Industrial Heat Pumps: Electrifying Industry's Process Heat Supply

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Summary

Industrial heat pumps (IHPs) are a demonstrated solution for efficiently recovering, upgrading, and supplying process heat. While IHPs have penetrated various European and Asian industrial applications, adoption in the U.S. has been limited due to several factors, including relatively low natural gas prices and specific process requirements. Yet, prior studies show that moderate deployment of IHPs in manufacturing could save 270-550 trillion Btu/year and avoid emissions of 12-25 million tons /year of CO_2 while electrifying select industrial processes (IEA 1995). IHP technology has advanced in the past 20 years with low environmental impact refrigerants that can operate at higher delivery temperatures (e.g., 160 ºC). IHPs are a key technology for lowering the energy and greenhouse gas (GHG) emissions due to process heat, and this has sparked renewed interest in their market potential, matching of their capabilities with industrial needs, and routes to accelerate adoption.

Introduction

Industry accounts for 28% of the energy related U.S. CO_2 emissions (Figure 1, EIA 2021), so it's a major opportunity area for emissions reductions that is receiving renewed attention (Whitlock, Rightor, Elliott 2020). Industry faces a multitude of challenges in reducing its atmospheric emissions of greenhouse gases (GHGs, e.g. a target referred to as decarbonization) including dependence on carbon based fuels and feedstocks for energy inputs and product composition, complex integration, high levels of capital investment, and relatively low margins for mature industries. Process heat, the use of thermal energy to prepare or make products in industry, is one of the primary uses of energy and opportunities for action as it accounts for approximately 70% of delivered energy in U.S. manufacturing, and about 7.7 quadrillion Btus of energy (EIA 2021) and 332 million $MTCO_2$ (DOE 2015). Yet, some 20-50% of the input energy is lost via hot exhaust gases, heated products, cooling water, etc. (AMO 2017). The portion of the process heating demand (and GHGs) that can be addressed by IHPs with energy and GHG reductions then is of interest. IHPs offer a means to reduce industry's carbon footprint in two ways: 1) by improving the energy efficiency of the process since waste heat can be captured and recycled back into the process, and 2) electrification of process heat, (as the renewable energy proportion of the electric grid increases, the carbon footprint will decrease).

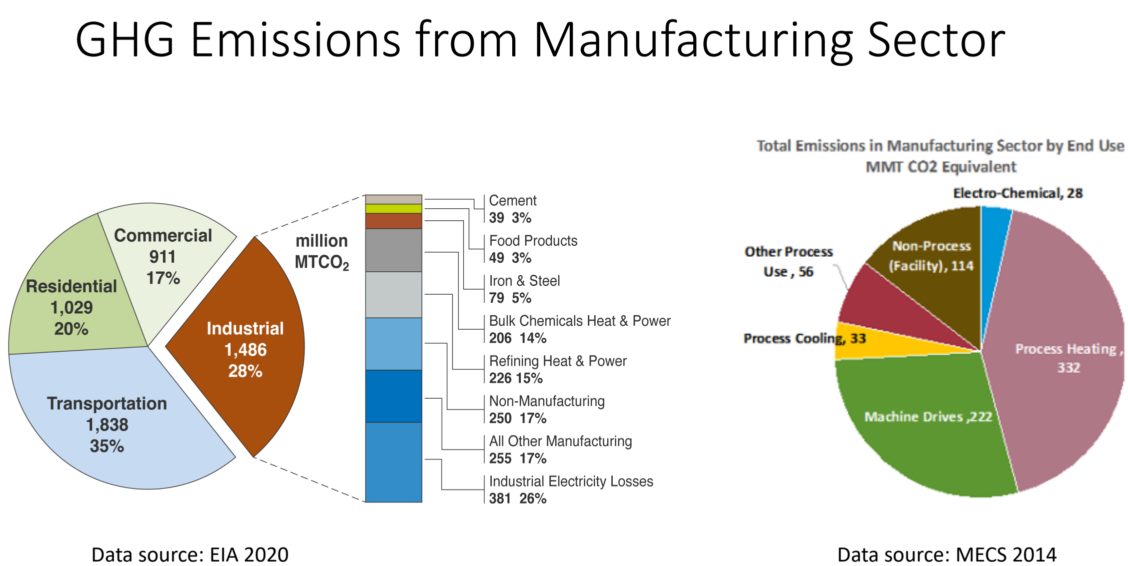


Figure 1. U.S. manufacturing sector greenhouse gas emissions. Sources EIA 2020, MECS 2014.

In the portfolio of electric technologies, IHPs are a demonstrated solution for efficiently recovering, upgrading, and supplying process heat (Rightor, Whitlock, Elliott 2020). Prior studies showed that moderate deployment of IHPs in manufacturing could save 270-550 trillion Btu/year and avoid emissions of 12-25 million tons/year of CO_2 (IEA 1995). IHPs are commercial in numerous industrial applications, yet adoption has been limited due to a relatively low upper temperature bound for conventional heat pumps (60 ^oC, primarily due to working fluid limitations), high cost of electricity vs. natural gas in some regions, compressor technology limitations, and lack of service capabilities in the field). IHP technology has advanced considerably in the past 20 years with low environmental impact refrigerants (McLinden 2014) that can operate at higher delivery temperatures (e.g., up to 160 ^oC) broadening the range of IHP applications, such as in recovery of waste heat streams and use in drying of industrial products, which can account for 12-25% of industrial energy consumption (Lauermann 2019). As the technology has advanced, so too has the understanding of IHP economics and favorable deployment scenarios (Arpagaus 2020, Arpagaus 2020a, Kosmadakis 2020). Further, new heat-activated IHP technology (driven mostly by waste heat), promises to supply process heat above 160 ^oC with lower IHP energy driver costs, more favorable economics, and thus even broader applicability (QPinch 2021).

This paper describes research examining the IHP market, capability fit with industrial needs, and enablers to accelerate RD&D of current and emerging IHP technologies in U.S. industry.

Market Potential and Fit of IHP Types

Multiple drivers are creating renewed interest in IHPs including more aggressive company GHG reduction/sustainability goals, non-energy benefits (e.g. improved controllability, reduced maintenance costs), and aggressive technology development and deployment overseas that can be leveraged. Industrial sectors with high levels of process heating demand in the temperature range accessible by IHPs (e.g. < 200 ºC), would be good starting targets for IHPs.

Figure 2 illustrates sectors with high IHP potential, especially applications where IHPs could target providing heat under 200 ºC, or possibly towards 300 ºC with advanced technology such as compatible compressors, heat exchangers and working fluids. Figure 3 shows how process heat is used currently prompting thoughts on IHP use. For example, in fluid heating IHP benefits could include more efficient temperature control. 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 an IHP) can offset significant fossil fuel use for steam generation while improving efficiency and reducing costs (Rightor, Whitlock, Elliott. 2020). In addition to replacements for steam generation, IHPs are being considered for drying of products and removal of water from solids, an important application as drying accounts for 15-25% of the energy associated with processes (Jakobs 2019). Applications for moisture removal are numerous and include proving bread dough, manufacture of bricks, purification of chemical products, and biosolids.

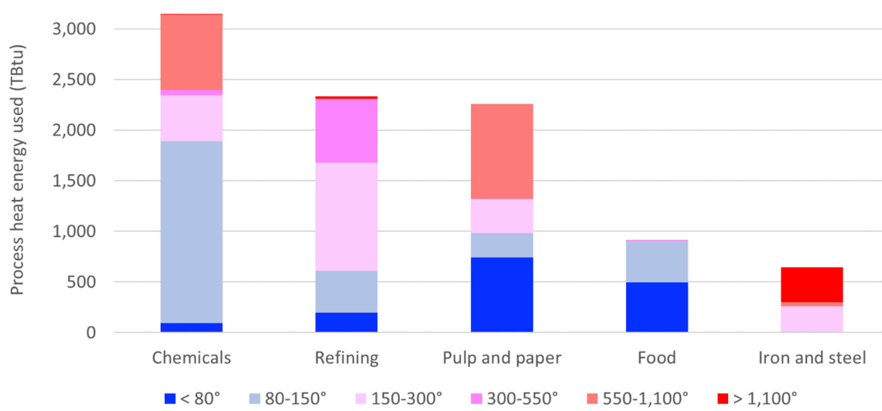


Figure 2 – Process Heat Energy in Industrial Segments. Data Source: McMillan 2019

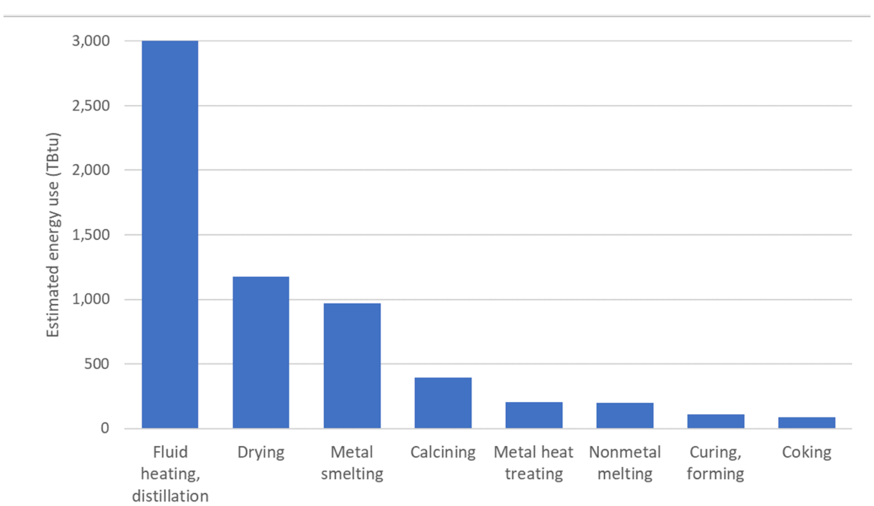


Figure 3. Distribution of process heat end uses across industries. Source: DOE 2015

The range of potential IHP applications is further illustrated in Figure 4 where heat sources (waste heat) and heat sinks (where upgraded heat is used) are shown. This illustration gives examples of where lifting/upgrading the temperature of potential heat sources (light blue) with heat pumps to applications for that heat (e.g. heat sinks, in light orange) would be beneficial.

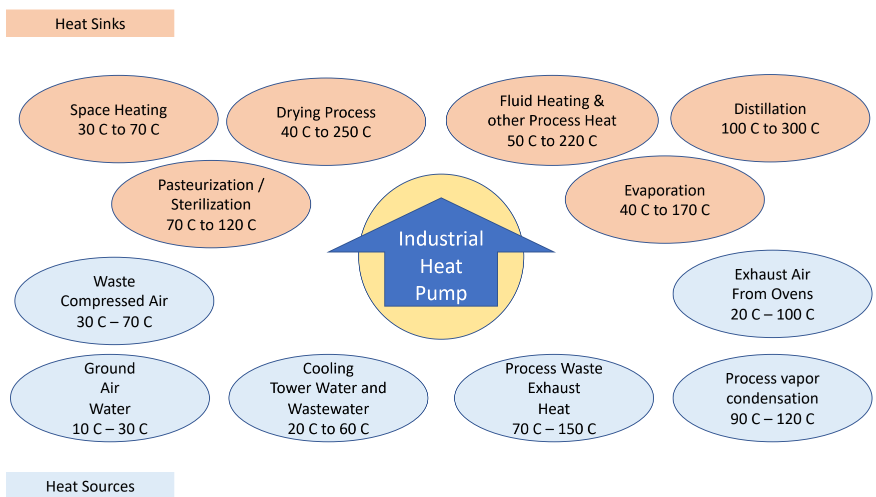


Figure 4 – Typical IHP heat sources and sinks. Source: this work.

The market and vendor capabilities for IHPs is most well developed in Europe and Japan (Arpagaus 2018), where there are strong economic and policy incentives (e.g. carbon tax), and IHPs are commercially available at scale. Figure 5 shows a calculated number of potential IHP units for sectors in Europe, where about 80% are under 5 MW (Marina et al. 2021). Recent IHP demonstrations include those at 1 - 2 MW (Borealis 2021). Also, IHPs were mentioned in BASF's goals of reducing CO_2 25% by 2030 and net zero CO_2 by 2050 (Nonnast 2021).

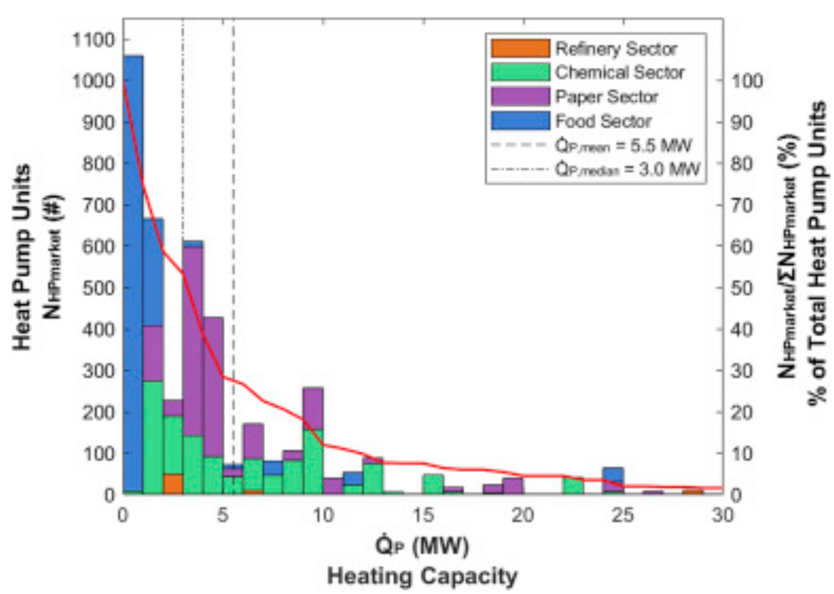


Figure 5 Calculated number of potential Industrial Heat Pumps in European Refinery, Chemical, Paper and Food sectors by IHP size (MW) (Marina et al. 2021)

To determine the most impactful sectors and processes to target for IHP applications, we screened at a high level using tw0 main criteria:

1. Process heat sink temperature supply by an IHP is 200 °C or below
   The IHP will pump heat around the process pinch point[1] to effectively save energy. Current vapor compression heat pump technology is limited to 160 °C IHP heat delivery temperature due to working fluid and compressor lubrication technical limits. Yet, new advanced, heat-activated technology is promising heat delivery temperatures of 200 °C or greater.

2. IHP lift temperature of 100 °C or less for the process application
   Figure 6 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 energy lowering the IHP coefficient of performance (COP). With U.S. energy prices, electric-driven closed cycle mechanical vapor compression heat pumps yield an economic (< 5 year payback) with a lift temperature of ~ 40 °C or less (Scheihing 2021). Advanced heat-activated heat pumps could technically lift heat at much higher levels and possibly yield economic energy savings. Therefore, including heat activated IHPs while keeping economics reasonabile we chose a maximum 100 °C lift.

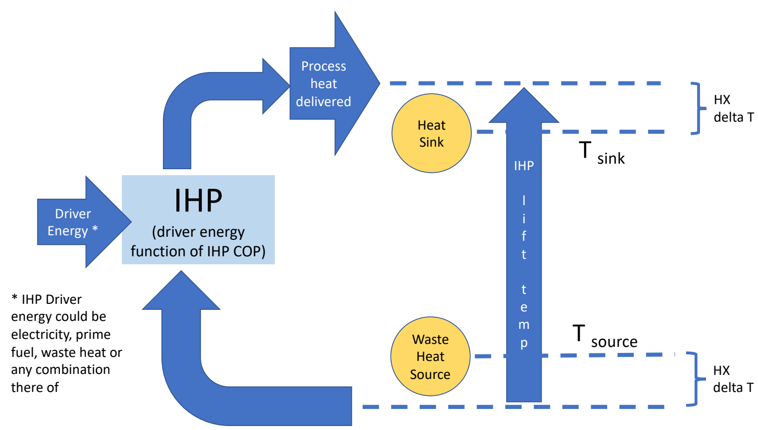


Figure 6 – Generic IHP diagram illustrating IHP lift temperature, T_{source} and T_{sink}

We also identifed leading processes in energy intensive sectors and for simplicity selected a subset as prototypical processes to perform more detailed techno-economic analysis based on:

1. Geography -as electricity to natural gas price (E/NG price) ratio.[2] A E/NG price ratio is preferrable for electrification cases as it has significant influence on the economics of electric-driven mechanical vapor compression IHPs.

[1] The pinch point is a critical location within an industrial process' pinch technology energy analysis. In pinch technology energy analysis there are hot streams (being cooled) and cold streams (being heated). 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.

[2] E/NG price ratio is electricity price ($ per kW-hr) divided by natural gas price ($ per MMBTU)..

2. Type and size of IHP. We selected the optimum IHP type from five possible IHP types that yield the best payback (see IHP Types below) using the process characteristics (pinch analysis and process heating and cooling stream data). Using the pinch analysis for each process, the size of the optimum IHP, allowed estimation of the capital cost.
3. Using the optimum IHP type, we determined the IHP heat source and sink (amount of heat and temperature) that pumps heat around the process pinch point (see Integration).
4. While renewed market interest is encouraging, economics are a key consideration so screening economics will be used including such factors as:
    - Installed capital cost of the IHP which is influenced by the IHP size (MW) and type;
    - Prime fuel cost being saved, typically natural gas;
    - Annual hours of IHP operation; and
    - IHP driver energy type(s) and cost of driver energy, typically electricity
    - Nonenergy benefits (increases in yield, production rate, health, safety, etc.)

IHP Types

As mentioned above, five IHP types will be evaluated for optimum fit within any process, and they are shown in Figure 7 along with a brief description of each IHP type with there pros and cons listed in Table 1. These are illustrative of process types and is not meant to be comprehensive.

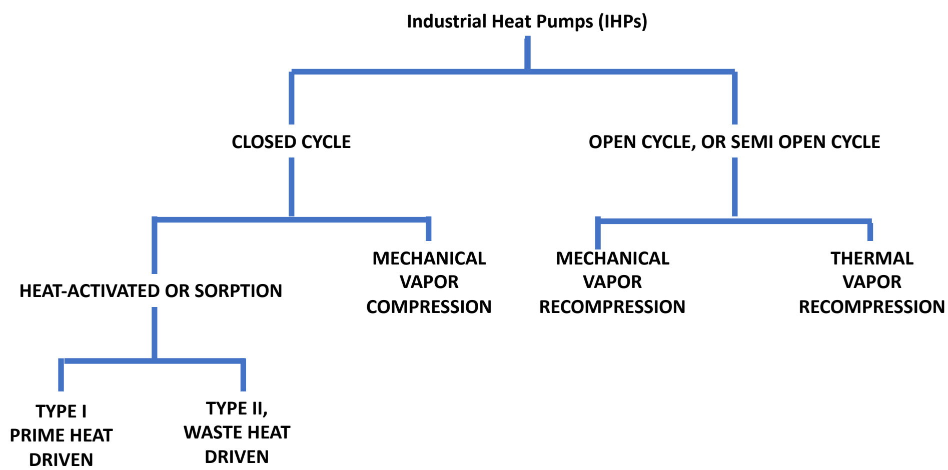
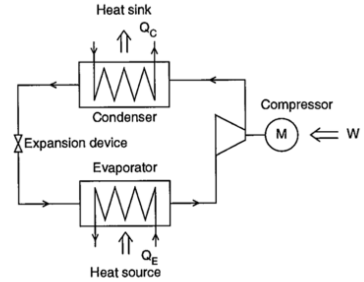
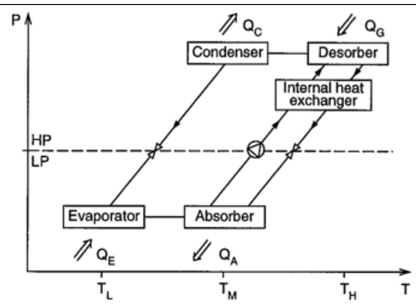
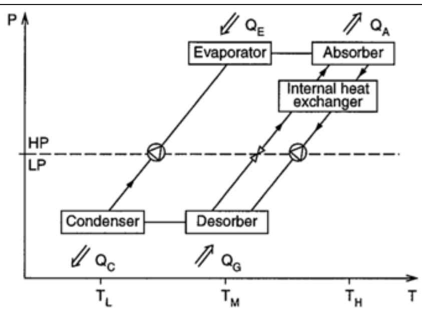
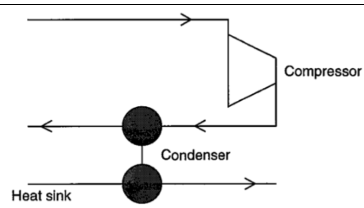
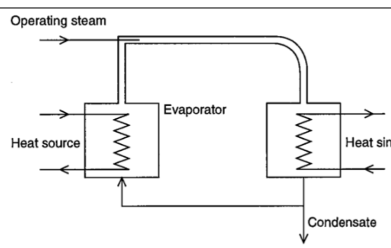


Figure 7 – High level classification of IHP types (EPRI 1988)

Table 1 – Description of five industrial heat pump types.

IHP Type	Description	Pros	Cons
Closed cycle, mechanical vapor compression		Good COP for moderate lift temperature (< 50 ºC) Multiple vendors Replaces onsite steam	- Requires low IHP lift temperature and/or low E/NG price ratio (< 3 to 5) - Limited supply temperature to 160 ºC
Closed cycle heat-activated (or sorption), Type I, prime heat-driven, Absorption heat pump (IEA 1995)		Uses lower cost fuel or steam as driver Minimal moving parts Higher supply temperature ~200 ºC	High CapEx Large footprint required Limited vendors Emerging technology
Closed cycle heat-activated (or sorption), Type II, waste heat-driven, heat transformer heat pump (IEA 1995)		Uses waste heat as driver Minimal moving parts Higher supply temperature ~200 ºC	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)		Good COP for moderate lift temperature Electricity only on site	Requires low electric-fuel price ratio High speed compressor
Open or semi open cycle thermal vapor recompression (TVR)		Uses lower cost steam as driver Low CapEx Simple and low maintenance	Low energy efficiency

IHP Process Integration

Pinch Technology was introduced in the 1980s as a more sophisticated approach to identifying improved heat integration of a facility's heating and cooling streams (NRCan 2003). Pinch technology is a systematic approach where all process streams are characterized by the enthalpy content (mass flow and specific heat) relative to the start and final temperatures. Hot streams are cooled and cold streams are heated. The plotting of the individual hot and cold stream vectors allows the two curves (hot and cold composite curves) to divide the process into two parts which are separated by a pinch point. The area where the hot and cold streams intersect and exchange heat with each other is where energy recuperation takes place. The area above the pinch point is an area of heat deficit and the area below the pinch point is an area of heat excess. By positioning the hot and cold composite curves on a temperature versus enthalpy plot, the minimum heat exchange approach temperature will identify the maximum heat integration (heat exchange) opportunity (IEA 1995) as shown in Figure 8.

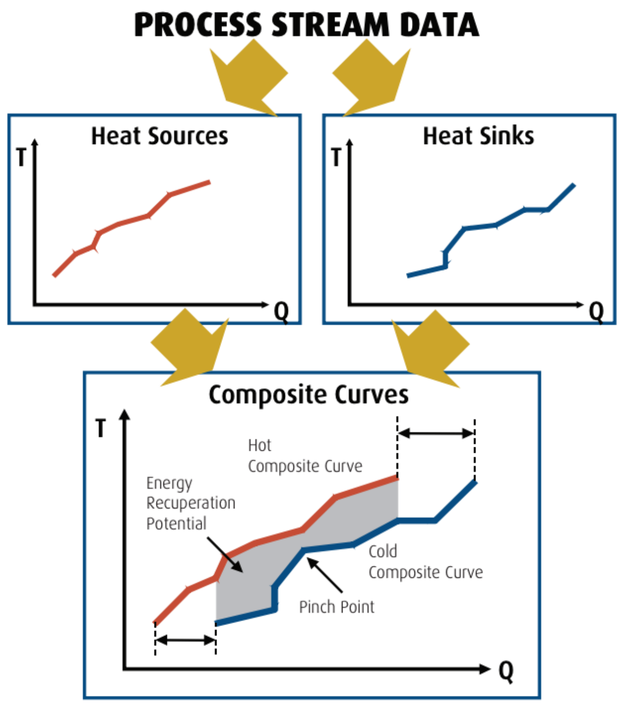


Figure. 8 – Explanation of pinch composite curves (NRCan, 2003)

More pertinent to IHPs, energy can only be saved in the process if heat is pumped from below to above the pinch point temperature. The optimum placement of the IHP is where heat can be pumped across the pinch, from just below the pinch (net heat source) and to above the pinch (net heat sink). The performance of the IHP depends on the temperature lift; the smaller the lift, the better its performance. It's important to note that the factors influencing practical IHP implementation are the quantity of heat available, its accessibility below the pinch point and the ability to deliver it above the pinch point while minimizing the need for additional heat exchangers or other process modifications.

Case Study for Ethylene

We used pinch analysis then to identify the best heat source (hot stream(s)) and heat sink (cold stream(s)) for the optimum IHP placement. Figure 9 shows the pinch analysis for a portion of the ethylene process, using a semi-open cycle mechanical vapor recompression heat pump.

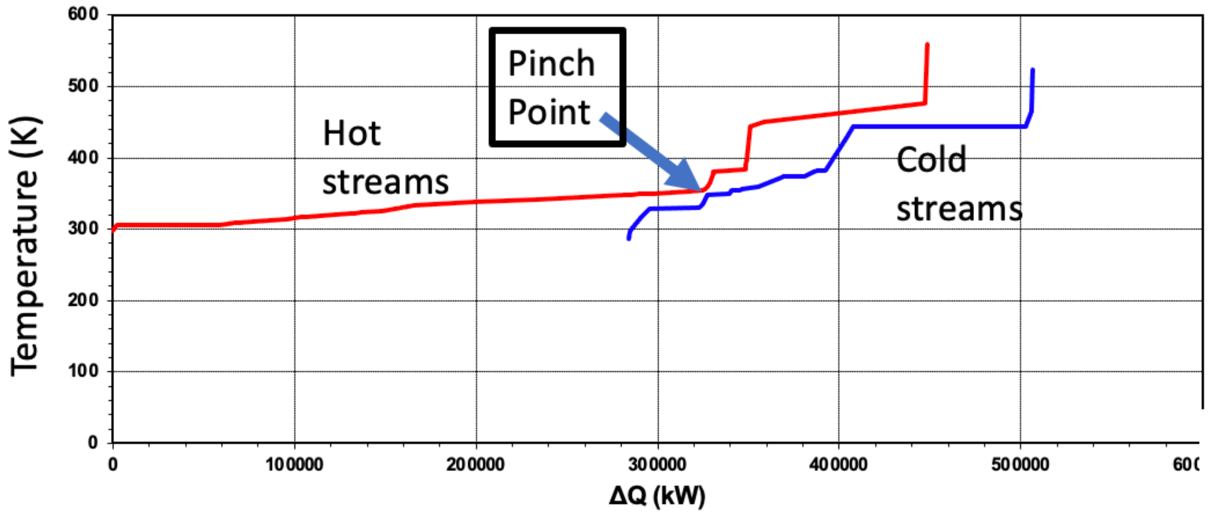


Figure 9. Pinch analysis for hot and cold streams for ethylene; quench water (hot stream, heat source) pumping heat to the boiler used to separate propylene (cold stream, heat sink). Data source: Franke 2021

An expanded view in Figure 10 shows the location in the hot stream (red) of the heat source (348 °K or 75 °C, light blue arrow) and the heat sink (358 °K or 85 °C, light orange arrow). Assuming a semi-open cycle mechanical vapor recompression (MVR) heat pump, 5 °K for a delta T for the heat pump's evaporator heat exchanger gives an overall IHP lift temperature of 15 °C (= (358 – (348 – 5)). The theoretical carnot coefficient of performance, COP is 23.9 (= 358 / (358 – 343)). Assuming a Carnot efficiency of 45% gives an actual COP of 10.7.

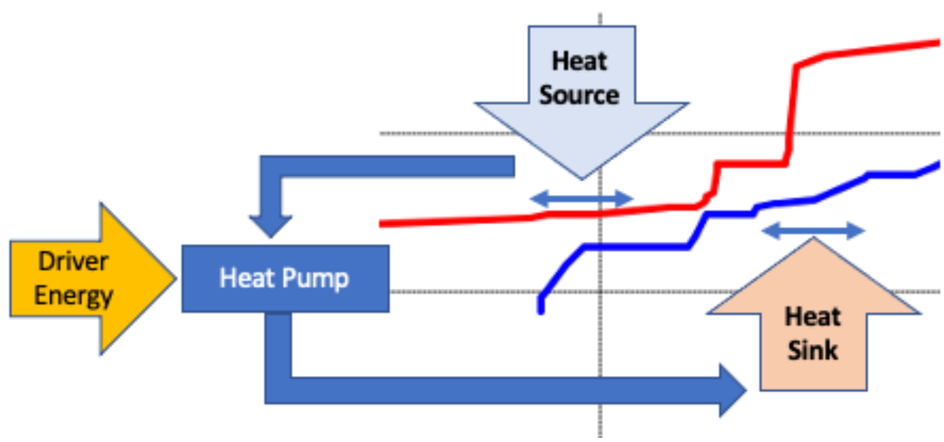


Figure 10. Expanded view of the pinch point for the ethylene case.

Prototypical Processes for IHP Techno-economic Analysis

Table 2 was created by examining pinch data from actual processes, starting with top candidate processes identified in a prior U.S. IHP market study performed (RCG 1994). The IHPs applied in these prototypical processes yielded a range of payback on total estimated installed cost of 3 to 6 years. For example, taking ethylene case again, if IHPs were applied to the heat source chosen, which is a fraction of the entire process heat use for an ethylene plant, and assuming a adoption rate of 25% across the 32 ethylene plants in the U.S. the total amount of potential energy savings after conversions comes to around 1.6 trillion Btus/yr. Although that sounds like a small number it is an equivalent amount of energy as almost 20,000 typical U.S. households consume in one year. It's likely that additional IHP opportunities could be found for IHPs within an ethylene plant itself when applying more advanced IHPs (e.g., heat-activated) that can lift heat over higher temperature ranges, as well as, other applications in associated downstream facilities. Therefore, there's significant potential energy savings and GHG reductions for IHP application.

Table 2 – Prototypical processes with results from early IHP case studies

Process	waste heat source (ºC)	heat sink temp. (ºC)	process energy savings (%)	heat sink (MW)	Estimated number of U.S. facilities	Payback (years)	Estimated IHP energy savings (TBtu/yr)*
TMP Pulp	45	63	26	6.0	28	5.5	0.8
High Fructose Corn Syrup (part of wet corn milling)	87	96	8.2	1.0	49	3.2	0.3
Synthetic rubber	110	115	17.2	4.4	85	2.7	2.5
Ethylene (part of petrochemicals)	75	85	12.6	7.4	32	2.6	1.6

- Assuming 25% market adoption

Fit with Current and Emerging Capabilities

The match between the need for various industrial processes for delivered heat and the capabilities of various IHP technologies is an important consideration for deployment. As shown in Figure 11 the temperature needed for industrial applications (shown here is the Food and Beverage sector extract from ECCA 2019) varies considerably. For the lower temperature applications commercially viable technologies are available. Above 100 ºC several technologies are in development.

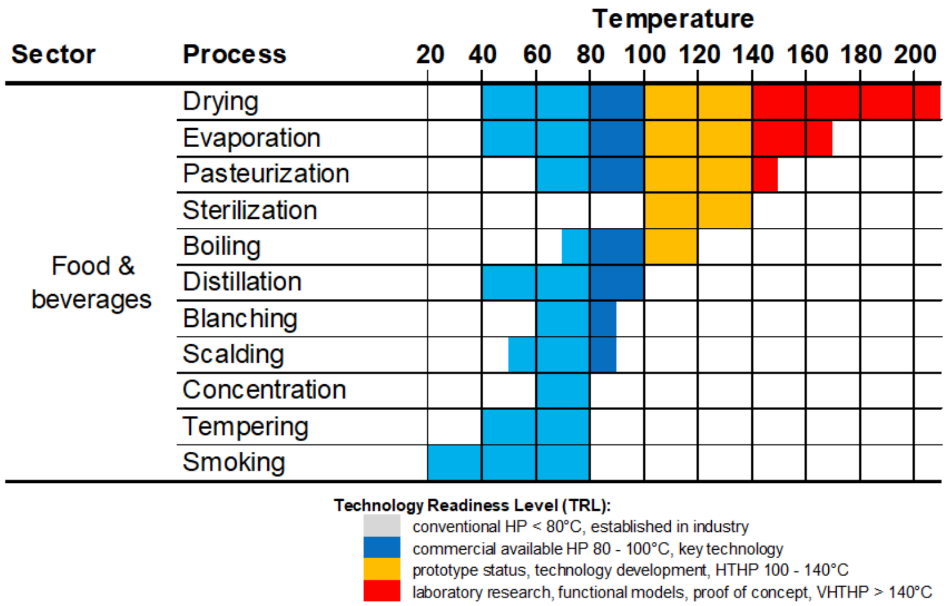


Figure 11. Temperature levels in °C for processes and IHPs in Food and Beverage. Source: ECCA 2020

Case Study for Dairy Processing

Dairy processing operations present a particularly apt use case for closed cycle mechanical vapor compression (MVC) heat pumps. Fluid milk production, and specifically pasteurization, requires heat at temperatures that can be economically delivered by today's commercial MVC heat pump technologies (with most processes operating in the mid 60's °C to the low 90's °C). Moreover, waste heat availability is sufficient—from cleaning fluids, chiller compressors, ventilation heating, and other sources) and temperature ranges are within temperature lift requirements for heat pumps where IHP COPs greater than 3 enable economic applications. IHPs evaporator heat exchangers also can deliver cool streams -offsetting a dairy facility's refrigeration requirements.

A technoeconomic model was used to determine the performance and financial characteristics of an IHP in the dairy context, demonstrating the sensitivity of economics to electricity and natural gas price ratio, capital and operating costs, and other factors. This model was used to calculate the IHP levelized cost of heating (LCOH) vs. a new-build natural gas boiler and to determine the net present value (NPV) of savings, the internal rate of return (IRR), and a payback period (PBP).[3] The analysis used industrial natural gas and electricity price data from the U.S. Energy Information Administration (EIA) on a state level. Also, more granular state-level electricity tariff data in Washington and Wisconsin allowed analysis to examine electricity to natural gas price ratio impact at the county level. Washington has relatively low electricity prices and relatively high natural gas prices, and Wisconsin has relatively high electricity and natural gas prices.

[3] Note: the model does not include financing costs, such as term debt, which are not sufficiently well-defined for a technology with scant deployment in the United States.

A hypothetical dairy pasteurization process (for fluid milk) was used for modeling closed cycle, mechanical IHP technoeconomic performance, where the IHP had access to a 45°C waste stream (from cleaning water), and delivery of upgraded heat at 85°C via hot water to the heat exchanger for pasteurization. Accounting for the temperature differential across the heat exchangers, the heat pump provided a final temperature lift of 40°C to 90°C. The model assumes capital and operating costs for the IHP and a comparative natural gas boiler based on published data. This modeled IHP was sized to completely offset the requirement for a natural gas boiler, which means that the IHP electrical capacity is quite large.

Figure 12 illustrates how the electricity to natural gas price ratio influences IHP economics for this modelled pasteurization process in top dairy-producing states. Blue bubbles represent a positive NPV and red bubbles negative. They are plotted according to gas prices (x-axis) and electricity prices (y-axis), and the bubble size is proportional to NPV magnitude. Included in the plot is an estimated 'break-even' line which shows the points at which energy price ratios produce a positive NPV[4] for the modeled IHP. The figure shows 8 cases run across six states with two states (Washington and Wisconsin) using some state-wide and some county-level data to better understand the variables that affect heat pump economics (such as demand charges).

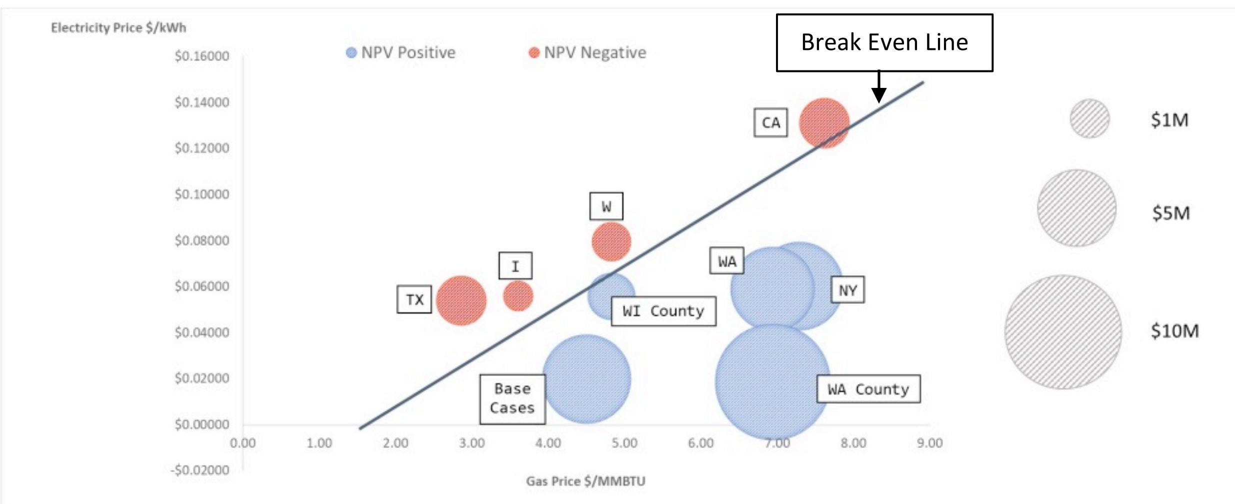


Figure 12. Net present value of case studies vs. energy costs for IHP use in Dairy Processing case study, reflecting the influence of electricity to natural gas price ratio. Source: this work

Additionally, a sensitivity analysis (Figure 13) showed a sharp drop-off in PBP at an electricity to gas price ratio of 0.01 (calculated as $/kWh / $/MMBTU. Payback periods of less than 2 years—a common threshold for industrial applications—persist below this ratio. This chart represents an IHP with a COP of ~4, indicating that the temperature lift is not so high as to detract from heat pump performance. Fluid milk processing provides such a temperature environment where the waste heat (source) and required process temperature (sink) are close enough to drive higher performance. This is not necessarily the case in other industries.

[4] The NPV was calculated using a discount rate of 4%, which is more common of established, low-risk technologies, which does not quite characterize IHP technology at present. However, the NPV figures in this analysis are largely illustrative in their relation to one another, not necessarily for their absolute dollar value.

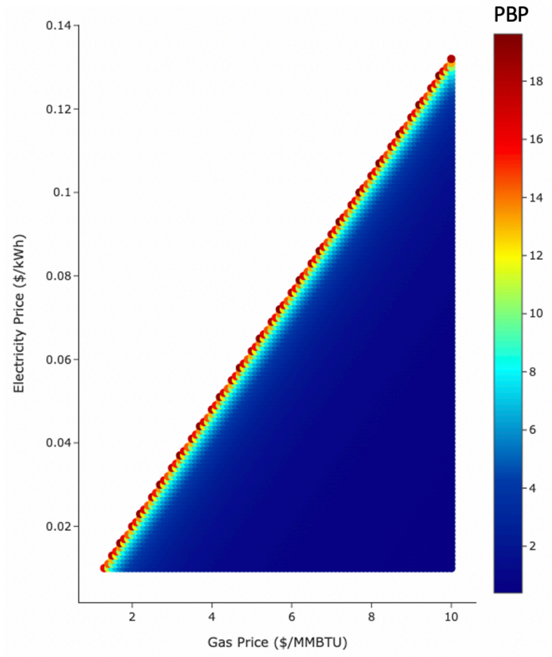


Figure 13. Payback period (PBP) of the modeled closed cycle, mechanical IHP vs. energy costs for the dairy process case study. Source this work.

Routes to Accelerate Deployment

Despite their benefits and increasing strength of drivers prompting their use IHPs face challenges that must be overcome to accelerate adoption. These include the areas shown in Figure 14.

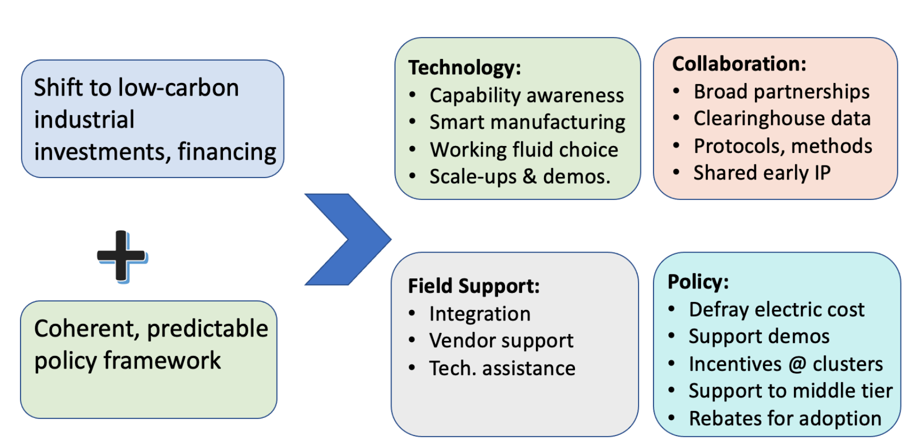


Figure 14. Enablers for IHP Adoption. Source: this work

Two essential ingredients are a shift in the strength of corporate commitments to reduce GHG emissions, and in parallel the development of a coherent, predictable policy framework for decarbonization that will be durable across decades. The former aligns with parallel investments to pursue GHG reductions via low-carbon technology adoption and development at scale of revolutionary processes with step-change reductions in energy use, emissions, waste, water use, etc. Numerous stakeholders will need to engage, including the investment community and supply chain partners to meet consumer demands for low-carbon products. In parallel, development of a policy framework is essential that is understandable, actionable without undue administrative burdens, and helps to reduce uncertainty and risk (e.g. it's predictable).

Several categories of enablers are shown to the right. Advances are needed in the understanding of technical capabilities of current, emerging, and transformative IHP technology. There are a lot of choices for IHP type, working fluid, location of heat exchangers, and integration aspects that require support from engineering firms. The integration with smart manufacturing is needed to ensure effective operation and cybersecurity, insure reliability, and quantify IHP benefits. Field-level support is needed so a cadre of organizations could help with engineering, economic evaluation, demonstrations, integration and ongoing maintenance of equipment.

Collaborations across industry partners, academics, national labs, government agencies, etc. can be key to the success of demonstrations at scale for emerging and transformative technology. Data and learnings from those demonstrations need to be visibile 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.

Policy can be a key enabler to address the major hurdles of E/NG price ratio, replacement of long-standing incumbent technology with long lifetimes, stranded assets, and the lack of domestic production of IHPs. Support for demonstrations is a key area where policy can make a difference -showing expanded IHPs applicability with energy and GHG savings and non-energy benefits. Industrial clusters are a key opportunity as the market for IHPs is concentrated there, successes will be highly visible, and integration benefits can be leveraged across multiple players. Policy can also help support development of middle layer service companies that provide engineering, integration advice, and field level maintenance.

Summary

Industrial heat pumps are one of the leading technology options for industry to transition to a lower carbon footprint via electrification. IHPs have been commercial for decades in the lower temperature ranges (<100 ºC delivery temperature), but the emergence of strong drivers for carbon reduction coupled with technical and economic advances in IHPs creates an opportunity for significantly increasing adoption and use of IHPs with broader capabilities and applications.

An exploration of the market and technical capabilities of current and emerging IHPs shows a strong fit for several types of IHPs across multiple industrial applications. A selection of the best application niches for IHPs narrowed the range of possibilities to 5 prototypical IHPs to further probe the energy and GHG impact potential. This work will spur conversations with industry, service providers, vendors, and policymakers on the next steps to increase adoption.

Acknolwedgements

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