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Industrial heat pumps: electrifying process heat supply in the United States through technology demonstration and market transformation actions

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Abstract

Industry accounts for almost a quarter of the energy use world-wide and energy-related carbon dioxide (CO_2) emissions. Industry has several pathways to step-change GHG reductions including electrification of process heat, which is responsible for 50% of on-site energy use. Industrial heat pumps (IHPs) can beneficially electrify much of the process heat needed for low to moderate temperature applications, helping to make dramatic cuts in industrial GHG emissions. Our research shows that moderate IHP deployment in industrial groups with high process heating demands (e.g., pulp and paper, chemicals, and food manufacturing) can save up to 30% of the source energy or 221.6 petajoules/year (equivalent energy use/year of 1.5 million U.S. homes). In parallel, IHPs can reduce CO_2 emissions up to 18.2 million metric tons /year (equivalent emissions from 4 million passenger cars or 1.3% of U.S. industrial CO_2 emissions). Expanded adoption of IHPs across all industrial sectors would save even more energy and CO_2 emissions.

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1. Introduction

The industrial sector, which accounts for almost a quarter of the world's greenhouse gases (GHGs) and energy use (including feedstocks) must be decarbonized in order to transition the economy towards a low-carbon future. One crosscutting industrial decarbonization pathway that has been under-explored is the electrification of process heat, the generation and use of which in U.S. industry accounts for 51% of on-site energy use at 7992.7 petajoules (PJ) (or 7,576 trillion Btu/year) (EIA 2014). The potential for electrification to transform the GHG footprint of process heat is significant, as electricity currently accounts for only 5% of this heat, while carbon intensive fossil fuels combine for the rest (Whitlock et al., 2020).

Industrial heat pumps (IHPs) are a key technology for industrial decarbonization through electrification (Whitlock et al., 2020). Using electricity generated from low-carbon sources, they can provide adequate supply temperatures of process heat to replace reliance on fossil fuels in industrial processes. IHPs were being commercialized in the late 90s (IEA 1995), but the availability of inexpensive natural gas in the U.S. cut into economic favorability, and adoption stalled. The urgency of the climate crisis and advancements in IHP technology (some IHP types can now reach 160° C (320° F), more than double the supply temperature of earlier models), make them a logical decarbonization pathway. In addition to electrifying process heat, IHPs can also reduce industry's carbon footprint by improving efficiency (by avoiding complex, unbalanced and inefficient steam operating systems) and reusing or recovering wasted low temperature heat.

Although there are multiple studies examining IHP potential, there is a significant gap in the analysis of actual process heating and cooling streams at the unit operations level. Our research aims to bridge this gap by

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examining the IHP market and demonstrations in varied industrial settings and geographical regions; matching capability fit with industrial needs via thermal energy analysis; determining the potential to reduce energy and GHGs; and finding enablers (including federal policy) needed to accelerate overall adoption.

2. Industry Processes and Heat Pumps

2.1. Process heat and thermal ranges of interest for IHPs

Figure 1 shows the temperature ranges of process heat demand in various industrial subsectors. Process heat is used in numerous applications that are common across these industry groups including fluid heating, distillation, evaporation, drying and melting. The temperature range of current IHP capabilities is between 60 and 160° C.

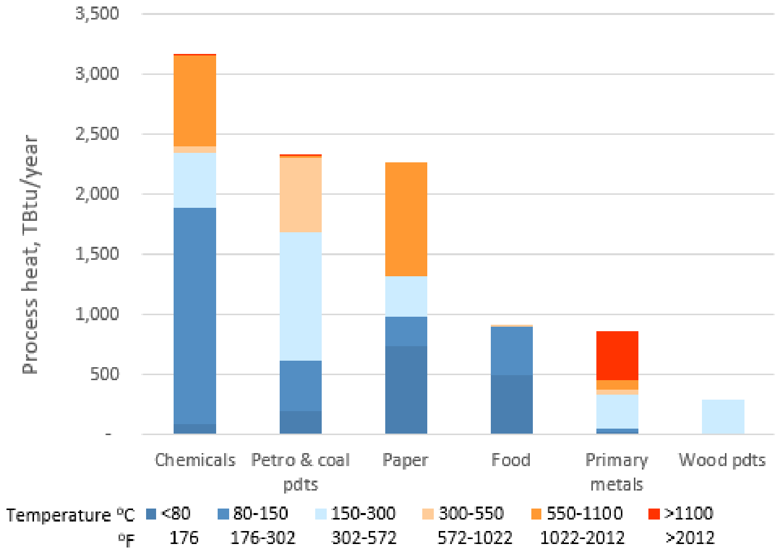

Fig. 1. Process heat demand at various temperature (°C) levels in select industries. Adapted from Adapted from "Manufacturing Thermal Energy Use in 2014," by C. McMillan, 2019, *National Renewable Energy Laboratory*

2.2. Industrial heat pumps

IHPs move heat up from a lower temperature heat source to a higher temperature heat sink. IHPs are similar in concept to residential/commercial heat pumps, however, they are more complicated, larger in capacity, engineered to integrate with industrial processes and expected to run continuously all-year round (high reliability). Figure 2 is a generic diagram of an IHP lifting waste heat at T_{source} and delivering heat to the process heat load at T_{sink}.

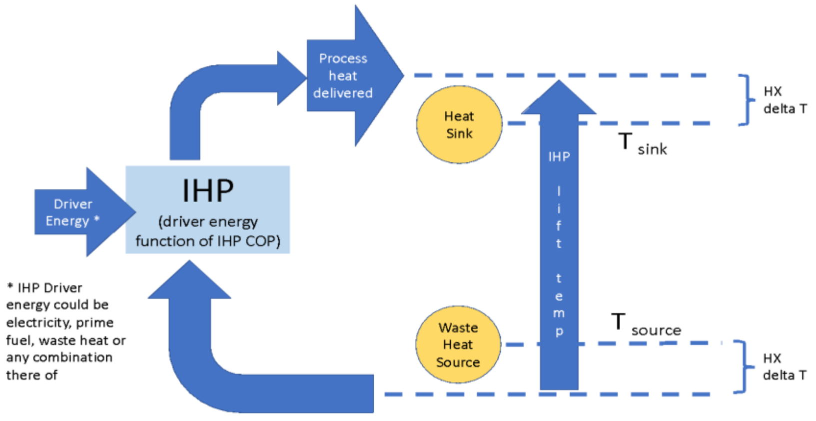

Fig. 2. Generic IHP diagram illustrating IHP lift temperature, T_{source} and T_{sink}. Source: this work

Our research examined six types of IHPs (more detail on their applications, data sources, and data treatment is provided below) (Rightor et al., 2022a). IHPs can be open cycle (where the heat pump working fluid is the process stream itself, such as, waste steam being compressed and returned to process) and closed cycle (where the heat pump has a heat exchanger on the heat source and sink sides to separate the heat pump working fluid from the processes). A classification of IHPs is provided in Figure 3.

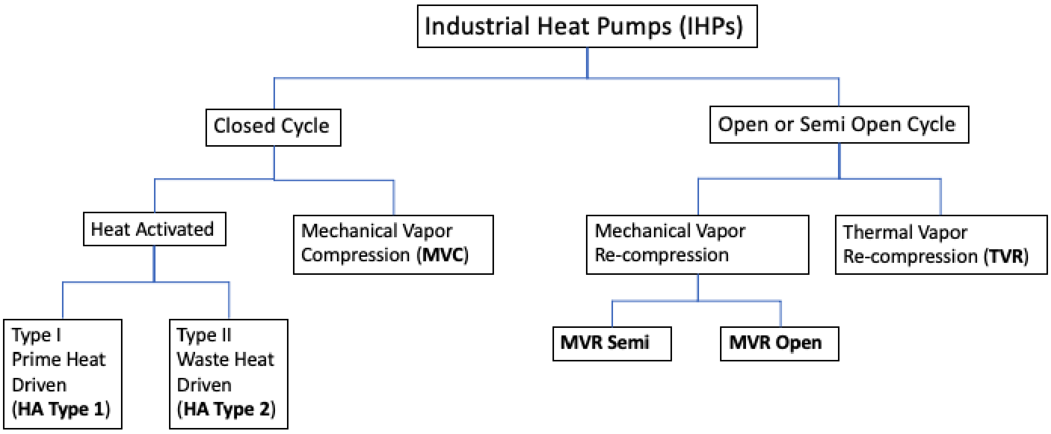

Fig. 3. Six different IHP types considered in this study (EPRI & RCG Hagler Bailly Inc., 1994). Adapted from "Industrial Heat Pump Report," by EPRI & RCG Hagler Bailly Inc, 1994.

The most common type of IHP is a mechanical vapor compression (MVC) heat pump which is a closed cycle system with an evaporator and condenser heat exchanger. Mechanical vapor re-compression (MVR) heat pumps are also applied in industry. MVRs directly compress the process fluid or steam without heat exchange on the heat sink or source side (semi-open cycle) or have no heat exchange (open cycle) on either side of the heat pump's compressor. Note: see appendix A of reference (Rightor et al., 2022a) for explanation of IHP types that were analyzed.

Prior studies show that moderate deployment of IHPs in manufacturing could avoid emissions of 12-25 million tons/year of CO_2 and save 2-5% of the total U.S. industrial process heat demand 180-370 PJ (or 170-350 trillion Btus/year) within 15 years (EPRI & RCG Hagler Bailly Inc., 1994). Advances in refrigerants (McLinden et al., 2014) and other working fluids to operate at higher delivery temperatures have broadened the range of IHP applications, such as in drying and recovery of waste heat, which can account for 12- 25% of industrial energy use (Lauermann et al., 2019). The market for IHPs is well-developed in Europe and Japan (Arpagaus et al., 2018), where there are strong policy incentives and economics. A recent study of the IHP potential in Europe indicates that 80% of the IHPs in industry would be less than 5 MW in thermal load capacity (Marina et al., 2021). Recent IHP demonstrations include those at 1 – 2 MW (Borealis, 2021).

2.3. Pinch analyses

Pinch analyses were used to find the optimum location for IHPs in the thermal flows of industrial processes (Rightor et al., 2022a). Pinch analysis is a method for minimizing energy consumption by optimizing energy supply and process heat recovery systems (Natural Resources Canada, 2003). It identifies the best hot streams which are being cooled (heat source) and cold streams which need to be heated (heat sink) for the heat pump to operate between heat source and sink. The Pinch analysis optimizes the heat transfer process between the hot and cold streams to minimize the amount of external process heating and cooling needed. This leads to defining a "pinch point" on the temperature scale in the whole process where heat transfer cannot occur anymore between the hot and cold streams since the temperature driving force required is not available. The ideally placed and integrated IHP takes heat from a heat source below the pinch point and upgrades or "lifts" the heat to a desired heat sink above the pinch point. An energy balance must be maintained between the heat source, heat sink, and the work done by the IHP. Optimal matching of the heat source temperature and the amount of heat required is the key to successful IHP implementation. If done efficiently, heat exchangers can be minimized, particularly above the pinch point.

Figure 4 shows an example of two pinch analysis simulations for a typical potato drying process. The x-axis shows the heat load (kW), and the y-axis shows the corresponding temperature levels for those heat loads. The blue lines represent the cold stream that needs to be heated and the red lines represent the hot stream that is being cooled. The overlap between the red and blue lines is the area of possible heat exchange. The difference between the cold stream heat load and the hot stream heat load, noted by the arrow in the upper right, represents the process heat demand which must be supplied by external sources (steam, direct firing) and is designated as Q_{hot}. The main goal of applying an IHP is to cost-effectively reduce Q_{hot} to the minimum possible amount. Figure 4 (left) shows the baseline case. Note the process heat demand of 3,725 kW and the pinch temperature at about 52°C. Figure 4 (right) shows the same process but with the application of an IHP used in an optimized configuration. Note that the process heat demand has been reduced to 2,314 kW and the pinch temperature has also moved up to about 70°C.

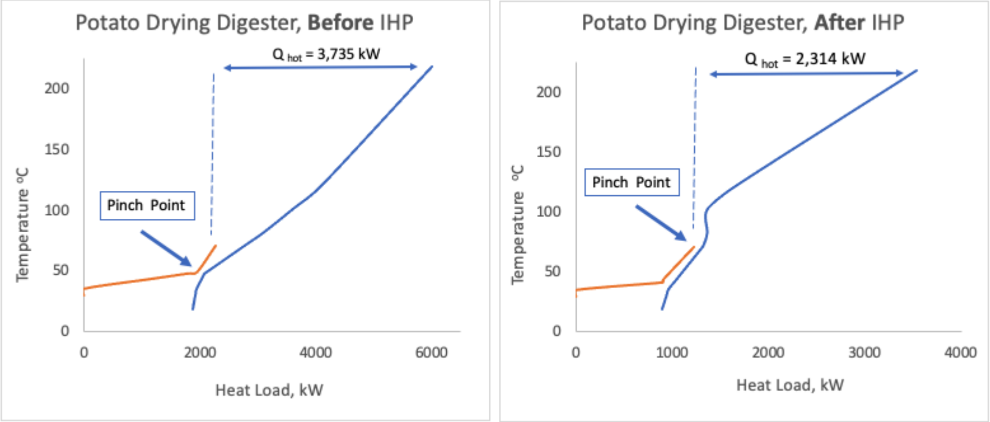

Fig. 4: Comparison of pinch analysis between the hot & cold composite curves for potato drying, with left being **Before** and right **After** the IHP installation. Source; this work.

3. IHP analysis

3.1. Industrial groups and unit operations analyzed.

The industrial groups and unit operations analyzed in this work are shown in Table 1 (Rightor et al., 2022a).

Table 1. Industrial groups and unit operation analyzed.

Industrial group	Unit operation
Paper	Pulp mill (PM)– digestor Pulp mill (PM)– multi-effect evaporator Non-integrated paper mill – pulper
Food	Wet corn milling (WCM) – steepwater Wet corn milling (WCM) – high fructose corn syrup starch conversion Potato processing – hot air dryer
Chemicals	Ethylene (above ambient) – process water stripper reboiler and debutanizer Ethanol fuel, dry mill

3.2. Industrial heat pump analysis approach.

All industrial process models used actual industrial heating and cooling stream data (ie., mass flow rate, specific heat and temperature increase or decrease for each stream) that was provided by Chalmers University from previous research (Franck et al., 2020). To assess the energy savings potential, we estimated both the "Economic" and "Technical" IHP potential. The Economic potential simply used one hot and one cold stream for the heat pump's heat source and sink. The IHP lift was limited to less than 40° C, which is within the capability of a single-staged compression IHP. The Technical potential case is more aggressive by using multiple heat sources and sinks at varying temperatures. Multiple staging of heat pumping (2 stages) were possible for the Technical case and the hot and cold streams were not limited to constant temperatures (Rightor et al., 2022a). Figure 5 illustrates the differences between the Economic and Technical IHP potential.

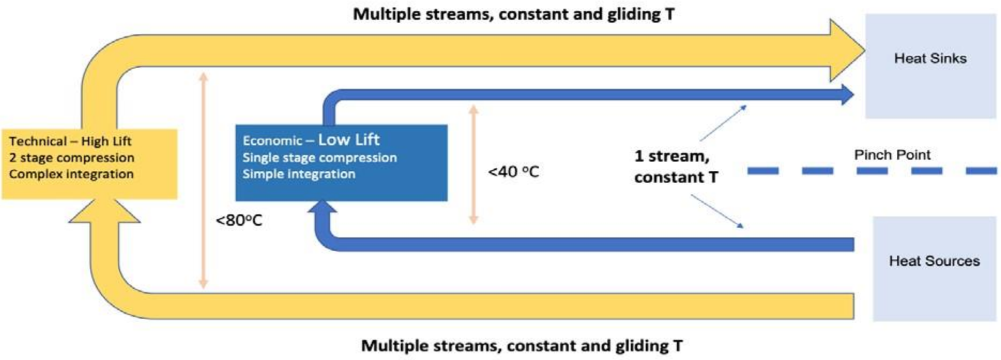

Figure 5. Economic and technical IHP potential energy savings

Energy savings across any sector were calculated based on the assumption that all U.S. production was impacted by heat pumping. Table 2 shows the overall approach to analyzing the energy savings and carbon reduction for the sectors shown in Table 1. The analysis progresses left to right: sector process analysis to pinch and heat pump analysis to sector energy savings and carbon emission analysis.

Table 2 – Heat pump analysis methodology to determine sector energy savings and carbon reduction.

Sector Process Analysis	Pinch and Heat Pump Analysis	Sector Energy Savings and Carbon Emissions
Overall U.S. sector production (tons product/year)	Process specific heating and cooling stream data – enthalpy and temperature for multiple streams	Apply heat pump unit operation savings for six IHP types across all sector facilities
Sector - # U.S. facilities with similar production	Pinch analysis of heating and cooling streams to identify streams (source/sink) for heat pumping	Calculate site and source energy savings based on natural gas saved and heat pump driver energy requirement for all 6 IHP types
Sector total process heat demand (GJ/year)	Calculate heat pump energy savings for 6 different IHP types	Calculate overall sector carbon emission reductions based on natural gas saved and heat pump driver energy type requirement for all 6 IHP types
Sector total carbon emissions (MMTCe/year)	Determine heat pump driver energy requirement for 6 IHP types – GJ and energy type (electricity, heat)	
Process heat unit operation hot utility targetable by IHP (GJ/ton)	Calculate heat pump energy savings on unit operation (site and source)	

The Pinch analysis model determined the amount of thermal energy recoverable by heat pumping relative to the overall process heat supplied. This represented the amount of thermal energy savings that was possible with the application of the heat pump. The actual percentage energy savings varied by heat pump type (Table 3 below shows results for MVC heat pump only) because different heat pump types could capture different amounts of waste heat (source) relative to the heat delivered (sink). Table 3 shows this as natural gas savings (%). Additionally, the different heat pumps have different COPs for the given lift temperature, and this results in different amounts of heat pump driver energy required. Table 3 below shows this as electricity increase (%). Therefore, unit operation natural gas savings for each heat pump type was found by multiplying tons of production for sector by production energy per ton and then by natural gas savings (%) per ton. Similarly, unit operation electricity increase for each heat pump type was found by multiplying tons of production for sector by production energy per ton and then by electricity increase (%) per ton.

Energy savings across any sector were calculated based on the assumption that all U.S. facilities making the product were impacted by heat pumping. This can 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.

3.3. IHP summary across all industrial groups and unit operations studies

Results for IHP application across all industrial groups and unit operations studied are summarized in Table 3 (Rightor et al., 2022b) for the MVC IHP case. The simple payback was based on natural gas prices of

$6.86/ billion joules (or $6.5/MMBtu) and electricity price of 6 cents/kWh.

Table 3. Summary of results across all unit operations for the MVC IHP. Source: this work.

		Natural gas savings		Electricity increase		CO_2 decrease		Simple payback
Industry group	Unit operation	PJ/ year	%	MM kWh/ year	%	MMTCe/ year	%	years
Food	Potato drying	6.0	40.4	962	11.2	0.4	24.3	4.5
	WCM steepwater	2.1	20.4	128	5.5	0.1	1.2	3.7
	WCM, high fructose corn syrup	3.3	75.8	173	17.9	0.1	1.9	4.4
Paper	PM Digester	40.4	34.6	2,384	9.2	1.0	21.7	4.2
	PM multi effect evaporator	90.4	45.1	4,169	9.4	2.6	34.5	3.8
	Non-Integrated mill pulper	3.3	9.3	197	2.5	0.1	5.7	2.5
Chemicals	Ethylene debutanizer	5.3	18.4	6	3.4	0.2	15.1	1.9
	Ethylene water strip reboiler	1.3	9.8	66	2.2	0.0	7.0	2.2
	Ethanol fuel, dry mill	260.4	90.0	10,313	16.0	8.2	52.0	1.9
	Total	**422.1**		**18,398**		**12.6**		

Across all industrial groups and unit operations the total source energy savings are shown in Fig. 6. This plot shows that the total source energy savings is significantly higher for the Technical potential cases as expected given the more extensive application of IHPs assumed. Although lower energy savings are shown for the heat activated (HA) IHP types, it's 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 the penalty of high electricity operational costs. The MVR-Semi Open 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 (e.g., high pump lift temperatures are lower than for the MVC type). The elimination of heat exchange translates into overall source energy savings.

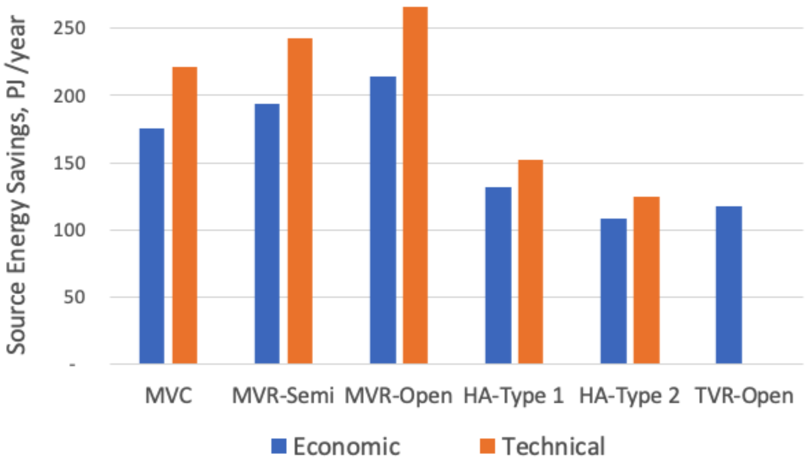

Fig. 6. Summary of source energy savings for all nine unit operations combined. Source this work.

While the IHPs save natural gas, electricity is required to run the compressors for the MVC, MVR Semi Open 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 Open and MVR Open heat pumps, but their COPs are lower and thus the thermal energy (natural gas) savings are lower.

3.4. Magnitude of energy and GHG reductions

Figure 7 shows the magnitude of the energy changes for natural gas and electricity usage for all nine unit operations analyzed. The increased electric load is shown to the right of the y-axis, and the natural gas reduction is shown to the left. Looking at the MVC, MVR-Semi, and MVR-Open types, the natural gas savings are similar, but the electricity demand 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 Open eliminates one heat exchanger and the MVR Open two heat exchangers, so the lift is lower resulting in lower electricity needs. The HA types require much lower amounts of electricity since they pump liquids and do not compress vapors but their lower heating COP vs. vapor compression heat pumps yield lower net energy savings.

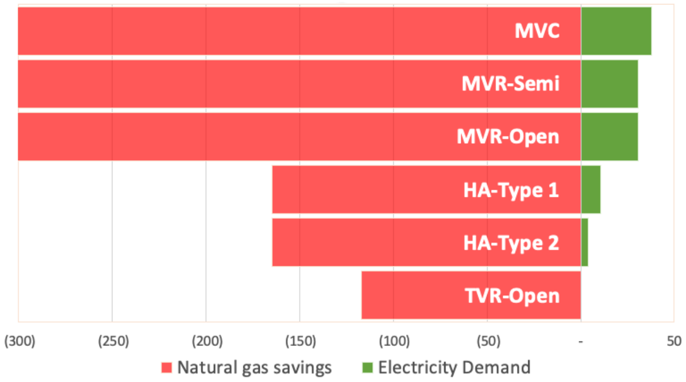

Fig. 7. Energy changes across all nine unit operations, Economic case, PJ/year. Source: this work.

Figure 8 shows the changes from a carbon perspective, where it's evident that the increase in carbon emissions from electricity (right, green) is significantly less than carbon emissions reduction from the decrease in natural gas use (red, left), indicating an overall net decrease in CO_2e emissions. As the electric grid incorporates more low-carbon energy and the emissions factors decrease, the carbon emissions footprint for electricity will also decrease, and the difference between the electricity and natural gas bars will become larger for the MVC types (as the electricity to run the compressors will have a lower carbon intensity).

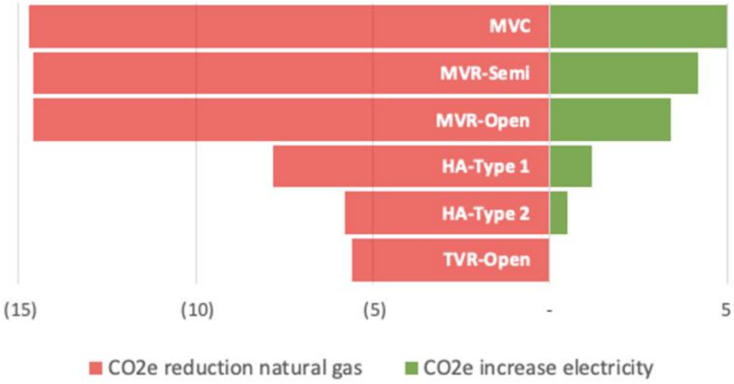

Fig. 8. Changes in CO_2e across all nine unit operations, Economic case, in millions of metric tons CO_2e/year. Source: this work.

3.5. 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). An estimate was made then for the application of IHPs not only in the nine unit operations analyzed but also an extrapolation across a broader application base in the three industrial groups examined. Table 4 summarizes the results for the nine unit operations analyzed in the 3 industrial groups, as well as the Industrial group-wide adoption extrapolation for natural gas, source energy savings, electricity demand increase and carbon reduction —near and long-term (when more low-carbon generation capacity decreases emissions factors for the electric grid).

Table 4. Energy savings and carbon reduction for IHP applications. Source: (Rightor et al., 2022a)

Unit Operations analyses only*	Food, min.	Food, max.	Paper, min.	Paper, max.	Chemicals	Total, min.	Total, max.
Natural gas savings, PJ/year	6.0	21.1	36.3	134.1	267.0	309.3	422.0
Source energy savings, PJ/year	2.9	7.5	20.1	61.2	152.6	175.6	221.6
Electricity consumption, MM kWh/year	288.0	1263.2	1500.0	6750.3	10595.4	12383.3	18609.0
Electricity demand increase, MW	32.9	144.2	171.2	770.6	1209.5	1413.6	2124.0
Heat pump output, MW	152.6	535.3	921.9	3402.8	6773.1	7847.6	10711.0
CO_2 savings, near term MTCe/year	0.20	0.50	1.10	3.70	8.40	9.7	12.6
CO_2 savings, long term MTCe/year	0.30	0.90	1.60	5.70	11.60	13.4	18.2
Sector-wide projection							
Natural gas savings, PJ/year	21.1	76.0	50.6	188.8	721.6	793.4	986.4
Source energy savings, PJ/year	10.2	26.8	28.1	86.2	412.3	450.4	517.9
Electricity consumption, MM kWh/year	1010.5	4547.8	2090.3	9504.1	28639.2	31761.0	43498.5
Electricity demand increase, MW	115.3	519.2	238.6	1084.9	3269.3	3625.7	4964.9
Heat pump output, MW	535.3	1927.1	1284.7	4791.0	18307.7	20127.7	25037.0
CO_2 savings, near term MTCe/year	0.7	1.8	1.5	5.2	22.7	24.9	29.5
CO_2 savings, long term MTCe/year	1.1	3.2	2.2	8.0	31.4	34.4	42.5

* PJ = petajoules, MM = millions, Ce = carbon equivalents for CO_2, M =1000, kW = kilowatts

4. IHP Deployment and Market Transformation

4.1. IHP Demonstrations

The next phase of our research includes IHP demonstrations where we are partnering with several utilities and a state research energy agency. Demonstrations aim to remove the technical risk, demonstrate IHP energy performance and economics in a variety of sectors and common industry processes. Evaluation factors in choosing at least 3-5 IHP demonstrations that will enable accelerate U.S. IHP deployment, include the following:

- Significant energy saving and GHG emission reduction potential in the currently available temperature range and IHP lift temperature required (e.g., <120° C heat sink range and <40° C lift) and thus favorable economics (e.g., < three-year payback)
- Widespread replicability potential within a sector or sectors due to common unit operation or process across the sector which minimizes technical risk.
- High replicability with a standard IHP designs that minimize significant site-specific engineering (e.g., fuel ethanol, alcoholic beverage, wet corn milling, lumber drying)
- High value product where non-energy benefits (better temperature control, lower maintenance costs, improved yield) are significant in addition to the energy saving benefits (e.g., applications in pharmaceutical, food & beverage.)

We are working with our regional utility and state energy agency partners and their customers to identify other good IHP candidates. Industrial sectors to pinpoint as good candidates for IHP application include the nine unit operations from our research (Rightor et al. 2022a), 13 industrial sectors and subsectors identified from another recent IHP study (Zuberi et al., 2022), and those highlighted by our regional partners with input from their industrial customers. Those high potential sectors include beer brewing, wet corn milling, high fructose corn syrup, lumber drying, paper drying, ethanol, ethylene, automotive processes, and metal manufacturing processes, among many others.

4.2. Regionality

The payback estimates above (Table 2) demonstrate that for the MVC and MVR IHPs with natural gas at \$6.86/ billion joules (BJ) (or \$6.5/MMBtu) and electricity at 6 cents/ kWh, the paybacks range from 2 to 4 years, which is considered economical for U.S. industry. This is a ratio of approximately 2.7 with electricity/natural gas price. Figure 9 shows the many U.S. states where the ratio of electricity/ natural gas is near that number (note data used was 2021 industrial rates). There could be early IHP adoption opportunities in those states.

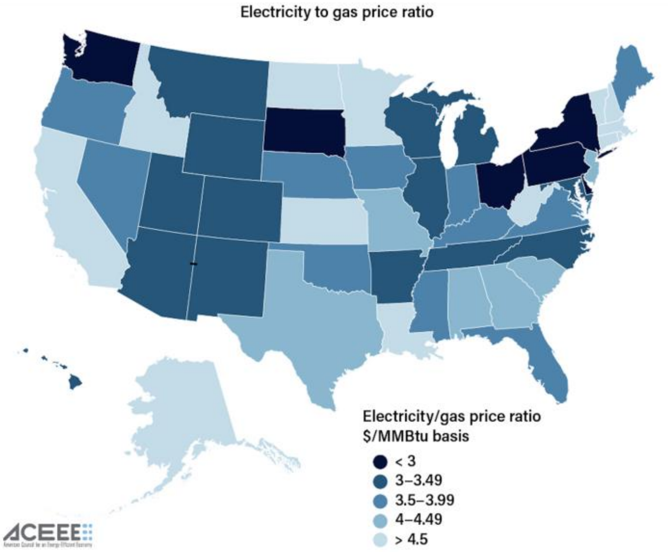

Fig. 9. Illustration of electricity/ gas price ratio by state. Source: this work. .

4.3. IHP market barriers

The barriers to IHP adoption must be identified and considered to form an effective market transformation strategy for IHP deployment that is scaleable throughout U.S. industry. IHPs are currently a niche product today in the U.S. market due to a variety of market constraints. The major constraints that a market transformation initiative will need to address are:

- *Limited product availability in North America:* A recent survey of IHP suppliers found that 24 of them were headquartered and manufactured in Europe and another 3 based in Japan (Arpagaus, 2022; IEA, 2022). Although, there are a few U.S.-produced products that center on industrial applications (mainly wood products and process heat as a service). IHPs are large products that can be expensive to ship so in order for a large IHP market to grow in the U.S., more products will need to be produced in North America. Additionally, European, Japanese and non-U.S. domestic IHP suppliers will need to modify their designs to account for U.S. code differences (heat exchangers, electrical service rating, etc.). IHP equipment manufacturers need to see sufficient market demand to justify both marketing of their products and/or investment to scale up North American production.
- *Limited knowledge by industrial decision-makers and engineers:* Most industrial decision makers are not familiar with IHPs and even many engineering firms have limited knowledge. Experienced engineers can optimize systems in ways that reduce system size and costs while providing important operating benefits, but most engineers presently lack this awareness, expertise, and experience. Many industrial applications cannot simply implement a one-size-fits-all solution so may require tailored system designs.
- *Economic challenges:* The economics of IHPs not only depend on the relative cost of electricity and natural gas, but also on the electric rate structures (e.g., demand and interconnection charges). Site specific timing and considerations are important. Strategies are needed to focus on the applications with the best economics, provide the tools to help manage project costs, and realize the greatest non-energy benefits for the process changes.
- *Service and maintenance:* Personnel to service and help maintain equipment are in limited supply and are often not local to the plants, risking extended production outages. More staff need to be trained and service infrastructure scaled up in parallel with expanding installations to support these projects in the field.

- *Electrical service capacity increase limitations:* U.S. industry is experiencing limitations on how much and/or how fast they can expand the amount of electric supply they can accommodate in their facilities due to long lead times by electrical equipment suppliers to increase electrical capacity. IHPs will require a substantial change in electricity capacity in facilities and could be limited by electrical service available.
- *Equipment certification:* IHPs made abroad haven't been through Underwriters Laboratory (UL) listing. Also, building code challenges exist for using some low-global warming potential, or regulations on using refrigerants that are potentially flammable.

4.4. Strategies to initiate market transformation.

The following strategic near-term actions could help to propel the manufacture and implementation of IHPs in the U.S.:

- *Support manufacturers to scale-up domestic availability of equipment:* Activities to expand domestic product offerings and bring manufacturing to the U.S., such as, government financial incentives to grow manufacturing for IHP technologies and components.
- *Coordinate with utilities, regulators, large customers, and federal agencies to foster a market for substantial growth in IHP sales:* Collaboration amongst the key IHP stakeholders to support technology demonstrations and education of large customers is critical. For example, U.S. Department of Energy announced the Industrial Heat Shot initiative in September 2022 (DOE Industrial Heat Shot, 2022) to drastically reduce emissions from the energy-intensive process heating applications. Industrial heat pumps can play an important role, as was identified in the recent DOE Industrial Decarbonization Roadmap (DOE, 2022).
- *IHP demonstrations, information and tools:* Support the identification, design, installation and validation of performance on IHPs in varied industrial applications with case studies documenting the cost-benefits of each demonstration.
- *Create awareness, knowledge, and workforce:* A communication campaign needs to be developed and deployed to raise the awareness of IHP technologies and benefits among utilities, engineering firms, service personnel and large customers. Training of engineering firms and service personnel needs to be delivered to build IHP related skills.
- *Work with utilities and regulators to develop rate structures in support of IHP:* Rate structures that incentivize IHP installation and yet fairly recovers the utility's fixed costs.
- *Tax incentives and low interest loans:* Federal tax credits for industrial end users to purchase IHPs and low interest loans for IHP equipment manufacturers to establish and/or expand IHP manufacturing capacity would further help to grow the U.S. IHP market.

5. Summary

IHPs can significantly improve the energy efficiency of process heating and cooling applications and reduce CO_2 emissions across the industrial sector. The sectors with applications that are most applicable for IHP implementations are pulp and paper, food and beverages manufacturing, and the chemicals industry, where there are significant proportions of process heating needs at low-moderate temperatures (60 to 200° C). Barriers must be overcome including economics, technical risk, integration, and development of local service capabilities. Enabling policies and programs by government and utilities would accelerate IHP adoption. IHPs can be a key technology in aiding beneficial electrification, with CO_2 reduction benefits increasing as the electric grid becomes less carbon intensive. Key learnings from our research include:

- IHPs were typically able to save 10 to 30% of the energy used for process heat generation.
- The vapor compression type IHPs natural gas savings were typically 2.7 to 3.7X the increases in electricity use . Similarly, the CO_2 reductions from natural gas savings were 3.5-4.7 X the CO_2 associated with electricity use. Simple paybacks for the compression type IHPs were near or under 3 years at a natural gas price of $6.86 /BJ when electricity/natural gas price ratio was 3 or less.
- 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 these type of IHPs can potentially have greater impact due to their flexibility and ability to lift heat higher without the penalty of higher electricity consumption and cost as with vapor compression systems.
- Across all unit operations, the IHP analyses showed the potential to reduce process heat energy 309 - 422 PJs/year (42-57% of the process heat energy in the industrial groups). The potential for CO_{2e}

reductions was 25 - 29 million metric tons CO_{2e} /year. With lower emissions factors for grid produced electricity by 2050, the reductions potential would be 34 - 43 MMT CO_{2e} /year.

A variety of market transformation initiatives could be deployed to build the U.S. market for IHPs, including:

- Support manufacturers to scale-up domestic availability of equipment
- Coordinating with utilities, regulators, large customers, and federal agencies to foster a market for substantial growth in IHP sales.
- Supporting IHP demonstrations with validation and verification of the cost/benefits as well as developing more up-to-date process data and IHP analysis tools
- Creating awareness, knowledge, and workforce with comprehensive training at all levels.
- Working with utilities and regulators to develop rate structures in support of IHP.
- Creating tax incentives and low interest loans

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Nomenclature

Acronym	**Definition**
Btu	British thermal unit
BJ	Billion Joules
CO_2e	Carbon dioxide equivalent
COP	Coefficient of performance
GHG	Greenhouse gases
HA	Heat activated (heat pump)
IHP	Industrial heat pump
KWh	Kilowatt hour
Lift	Lift is the magnitude of temperature, by which the IHP raises the temperature from T_{source} to T_{sink}
MMBtu	Millions of British thermal units
MT	Metric tonne
MMT	Millions of metric tons
MVC	Mechanical vapor compression
MVR	Mechanical vapor recompression
MW	Megawatt
PJ	Petajoules
Q_{hot}	Process heat demand which has to be supplied by external sources
RD&D	Research development and deployment
TBtus	Trillions of British thermal units
T_{source}	Temperature of the waste heat or heat source of the industrial heat pump to be lifted to the heat sink
T_{sink}	Temperature of the heat sink to be heated by the industrial heat pump
TVR	Thermal vapor recompression
WCM	Wet corn milling

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