	100-140° C
Starch	Hot air	140-160° C
Chemical	Hot water or saturated streams	80-159° C
Sugar	Hot water or saturated streams	80-160° C

Figure 16. Illustration of potential IHP applications from lower (blue) to higher (orange) temperatures. Source: DryFiciency 2021 chart and data augmented in this work.

Regionality. The payback estimates shown earlier for potato drying (figure 10, table 6) show that for the MVC and MVR IHPs with natural gas at $6.5/MMBtus and electricity at 4–8 cents/kWh, the paybacks range from two to four years, which will be worthy of discussion at industrial companies. This is a ratio of about 1.8–3.6 for electricity/natural gas price on an equivalent MMBtus basis. There are already a number of states where the ratio of electricity/natural gas is currently below that number, as shown in figure 17. In these states there could be early IHP adoption opportunities, especially in the food industry where the capital costs, integration, and complexity are relatively low. Locally the ratio will also vary as different providers can have different electricity prices, and large industrial companies may have negotiated rates lower than the state average. Volatility in energy prices may change the map shown in figure 17, based on 2020 data, so local updated information should be considered as policy approaches are developed.

[5] J. Leak, Australian Alliance for Energy Productivity, pers. comm., October 2021.

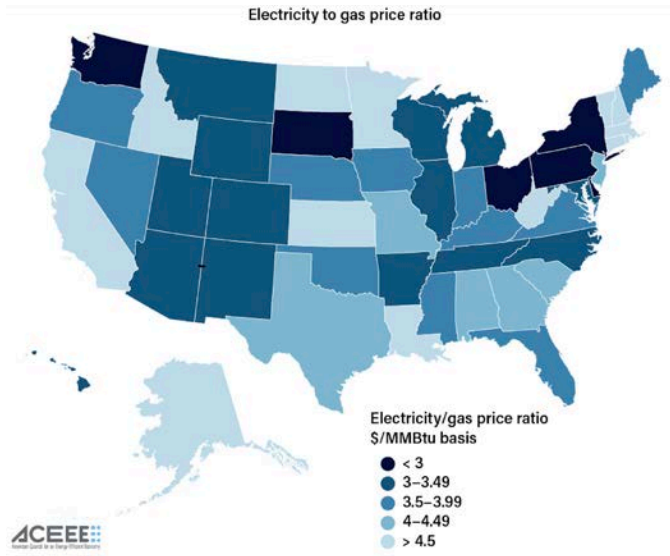


Figure 17. Illustration of electricity/gas price ratio by state

ECONOMIC GAP

Figure 18 shows the influence of the electric/natural gas price ratio on payback for the paper digester example with the three mechanical vapor compression type IHPs. The payback results are influenced by having two heat exchangers (MVC, closed cycle), one heat exchanger (MVR, semi-open cycle), and no heat exchangers (MVR, open cycle). The use of heat exchange influences the heat pump lift temperature, heat pump COP, electricity consumption, and capital cost. The electricity/gas price ratio can lead to an economic gap that needs to be closed for IHPs, particularly in states where the ratio is high. For example, with the paper digester unit operation, when the electric/gas price ratio is greater than 4 and the natural gas price = $3/MMBtus, the simple payback will be more than two years for the MVR IHPs, except for MVR open cycle, as shown in figure 18.

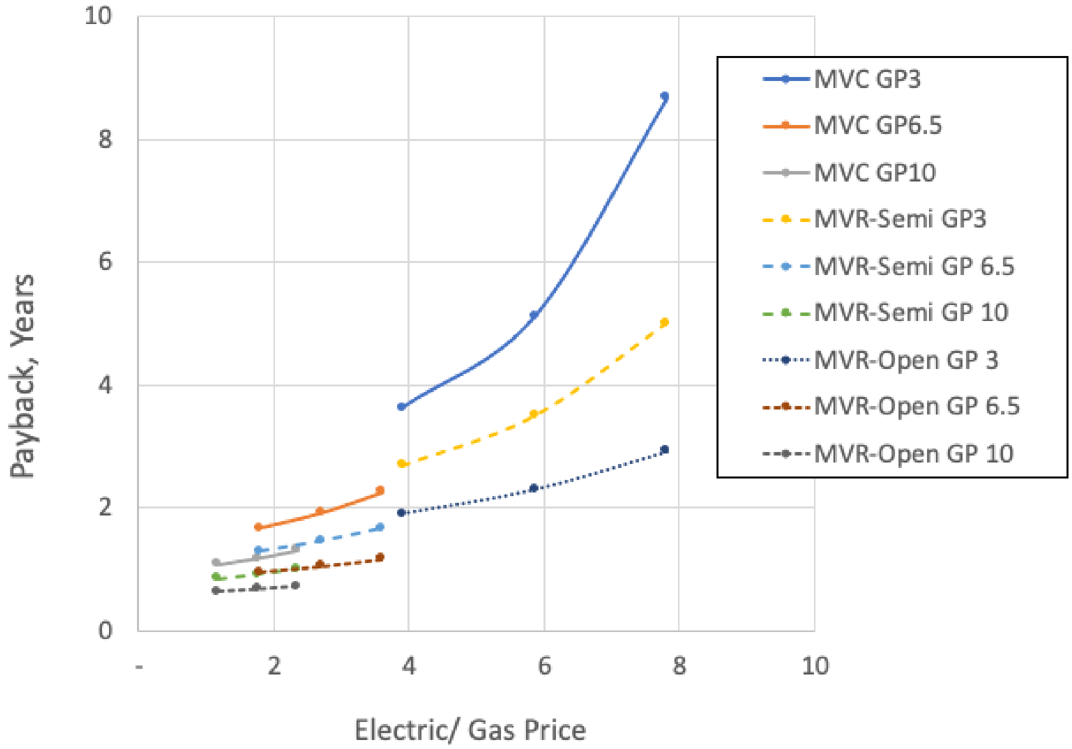


Figure 18. Payback as a function of electric/gas price for the paper digester, economic case

Examining this economic gap further when the natural gas price = $3/MMBtus shows that to reach the payback target of two years the capital for the IHP would have to be reduced 22% for the MVR, open and 40–67% for the MVC IHP, as shown in figure 19.

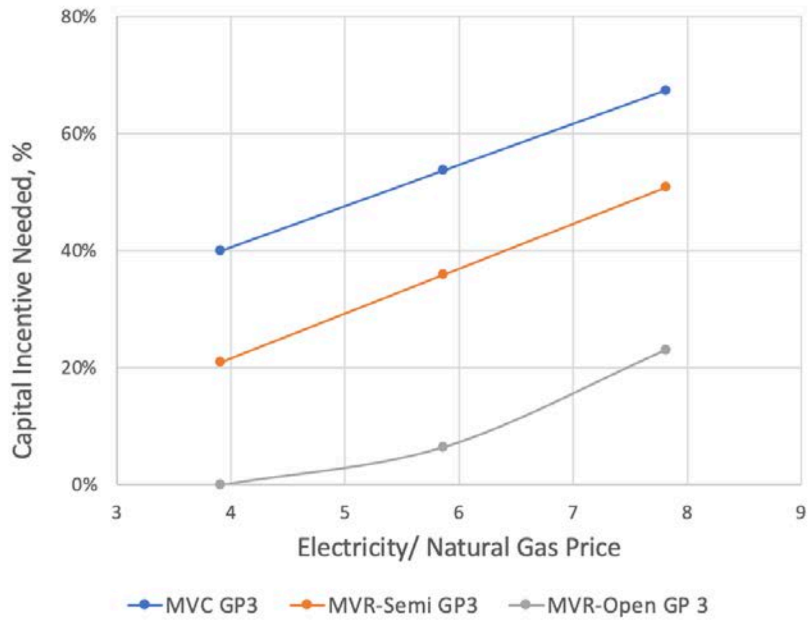


Figure 19. Capital adjustment needed to reach a two-year payback for the paper digester

SCALE OF IMPACT

There can be multiple unit operations for each process considered in this work, so it can be challenging to understand the scale of impact. For example, the ethylene debutanizer and the process water stripper reboiler were examined for IHP potential, but these operations are a small portion of those in ethylene production, and only the unit operations above ambient were considered in this work (e.g., no analysis was performed in the cold section). In figure 20, a high-level perspective is given of the total industrial energy consumption with the three industrial groups examined in this report (left; chemicals, food, paper), and an expansion of those industrial groups' total energy use (right). The industrial groups where unit operations were analyzed are pulled out on the right (paperboard mills, pulp mills, fruit and vegetables, and ethyl alcohol).

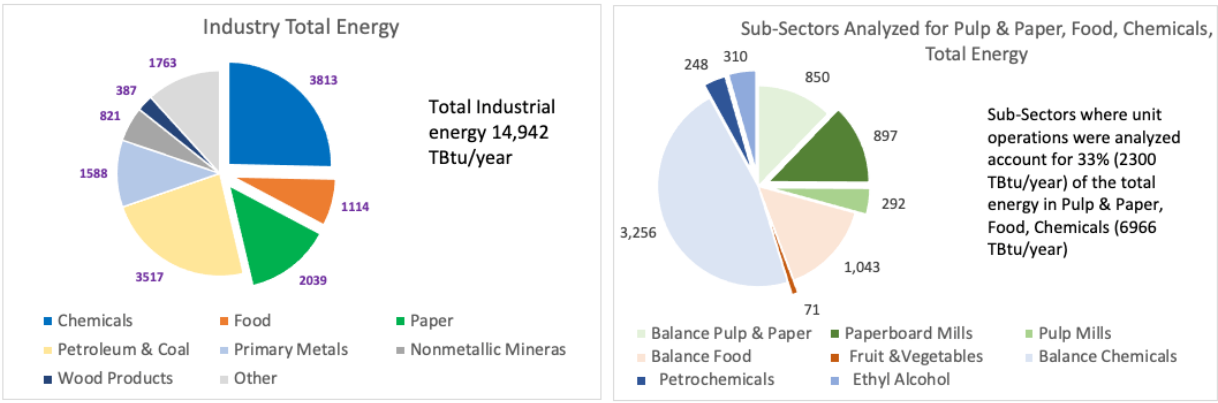


Figure 20. Energy use across all of industry (left; industrial groups examined in this work are in expanded slices), and proportion of in process heat energy for industrial groups examined in this work (right)

The potential for IHPs to save energy and reduce emissions in these industrial groups (separated in figure 20) is examined further for each industrial group below.

IHP Impact in Food

In the food industrial group, three unit operations were analyzed (wet corn milling, corn steeping; wet corn milling, high fructose corn syrup; and potato drying) that account for approximately 10% of the industrial group's process heating demand, as shown in figure 21. For the MVC heat pump energy savings estimates, these three unit operations are projected to save between 11.3% (economic potential) and 39.6% (technical potential) of the process heating demand, if fully implemented in all facilities with these unit operations. Across all 78 facilities, IHPs could supply an estimated 535 MW of process heat through heat pumping. As noted earlier this would be considered a conservative, upper bound.

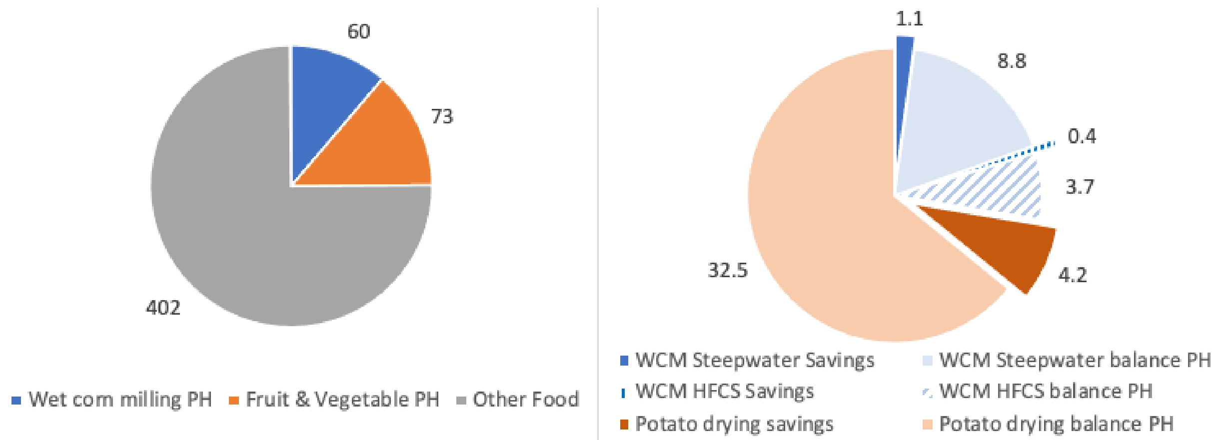


Figure 21. Food industrial group process heat energy (PH) by industrial group (left), and unit operations analyzed within those groups (right) with the IHP process heat savings (slices pulled out) and PH balance for the three unit operations analyzed within the food industry. Units are in TBtus/year.

Within these 78 facilities, under the technical scenario, natural gas savings are estimated at 20.0 TBtus/year with an IHP electricity requirement (increase) of 1,263 million kWh/year and 7.1 TBtus/year (4.8%) source energy savings, in aggregate. Carbon savings are estimated to be 0.5 MMTCe/year using the current U.S. average carbon intensity for electric power generation but could be 0.9 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings are possible for the other 90% of the food industrial group's process heating demand, with the industrial group's widespread evaporation and drying unit operations. We estimated 400 TBtus/year of process heating energy demand could be targeted by IHP applications within the food industrial group (the remaining process heating demand was not analyzed). If IHP implementation resulted, conservatively, in energy savings of one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed (about 5% savings), this would amount to an additional 19 TBtus/year of source energy savings, making the overall energy savings potential for the food industrial group 26 TBtus/year. Carbon savings are estimated at 1.8 MMTCe/year using current carbon intensity for U.S. power plants but could be 3.1 MMTCe/year by 2050.

Extrapolated Paper Industrial Group IHP Energy-Saving Results

In the paper industrial group, three unit operations were analyzed (digester and multi-effect evaporator in Kraft paper mills, and the pulper in non-integrated paper mills) that account for approximately 43% of the industrial group's process heating demand. For the MVC heat pump energy savings estimates, these three unit operations are estimated to save between 10.3% (economic potential) and 41.3 % (technical potential) of the process heating demand, if fully implemented in all facilities with these unit operations. Across all the estimated 338 facilities, IHPs could save 127 TBtus/yr. natural gas through 338 facilities with an estimated cumulative 3,402 MW of heat pumping capacity (technical potential).

Within these 338 facilities, under the technical potential case, natural gas savings are estimated at 127 TBtus/year with an IHP electricity requirement (increase) of 6,750 million kWh/year and 58 TBtus/year (16.4%) source energy savings, in aggregate. Carbon savings are estimated to be 3.7 MMTCe/years using the current U.S. average carbon intensity of electric power generation but could be 5.7 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings for the other 57% of the paper Industrial group's process heating demand are possible with the industrial group's widespread evaporation and drying unit operations. We estimated that 455 TBtus/year of process heating energy demand could be targeted by IHP application within the paper industrial group. If IHP implementation resulted, conservatively, in one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed (about 6% savings), this would amount to an additional 25 TBtus/year source energy savings, making the overall energy savings potential for the paper industrial group 83 TBtus/year. Carbon savings are estimated at 5.2 MMTCe/year using current carbon intensity for U.S. electric power generation but could be 8.0 MMTCe/year by 2050.

Extrapolated Chemicals Industrial Group IHP Energy-Saving Results

In the chemicals industrial group, three unit operations were analyzed (ethylene debutanizer, process water stripper reboiler, and ethanol dry mill distillation of ethanol-water mixture) that account for approximately 16.2% of the industrial group's process heating demand. Ethanol (fuel) makes up a large portion of that contribution. Although ethylene is also a large energy-consuming process, the two unit operations selected are just a small portion of the overall energy use. For the MVC heat pump energy savings estimates, these three unit operations are projected to save 80% of the process heating demand if fully implemented in all facilities with these unit operations; the heat pump applied to the ethanol distillation to remove water from ethanol saved 90% in process heat. Across all 256 facilities, IHPs could supply an estimated 6,773 MW of process heat through heat pumping.

Within these 256 facilities, under the technical potential case, natural gas savings are estimated at 253 TBtus/year with an IHP electricity requirement (increase) of 10,595 million kWh/year and 145 TBtus/year (26.7%) source energy savings, in aggregate. Carbon savings are estimated to be 8.4 MMTCe/year using the U.S. average carbon intensity of electric power generation but could be 11.6 MMTCe/year by 2050 with the projected electric grid providing 75% lower carbon intensity.

Additional IHP savings are possible for the other 84% of the chemicals industrial group's process heating demand, with the industrial group's widespread distillation, evaporation, and drying unit operations. We estimated 1,624 TBtus/year of process heating energy demand could be targeted by IHP application within the chemicals industrial group. If IHP implementation resulted conservatively in one-third of the technical potential percentage savings from IHPs of the three unit operations analyzed this would amount to an additional 273 TBtus/year of source energy savings, making the overall energy savings potential 418 TBtus/year (about 20% process heat savings). Carbon savings are estimated at 23.5 MMTCe/year using the current carbon intensity for U.S. electric power generation but could be 30.5 MMTCe/year by 2050.

Table 7 summarizes the results for the nine unit operations analyzed in the three industrial groups, as well as the overall Industrial group extrapolated for natural gas, source energy savings, electricity demand increase, and carbon reduction near and long term.

Table 7. Energy savings and carbon reduction industrial heat pump estimates

Unit Operations analyzed only	Food, min.	Food, max.	Paper, min.	Paper, maxi.	Chemicals	Total, min.	Total, max.
Natural gas savings, TBtu/yr	5.7	20.0	34.4	127.1	253.1	293.2	400.0
Source energy savings, Tbtu/yr	2.8	7.1	19.1	58.0	144.6	166.4	210.0
Electricity consumption, MM kWh/yr	288.0	1,263.2	1,500.0	6,750.3	10,595.4	12,383.3	18,609.0
Electricity demand increase, MW	32.9	144.2	171.2	770.6	1,209.5	1,413.6	2,124.0
Heat pump output, MW	152.6	535.3	921.9	3,402.8	6,773.1	7,847.6	10,711.0
Carbon savings, near term carbon intensity, MTCe/yr	0.2	0.5	1.1	3.7	8.4	9.7	12.6
Carbon savings, long term carbon intensity, MTCe/yr	0.3	0.9	1.6	5.7	11.6	13.4	18.2
Sector-wide projection							
Natural gas savings, TBtu/yr	20.0	72.0	48.0	179.0	684.0	752.0	935.0
Source energy savings, Tbtu/yr	9.7	25.4	26.6	81.7	390.8	426.9	490.9
Electricity consumption, MM kWh/yr	1,010.5	4,547.8	2,090.3	9,504.1	28,639.2	31,761.0	43,498.5
Electricity demand increase, MW	115.3	519.2	238.6	1,084.9	3,269.3	3,625.7	4,964.9
Heat pump output, MW	535.3	1,927.1	1,284.7	4,791.0	18,307.7	20,127.7	25,037.0
Carbon savings, near term carbon intensity, MTCe/yr	0.7	1.8	1.5	5.2	22.7	24.9	29.5
Carbon savings, long term carbon intensity, MTCe/yr	1.1	3.2	2.2	8.0	31.4	34.4	42.5

Research, Development, and Deployment (RD&D) Needs

Our work and that of others (A2EP, Sintef, DryFiciency, and IEA Annex 58) applying IHPs to industrial applications highlights several areas for additional RD&D to advance deployment, application scale, and dispersion including the following.

IHP DEMONSTRATIONS

A variety of IHP technologies need to be demonstrated in various industrial groups and process applications, along with the engagement of industrial, service, and engineering companies so they can partner on lowering adoption hurdles and gain insights into energy/carbon/nonenergy benefits. These demonstrations would benefit from third-party (DOE and National Labs) verification and communication of the cost and benefits. Standardized IHP designs that are integrated into common applications (e.g., food evaporation, drying) and supplement utility steam supply need widespread demonstration. Demonstration would also benefit from common field test procedures and performance measurement approaches to calculate and report key parameters (COP, lift) and document and communicate key parameters consistently and transparently.

IHP equipment supplier market development would benefit from more standardized base IHP componentry, modularization, and base case installation design and parameters, which could help deliver relatively low-cost IHPs for the market segment below 10 MW heat delivery. More importantly, the IHP supplier base within the United States is extremely limited: A summary of global IHP suppliers did not show one U.S. supplier (Arpagaus 2021). Accordingly, activities in the United States to cultivate IHP equipment suppliers and service providers are needed. Australia has been successful in attracting IHP equipment suppliers through a robust IHP promotion, demonstration, and deployment collaboration,[6] and the United States should follow similar strategies.

IHP RANGE OF APPLICABILITY

To increase IHP energy savings and carbon reduction potential, IHP technology must be able to deliver heat at higher temperature (e.g., to 200°C) and lift heat without large capital cost (e.g., lift heat at 80°C at a cost of at most $900/kW heat delivered (Scheihing 2021)) for the advanced heat pumps to achieve a payback of five years or less (natural gas price = $5/MMBtus). A variety of R&D areas would enable these objectives:

- New vapor compression working fluids that can operate up to 200°C (heat sink temperature) with minimal environmental impact (GWP < 10)

[6] J. Leak, Australian Alliance for Energy Productivity, pers. comm., October 2021.

- New innovative and optimized hybrid/compression: heat activated cycles to allow flexibility for varying source/sink/lift temperatures.

Any advanced IHP design must offer flexibility in retrofit versus new installation since industry operations can change over time. IHPs must be available in a variety of sizes, such as a small size < 100 kW for dedicated end use; a medium size at 500–2,000 kW for unit operations; and a large size at > 2,000 kW for utility steam heat delivery for entire processes and facility operations, for example, replacing or supplementing existing boiler house steam system. IHP designs that are modular would offer more flexibility in adaptation to industrial processes.

IHP ECONOMICS AND DECARBONIZATION POTENTIAL

As mentioned, IHP technology adoption will be determined by several considerations, including the electric/natural gas price ratio, which influences the payback. Likewise, IHPs will need to compete with other process heating decarbonization technology choices, such as electric boilers, renewable fuels for boilers, combined heat and power, and solar thermal. IHP R&D must address lower capital cost without operational cost penalties (lower COP) to be competitive. Several other considerations need to be addressed, including the R&D areas noted below:

IHP Economics

- New IHP construction materials to enable lower IHP capital cost, especially in heat activated heat pump systems that cost < $900 per kW.
- New IHP designs that are system-integrated with advanced energy efficiency, initiatives and technologies (whole system optimization and control, CHP, waste heat, solar thermal, ground source)
- IHP designs for industrial parks and district heating/cooling: IHP heat and cooling/refrigeration co-sharing between neighboring facilities (industrial, commercial, and residential).

Economic performance could be extended to IHP carbon reduction potential in areas such as:

- Renewable heat and power supply integration: integrate IHPs with renewable energy generation technology, hot and cold energy storage, and dynamic load response/control.
- IHP application in conjunction with power generation and storage (electrical, thermal, chemical, and mechanical) technologies such as renewable hydrogen generation, gas-to-liquids, carbon capture, and storage.
- Further optimization and use of low GWP refrigerants.

IHP KNOWLEDGE, TOOLS, AND CAPACITY BUILDING

Advanced IHP equipment designs, development of knowledge, information, and tools would assist in IHP scale and deployment including:

- State-of-the-art process-specific data in the industrial groups with significant IHP opportunity, including, chemicals, paper, food processing, and petroleum refining. Pinch analysis or other process integration methods to assess IHP fit needs should be further developed in cooperation with industry to create more accurate process data representative of current process technology.
- Workforce development: Basic informational technical material and training as appropriate to introduce mechanical and process engineers to the fundamental principles of IHPs would be valuable. Also, more advanced skills are needed, such as pinch analysis, process integration, and maintaining and optimizing IHPs. Industrial group-based, expert-level IHP training targeting process and utility engineers would educate key personnel responsible for modifying processes to save energy and decarbonize facilities.
- New software tools for IHP implementation would help energy engineers to assess IHP opportunities. Some pinch analysis tools are already available such as the IChemE (UK) and PinCH 3.2 (Lucerne University 2022) tools.
- Energy assessments to examine unit operation and plant-level IHP opportunities.
- University-based "Centers of Excellence for IHP Technology & Applications" would build knowledge and experience. European and Japanese IHP expertise is deep, and the United States could benefit from building similar technical expertise.

COMPLEMENTARY CHALLENGES

IHPs face adoption challenges like those experienced by other electrification and emergent or transformative technologies. Additional study is needed to address these obstacles, which include:

- IHPs can replace a large component in an industrial process but sometimes not the whole system (e.g., meeting needs that were supplied by part of a steam system but not all of it). There is a need to understand how IHPs interface with whole system capacity and ways to increase the proportion of service provided.
- Research abroad has found that getting users involved in IHP deployment, integration, and optimization is essential and that how IHPs are used can influence the type of users (Martiskainen, Schot, and Sovacool 2021). This work also notes that in addition to providing incentives, policy should aim to mobilize users.
- Integration with systems upstream and downstream and the interface with lifetimes of equipment, economics, and reliability are needed.
- Integration research is also needed for hybrid systems such as IHP/solar thermal and IHP/thermal energy storage.

- R&D could aim to reduce mean time between failure to increase IHP reliability. R&D could provide a better balance of the use of novel technology and of time-tested and proven equipment, materials, and controls. This would help reduce IHP equipment downtime by supporting the industry with ease of repair and a widely available contractor base.

Policy and Program Opportunities

IHPs face challenges that must be overcome to accelerate adoption, despite their benefits and the increasing strength of the drivers of their acceptance. These include categories illustrated in figure 22 and described further below.

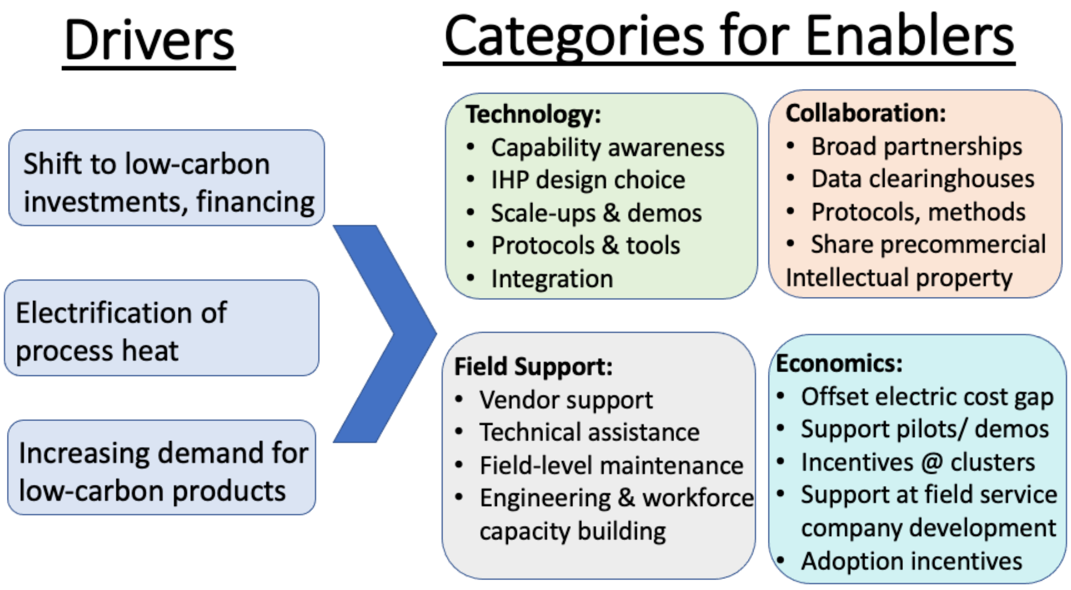


Figure 22. Enablers for IHP adoption

ECONOMICS

This work shows that IHPs can have simple paybacks within the range of acceptability for industry when the natural gas price is high. However, as IHPs, especially those with higher temperature capabilities, are not widely used in the United States and industrial companies face uncertainties on capital, integration, and maintenance costs, economics will be a significant hurdle to adoption.

Policy can be a key enabler to address the electricity/natural gas price ratio. Multiple approaches could be considered to close the cost gap, including a cost of differences approach (CfD). This approach has been successful in addressing the higher starting cost of low-carbon technologies in the United Kingdom and Canada (Sartor 2019). Another approach would be incentives for utilities in the form of favorable electricity rates for beneficial electrification, where industry transitions from fossil fuels to low-carbon sources utilizing IHPs and other electric technologies. Incentives could also be considered for the places in the value chain that will be vital for success (e.g., adopters, vendors, third-party installers, and engineering and service companies).

Support for pilots and demonstrations at larger scale for IHPs can also play a role in lowering economic hurdles, as new knowledge will improve implementation and operational efficiency and identify value-returning nonenergy benefits.

TECHNICAL

There needs to be increased awareness for industrial decision makers and plant engineers to understand that the capabilities of IHPs have advanced significantly in the last decade. Advances in understanding the choices for IHP type, working fluid (including choice of low GWP refrigerants), location of heat exchangers, and integration and control aspects are needed, as well as developments to accelerate electrification using increasing levels of low-carbon electricity while mitigating the variable aspects to delivering reliable electricity with quality that is similar to or better than that of baseload power.

Programmatic support and engagement with pilots and demonstrations at larger scale are key to address technical uncertainties and to minimize deployment risk. Agencies such as DOE and AMO can play a role helping with development of methods/protocols/evaluation tools, supporting the pilots, providing expertise to address scale-up and integration issues, providing test facilities at national labs, and facilitating partnerships across engineering, vendor, service, and industrial companies. Industrial clusters are a key opportunity for advancing IHPs as the market becomes concentrated: successes will be highly visible, and integration benefits can be leveraged across multiple players. As programs develop project portfolios for clusters or hubs, IHPs could be a key solution that addresses multiple objectives.

PRODUCT AVAILABILITY

Currently the domestic supply of IHPs is quite limited. In the United States, Nyle Corporation sells IHPs for modest food dehydration and water heating applications with capabilities up to 72°C. Johnson Controls provides a range of IHP products in Europe, but they would need to be custom built in U.S. facilities. However, the upper temperature limit, heat pump thermal output (kW - MW), compressor and refrigerant capabilities, and flexibility of these domestic IHPs are limited. For example, commercial IHPs above 300–400 kW and with capabilities above 80°C are not available from U.S. vendors. Conversely, there are a wide range of IHP types and capabilities available from vendors in Japan and Europe with upper temperature limits to 160°C, several MW, and a wide range of compressor and refrigerant choices (Arpagaus 2021). To develop a domestic market for IHPs and suppliers we should encourage global suppliers to support pilots and large-scale demonstrations in the United States. Encouraging suppliers to be aware of these U.S. pilots and to participate in efforts to lower hurdles is a path towards establishment of domestic supply, and preferably manufacturing capabilities for IHP equipment and service support. Policy support for the pilots, demonstrations, and early adoption would significantly help to accelerate progress.

FIELD SUPPORT

Field-level support is needed so a cadre of organizations can help with these activities and foster development of capabilities and expertise that support the ongoing maintenance and optimization of equipment. Pilots and demonstrations can be a starting point providing clarity on needs, but from history with earlier IHPs and recent experience accelerating adoption of IHPs in Australia, Europe, and New Zealand, it is clear that a domestic capability for field-level support needs to be developed. The drivers for establishing domestic chain capabilities include the need for local service of IHPs (reliability is crucial), trained and experienced process engineers to work directly with end-users on integration and optimization questions, and expertise to design new process implementations.

This is a prime area for workforce development and training. National labs and agencies could help provide training curricula. Engagement with the pilots and demonstrations is a good starting point to develop expertise, but a strategy for capability development is needed that could support field level installation, maintenance, and further optimization.

COLLABORATION

Collaborations across industry partners, academics, national labs, and government agencies can be key to the success of demonstrations at scale for emerging and transformative technology. Data and learnings from those demonstrations need to be visible for the end-user community to readily adopt IHPs, which is where data clearinghouses can help, along with the development of standard design and field-testing methods, protocols, and metrics. The development of commonly recognized protocols and methods (e.g., for evaluation of COP) would be very helpful to lower communications barriers.

Recommendations

Field-level studies are a key next step to spur an IHP user community, accelerate learning, lower barriers, and scope additional applications. Key recommendations include the following.

INDUSTRY

- Probe the application aspects of this work and engage in conversations during field demonstrations and/or pilots with IHP vendors and local engineering service firms.
- Discuss with international vendors prospects for IHP applications in the United States to stir the market and probe integration issues.
- Consider which potential IHP applications would provide the greatest benefits/costs.

UTILITIES

- Discuss with industrial customers and local engineering service firms where IHPs could provide benefits.
- Probe the demand response attributes of IHPs.

- Engage with partners to support pilots and/or demos, potentially at industrial clusters where there are shared learning opportunities.
- Work with industry and policymakers to describe what is needed for expanding the ability of industry to use variable electricity (e.g., from wind or solar).
- Provide incentives such as rates that encourage adoption of IHPs by end-users by defraying the price differential between electricity and natural gas, use of electric technologies, active use of curtailed energy, and education to encourage effective use of demand response approaches).

POLICYMAKERS

- Develop policy enablers to accelerate the demonstration of IHPs at increasing scale at industrial facilities.
- Seek ways to offset the difference in electricity/natural gas prices, perhaps by a contract for differences approach, to accelerate adoption.
- Encourage increased product availability, developing an understanding of obstacles and working with domestic manufacturers, foreign manufacturers, importers, and others to address these obstacles.
- Devise incentives for engineering service firms to build IHP expertise, a qualified workforce to design and service IHP applications, and routes to spur engagement in user communities.
- Support infrastructure expansion for providing more variable electricity to industry and provide support to defray the higher price of electricity versus natural gas to spur investment of electric technologies such as IHPs.

FEDERAL/STATE AND RD&D AGENCIES AND COLLABORATIVES

- Educate federal and state policymakers on IHP technology and benefits, as European IHP technologists have informed EU policymakers (De Boer et al. 2020).
- Accelerate IHP demonstrations at increasing scale at industrial facilities.
- Study further technical details in actual field applications to screen for IHP potential at the manufacturing process level. Process design studies on steam and other process heat, pilots, and/or with techno-economic studies in partnership with industry, IHP providers, and service companies are needed.
- Design metrics, standards, evaluation tools and protocols to clarify how IHP performance is evaluated in industrial applications and communicate case study results.
- Engage on advancing IHP technology, materials, and working fluids that allow higher temperature IHPs, improving reliability and performance, while reducing or maintaining IHP capital cost.
- Participate in international research collaboratives to promote technology transfer of advanced IHP concepts (e.g., leverage European and Japanese IHP technical expertise).

- Support academic institutions to build IHP technical expertise and establish research programs to build engineering workforce trained in IHP fundamentals.

Summary and Conclusions

IHPs have significant potential for reducing energy and CO_2 emissions across the industrial sector, with particular applicability to the paper, food, and chemicals sectors where there are significant proportions of process heating needs requiring relatively low temperature (60°C to 200°C). Our research found:

- IHPs were typically able to save 26–32% of the source energy used for process heat generation.
- The vapor compression type IHP decreases in natural gas use were typically 2.7–3.7x the increases in electricity use across all unit operations. Similarly, the CO_2 reductions from natural gas savings were 3.5–4.7x the CO_2 associated with electricity use.
- Simple paybacks for the compression type IHPs were near or less than three years at a natural gas price of $4.50/MMBtus.
- Although the energy savings potential for heat activated type IHPs was lower than vapor compression heat pumps for the applications studied, as the technology advances and more opportunities are pursued for reusing waste heat between 60°C and 250°C there is a strong potential for these IHPs to have greater impact due to their flexibility.
- Across all unit operations, the IHP analyses showed the potential to:
  - Reduce process heat energy 293–400 TBtus/year (42–57%) of the 704 TBtus/year of process heat energy in the subsegments analyzed for the economic and economic + technical cases, respectively. A large portion (58%) of this reduction comes from potential application of IHPs in ethanol production.
  - Reduce CO_{2e}, 9.7–12.6 MMT CO_{2e}/year, which is equivalent to the emissions from 2.1–2.7 million passenger cars/year.
    - With lower emissions factors for grid produced electricity by 2050, the reductions potential would be 13.4–18.2 MMT CO_{2e}/year.
  - Expansion of IHP use across the far greater breadth of industry would save even more energy and CO_2 emissions.

The relationship between electricity and natural gas prices influences the economics for IHP application. Our study found that where the ratio of electricity/natural gas price is less than 3 there are simple paybacks that would already meet the bar of cost effectiveness for several IHP types. In states where this ratio is greater than 3, the need for incentives to accelerate IHP adoption is even greater.

We also found that several factors influence adoption by the industrial customer, including economics, technical risk, integration challenges, and local capabilities for maintenance. Enabling policies and programs by government and utility programs would accelerate IHP adoption. This work also shows that IHPs can be a key technology in aiding beneficial electrification in parallel with the grid moving to a higher proportion of low-carbon generation capabilities.

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Appendix A. IHP Types

Six IHP types were considered in this work for optimum fit within any process.

Mechanical vapor compression (MVC), closed cycle

Mechanical vapor recompression (MVR), semi-open cycle

Mechanical vapor recompression (MVR), open cycle

Thermal vapor recompression (TVR), open cycle

Heat activated Type 1 (HA Type 1), closed cycle

Heat activated Type 2 (HA Type 2), closed cycle

These types are shown in figure A1. A brief description of each IHP type with their pros and cons is listed in table A2. These types are illustrative of process types and not meant to be comprehensive. They are described and illustrated briefly below.

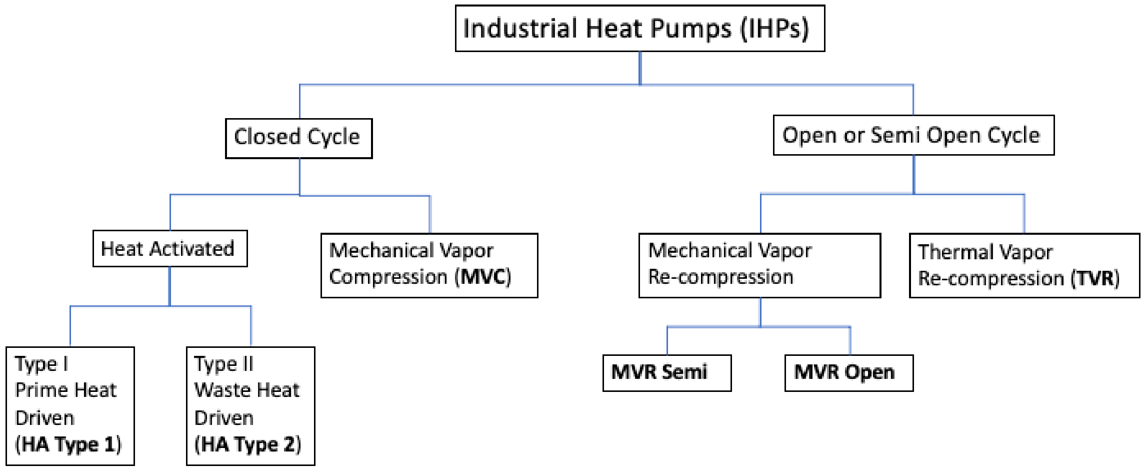


Figure A1. Illustration of IHP types. Adapted from Gluckman and McMullan 1988.

MECHANICAL VAPOR COMPRESSION (MVC), CLOSED CYCLE

The MVC heat pump relies on a refrigerant loop, which could vary widely. A key thermodynamic property of the MVC refrigerant is the critical temperature of the fluid. The fluid will also have a lubricant to allow the heat pump compressor to operate. Both the refrigerant critical temperature and the lubricant properties will set the upper temperature of the MVC heat pump. It requires a heat exchanger on both the cold side (evaporator) and hot side (condenser) and therefore additional lift temperature must be provided to accommodate the heat source and sink heat exchanger temperature drop (delta T) to lift the heat. Figure A2 shows the MVC heat pump.

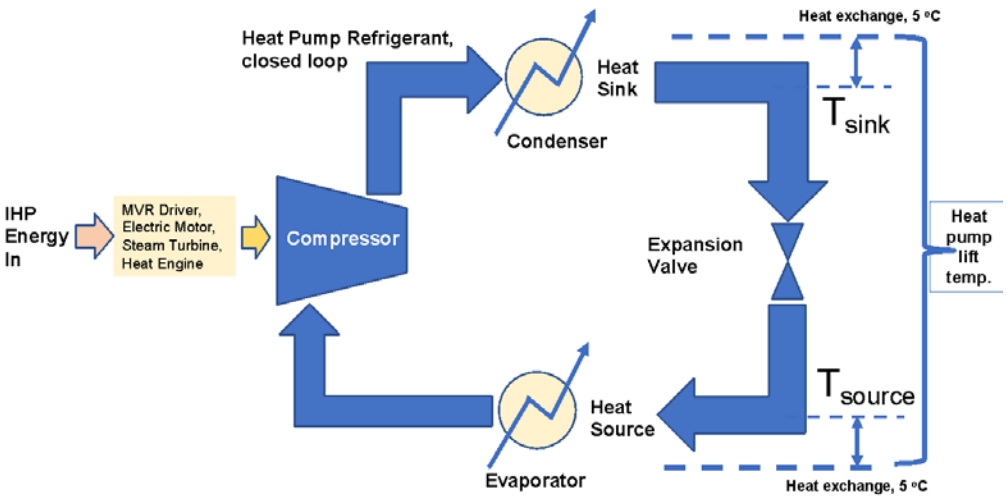


Figure A2. Mechanical vapor compression, closed cycle heat pump

MECHANICAL VAPOR RECOMPRESSION (MVR), SEMI-OPEN AND OPEN CYCLE

The MVR heat pump has been applied in various industrial operations. It typically will take advantage of recompressing waste low-pressure steam, such as in a dairy processing plant or pulp mill, or capturing a process fluid, such as hydrocarbons in a petrochemical plant or refinery that would otherwise be condensed and heat transferred to the atmosphere. Typically, the compressor will be driven by an electric motor, but a heat engine (steam turbine) could serve as the prime mover. The difference between the semi-open and open cycle is a heat exchanger used for the semi-open cycle system to separate waste vapors from the new process steam or other fluid (figure A3). In the open cycle the waste vapors are reinjected directly back into the process without heat exchange.

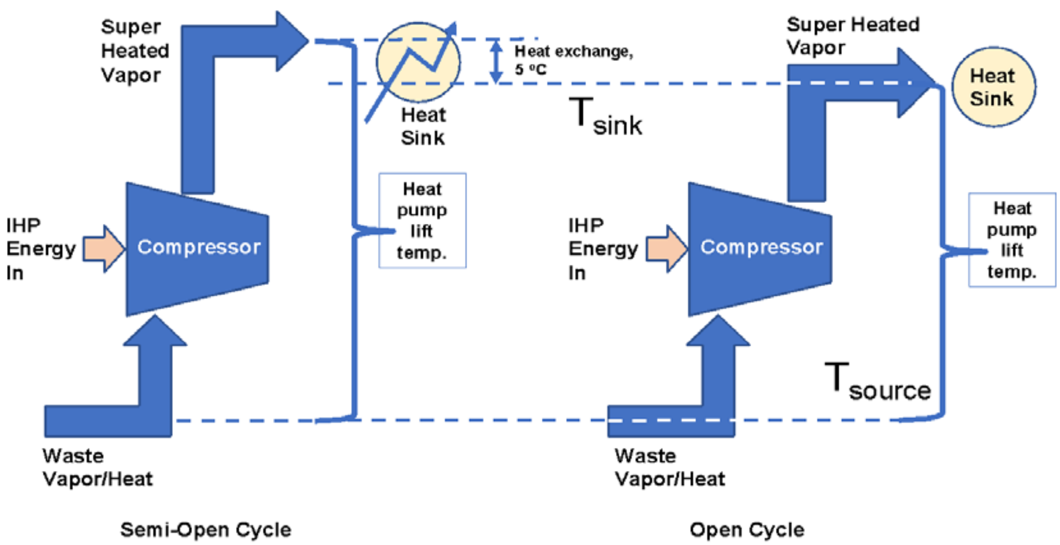


Figure A3. Mechanical vapor recompression (MVR), semi-open and open cycle

THERMAL VAPOR RECOMPRESSION (TVR), SEMI-OPEN CYCLE

The TVR heat pump is perhaps the most common in industry today, although it is typically not characterized as a heat pump by industrial facility personnel. It is the simplest type as it has no moving parts, but it is restricted to pumping heat from a steam waste heat source to a steam heat supply requirement (heat sink). The TVR works by injecting higher pressure steam, typically at medium pressure (e.g., 200 psig), into the steam ejector, which induces the low-pressure waste steam into a mixed stream, resulting in an intermediate steam pressure (figure A4). The TVR system is low cost but will only make sense for applications that require steam saturated temperatures be lifted 20°C or less (waste steam to process steam requirement). Appendix D further explains TVR applications and limitations.

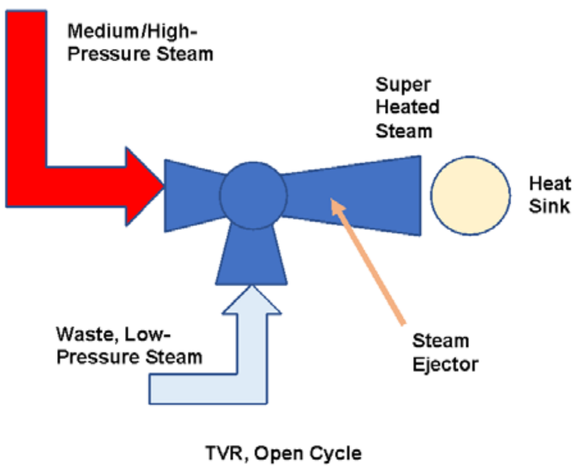


Figure A4. Thermal vapor recompressor, open cycle

HEAT ACTIVATED TYPES 1 AND 2, CLOSED CYCLE

The heat activated (HA) heat pump technology can be designed to work by various chemical processes, such as absorption, adsorption, or reversible chemical reaction. The common thread in these systems is that the heat pump cycle is predominantly heat activated, unlike vapor compression heat pumps. However, they do require a small amount of electricity for pumping the working fluids. Figure A5 shows a comparison of the HA Types 1 and 2 heat pump concepts.

The HA Type 1 design requires a supply of prime heat at a temperature above the sink temperature to lift the waste heat from the source temperature to the sink temperature.

The HA Type 2 design is waste-heat driven: For approximately two units of waste heat delivered to the heat pump, one unit is lifted up to the sink temperature and one unit is dropped to the ambient temperature, requiring enough driving force between the source heat and ambient temperatures. As a rule, the HA Type 2 heat pump can lift heat 80% of delta T of the source heat and ambient temperature.

The HA heat pumps are more capital intensive than the compression heat pumps (MVC and MVR) and the TVR heat pump. As mentioned, one of their advantages is lower electricity requirements. In our analysis, we have assumed that 4% of the heat sink's energy is required for electrical energy to circulate the HA's working fluid.

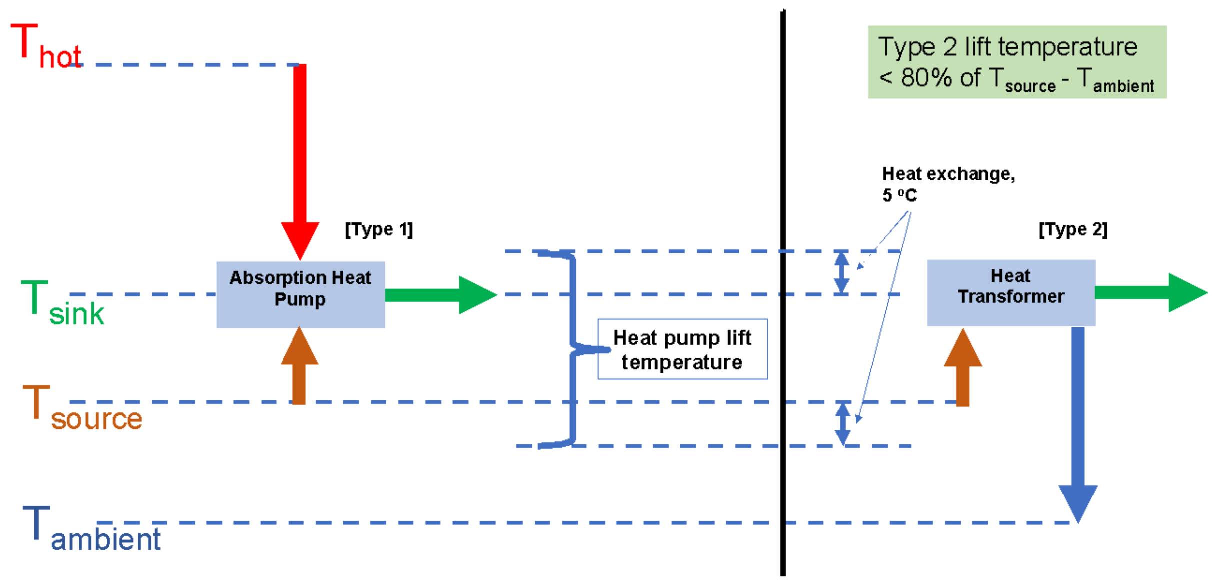


Figure A5. Heat activated Types 1 and 2 heat pumps

IHP ENERGY PERFORMANCE

The energy performance of any of the six IHP types are determined by the type of IHP driver energy (E_{driver}) and the coefficient of performance (COP).

$$COP = Q_{sink} / E_{driver}$$

$$Q_{sink} = Q_{source} + E_{driver}$$

$$COP = COP_{Carnot} * IHP_{Carnot\ efficiency}$$

Table A1 summarizes the assumed characteristics and COP equations that determine the energy performance of each of the six IHP types.

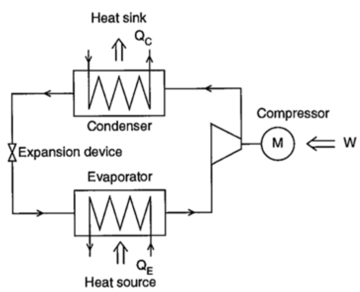
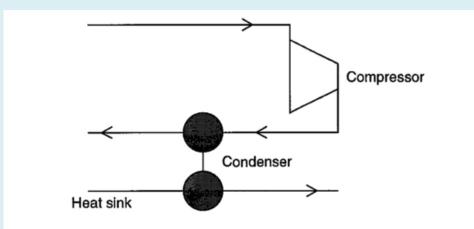
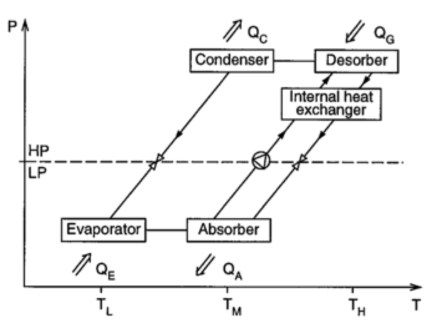
Table A1. IHP energy performance characteristics

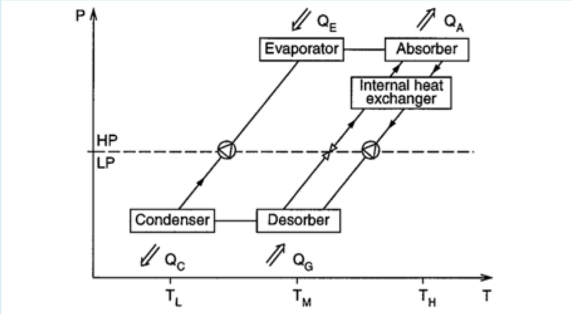
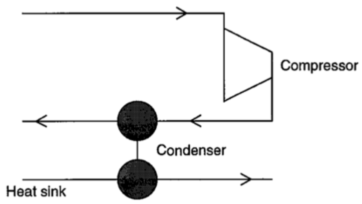
IHP type	E_{driver} type	$COP_{Carnot.}$ (T in absolute temperature, K)	IHP Carnot efficiency assumed
MVC, closed cycle	Electricity, electric motor, shaft power	$\frac{(T_{sink} + DX^1)}{[(T_{sink} + DX) - (T_{source} - DX)]}$	50%
MVR, semi-open cycle	Electricity, electric motor, shaft power	$\frac{T_{sink}}{[T_{sink} - (T_{source} - DX^1)]}$	50%
MVR, open cycle	Electricity, electric motor, shaft power	$\frac{T_{sink}}{[T_{sink} - T_{source}]}$	50%
TVR, open cycle	Medium/High-pressure steam	$\left[\frac{(T_{sink} + DX)}{[(T_{sink} + DX) - (T_{source} - DX)]}\right] * \left[\frac{[(T_{steam} - DX) - (T_{source} - DX)]}{(T_{steam} - DX)}\right]$	NA
HA Type 1, closed cycle	Prime heat, steam or process heat	$\left[\frac{(T_{sink} + DX)}{[(T_{sink} + DX) - (T_{source} - DX)]}\right] * \left[\frac{[(T_{steam} - DX) - (T_{source} - DX)]}{(T_{steam} - DX)}\right]$	70%
HA Type 2, closed cycle	Waste heat	$\left[\frac{(T_{sink} + DX)}{[(T_{sink} + DX) - (T_{amb.} + DX)]}\right] * \left[\frac{[(T_{steam} - DX) - (T_{amb} + DX)]}{(T_{source} - DX)}\right]$	70%

1 - DX = delta T across heat exchanger, assumed 5°C; closed cycle has heat exchanger on heat source and sink, semi-open cycle has heat exchanger on heat source only, and open cycle has no heat exchangers.

Table A2 lists the pros and cons for the six IHP types.

Table A2. Description of industrial heat pump types

IHP type	Description	Pros	Cons
Closed cycle, mechanical vapor compression (MVC)		Good COP for moderate lift temperature (< 40 °C) Multiple vendors Replaces onsite steam or direct fired process heat	Requires low IHP lift temperature and/or low E/NG price ratio (< 3–5) Limited supply temperature to 160 °C
Open or semi-open cycle mechanical vapor recompression (MVR, semi-open, and open)		Good COP for moderate lift temperature (< 40 °C) Electricity only on site High volume flow compressor to compress steam Can be combined with a closed cycle MVC	Requires low electric-fuel price ratio High speed compressor
Closed cycle heat activated (or sorption), Type I, prime heat-driven, Absorption heat pump (IEA 1995) (HA Type 1)		Uses lower cost fuel or steam as driver Minimal moving parts Higher supply temperature ~200 °C	High CapEx Large footprint required Limited vendors Emerging technology

IHP type	Description	Pros	Cons
Closed cycle heat activated (or sorption), Type 2, waste-heat-driven, heat transformer heat pump (IEA 1995) (HA Type 2)		Uses waste heat as driver Minimal moving parts Higher supply temperature ~200 °C	High CapEx Large footprint required Limited vendors Emerging technology Requires adequate temperature drop from waste heat to ambient
Open or semi-open cycle mechanical vapor recompression (MVR, semi-open and open)		Good COP for moderate lift temperature (< 40 °C) Electricity only on site	Requires low electric-fuel price ratio High speed compressor

Appendix B. IHP Economics and Capital Cost Parameters

Capital cost estimates for the six IHP types are shown in table B1. The MVC capital cost (CapEx) for the economic scenario is based on values from previous research (Arpagaus 2020), but we raised the CapEx to account conservatively for added design and installation costs. Likewise, with the MVR systems we referenced previous research (De Boer et al. 2020) and increased CapEx as we did for the MVC estimate. For the TVR CapEx estimate, TVR vendor data and the total installed cost for a specific end-user TVR installation informed our estimate. The HA Types 1 and 2 CapEx estimates referenced estimates from previous research (QPinch 2021) and experience with absorption technology (lithium-bromide, ammonia-water systems). We increased the capital cost for the technical scenario over the economic scenario by at least 50% to account for an added stage of compressors in the MVC and MVR application and added complexity with all heat pump systems. For the technical scenario, the TVR heat pump technology is not applicable since the IHP lift temperature is not possible or practical.

Table B1. Capital cost estimates for the six IHP types for economic and technical scenarios.

IHP type	Economic scenario capital cost, \$U.S./Q_{sink} (kW)	Technical scenario capital cost, \$U.S./Q_{sink} (kW)
MVC, closed cycle	400	800
MVR, semi-open cycle	325	650
MVR, open cycle	250	500
TVR, open cycle	150	NA
HA Type 1, closed cycle	1,000	1,500
HA Type 2, closed	1,250	1,875

IHP ENERGY SAVINGS AND SIMPLE PAYBACK

The energy savings and simple payback were calculated for both the economic and technical IHP scenarios. The energy savings from both scenarios are additive, therefore, two or more IHPs are required within the same unit operation to reach the full IHP technical potential.

The economics of the IHP are greatly influenced by the IHP lift temperature, which determines the IHP energy in, and thus the IHP operating cost, as well as the prime fuel consumption that is avoided: the energy saved. We used simple payback (PB) as a measure of IHP economics.

PB is determined by the capital cost of the IHP (IHP_{capex}) and the IHP net energy cost savings, $IHP_{savings}$:

$PB = IHP_{capex} / IHP_{savings}$.

IHP_{capex} is listed above in table B2.

$IHP_{savings}$ = IHP net fuel savings – process heating cost avoidance (savings) – IHP operating cost – IHP maintenance cost.

IHP net fuel savings = heat pump natural gas cost savings – heat pump electricity operating cost.

The process heating cost avoidance is determined through the pinch analysis and specifically by the change in "hot utility" demand (MMBtus/ton product) as described in the Annex, section 1.

Process heating cost avoidance = [IHP Heat Sink (MMBtus/ton) / [combustion efficiency (%)/100] * IHP annual operation (hours/year) * [fuel cost ($/MMBtus) + fuel combustion added cost ($/MMBtus)].

Combustion efficiency was assumed to be 80%.

IHP annual operation was assumed to be 8,760 hours per year. This is an upper bound; fewer hours would lengthen payback periods.

Fuel cost was varied in the economic analysis at $3.00, $6.50, and $10.00 per MMBtus.

The fuel combustion added cost, beyond the energy fuel cost, was assumed to be a fixed cost at $2.00 per MMBtus. It accounts for the cost of emissions control, steam condensate loss, boiler steam water treatment, and boiler or process heater maintenance costs.

IHP operating cost = IHP Energy In (kWh/ton) * IHP annual operation (hours/year) * electricity cost ($/kWh) /production rate (tons/year).

IHP maintenance cost varied from 1–3% of IHP_{capex} per year based on the type of IHP, as in table B2.

Table B2. Maintenance cost factor for six IHP types

IHP type	Maintenance cost (% of IHP CapEx)
MVC, closed cycle	3
MVR, semi-open cycle	3
MVR, open cycle	3
TVR, open cycle	1
HA Type 1, closed cycle	2
HA Type 2, closed	2

The overall unit operation Btu % energy savings resulting from the IHP heat pump =

$IHP_{Btu\ savings,\ economic}$ + $IHP_{savings,\ technical}$ /Unit operation total site energy consumption * 100 (%)

$IHP_{Btu\ savings,\ economic}$ = Qsink (MMBtus/ton product) in economic IHP scenario

$IHP_{Btu\ savings,\ technical}$ = Qsink (MMBtus/ton product) in technical IHP scenario

Appendix C. Emission and Carbon Intensity for Energy

The carbon intensity of the electrical grid and natural gas energy used were obtained from the EIA for 2020. We used a projection of carbon intensity values to 2050 as a reference for anticipating future values as the electrical grid becomes further decarbonized, as shown in table C1. With many states setting aggressive grid decarbonization goals recently, more aggressive factors were used than in the EIA projections.

Table C1. Emissions factors for carbon

	Carbon emissions factors		
	2020*	2035	2050
Natural gas, metric tons CO_2e/therm	0.005	0.005	0.005
Electricity, metric tons CO_2e/kWh	0.0004	0.00025	0.0001

*** Based on EIA numbers for 2020. For 2035 and 2050 more aggressive carbon factors were chosen.**

Source: Adapted from EIA 2021c.

Appendix D. TVR Applicability

The thermo vapor recompression (TVR, thermocompressor) is limited to operations that require certain operating conditions to be satisfied between the heat sink and heat source temperatures for different working fluids. Additionally, the driving heat (e.g., temperature) also has a strong impact on the COP of the TVR. In this IHP report, TVRs are limited to steam as the working fluid and thus further constrain the cost effectiveness and potential TVR applications where there is an open cycle steam-to-steam system IHP.

Some of the most common applications or areas in industry where TVRs are used to capture and recover the steam are:

- Very-low-pressure (almost atmospheric) steam is vented
- Steam vapors are sent to the surface condenser after the last stage of a unit operation (multi-effect evaporator)
- Condensate flashing steam

There are thermodynamic constraints and design limitations that come into effect with a simple TVR. The main thermodynamic constraint is the compression ratio: the ratio of the absolute discharge pressure to the absolute suction pressure, which limits the amount of temperature lift in the TVR. Most manufacturer's design data limit TVR applications with steam to less than 20°C temperature lifts, with the heat source as atmospheric pressure steam typical of vented steam, condensate flashing steam. That same design data limit TVR applications with steam to temperature lifts of less than 15°C, with the source being sub-atmospheric pressure steam typical of process steam at the end of the unit operation (multi-effect evaporator) headed to surface condensers, that is, fin-fans.

Due to this temperature lift constraint, and the heat source being atmospheric and sub-atmospheric steam, TVRs see applicability only in the economic potential cases that are evaluated in this report. Even then, several economic potential cases presented in this report may require a higher lift temperature and a complex design or a multi-stage TVR. Technical potential cases require much higher temperature lifts and a significantly complex TVR system as well as multiple driving sources of steam that reduce the overall IHP COP and negate all benefits of the TVRs for both energy savings and carbon emissions. Hence, TVRs were not considered to be part of the IHP solution in the technical potential cases.

It is clear that the TVR application becomes restrictive among all the different IHP economic and technical potential cases considered in this report. Nevertheless, the simplicity of the TVR—having both the smallest capital cost of all the IHP technologies available today and having no moving parts, implying negligible maintenance expenses—deserves consideration when evaluating IHP applications. We encourage direct communication with any of the TVR manufacturers in describing the IHP application, which would provide valuable information on whether the TVR will be a suitable option for that specific IHP application in industry.

Appendix E. Heat Activated (HA) Type 1 and Type 2 Efficiency

This report uses an optimistic 70% as the Carnot efficiency possible for the actual COP achievable by the IHP types, HA Type 1 and HA Type 2. This is debatable; the reader can choose to reduce that Carnot efficiency number to 50%, which is the assumption used to arrive at the actual COP for the other electrically driven IHP types: MVC, MVR Semi, and MVR Open.

The calculation of the COP in a IHP is specifically and heavily dependent on the source and sink temperatures. In this report, these temperatures were chosen so that the source temperature always represented the lowest temperature of any available heat while the sink temperature always represented the maximum temperature of the heat delivered to a process. This is automatically the case when an electrically driven IHP is used with a pure working fluid because the heat transfers at the source and sink happen at a constant temperature (evaporation and condensation). Nevertheless, depending on the actual application in the process, most applications may have a sensible temperature glide, which could be a huge advantage in a heat activated IHP as there is a significant glide in the heat given out or absorbed due to the working fluids concentration differences. The net result of this temperature glide allows for a much lower effective lift compared to the electrically driven IHP. Since it was very difficult to identify each specific situation in all the cases considered here in this report, we decided to compensate the heat activated IHP with a higher Carnot efficiency rather than calculating the actual COP with the specific temperature glides of the application.

We believe that the heat activated IHPs have not been pushed to their performance limits given their limited applications, few manufacturers, and lack of understanding by the industry. Combined with the advent of extremely sophisticated heat exchange technology, the heat activated IHPs also allow for a higher internal heat exchange between the hot and cold streams. Hence, the higher Carnot efficiency used in this report could be justified given the standard calculation of the ideal COP with fixed sink and source temperatures and assuming no internal heat recovery per se. Lastly, with no moving parts such as a compressor, the heat activated IHP's performance does not degrade significantly with varying loads, while the isentropic efficiency of the compressor would surely see a significant variation with load and thus a direct impact to the system's COP. We note that there are several advances in the compressor technology, including variable speed drives, that can allow for a relatively high level and constant compressor isentropic efficiency.

Appendix F. Rationale for Excluding Select Unit Operations from the Technical Scenario

The authors were sensitive to the stream data (temperatures and heat duties) in each of the unit operations as well as the limitations of the IChemE Pinch Analysis software tool. The concerns ranged from the validity of the data to the general applicability of these data in each industrial group. The data used for the unit operations pinch analysis were dated (probably early 1990s), and the unit operations may have undergone significant changes. Whenever it was questionable to implement IHPs, the IHP was not evaluated in that specific case. This situation occurred in three different unit operation cases, all technical scenarios: ethylene debutanizer reboiler; ethylene water stripper reboiler; and non-integrated paper mill pulper.

In the ethylene unit operations case, two IHPs were implemented: the first between the quench water (source) and the debutanizer reboiler (sink) and the second between the quench water (source) and the water stripper reboiler (sink). These were both economic scenarios and were found to be excellent applications for IHPs. Additional technical scenario IHP opportunities clearly exist, but that analysis will require a much more sophisticated and higher-fidelity level of the pinch analysis tool than used for this report. We could have made certain assumptions with the stream data as well as with the IChemE pinch analysis model and identified significant technical IHP opportunities in the ethylene industrial group, but did not feel confident that we could provide a solid basis and foundation for such analysis.

In the non-integrated paper mill pulper unit, there were five different data sets that were evaluated for pinch analysis and an IHP economic scenario was implemented in each of the five different data sets. Based on the stream data descriptions, it was unclear if implementation of additional IHP opportunities was actually feasible. We believe that there could be significant IHP opportunities in the paper drying process but, given the data sets and their validity, refrained from undertaking the technical IHP scenario in the non-integrated paper mill pulper unit operations.

Lastly, both IHP economic and IHP technical analysis scenarios were terminated when the pinch temperature moved significantly (>25°C) and when the sink temperatures were higher than 150°C.

The ethyl alcohol, ethanol fuel sub-industrial group was the fourth unit operation where only an economic potential case was evaluated. It was also the only sub-industrial group in which the IChemE pinch analysis tool was not applied, due to a lack of adequate hot and cool stream data to perform pinch analysis. However, there was an alternative approach to evaluate IHP potential using energy intensity data from literature on the distillation tower, which removes water from the 85% water/15% ethanol mixture downstream of the fermentation process. Sufficient data existed to analyze the six IHP types pumping heat from the distillation tower's condenser heat (source) to the reboiler where steam is normally supplied (sink), but only for the economic potential case.

Appendix G. Pinch Analysis

One of the principal tools is the representation of composite curves of heat flow in the system to determine the minimum energy consumption target for a given process. This includes generation of a composite curve, where the profiles of process heat availability (heat sources or hot composite curve) are combined with the heat demands (heat sinks or cold curve). The degree of overlap provides a measure of the potential for heat recovery, and where the curves most closely approach each other is called the “pinch point,” as shown in figure G1. The pinch point temperature divides the hot and cold streams that are exchanging heat with each other into two separate parts. Above the pinch point there is a heat deficit and below the pinch point there is a heat excess. Optimum placement of the IHP would be to pump heat from below to above this pinch point.

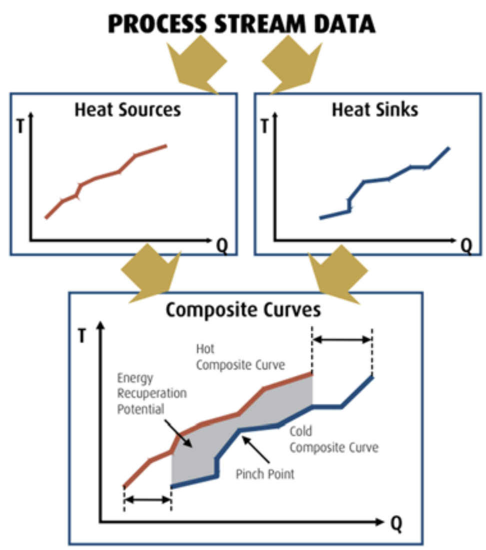


Figure G1. Illustration of the grand composite curve and pinch point. Source: NRCan 2003.