Industrial Heat Pump Market Study

Final Report

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Disclaimer

Executive Summary

To date, less than five percent of process heat uses electricity, generally relying more on fossil fuels (Rightor et al., 2022). The industrial sector, which includes process heat, accounts for more than 25 percent of greenhouse gas (GHG) emissions in the United Sates (U.S.) with 50 percent of thermal energy being produced on-site (U.S. EIA, 2021a). This report outlines the findings for a market study on industrial heat pumps (IHP). Although IHP installations are growing around the world, especially in Europe, Japan, and Australia, there are few installations in the U.S. This presents a large growth opportunity for this technology across multiple industries and applications as proliferation of IHPs can directly impact GHG emissions.

Heat pumps have wide applicability to industrial process loads. However, the efficiency of heat pumps declines as temperature lift increases thereby limiting target industries for IHPs because of the high process temperature requirements. Currently, commercially available IHPs can supply temperatures up to 165°C (329°F) and approximately 35 percent of industrial heat processes fall within this range (Arpagaus et al., 2017) (Rissman, 2022).

This study investigated IHP applications for eleven industrial subsectors including meat processing, dairy, beer, canned vegetable and fruit processing, cane sugar refining, beet sugar, corn wet-milling, soybean oil, textiles, pulp and paper, and automotive industries. The evaluation was performed based on the Lawrence Berkeley National Laboratory's analysis, which estimated IHP potentials using two scenarios: a conservative use case and aggressive use case (Zuberi et al., 2022). The conservative case considered only high temperature heat pump (HTHP) applications, requiring process temperatures less than 100°C (212°F) and boiler pre-feed. The aggressive case considered both HTHPs and steam generating heat pumps (SGHPs).

The total U.S. potential IHP heating capacity was found to be 9,870 MW and 21,726 MW for HTHP and SGHP, respectively. (Zuberi et al., 2022) From the industries analyzed, California contributes approximately seven percent of the total potential IHP heating capacity of the U.S. with a total potential IHP heating capacity of 1,051 MW and 1,069 MW for HTHPs and SGHPs, respectively.

As California continues to decarbonize its grid, both HTHPs and SGHPs have the potential to be part of the industrial sector electrification solution to meet net-zero emissions goals. Furthermore, if electricity is supplied to IHPs from zero-emissions sources, a significant amount of heat can be considered emissions-free.

This report reviewed the status of the technology by identifying current demonstrations and IHP manufacturers. Industry experts and manufacturers were interviewed to obtain additional information about the market, high value applications, market adoption drivers, market challenges and barriers, and future developments. Additionally, recommendations for utility program pathways were summarized from the findings. IHP technology and industrial markets are both evolving at a rapid pace, so this report may not address all current issues or opportunities in the marketplace.

Abbreviations and Acronyms

Acronym	Meaning
°C	Degrees Celsius
°F	Degrees Fahrenheit
€	Euros
ACEEE	American Council for an Energy-Efficient Economy
AHRI	Air-conditioning, Heating, & Refrigeration Institute
ANSI	American National Standards Institute
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BAU	Business-as-Usual
Btu	British thermal unit
CAD$	Canadian Dollars
CARB	California Air Resources Board
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DOE	Department of Energy
EE	Energy Efficiency
EPA	Environmental Protection Agency
ESG	Environmental, Social, and Governance

Acronym	Meaning
ETL	Electrical Testing Laboratories
E.U.	European Union
GHG	Greenhouse Gas
GW	Gigawatt
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbons
HFO	Hydrofluroolefins
HP	Heat Pump
HTHP	High Temperature Heat Pump
IHP	Industrial Heat Pump
IIAR	International Institute of Ammonia Refrigeration
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
M	Million
MMBTU	Million British thermal units
Mt	Million tons
MW	Megawatt
MVC	Mechanical vapor compression
MVR	Mechanical vapor recompression
NAICS	North American Industry Classification System
NASA	National Aeronautics and Space Administration
NEMA	National Electrical Manufacturers Association

Acronym	Meaning
NH_3	Ammonia
NMEC	Normalized Metered Energy Consumption
PJ	Petajoule
PFA	Per- and polyfluoroalkyl substance
psig	pounds per square inch gauge
SB	Senate Bill
SGHP	Steam Generating Heat Pump
TAP	Technical Assistance Partnership
TJ	Terajoules
TWh	Terawatt Hours
UL	Underwriters Laboratory
US$	U.S. Dollars
VHTHP	Very High Temperature Heat Pump

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Introduction

Industrial heat pumps (IHPs) are used to efficiently generate heat for large-scale industrial processes. When compared to residential and commercial heat pumps, IHPs are typically designed to handle much larger heating loads, higher temperatures, and higher pressures. Industrial heat pumps are an underutilized technology, mostly due to the critical roles the incumbent technology plays within existing industrial processes (such as natural gas boilers). For example, in the pasteurization process of many food and beverage products, it is essential that process temperatures are kept high enough to prevent bacteria growth to avoid health risks (Virginia Department of Health, 2017). End users are generally hesitant to embrace unfamiliar technology that is less common or mature. Existing studies indicate that there is significant and quantifiable energy and greenhouse gas (GHG) savings potential by replacing more common natural gas heating technologies with IHPs. This study will serve to provide additional context as to how this technology can play a role in decarbonization and reducing energy usage within California.

Industrial heat pumps can reduce the energy consumption of processes due to their high thermal efficiencies when compared to traditional gas heating technologies. They are especially efficient for low-temperature heating applications or when waste heat can be recycled from other processes within the same facility. These reductions in energy consumption can translate to decreased operating costs for facilities depending upon the price of fuel and electricity. In addition, IHPs can reduce carbon emissions by displacing fossil fuel usage with renewable electricity. Through electrification, IHPs can enable other potential revenue generating opportunities such as incentives from utility grid-flexibility programs. By using IHPs, the heat quality may also be improved, making it easier to precisely control the temperature of processes compared to combustible fuels. Industrial heat pumps may be more scalable compared to other technologies in several scenarios such as facilities in mild climates without significant seasonal temperature fluctuations. Some technologies, such as solar thermal or geothermal solutions, may not be readily available due to local climate and geographic location and may also require more space for equipment at industrial sites (WBCSD, 2022). Industrial heat pumps typically require less maintenance compared to combustion systems and may produce a safer air quality environment. They are known to be reliable with a very long lifespan of over 20 years (RPS Group, 2022).

Background

The Industrial sector in the U.S. uses approximately 7,576 trillion BTUs of heat annually for process heating, with 51 percent being produced on-site (EIA 2021a). Only five percent of the process heat is generated by electricity today, with the rest generated from fossil fuels (Rightor et al., 2022). The thermal processes are responsible for approximately two-thirds of the usage (U.S. DOE/Energetics, 2022; U.S. EIA, 2021b) and account for approximately 25 percent of the country’s total energy use and GHG emissions (U.S. EIA, 2021a). With this large amount of GHG emissions, an effort to decarbonize industrial processes plays a critical role in attaining a net-zero carbon future.

IHPs were developed and commercialized in the U.S. from 1980 to 2000. However, the low cost of natural gas made IHP installations uneconomical and unattractive. Now, more than a quarter-century later, IHPs are getting more attention due to the urgency to cut industrial GHG emissions. In addition, the advancements made to the IHP technology in recent years has made them more technologically and economically feasible. The recent increase in corporate appetite for sustainable energy and GHG reduction is yet another argument for implementing IHPs without delay (Chudnovsky, 2023).

Technical Description

A heat pump is a device that moves heat from a lower temperature (heat source) to a higher temperature (heat sink). They were first developed for use in refrigeration systems where the heat rejected at the condenser is used instead of simply rejected to the atmosphere. In some cases, a heat pump can simultaneously perform cooling and heating by recovering heat rejected from the condenser (Stoeker et al., 2001).

Heat sources can be air, water, geothermal, waste heat from an industrial process, or recycled wastewater. A liquid refrigerant with a low boiling point absorbs the heat in the evaporator from the heat sources and becomes gas. The compressor then compresses the refrigerant gas to a higher pressure and the heat is rejected to the heat sink at the condenser. The heat sink can be used for space heating, water heating, process heating, and so on. The refrigerant gas is throttled in the expansion valve to a lower temperature and pressure and returns to the evaporator to complete the cycle. Figure 1 shows the thermodynamic representation of a heat pump.

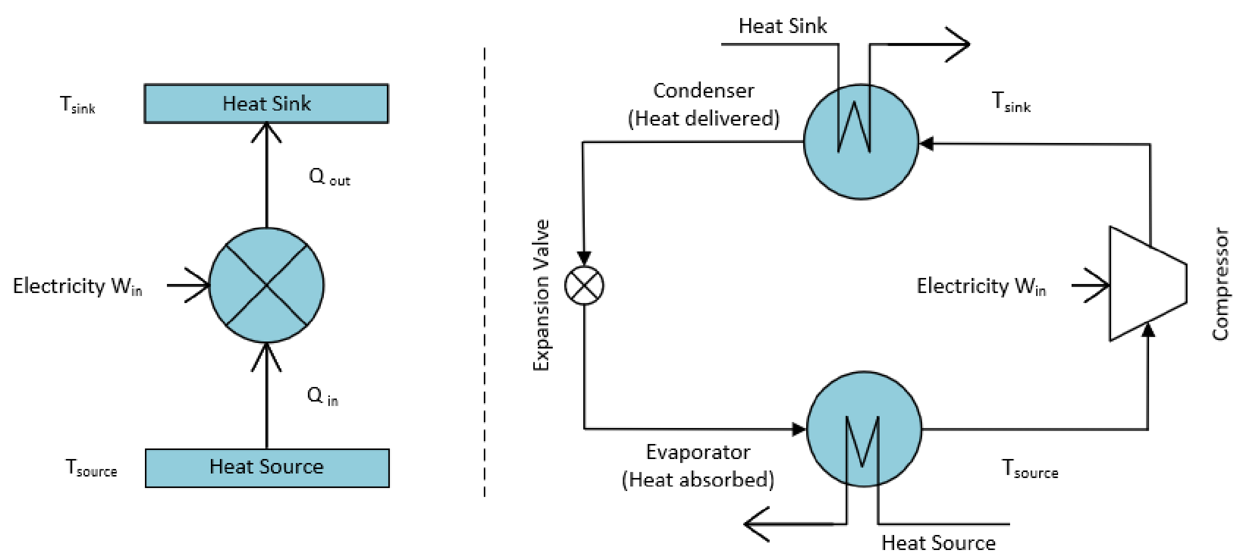


Figure 1 – Thermodynamic representation of a HP

Source: Zuberi et al., 2022

Classification of IHPs

The configuration of an IHP can differ greatly based on its application, and temperature difference of the source and sink. One way to classify IHPs is based on the sink temperature or supply temperature of a process. In general, IHPs with a heat sink temperature below 80°C (176°F) are called conventional heat pumps Those below 100°C (212°F) are high-temperature heat pumps (HTHPs), and IHPs with sink temperatures greater than or equal to 100°C (212°F) are referred to as steam-generating heat pumps (SGHPs) or very high temperature heat pumps (VHTHPs). Commercially available IHPs have a supply temperature range between 90°C and 165°C (194°F and 329°F) (Arpagaus et al., 2017).

Table 1: HP Classifications by Heat Sink Temperature

HP Classifications	Heat Sink Temperature
Conventional HP	<80°C (176°F)
High-Temperature Heat Pump (HTHP)	≥80°C (176°F), < 100°C (212°F)
Steam-Generating Heat Pump (SGHP) or Very High-Temperature Heat Pump (VHTHP)	≥100°C (212°F)

Source: Arpagaus et al., 2017

An example of IHP classification and application is illustrated in Figure 2. At this meat processing facility, feedwater enters an HTHP at 25°C (77°F), and outputs hot water at 60°C (140°F) to be used for the evisceration and viscera handling steps directly during meat production. The rest is used as makeup water to a second HTHP that will further heat the makeup water from 60°C (140°F) to 82°C (180°F) to reduce energy loss when mixing condensate within the condensate tank for steam generation. Finally, the mixture of makeup water and condensate water is used by an SGHP to produce steam at 120°C (248°F) for the relevant processes in the production facility (Zuberi et al., 2022).

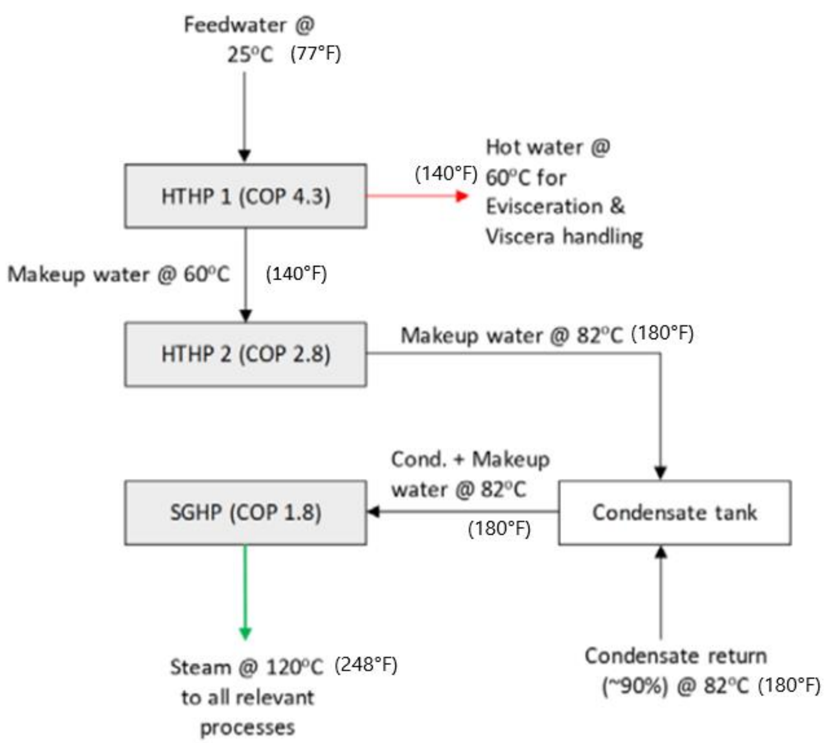


Figure 2 – Example of a proposed heat pump revamp in a meat processing facility

Source: Zuberi et al., 2022

IHP Types

Industrial heat pumps can be largely categorized as open/semi open cycle HPs or closed cycle HPs. Open cycle heat pumps use process stream as the working fluid while closed cycle heat pumps use heat exchangers both on the source and sink sides to separate the heat pumps working fluid (i.e., refrigerant) from the environment and/or process stream. Figure 3 shows six types of IHPs typically considered for industrial processes (Rightor et al., 2022).

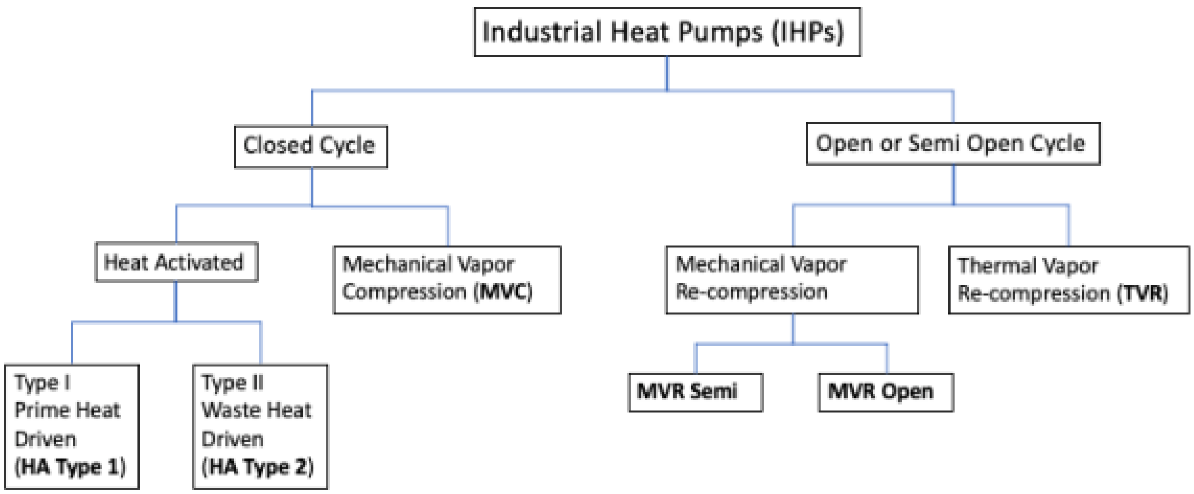


Figure 3 – IHP types

Source: Rightor et al., 2022

Objectives

The purpose of this technology and market assessment is to:

- Size the potential market of IHPs in California.
- Identify the highest benefit applications and locations.
- Review current studies and evaluations available to assess IHP performance.
- Identify commercial and pre-commercial technologies and manufacturers.
- Identify technology feasibility including technology and market barriers and opportunities.
- Recommend possible utility interventions to support market adoption.

Methodology and Approach

To achieve the study's objectives, the following methodologies and approaches were used:

- Review literature and conduct secondary and primary research through interviews to inventory IHP technologies and products available in the industrial market space. The research included product size, features, attributes, claimed benefits (kWh, kW, GHG, operational, maintenance, etc.), cost, and market barriers. When identifying commercial and pre-commercial technologies and manufacturers, necessary technology safety standards (e.g., UL Standards, EE ratings, ETL Certification for Life Safety & Security Industry) were identified.

- Leverage market research to size the potential market in California, identify highest benefit applications and locations, and identify possible utility program pathways for the technology (downstream, midstream, upstream, codes and standards). Market sizing estimates for California leveraged previous market research on the total U.S. market and were then scaled down using state employment numbers per industry as a proxy if state production data was not available.
- Report on key opportunities, barriers, next steps, and strategies for utility intervention to advance adoption including additional field studies, workforce education and training, and evaluation of technology adaptability for potential applications that have not yet been evaluated.

Industrial Heat Pump Applications

In industrial settings, heat pumps typically have source temperatures ranging between 25 to 35°C (77 and 95°F) and sink temperature as high as 165°C (329°F). As illustrated in Figure 4, the efficiency of IHPs diminishes as the temperature differential between the source and sink increases. Consequently, this restricts the industrial processes where IHPs can be effectively employed. The efficiency of a heat pump is gauged by the coefficient of performance (COP), with a COP of 1 signifying a complete conversion of electricity into heat without loss (i.e., an ideal electric resistance heater). A higher COP denotes better performance of a heat pump. Notably, heat pumps that can boost temperatures by 40–60°C (104 to 140°F) typically exhibit a COP of 3 to 4, making them three to four times more efficient than an ideal electric resistance heater (Rissman, 2022).

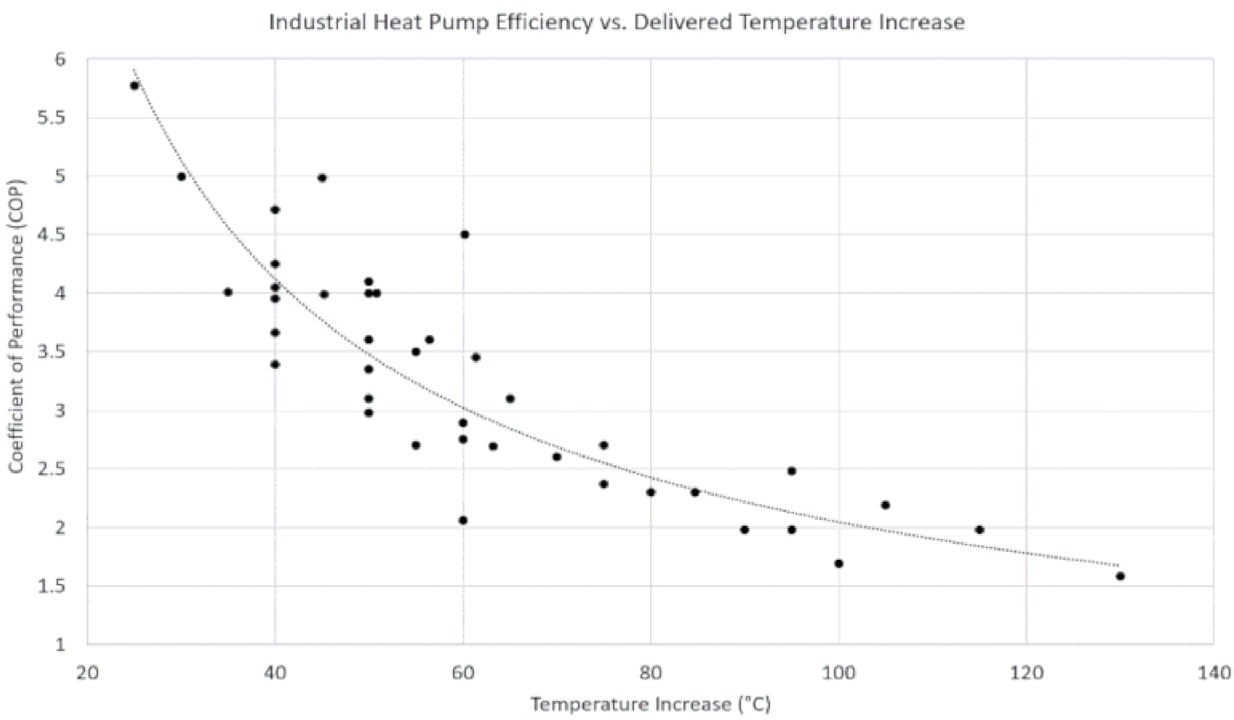


Figure 4 – Industrial Heat Pump Efficiency Vs Temperature Increase

Source: Rissman, 2022; Data Source: Arpagaus, et al., 2018

Due to the technological benefits of HPs and operating temperature limitations, much research has been conducted to identify potential applications of IHPs. Figure 5 below displays temperature requirements by percentage of heat demand across eight different industries. As shown, the proportion of heat demand varies greatly from industry to industry. Approximately 35 percent of industrial heat requirements are below 165°C (329°F), which aligns with the upper limit achievable by commercially available IHPs (Rissman, 2022). If IHPs can be installed across the U.S. for all applications, there is great potential for decarbonization. Additionally, if IHPs are powered by emission-free sources such as solar, wind, hydro, and nuclear energy, emission-free heat can be generated. This could lead to a reduction of 344 million metric tons of CO_2 emissions annually in the U.S., equivalent to approximately seven percent of the nation's total energy-related CO_2 emissions (Rissman, 2022).

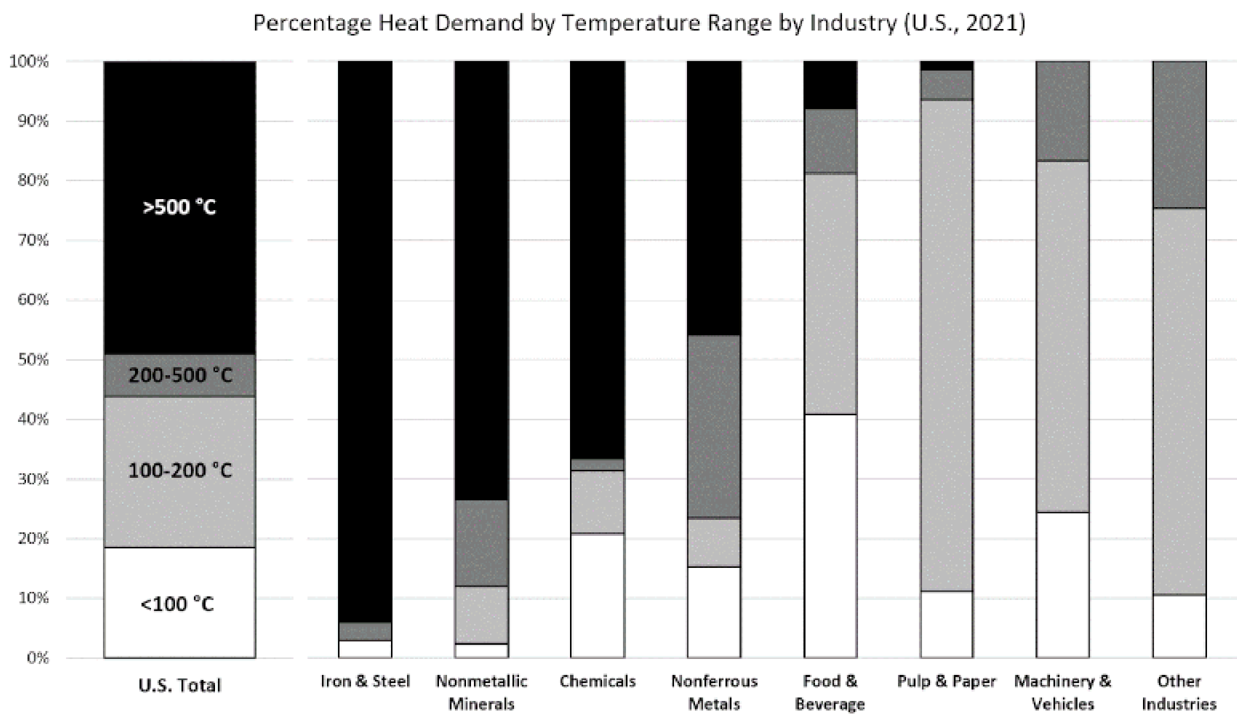


Figure 5 – Percentage of Heat Demand by Temperature and Industry for the U.S.

Source: Rissman, 2022; Data Source: U.S. EIA, n.d.

Lawrence Berkeley National Laboratory (LBNL) conducted an analysis on IHP applications for the following eleven industrial subsectors: meat processing, dairy, beer, canned vegetable and fruit processing, cane sugar refining, beet sugar, corn wet-milling, soybean oil, textiles, pulp and paper, and automotive industries. According to the study, IHPs can decrease CO_2 emissions by approximately 17 Mt CO_2 per year across the U.S. when compared to the base year 2021 if a 100 percent adoption rate was achieved in these industrial processes. With production growth and further decarbonization of electricity grids, the total CO_2 abatement potential is projected to be even greater at 58 Mt CO_2 per year in 2050, which is equivalent to 5 percent of the total GHG emissions from U.S. manufacturing (Zuberi et al., 2022). This study does not address the market sizing of the chemicals industry, which may also have potential IHP heating capacity.

LBNL's study estimated the potential fuel energy savings of IHPs in the eleven industries using two different scenarios:

- Scenario 1: A conservative case where only HTHP applications requiring temperatures less than 100°C (212°F) and boiler pre-feed were considered.
- Scenario 2: An aggressive case where both HTHPs and SGHPs were considered. In this case, the maximum heat sink temperature of an SGHP was 150°C (302°F) because of the lack of SGHPs that can deliver temperatures over 150°C (302°F). Additionally, temperature lift higher than 130°C (266°F) was considered not techno-economically favorable.

Due to the range of temperature requirements of different IHP applications, Scenarios 1 and 2 showed varied potential across the industry. Figure 6 illustrates LBNL's estimated fuel energy savings as a percentage of total fuel used in each scenario. This is the percentage of fuel saved by using electricity instead of other fuel sources. If electricity could be provided by carbon-free sources, some industries such as canned fruits, canned vegetables, and textile weaving processes could become carbon-free with no direct fuel usage when switched to HTHPs and SGHPs.

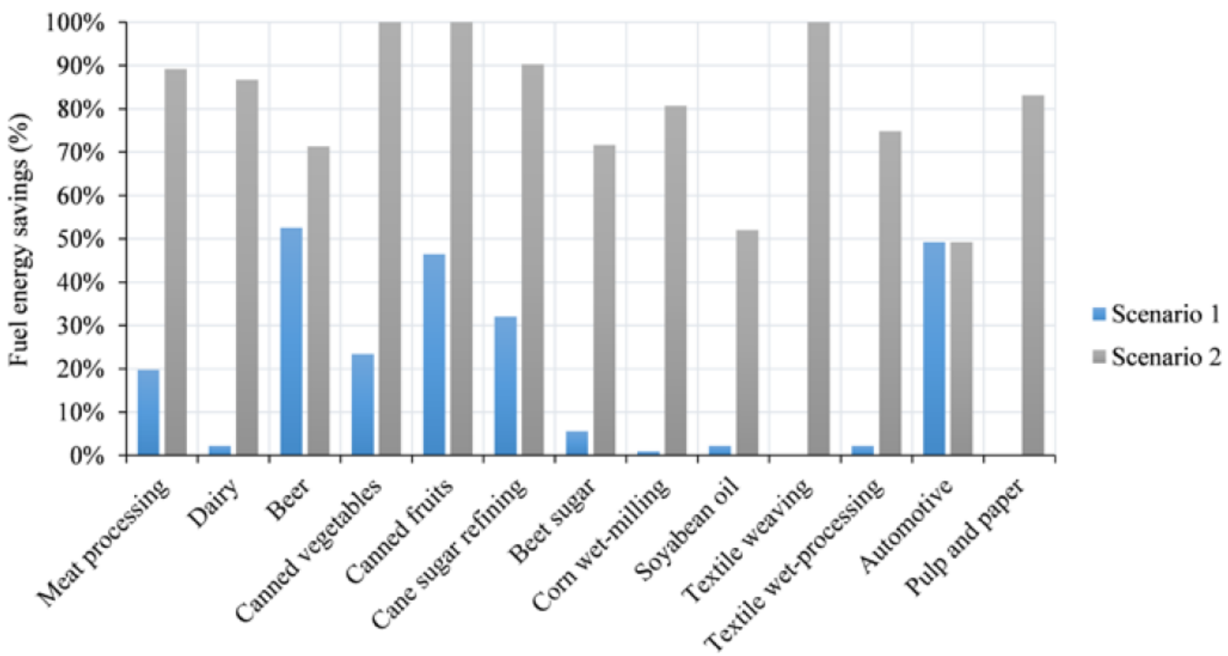


Figure 6 – Percent of fuel energy savings for industries by scenario

Source: Zuberi et al., 2022

Figure 7 illustrates the total final energy savings by industry for the two scenarios, accounting for the increase in electricity usage. This is the net energy savings with decreased fuel demand and increased electricity demand and is a percentage of total energy used. In some industries such as dairy, beet sugar, corn wet-milling, soybean oil, textiles, and pulp and paper, Scenario 1 with only HTHPs have less than 10 percent impact on both fuel and total final energy savings. However, fuel and total final energy savings increase significantly in Scenario 2 (Zuberi et al., 2022).

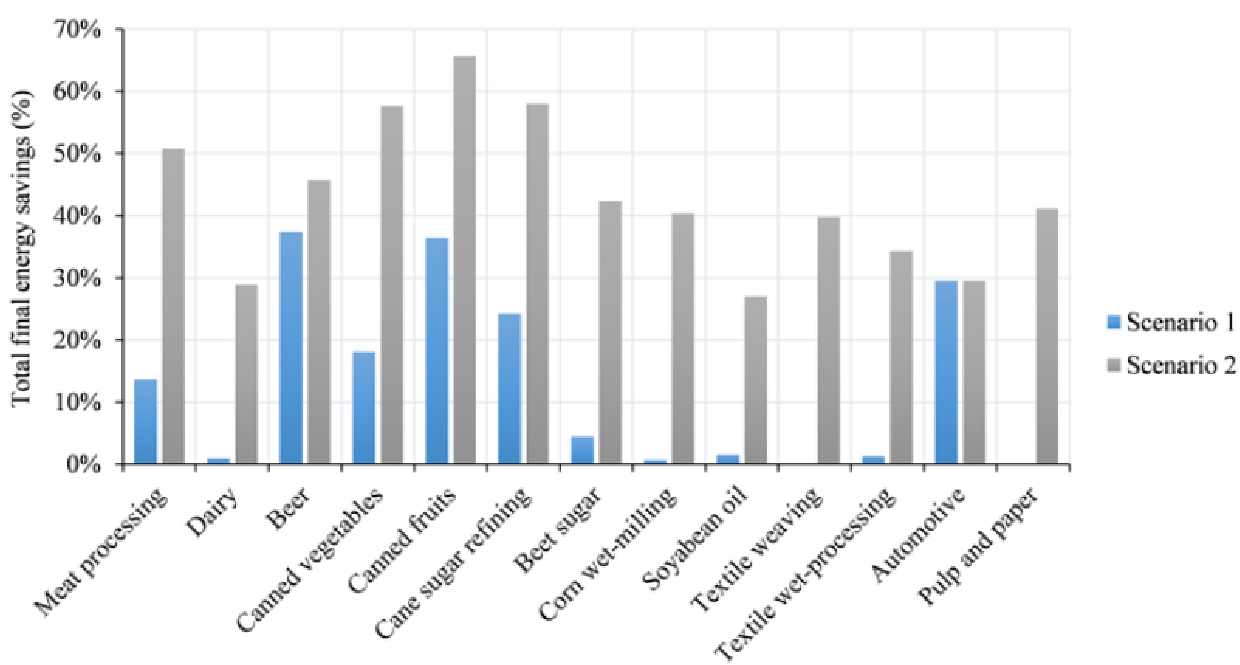


Figure 7 – Percent of total final energy savings by scenario

Source: Zuberi et al., 2022

Market Sizing

Using the information obtained from LBNL's report, the same eleven industries were targeted for the analysis of IHP potential in California. The comprehensive analysis of each industry can be found in Appendix A: Analysis of Industries.

The total potential IHP heating capacity potential in the U.S. was estimated to be 9,870 MW and 21,726 MW for HTHPs and SGHPs, respectively (Zuberi et al., 2022). For California, the total potential IHP heating capacity potential was calculated to be 2,021 MW or seven percent of the national capacity, as seen in Figure 8. Of the total potential heating capacity, 1,051 MW was estimated for HTHPs and 1,069 MW for SGHPs. Compared to the national capacities, California has relatively low total potential heating capacity for SGHPs due to very limited pulp and paper, and no corn wet-milling sectors. For example, corn wet-milling is estimated to have 2,700 MW of SGHP potential heating capacity nationwide, but California has no corn wet-milling production facilities within the state. Across the U.S., pulp and paper was estimated to have 6,800 MW of potential SGHP potential heating capacity, where 77.4 MW was estimated for California.

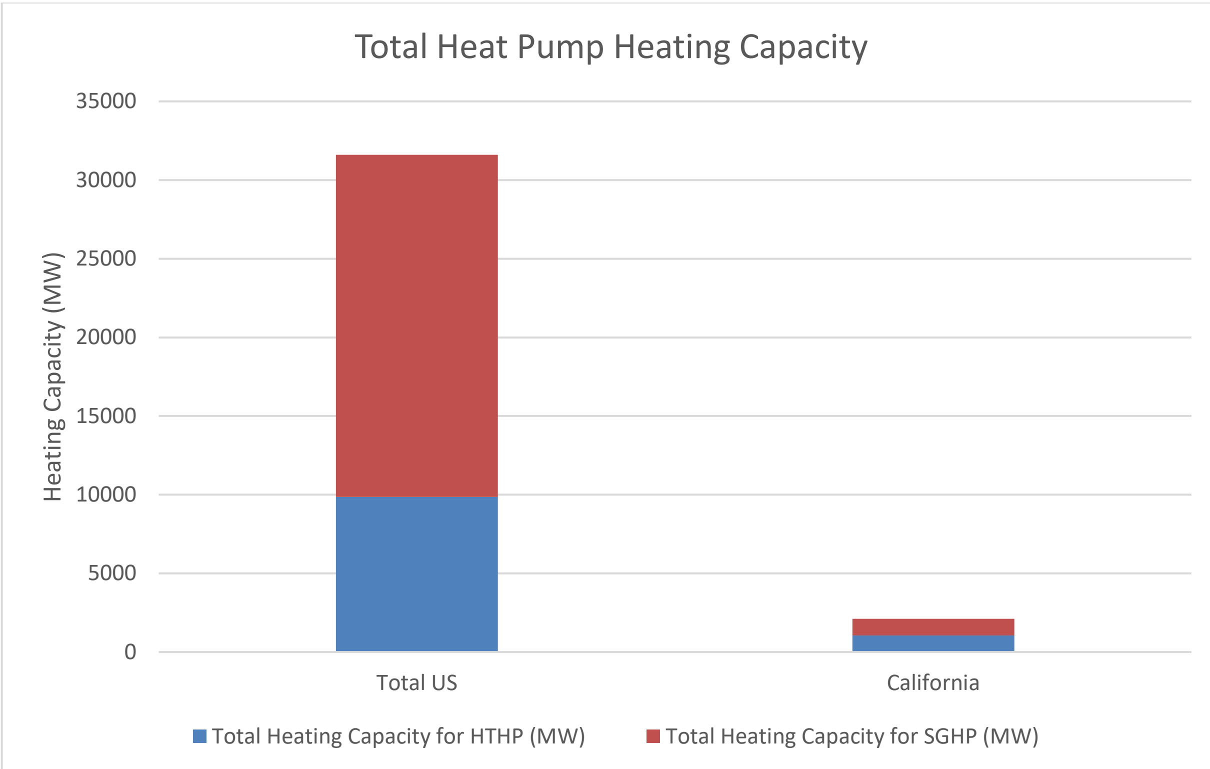


Figure 8 – Total Potential Heat Pump Heating Capacity for U.S. and California

Source: AESC Inc. Data Sources: Zuberi et al., 2022, AESC Inc.

The total estimated heating capacity potential of IHPs in the U.S. varies by the industry type and application. The industries estimated to have the most demand for HTHPs are the automotive and beer production sectors, while the most demand for SGHPs are pulp and paper, corn wet-milling, and beet sugar sectors, as shown in Figure 9.

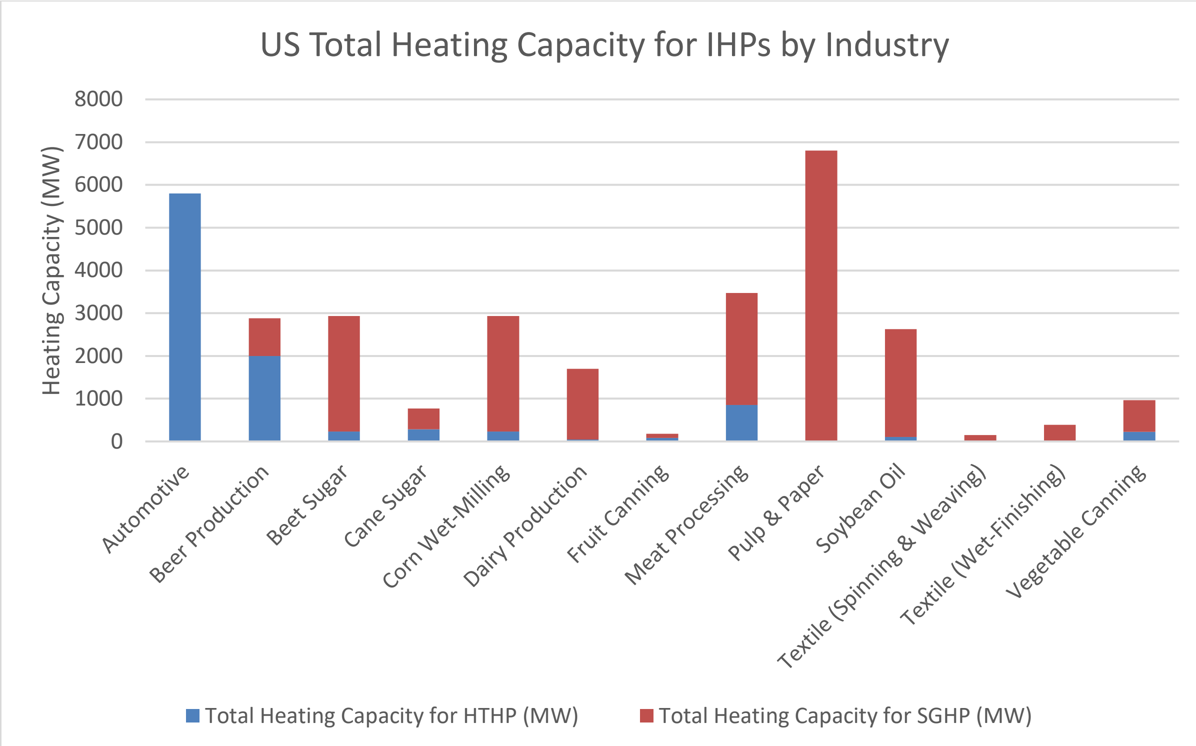


Figure 9 –Total Potential Heating Capacity for IHPs in the U.S. by Industry

Source: AESC Inc.; Data Source: Zuberi et al., 2022

The total heating capacity potential of IHPs in California differs from the national trend, as seen in Figure 10. The automotive industry remains the largest heat capacity for HTHPs, however, industries such as corn wet-milling and pulp and paper have less potential in California, resulting in a significant decrease in total potential heating capacity for SGHPs. Since current SGHP technology has relatively low efficiency resulting from the high temperature lift needed, HTHPs may be a better starting point for electrification within California's industrial sectors. The large total potential heating capacity of HTHPs within the automotive and beer production industries shows the most potential for HTHP applications and may be a prime target for electrification and market transformation within California in the near future.

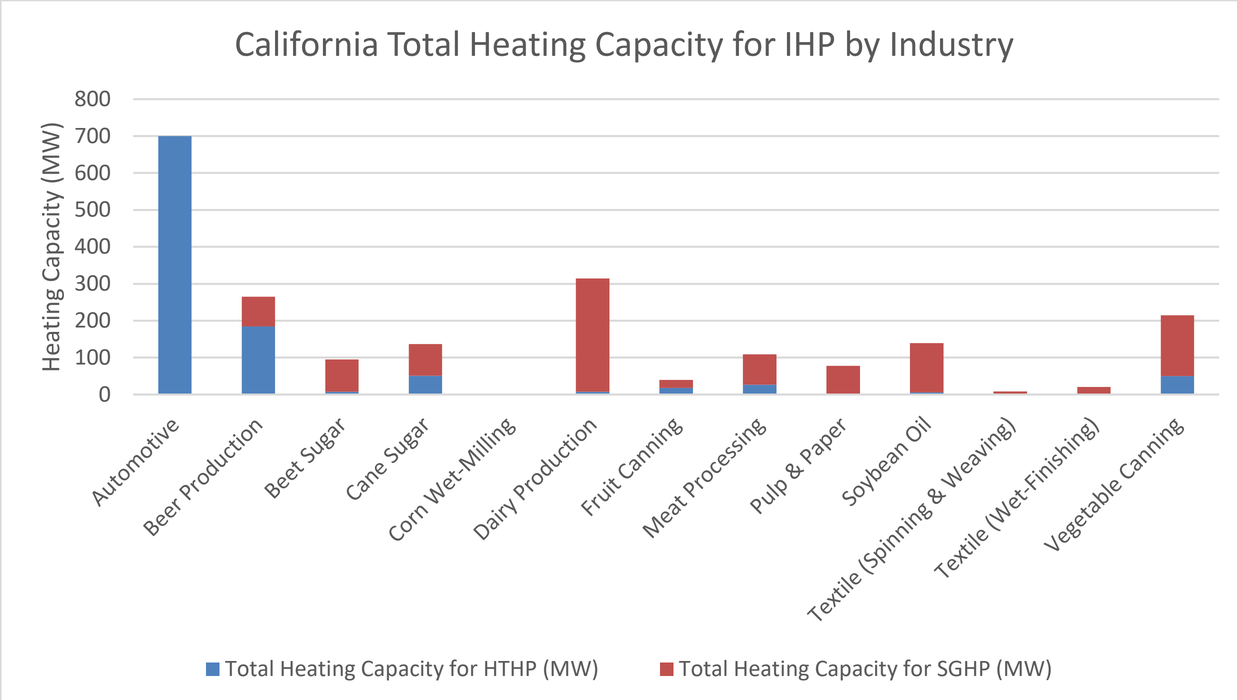


Figure 10 – California Total Potential Heating Capacity for IHP by Industry

Source: AESC Inc.

Review of Current IHP Studies and Evaluations

Currently, most studies of IHP uses and demonstrations have been conducted outside of the U.S. The following are some examples of IHP performance evaluations conducted overseas:

An example of an IHP revamp at a meat processing facility was seen in a slaughterhouse in Switzerland (Arpagus and Bertsch, 2020). The HTHP system was comprised of three CO_2 HPs with a heating capacity of 800 kW and COP of 3.4, and was used to heat process water to 90°C. The heated water was used for cleaning, slaughtering, boiler feedwater, and space heating. This installation resulted in a 30 percent reduction in annual CO_2 emissions (510 tons) (Zuberi et al., 2022).

In Norway, an IHP revamp in a dairy facility was used for cooling and heating of all processes (de Boer et al., 2020). The IHP had a heating capacity of 940 kW and a COP of 5. This resulted in a 40 percent reduction in annual energy consumption, and reduced CO_2 emissions to zero (de Boer et al., 2020).

At a brewery in Austria, an HTHP was installed to heat process water to 77°C. The HTHP had a heating capacity of 370 kW and a COP of 4.4. By using waste heat from the facility's chillers, the HTHP system was able to reduce 6.6 TJ per year of natural gas demand and only consumed 1.5 TJ (417 MWh) per year of electricity for operation (IEA Members of Annex 35/13, 2014).

An example of an IHP revamp in a vegetable production plant was seen in Switzerland where an IHP was used for heating and cooling. The air was heated for tomato growing while salads and finished products were cooled before distribution. The IHP had a capacity of 1 MW and a COP of 3.6 for heating mode. This system was coupled with their refrigeration system, reducing the costs of refrigeration and heat generation. The IHP was able to generate between 14.4 and 18 TJ per year of thermal energy, saving approximately 500,000 m^3 (17,700 MMBTU) of natural gas for heating their greenhouses (Arpagaus and Bertsch, 2020).

An example of an automotive industry IHP revamp was seen in a German Volkswagen plant where an IHP was used to heat process water to 65 -75°C (149 - 167°F) by recycling waste heat from the plant's dip-coating process using an HTHP. The HTHP had a heating capacity of 1.7 MW and a COP of 5.6 (IEA, 2020).

The above examples illustrate the installation of IHPs with supply temperatures less than 100°C. An overview of demonstration cases with supply temperatures over 100°C (212°F) outlined by the IEA Annex 58 can be found in "Appendix B: Overview of Demonstration Cases with Supply Temperatures >100°C" (IEA, 2023b).

Industrial Heat Pump Manufacturers

Industrial heat pump manufacturers have been identified for potential outreach to obtain additional information about the market for this report. Table 2 shows a list of manufacturers with offices in the U.S. The table has details of the products' refrigerant, maximum supply temperature, heating capacity, compressor type and product model. The full table, including manufacturers without offices in the U.S., is shown in "Appendix C: List of IHP Manufacturers." Since the market is rapidly changing, this list may not be inclusive of all manufacturers in the market.

Table 2: Commercially available IHPs with offices in the U.S.

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type
Vilter	Modular	R717 (NH_3)	150 (Available in 2024)	600-5,000	Single Screw
	VSH/VSSH	R744 (CO_2)	70	1,700	Single Screw
	VHP	R717 (NH3)	90		Single Screw
Kobelco	SGH 165	R134a+R245fa	175	624	Twin Screw
	SGH120	R245fa	120	370	Two-stage Twin Screw

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type
	MSRC 160	R-718 (Water)	175	800	Twin Screw
	HEM-90A	R134a+R245fa	90	176	Semi Hermetic Two-stage Twin Screw
	HEM-HR-90	R134a+R245fa	90	357	Two-stage Twin Screw
Fuji Electric	Steam Generating Heat Pump	R245fa	120	30	Reciprocating
Mayekawa	unimo AW	R-744	90	74	Reciprocating
	unimo WW	R-744	90	91.9	Reciprocating
	unimo AWW	R-744	90	92.3	Reciprocating
	Ecosirocco	R-744	120	123	Reciprocating
	Plus+HEAT	R717 (NH3)	85	85	Reciprocating/ Screw
	Ecocircuit	R1234ze(E)	100	100	Reciprocating
GEA	RedGenium	R717 (NH3)	95	1,800	Reciprocating
	RedAstrum	R717 (NH3)	80	2,900	Screw
	Open Type HP	R717 (NH3)	95	3,500	Reciprocating
Johnson Controls	Sabroe HeatPAC/ DualPAC/ Customized	R717 (NH3)	90	300-13,000	Reciprocating/ Screw
Turboden S.p.A.	Turboden Large Heat Pumps	Various	200	3,000-30,000	Turbo compressor

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type
MAN Energy Solutions	ETES CO_2 Heat pump	R744 (CO_2)	150	10,000-50,000	Centrifugal Turbo-Compressor
Piller	MVR	R718 (water), and process vapors (ethanol, methanol, IPA, mixtures, on demand)	230	1,000	Turbo
Siemens Energy	MVV	R1233zd(E), R1234ze(E)	180	8,000-70,000	Centrifugal Compressor
Viessmann	Vitocal 350-HT Pro	R1234ze	90	148-390	Piston
Skyven Technologies	Arcturus SGHP	R718 (Water)	215	37,000	Centrifugal Compressor

Source: AESC Inc.

Interviews with Manufacturers and Collaborators

As part of this report, industry experts were interviewed to understand more about the current IHP industry and technology; these included a total of nine different individuals from a nonprofit research organization, four IHP manufacturers, and one government research institution.

The questionnaire used for discussion can be found in "Appendix C: List of IHP Manufacturers." Reponses were used to inform IHP's high-value applications, market adoption drivers, and market challenges and barriers, which are detailed in the subsequent sections.

High Value Applications

Operational Cost Savings

Due to the greater energy efficiency of IHPs compared to traditional boilers, there are some high value applications that can reduce operational costs enough to achieve a reasonable return on investment. Anecdotally, industry experts usually target a three-year payback period for IHP capital expenditures, but this may vary, especially with sustainability targets being important in some firms as discussed in the section below. Examples of applications known to have higher returns are:

- Facilities with electric boilers:
  If the facility is currently using electric boilers for process heating, replacing them with IHPs can yield higher returns on investment because IHPs can perform more efficiently than electric boiler systems, which can have a maximum theoretical COP of 1. Additionally, electrical infrastructure upgrade is likely not necessary at these facilities since they already have the capacity needed to support the load.

- Facilities that purchase steam:
  In some cases, steam and hot water can be purchased from a neighboring site or utility, instead of being produced at the facility on-site. Importing heated process water can be more costly than on-site production, leading to potential cost saving benefits for installation of new IHP systems.

- Facilities with high-cost fuel boiler systems:
  Depending on the facility, some boiler systems are expensive to operate. For example, large boiler systems may require boiler insurance, 24/7 certified boiler operators, water treatment chemicals, air quality permits for exhaust, and additional pump and boiler maintenance that increases operational costs.

IHP Efficiency

Instead of evaluating an IHP solely on its COP, the entire manufacturing process COP should be considered. Due to an IHP's ability to move heat, recycling waste heat from refrigeration processes or areas of excess heat production and using it as a heat source for heating applications can improve the overall COP of a process. Examples of industries where both heating and refrigeration applications can be taken advantage of are food and beverage and dairy industries where heating can be used for pasteurization, and refrigeration is necessary for storage of products. Other process applications where there may be a significant amount of excess heat that can be recycled to improve overall COP are the chemical and pulp and paper industries.

COP may also be impacted by operating conditions. As previously shown in Figure 4, as the temperature lift increases, the COP of an IHP decreases, meaning low-medium heat sink temperatures are more suitable for high COP applications. In addition to this, environmental conditions can impact IHP COP as well. IHPs have ideal COP in environments where there are few changes in ambient conditions.

Efficiencies are also impacted by breaks in operations. Several IHP manufacturers interviewed emphasized that IHPs work best when they serve constant load. When an IHP must start or stop, there is potential for condensation buildup resulting in reduced efficiencies. Therefore, applications with high and consistent use rates handling the baseline process heating loads are preferred for increasing system COP of IHPs and reducing operational costs.

Energy Prices

Since many facilities are considering switching from fossil fuels to electricity, the commodity's price difference must be considered when evaluating cost effectiveness. The difference between the price of electricity received by a generator and the cost of natural gas needed to produce electricity is known as the spark spread. This can vary over time and by region across the U.S. and is a key factor in determining the return on investment of fuel switching initiatives. The spark spread is defined by the following equation (EIA, 2023):

$$\begin{aligned} &Spark\ spread\ (\$/MWh) \\ &\qquad = power\ price\ (\$/MWh) - [natural\ gas\ price\ (\$/mmBtu) \\ &\qquad * \ heat\ rate\ (mmBtu/MWh)] \end{aligned}$$

A higher spark spread signifies higher electricity prices compared to natural gas prices in the region, and therefore lower cost savings when fuel switching from natural gas to electricity. These prices have a significant impact on operational costs when using an IHP and are a major determinant of the return on investment. Table 3 shows an example of the natural gas vs. electricity prices per region in the U.S. on October 4, 2023.

Table 3: Example Spot prices for natural gas and electricity by region (on 10/4/2023)

Region	Natural Gas ($/million Btu)		Electricity ($/MWh)		Spark Spread ($/MWh)
	Price	Percent Change*	Price	Percent Change*	
New England	1.55	+3.2	33.48	+19.8	22.63
New York City	1.32	+0.2	38.34	+8.6	29.10
Mid-Atlantic	1.31	+3.6	61.59	+1.5	52.42
Midwest	2.42	+5.0	51.39	-13.8	34.48
Louisiana	2.71	+0.3	39.75	-8.1	20.80

Region	Natural Gas ($/million Btu)		Electricity ($/MWh)		Spark Spread ($/MWh)
	Price	Percent Change*	Price	Percent Change*	
Houston	2.64	+4.7	38.25	+1.3	19.77
Southwest	2.40	+12.9	24.25	-4.9	7.45
Southern CA	2.65	+13.1	46.40	+5.8	27.85
Northern CA	4.58	-7.4	56.14	+6.9	24.11
Northwest	2.50	+10.4	50.25	+8.0	32.75

*Percent changes based on daily settlement price from previous business day

Source: EIA, 2023

In 2022, the Renewable Thermal Collaborative conducted an analysis of the relative fuel costs between operating an electric heat pump and natural gas heating. Their analysis assumed a heat pump COP of 3 and a natural gas combustion efficiency of 85 percent, with results for each state shown in Figure 11 (Renewable Thermal Collaborative, 2022). California was one of the ten states that was likely to have higher costs for operating electric heat pumps compared to natural gas combustion. However, this does not rule out potential operational cost savings within the state as fuel and electricity prices can vary within each territory and each IHP application can have different system COPs as described in the section above.

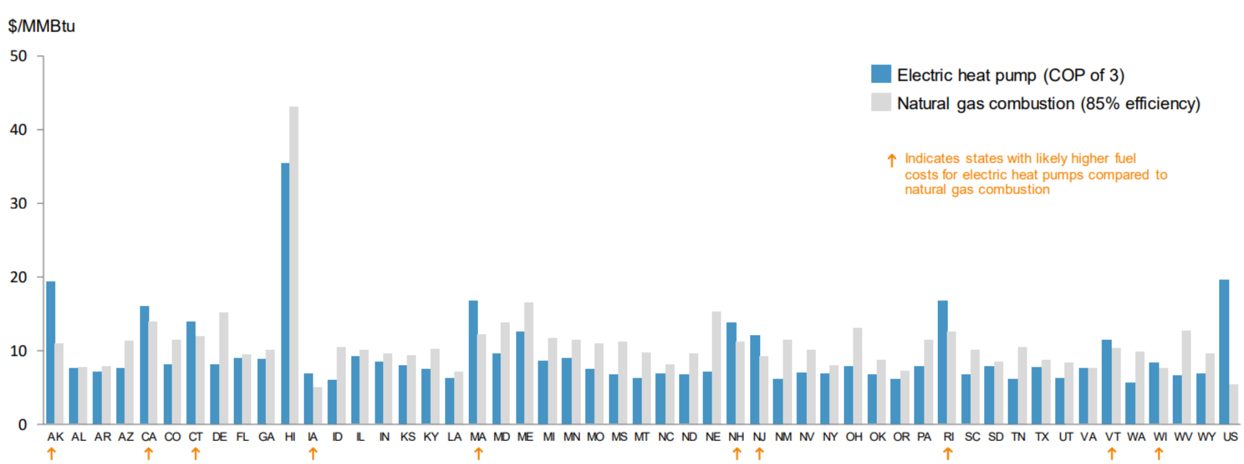


Figure 11 – Relative fuel costs between electric heat pump and natural gas combustion heating in 2022

Source: Renewable Thermal Collaborative, 2022

Corporate Goals for Sustainable Products and Reputation

Due to the importance of global environmental, social, and governance (ESG) impacts a corporation may have, IHPs may be highly valued in industries where a reputation of sustainability adds additional value to its products. A recent study by McKinsey & Company showed that consumers are shifting their spending toward products with ESG-related claims. The study found products making ESG-related claims had a 28 percent cumulative growth over the last five years compared to 20 percent for products that made no such claims (Bar Am, J. et al, 2023). Since consumers are changing their buying behavior to value sustainable products, companies may see IHPs as an attractive solution for achieving ESG goals and growing their sustainability reputation. Cosmetics and fashion are examples of consumer products where customers strongly value sustainability. Aviation fuel production is another example that places a high value on ESG reporting across multiple industries due to its impact on reported indirect emissions across the corporate value chain (Scope 3 emissions). Some companies also have an internal price for carbon emissions savings that is not disclosed to the public. Many companies have set net-zero emissions timeline targets for their operations. These goals may be an indication of how willing they are to spend on ESG initiatives.

				Enterprise Level
	Reporting for Calendar-Year-End Filers			
	2024 (Reporting in 2025)	2025 (Reporting in 2026)	2026 (Reporting in 2027)	2028 (Reporting in 2029)
Scope	Companies already subject to the NFRD,* including large U.S. companies with more than 500 employees and listed on an E.U.-regulated market	All large** U.S. companies listed on E.U.-regulated markets and all large E.U. subsidiaries of U.S. companies	SME subsidiaries of U.S. companies listed on E.U.-regulated market***	U.S.-based companies that generate a net turnover of more than €150M in the European Union in each of the last two financial years and have at least one large subsidiary or a subsidiary listed on an E.U.-regulated market (or branch when there are no E.U. large or listed subsidiaries) in the European Union with more than €40M net turnover
Required standards	ESRS (or equivalent† standards)		ESRS or specific standards for SMEs	ESRS, equivalent standards, or alternative specific standards for non-E.U. entities to be developed
Reporting level	Stand-alone subsidiary, unless included in the parent's report prepared under ESRS or equivalent standards for non-E.U. parent (i.e., consolidated group level)			Consolidated group, including non-E.U. activity
Assurance	Yes, limited assurance over all reported sustainability information			Yes, limited assurance over all reported sustainability information

* Companies already subject to the Non-Financial Reporting Directive (NFRD) are large public-interest companies with more than 500 employees. Public-interest companies include companies listed on an E.U.-regulated market, banks, insurance companies, and other companies designated by national authorities as public-interest entities.

** Large undertaking is defined by the CSRD as an entity that meets two or more of the following three criteria: >250 employees, >€20M balance sheet, >€40M turnover in the European Union.

*** SMEs can choose to defer reporting for two years until 2028.

† What may be deemed "equivalent" is yet to be determined by the European Commission (EC).

Figure 12 – ESG reporting calendar for U.S. companies listed on an E.U. market.

Source: Deloitte, 2023

ESG standards are continually updating with the E.U. Corporate Sustainability Reporting Directive (CSRD) being put in place for U.S. companies listed in the E.U. market starting in 2024. The CSRD is a new directive that requires companies to disclose climate change and environmental information such as GHG emissions, reduction targets, and climate risk assessments in publicly disclosed management reports. Figure 12 shows the expected ESG reporting calendar for U.S. companies listed on an E.U. market. By 2029, U.S. companies of a certain scope in the E.U. will have to report at the 'Consolidated group' level, meaning non-E.U. activity will have to be reported as well. (Deloitte, 2023). This means there will be an increase in public awareness of ESG impacts of companies and their products in the U.S. in the future.

Market Adoption Drivers

Energy Efficiency Cost Savings

One of the primary reasons for adopting energy efficiency technologies is operational cost savings. Corporations are willing to invest in technologies if they can produce long-term operational savings to increase profits. From the interviews with manufacturers, corporations commonly desire a two-to-three-year simple payback period on capital expenditures. However, the payback requirement may not apply for all customers. District heating customers or customers with higher risk tolerance may be willing to look at a longer-term horizon over the entire lifespan of the equipment. As mentioned in the above section on Operational Cost Savings, COP and cost of energy have significant impacts on IHP cost effectiveness. In cases where energy efficiency cost savings are not feasible, corporations may still want to adopt IHPs for other reasons discussed below.

Corporate ESG Initiatives

Corporate ESG initiatives are another driver for adopting IHPs. Due to IHPs' efficient use of electricity, the switch from combustion fuels to an IHP in process heating may lead to significant GHG emissions reductions, especially if grid power originates from renewable sources. Depending on the application and fuel used, the amount of GHG reduction can have a significant impact on the environment and health of surrounding communities. A NASA study showed that air quality improvements due to reducing emissions could improve human health and economic losses with fossil fuel pollutants linked to premature death and respiratory illness (Mersmann, 2021). Some corporate leaders may be motivated to assist with environmental and health concerns, leading to increased electrification efforts to reduce emissions to improve society. As mentioned in the section above, Sustainable Products and Reputation may also be a motivator for IHP adoption.

Federal and State Programs

In the U.S., there are a variety of state and federal programs that can assist with funding decarbonization and energy efficiency efforts. Depending on the program and project, a single project may be qualified for multiple programs. Some incentives include, but are not limited to the following:

FEDERAL PROGRAMS

- The Department of Energy (DOE) awards research and development grants to promote the commercialization of HP technologies. In 2023, $900,000 was awarded to advance HP technologies with a focus on the decarbonization of industrial drying applications through innovative IHP technology (U.S. DOE, 2023a).

- The Inflation Reduction Act (IRA) of 2022 is the single largest investment in climate and energy in American history, focusing on a net-zero economy by 2050. The IRA directs almost $400B in funding to clean energy through a mix of tax incentives, grants, and loan guarantees. (McKinsey, 2022)
    - The Qualifying Advanced Energy Project Credit (48C) program was recently expanded with a $10B investment under the IRA in 2022. This program provides tax credits for investments in advanced energy projects. (U.S. DOE, 2023b).
    - The Bipartisan Infrastructure Law (BIL) is another initiative that was passed in 2021 that expands funding for new and existing DOE programs. (U.S. DOE, 2023c)
    - Industrial Research and Assessment Center Implementation Grants are designed to provide up to $400 million in grants, funded by section 40521 of the Bipartisan Infrastructure Law to small and medium-sized manufacturers (SMMs) to implement recommendations made in Industrial Assessment Center or Combined Heat and Power Technical Assistance Partnership assessments. (U.S. DOE, 2023d)
    - The Office of Clean Energy Demonstrations (OCED) is another effort established in 2021 that manages more than $25 billion in funding to deliver clean energy demonstration projects at scale in partnership with the private sector to accelerate deployment, market adoption, and the equitable transition to a decarbonized energy system. Funded by the BIL, $6.3 billion is allocated to support the advancement of transformational technologies needed to decarbonize the industrial sector. (U.S. DOE, 2023e)
- U.S. Department of Agriculture's (USDA) Rural Energy for America Program (REAP) grants and loans and Rural Energy Savings Program (RESP) loans may allow small rural business and agricultural producers to qualify for loan guarantees on project costs. Replacing energy inefficient equipment or implementing energy-saving measures, including IHPs may be eligible. (Hoffmeister, A., Elliott, N., 2023)
- There are some multistate initiatives that are increasing in membership to reduce CO_2 emissions. These include the Regional Greenhouse Gas Initiative, the Western Climate Initiative, the U.S. Climate Alliance, the Governors Accord for a New Energy Future, and the Pacific Coast Collaborative (Center for Climate and Energy Solutions, n.d.-a).

CALIFORNIA INITIATIVES

The state of California has passed the following senate bills (SB), which can promote the low-carbon high-temperature IHPs:

- SB 32 aims to reduce GHG emission to 40 percent below 1990 levels by 2030.
- SB 100 ensures that California’s transition to a zero-carbon electric system does not cause or contribute to GHG increases.
- 2019 California Energy Efficiency Action Plan expands SB 350, doubling energy efficiency by 2030 to include agriculture, industry, and electrification.

The California Energy Commission also releases solicitations and funding to promote technology development and demonstration projects of promising pre-commercial technologies to accelerate industrial decarbonization and increase overall energy efficiency to reach statewide goals (California Energy Commission, n.d.). Recently, a grant of $2.97 million was given to Skyven Technologies to bring an innovative, industrial steam-generating, HP technology to low-rate initial production (California Energy Commission, 2023).

The state of California also manages its own cap-and-trade program. This is a key element used to reduce GHG emissions by creating economic incentives for investment in cleaner, efficient technologies. The California Air Resources Board (CARB) manages the program and creates allowances equal to the total amount of permissible emissions. Every year, these allowances are auctioned for, creating a sustained carbon price signal to prompt action to reduce emissions (California Air Resources Board, 2023).

Market Challenges and Barriers

Despite the large potential for energy and CO_2 emissions reduction in U.S. manufacturing, there are many barriers associated with wide-scale implementation of IHPs. The results from the interviews and research identified the following:

Capital Costs

Industrial heat pumps are extremely expensive assets with some manufacturers' HTHP base models costing $800,000 or more for a 500-kW heating capacity rated IHP. Installation costs at a facility may be an additional 50 to 100 percent of the equipment cost depending on the site modifications and engineering required.

The cost can also increase depending on the heat sink temperatures of the IHP. Water and steam temperatures dictate the refrigerant pressure with higher temperatures requiring higher operating pressures. To operate at higher design pressures, compressors may need more horsepower, increasing the cost. One SGHP manufacturer had an estimate of at least $10M per installation for high temperature applications.

Compressor casing and heat exchanger design may also increase costs. Some applications may require only one condenser, whereas others may also need a sub-cooler or desuperheater for the system. Heat source and heat sink temperatures determine if the system is single or two-stage compression, with two-stage increasing the price of the IHP system. Generally, mechanical vapor recompression (MVR) systems are costlier than mechanical vapor compression (MVC) systems. Today, most SGHPs and VHTHPs use MVR technology and systems have a higher heating capacity (in the MW range). HTHPs usually use MVC technology and are modularly sized starting from the kW range and have lower capital costs compared to MVR. The cost of MVR projects is highly influenced by electric infrastructure cost to accommodate the higher power of compressors. The high capital costs also mean there is a high level of risk involved and financing may be necessary for purchase. Thus, decisions for purchasing IHP equipment are usually made at the executive level, subject to more scrutiny.

Operational Costs

As mentioned in the sections above, IHP Efficiency and Energy Prices can vary by location and application, making it more costly to operate an IHP. In addition to the day-to-day operation of the IHP, occasional maintenance is necessary. One manufacturer stated an IHP requires more maintenance compared to boilers with scheduled maintenance required after 8,000, 18,000, and

40,000 hours of operation with increasing severity of service. Due to the unfamiliarity of IHP technologies, operators may also need to be educated in how to operate IHPs, adding an increased training cost on operations.

Facility Requirements

Depending on the location and application, physical requirements may restrict IHP installations or may increase the cost of installing an IHP in an existing facility. Interviewees discussed situations where the facility building could not handle the weight of additional piping, or where there was not enough space available for the IHP. The facility may also not have the electrical capacity to handle the IHP's large demand, thereby requiring the installation of transformer(s) and additional electrical work on site.

Each facility may also have different safety requirements and tolerances due to its size. Safety requirements for each company may vary depending on the corporation. Larger companies may have necessary insurance policies and safety training available to handle IHP equipment whereas smaller companies may be less familiar with operating the equipment and may not be willing to take on the risk. For example, facilities with an existing ammonia-based refrigeration system may be more willing to install IHPs that use ammonia as a refrigerant, because they have the safety requirements and procedures already in place. However, corporations that are unfamiliar with ammonia hazards may be more hesitant to adopt the technology. Therefore, for smaller firms, hydrofluroolefins (HFOs) may be emerging as the refrigerant of choice. For smaller packaged IHPs, HFOs and hydrocarbons seem to be a preferred option. Being able to complete an IHP installation without significant impacts to facility uptime is also important.

Process Temperature Knowledge

Boilers are often oversized due to historical methods of sizing them for processes. Therefore, the exact heat demand of the process may not to be known, resulting in inefficient heating. Oversized boilers may output excess heat that is unused by the facility thereby leading to an overestimation of the heat demand needed to retrofit applications with an IHP and falsely making them seem unfeasible. For example, a pasteurization process may only require 71°C (160°F) water, but the facility outputs much higher temperature steam.

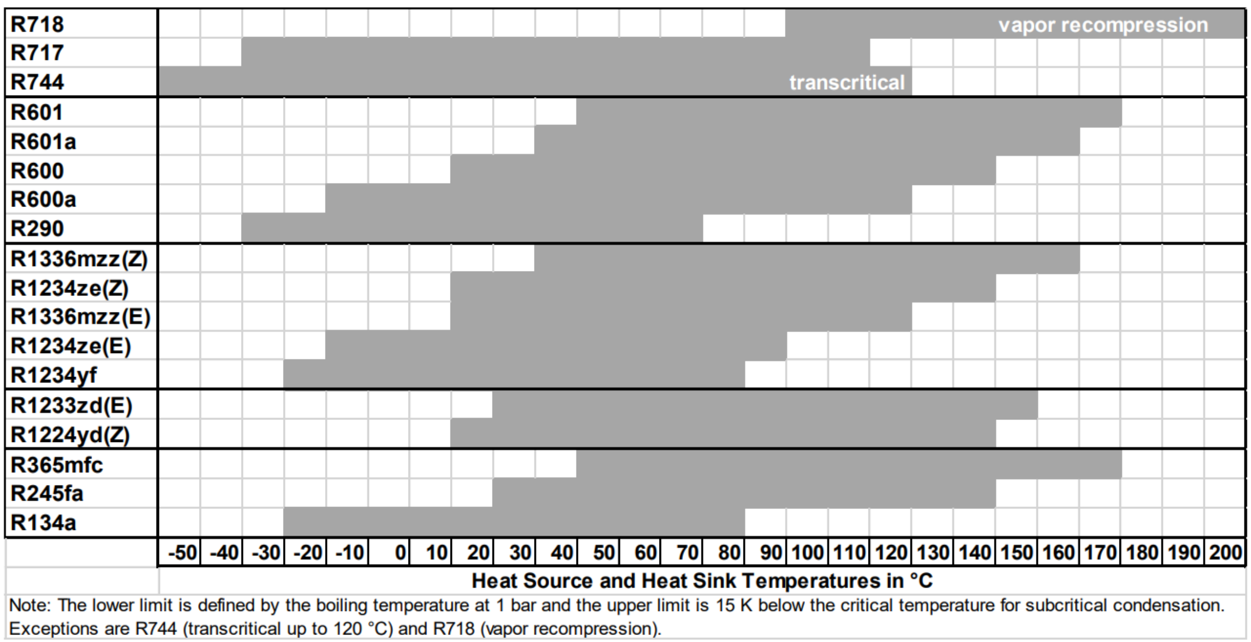
A lack of knowledge of neighboring facility processes can be a barrier to IHP adoption. In some situations, waste heat from a refrigeration system in a facility can be recycled using an IHP for use in heating a neighboring facility, leading to a combined increase in overall COP.

Refrigerant Properties

Refrigerants are the main working fluids used in HPs where phase transition between liquid and gas occurs to enable heating and cooling. For refrigerants to perform well in these systems, they must have a boiling point below their target temperature, a high heat of vaporization, and a high critical temperature. With these desirable properties, refrigerants may be in gaseous form at standard atmospheric conditions and can have environmental impacts causing global warming and ozone depletion. These chemicals may also have toxic and flammability properties that need to be considered when considering an IHP installation.

The refrigerants are regulated by the U.S. Environmental Protection Agency (EPA) at the federal level, and by CARB at the state level. Currently, CARB requires new refrigeration systems containing more than 50 pounds of refrigerant to use refrigerants with a Global Warming Potential (GWP) of less than 150 (California Air Resources Board, 2020). Recent research and developments surrounding per- and polyfluoroalkyl substances (PFAs) have also sparked potential restrictions of some refrigerants that contain PFAs, limiting the types that can be used in IHPs.

The lack of allowable refrigerants based on environmental concerns is also making it more difficult to develop higher temperature applications of IHPs. Figure 13 shows an example list of available refrigerants used in IHPs and their working range of heat source and heat sink temperatures. Currently, R718 (water) is one of the few refrigerants used to generate high temperature steam in SGHPs using an MVR HP (IEA, 2023a).



1st group: Natural refrigerants, 2nd group: Hydrocarbons, 3rd Group: Hydrofluoroolefins, 4th group: Hydrochlorofluorocarbons, 5th group: Hydrofluorocarbons

Figure 13 – Example heat source and heat sink temperatures of IHP refrigerants

Source: IEA, 2023a

Knowledge and Awareness

Knowledge and awareness of IHPs within manufacturing industries is relatively limited. Many manufacturing industries are slow to adopt new technologies due to a low risk tolerance, leading to a lack of knowledge and awareness. This lack of knowledge can be also attributed to the following:

LACK OF U.S. DEMONSTRATIONS

When speaking with manufacturers and industry experts, it was difficult to identify IHP demonstrations within the U.S. While there are known installations, they were unable to speak about them due to nondisclosure agreements. This lack of openly available information about the operation and benefits of IHPs across the U.S. has hindered widespread adoption of the technology.

LACK OF U.S. MANUFACTURERS

With most of the manufacturers of IHPs located in Europe and Asia, the lack of U.S. manufacturers makes it difficult to deploy IHPs domestically. Many of the federal and state funding opportunities for emerging technologies are allocated for U.S. manufacturers, making foreign-made IHPs ineligible for funding. A lack of U.S. manufacturers also reduces the availability of IHPs in the U.S. with foreign manufacturers quoting a 52-week lead time on products.

Grid Readiness

Industrial heat pumps add a significant electrical load, with some systems providing a total heat capacity of 160 MW (Euroheat & Power, 2017). If IHPs were deployed across the U.S., there would be a considerable increase in electricity demand that the electric grid may not be ready for. Continued efforts for industrial electrification could more than double current U.S. power demand (Gimon, E., 2023).

For IHPs to truly produce carbon-free heat, electrical grids must also continue aggressive decarbonizing efforts. This may include implementing distributed energy resources, intelligent systems for energy storage, and decoupling thermal loads from the grid.

Codes and Standards

Depending on the location of the industrial site and the type of IHP, a variety of codes and standards need to be followed before installation in the U.S. These may include but are not limited to the following:

- American Society of Mechanical Engineers (ASME):
  - ASME B31.1 – Power Piping Code, Mechanical
  - ASME B31.3 – Process Piping Code
  - ASME Boiler and Pressure Vessel Code Section VIII
- Air-conditioning, Heating, & Refrigeration Institute (AHRI):
  - AHRI Standard 340-360-2022 (I-P) Performance Rating of Commercial and Industrial Unitary Air-Conditioning and Heat Pump Equipment.
  - AHRI 550/590 (I-P) and 551/591 (SI): Performance Rating of Water-Chilling and Heat Pump Water-Heating Packages Using the Vapor Compression Cycle
- Underwriters Laboratory (UL):
  - UL 508A- Control Panel Wiring
- International Organization for Standardization:
  - EN/ISO 3744:2010 – Acoustics
  - EN/ISO 45001 – Occupational Health & Safety
- International Institute of Ammonia Refrigeration (IIAR) standards for IHPs involving ammonia
- National Electrical Manufacturers Association (NEMA)/American National Standards Institute (ANSI):
  - ANSI/NEMA MG 1-2021 – Motors & Generators

- California Title 24 Building Standards Code
- Local Building and Fire Safety Codes (may vary by county)
- EPA, CARB, and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) regulations on refrigerant properties
- Industry Standards by Application
    - e.g., American Petroleum Institute (API) – API RP 500 - Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class 1, Division 1, and Division 2
- A company's insurance policy may have restrictions on assets owned and operated.

Future Developments and Opportunities

There are a variety of pre-commercial technologies currently in development by manufacturers that are primarily focused on improving COP for higher temperature applications and using low-GWP and natural refrigerants.

The development of positive rotary displacement compressors is a technology that can potentially replace MVR technology, capable of making steam up to 200°C. Mechanical vapor recompression HPs are also being further developed to be able to produce up to 290 psig steam at temperatures up to 200°C. Being able to produce IHPs that can match the steam quality produced by existing boilers can help decarbonize steam production without significant process modifications at existing facilities.

Many manufacturers are also choosing to develop their products to use natural refrigerants to avoid the use of PFAs that may be present in synthetic blends of refrigerants. Some manufacturers are developing hydrocarbon refrigerants such as pentane and butane, or water for supply temperatures above 100°C (212°F).

In addition, manufacturers are currently working to standardize their products. This is likely to reduce the manufacturing and installation costs of IHPs in the future and assist with long production lead times.

Conclusions and Recommendations

When quantifying California's potential market size of IHPs in specific industries, this study found that the heating capacity potential of the industrial sector was 1,051 MW for HTHPs and 1,069 MW for SGHPs. From the industries analyzed, California contributes approximately seven percent of the total potential IHP heating capacity potential of the U.S. with the automotive sector being the highest potential heating capacity for HTHPs. Due to the higher efficiency of HTHPs compared to SGHPs, current HTHP technology may be adopted quicker in this sector compared to others that require SGHPs. Other high benefit applications include those with a higher COP from recycling waste heat from other processes. This may include processes in the dairy, food and beverage, chemicals[1], or

[1] The potential heat capacity of the chemicals industry was not studied in detail in this report.

pulp and paper industries — however California was seen to have a limited pulp and paper industry. Locations where there is a low electricity price compared to gas may also benefit from IHP installations by having a higher return on investment. Corporations that value sustainable products and company reputation are also high benefit applications. Currently, most installations and demonstrations of IHPs are happening outside of the U.S. with supply temperatures reaching up to 211°C (412°F) and COPs varying by temperature lift. Lower temperature applications currently have higher technology readiness levels due to their techno-economic viability compared to high temperature applications.

The main drivers for adopting IHPs are their energy efficiency cost savings, corporate ESG initiatives, and federal or state-level incentive programs. However, there are a variety of market challenges and barriers such as high capital and operational costs, facility requirements, process temperature knowledge, refrigerant properties, lack of knowledge and awareness, grid readiness, and codes and standards. Developments of IHPs are continuing to advance the techno-economic viability of high temperature applications with a focus on low-GWP, natural refrigerants.

Utility Program Recommendations

Recommendations for utility interventions to support market adoption include the following:

Increasing Knowledge and Awareness

Educating industry professionals, design engineers, consultants, and manufacturers about the benefits of IHP technology and funding available can lead to further dissemination of the technology. This can be done through stakeholder engagement using webinars, collaboration at industry events. Professional organizations, universities, and technical schools, as well as development of educational tools. Some examples of potential tools include calculators for IHP COP, return on investment, CO_2 emissions reduction, process water tank sizing, etc.

Technical Assistance Partnerships (TAPs) established by DOE's Industrial Efficiency and Decarbonization Office help industrial facilities install and implement the latest technologies, including IHPs for specific regions. Industrial end-users interested in IHPs should look to engage with the regional TAPs as they are announced (Hoffmeister, A., Elliott, N., 2023).

Having domestic pilots or field demonstrations of IHP technology can be useful in showcasing the benefits of the technology to potential stakeholders. Publicly available information on the performance of IHP systems can be beneficial to increase transparency and gain trust of the technology.

Research and Development

Further research and development of IHP technology focusing on improving the COP of high temperature applications can improve the techno-economic feasibility of installations. Developments in standardizing product lines can also assist in lowering capital costs of equipment, improving the payback of projects.

Another approach, other than improving temperature operating ranges, is to refocus on application related research such as required thermal process analysis, refrigerant choices, and opportunity identification. This technology transfer can be done through TAPs or organizations such as Electrified Processes for Industry Without Carbon to improve technology dissemination for IHPs.

Industrial heat pumps are large electrical loads and will increase stress on the grid. Therefore, research and development on the impact of large-scale industrial electrification should also be incorporated into grid system planning and assessments (Hoffmeister, A., Elliott, N., 2023). With recent incentive programs established to motivate electrification and energy efficiency, utility and system planning may not be adequately modeling potential industrial electrification loads and may need to be updated.

Incentive Mechanisms

While there are currently funding opportunities at the federal and state level, due to the high upfront costs of IHPs, additional incentives may be needed to promote the transition to IHPs. Additionally, consolidating the funding opportunities and simplifying the application and funding processes is critical in increasing market traction.

INCENTIVIZATION OF METERED ENERGY SAVINGS AND EMISSIONS REDUCTION

The GHG emissions reduction and energy savings from IHPs are proportional to the amount of process heat produced. The savings come from reducing or eliminating the use of gas boilers and the IHP's efficiency gain. These savings can be quantified by direct metering of IHPs and boiler systems, reducing the need for complex modeling and rigorous verifications. With the metered data, a performance-based incentive using a method such as normalized metered energy consumption (NMEC) could assist in accelerating the payback for IHP projects.

By including the cost of carbon in projects, there will be further incentive to decarbonize industrial processes. CARB's cap-and-trade program has set a price on carbon, reaching its highest price of $36.14 per metric ton this year (Qin, B., 2023). However, this program only applies to industrial plants that emit 25,000 tons of CO_{2e} per year or more (Center for Climate and Energy Solutions, n.d.-b). Implementing a standardized price of carbon emissions across all plant sizes can further incentivize operational changes to decarbonize industry. The price of carbon varies around the world. The E.U. has a price of over €50 (US$ 53[2]) per ton and Canada announced its emissions price will rise to CAD$170 (US$ 124[3])by 2030. However, the global average price is only $3 per ton, far from the $75 per ton 2030 price target that the International Monetary Fund predicts is needed to keep global warming below two degrees (Parry, I., 2021).

INCREASED LOCAL LEVEL FUNDING

While there are funding opportunities at the federal and California state level as discussed earlier, there are limited funding initiatives targeting industrial decarbonization by utilities and at the regional level. Financial incentives for projects in disadvantaged communities (DACs) and hard-to-reach (HTR) communities may be of interest. DACs and HTR communities may be located near industrial sites that negatively impact them due to high emissions. Designing incentive programs to assist these communities may be necessary to accelerate decarbonization and improve their air quality.

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[2] 1 € = 1.06 US$

[3] 1 CAD$ = 0.73 US$

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Appendix A: Analysis of Industries

The following sections analyze industrial heat pump (IHP) potential in California by industry. The analysis was conducted using the LBNL's report as a major reference (Zuberi et al., 2022).

Food and Beverage Industries

Within the food and beverage industry, the manufacturing process can vary depending on the end-product. The following products lines were identified by Berkeley Lab as having opportunities for electrification and decarbonization by IHPs.

- Meat processing
- Dairy
- Beer
- Canned vegetables and fruits

As with all industrial plant process integration, nearby heat sources may impact environmental temperatures and therefore impact the performance of an IHP. In LBNL's analysis, a heat source temperature of 25°C was assumed (Zuberi et al., 2022)

Meat Processing

The meat processing industry within the U.S. produced approximately 25M tons of red meat in 2021 and is expected to grow to 30M tons by 2050 (USDA ERS, 2022a). The production process starts with the slaughtering of livestock and letting it bleed to prevent decay. Next, the blood is heated to coagulate the albumin. The albumin and fibrin are then separated from the blood water and the carcass has its hide removed and is eviscerated. Internal organs, waste products, and bones are then removed as well throughout the cutting process. Edible products that are not directed to other byproducts such as canned meat or sausages are then sent to rendering. This is a secondary process that separates fats and water from tissues. Inedible byproducts are then processed separately for producing animal feed (Zuberi et al., 2022)

The energy consumption of conventional meat processes was compared to IHP modified processes in Figure 14. The steps highlighted in green indicate process steps suitable for IHP applications. With Scenario 1, the conservative scenario, evisceration and viscera handling can be handled by HTHPs. Additionally, makeup feed water can also be preheated by HTHPs up to 60°C. Moreover, another HTHP can be used to further preheat makeup water from 60°C to 82°C to reduce energy loss when mixing condensate within the condensate tank for steam generation. With these applications, the total heating capacity of HTHPs for the U.S. red meat processing industry was estimated to be 850 MW (Zuberi et al., 2022)

In Scenario 2, the ambitious scenario, SGHPs can be used to generate process steam at 120°C for blood drying, scalding and dehairing, rendering and other processing. The required heating capacity for SGHPs was estimated to be 2620 MW and the COP of SGHPs was assumed to be low (1.8) due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	GJ/t	°C	kWh/t		GJ/t	kWh/t	kWh/t
			2.6	Slaughter			2.6
			0.3	Blood processing			0.3
	0.2	120	0.3	Blood dryer			0.3
	0.2	120	2.3	Scalding & dehairing			2.3
			1.0	Hide removal & proc.			1.0
0.1				Singeing & polishing	0.1		
	0.3	60		Evisceration			
	0.5	60		Viscera handling			
			1.0	Trimming		313.0	1.0
			1.9	Cutting & deboning			1.9
	0.4	120	6.1	Edible rendering			6.1
	1.5	120	24.3	Inedible rendering			24.3
	0.2	120		Inedible rend. drier			
			8.1	Recovery system			8.1
0.3	0.1	120	19.3	Processing	0.3		19.3
			36.5	Packaging			36.5
			93.7	Chiller			93.7
0.4	3.4		197.5	Total	0.4	313.0	197.5

Notes:
SEC values are per tonne of meat production.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 14 – Energy consumption of conventional and modified meat processing

Source: Zuberi et al., 2022

Berkeley Lab estimated the implications of annual final energy demand in the U.S. meat processing industry up to 2050 as shown in in Figure 15. It was estimated that almost 18 PJ per year of final energy could be saved by 2050 if only HTHP applications were considered in Scenario 1. This number increased to approximately 69 PJ per year if both HTHP and SGHP applications were adopted by 2050. By 2050, 23 and 102 PJ of fuel demand could be reduced with a 4 and 33 PJ per year (1.1 and 9.2 TWh per year) electricity demand increase for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

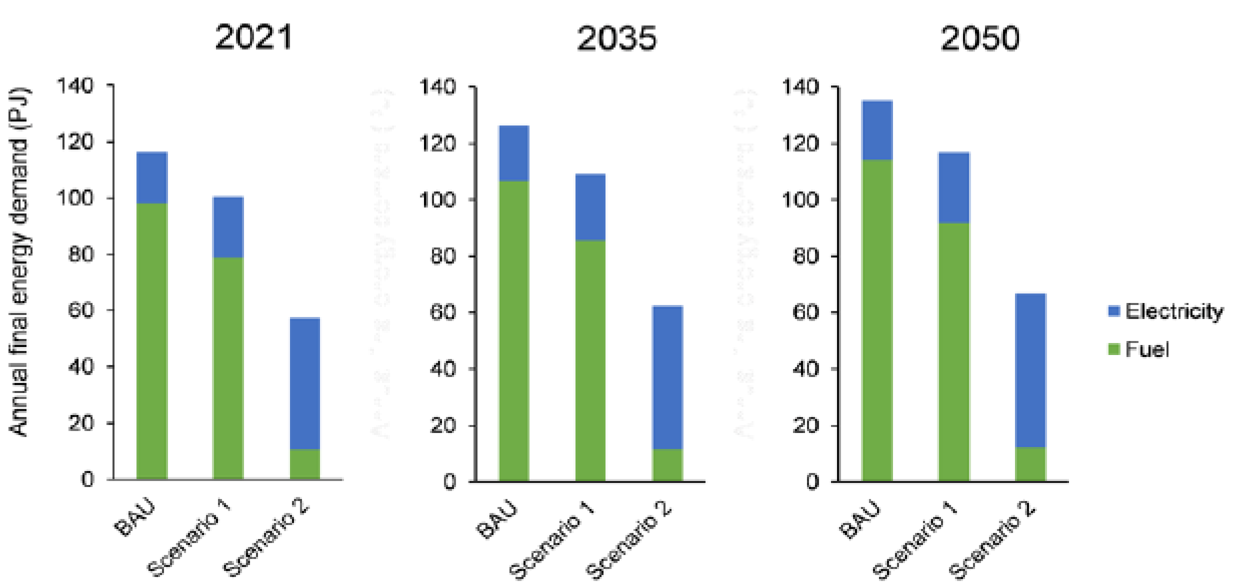

Figure 15 – Annual final energy demand in the U.S. meat processing industry up to 2050

Assuming a 100 percent adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

An estimated 3.1 percent of meat production within the U.S. comes from California, meaning approximately 0.785M tons of red meat was produced in 2021 (USDA ERS, 2023a). With this, the total heating capacity for the California red meat processing industry is estimated to be 27 MW[4] for HTHPs and 82 MW[5] for SGHPs. By 2050, approximately 0.57 PJ and 2.1 PJ can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 0.72 and 3.2 PJ of fuel demand being reduced with a 0.13 and 1.0 PJ per year (0.03 and 0.29 TWh per year) electricity use increase for Scenarios 1 and 2, respectively.

Dairy

The dairy industry in the U.S. produced approximately 103 Mt of milk in 2021 and is expected to grow to 118 Mt tons in 2050 (estimate based on (USDA ERS, 2022b)). The production process starts with raw milk entering a dairy plant with a variety of analytical tests to check the quality of milk. After passing quality control, the milk is stored before entering a clarifier to remove dirt and other particulates and globular milk is separated to produce skim milk. Skim milk is then used for cheesemaking while the rest of the fluid is pasteurized through a heat exchanger using steam to destroy pathogens. The pasteurized milk is homogenized to disperse fat globules and a steam distillation of the milk is performed to remove odorizing materials. The fluid milk is then packaged and stored for distribution.

[4] 850 MW (Total U.S. Capacity) * 3.1% (California Production) = 27 MW

[5] 2620 MW (Total U.S. Capacity) * 3.1% (California Production) = 82 MW

For cheese production, skim milk is first pasteurized before pumping into cheese vats where it is cooked slowly using steam and mild agitation. The resulting curds are either moved to a silo where they are separated from the whey and dried or washed with water, cooled, and mixed with cream to produce cottage cheese (Zuberi et al., 2022)

The specific energy consumption of conventional milk processing versus an IHP modified process can be seen in Figure 16 with the green highlighted process steps meeting heat demand temperatures suitable for IHP applications. In the conservative case, an HTHP can be used to preheat makeup water up to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHPs for the U.S. dairy industry is estimated to be 43 MW in the conservative scenario (Zuberi et al., 2022)

In an ambitious scenario, SGHPs can be used to generate process steam at 120°C for pasteurization and deodorization for fluid milk and cream production, as well as pasteurization, and settling and cooking in cheese production. The required heating capacity for SGHPs is estimated to be 1,656 MW. It should be noted that the COP of the SGHPs used is assumed to be low (1.8) due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use for boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	*GJ/t*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
Raw milk processing							
0.02				Receiving	0.02		
			4.4	Standard. & Clarification			4.4
			9.3	Separator			9.3
Fluid milk and creme production							
	0.21	120		Pasteurization			
			5.3	Homogenizing & Cooling			5.3
	0.06	120		Deodorization			
0.03			27.8	Package & Storage	0.03	41.7	27.8
Cheese production							
	0.004	120		Pasteurization			
	0.09	120		Settling & Cooking			
			1.2	Drawing/Wash/Cooling			1.2
0.01				Dryer	0.01		
			1.0	Creaming			1.0
			0.5	Packaging & Storage			0.5
			38.8	Chiller			38.8
0.06	0.36		88.2	Total	0.06	41.7	88.2

Notes:
SEC values are per tonne of whole milk input.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 16 – Specific energy consumption of conventional and modified dairy processing

Source: Zuberi et al., 2022

The projected annual final energy demand of the U.S. dairy industry up to 2050 is shown in Figure 17. LBNL estimated that only 0.8 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increased to approximately 26 PJ if both HTHP and SGHP applications were adopted by 2050 (Scenario 2). By 2050, 1.1 and 45 PJ of fuel demand could be reduced with a 0.3 and 19 PJ per year (0.1 and 5.1 TWh per year) electricity demand increase for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

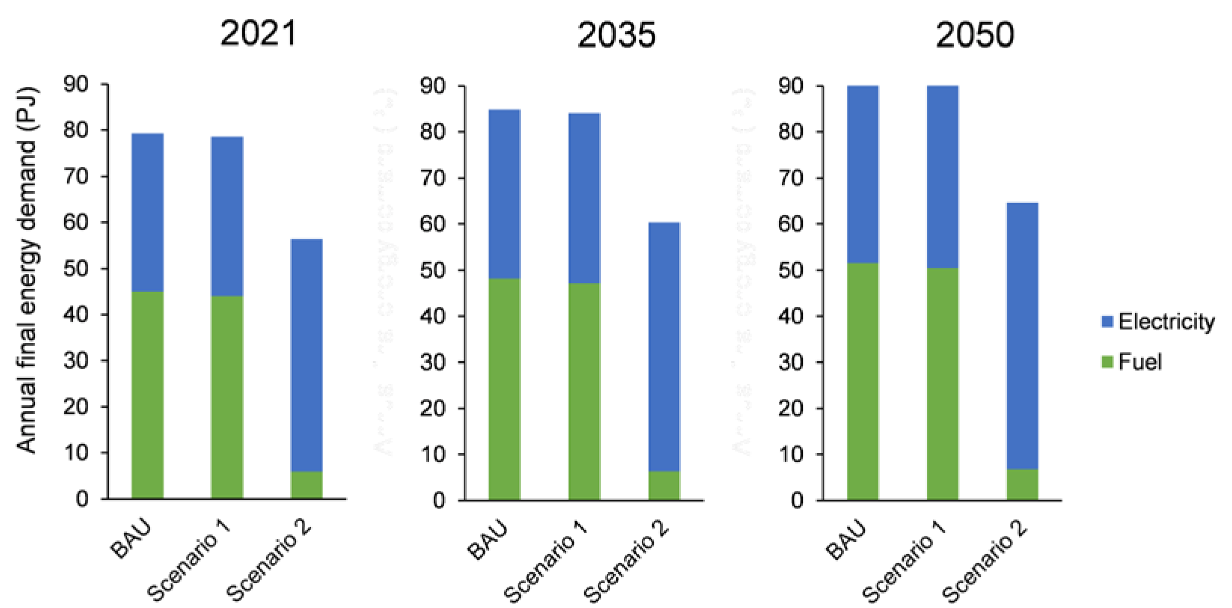

Figure 17 – Annual final energy demand in the U.S. dairy industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

An estimated 18.5 percent of dairy production within the U.S. comes from California, meaning approximately 19Mt of dairy product was produced in 2021 (USDA ERS, 2023b). With this, the total heating capacity for the California dairy industry was estimated to be 8.0MW[6] for HTHPs and 306MW[7] for SGHPs. By 2050, approximately 0.15 PJ and 4.8 PJ of energy can be saved in Scenarios 1 and 2, respectively, across California. This equates to approximately 0.2 and 8.3 PJ of fuel demand being reduced with a 0.06 and 3.5 PJ per year (0.02 and 0.98 TWh per year) electricity use increase for Scenarios 1 and 2, respectively.

Beer

The beer industry in the U.S. produced approximately 180 M barrels of beer in 2020 and is expected to grow to 210 M barrels in 2050 (Statistica, 2021). The general brewing process can use a variety of ingredients such as barley or other cereals depending on the type of beer produced. First, the grain is modified to malt and then milled to produce grist, a coarse powder. The grist is mixed with warm water for about an hour, followed by hot water to break down starches into sugar using enzymes to create a mixture known as the wort. The wort is heated by steam jackets and separated from residual grains in a filter called lautering. These residual grains may be used to produce animal feed in a separate process. The wort is then sterilized through boiling which stops enzyme activity. After boiling, the wort is cooled and condensed to around room temperature where yeast is added to

[6] 43 MW (Total U.S. Capacity) * 18.5% (California Production) = 8.0 MW

[7] 1656 MW (Total U.S. Capacity) * 18.5% (California Production) = 306 MW

start fermentation. The beer is chilled and stored in a tank for maturation. After another filtration step, the beer can be kegged, or bottled and carbonated. Some processes may also pasteurize their beer to improve shelf life and clarity (The Beer Connoisseur, 2016)

The energy consumption of conventional beer production was compared to IHP modified processes in Figure 18. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to provide process hot water at temperatures from 54 to 82°C for applications such as mash tun, cleaning, filtration, and pasteurization. These HTHPs can also be used to preheat makeup feed water to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHPs for the U.S. beer industry was estimated to be 2 GW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for cooking, mashing, and brewing. The required heating capacity for SGHPs was estimated to be 880 MW. It should be noted that the COP of the SGHPs was assumed to be low (1.8) due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	GJ/t	°C	kWh/t		GJ/t	kWh/t	kWh/t
			8.9	Malting & Milling			8.9
	0.1 & 0.1	82 & 120		Cooker			
	0.1 & 0.1	54 & 120		Mash tun			
	0.1	74	5.4	Filter lauter tub			5.4
			5.4	Screen mix & press			5.4
0.7			3.2	Dryer	0.7		3.2
	0.2	120		Brewing			
			1.4	Set. Cooling aerator		133.7	1.4
			0.0	Fermenting			0.0
			4.8	Cooling aging filter			4.8
			5.7	Compressor			5.7
	0.3	71		Container washing			
			3.2	Filling/Kegging			3.2
	0.8	82		Pasteurization			
			8.4	Packaging			8.4
			42.0	Chiller			42.0
0.7	1.7		88.4	Total	0.7	133.7	88.4

Notes:
SEC values are per tonne of beer production. The density of beer is taken as 1008 kg/m³.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 18 – Specific energy consumption of conventional and modified beer production

Source: Zuberi et al., 2022

The projected annual final energy demands of the beer industry in the U.S. up to 2050 are shown in Figure 19. Berkeley Lab estimated that 26 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 32 PJ if both HTHP and SGHP applications were adopted by 2050 (Scenario 2). By 2050, 33 and 44 PJ of fuel demand could be reduced while electricity demand increases 6 PJ and 12 PJ per year (1.8 TWh and 3.4 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

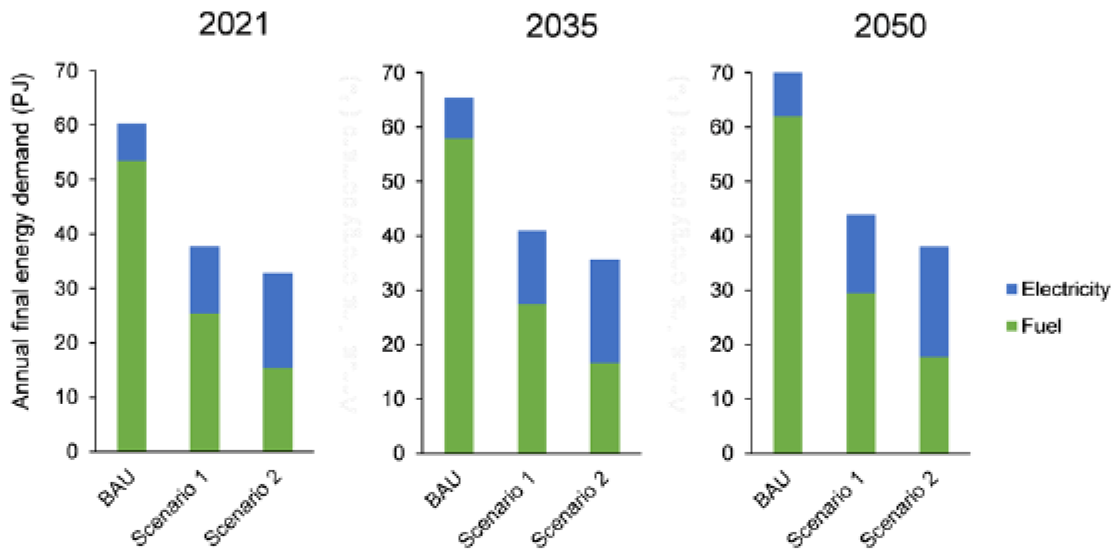

Figure 19 – Annual final energy demand in the U.S. beer industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

In 2020, California produced 16.6 million barrels of beer products in 2020 (TTB, 2020), which amounted to 9.2 percent of beer production in the U.S. With this, the total heating capacity for the California beer industry was estimated to be 184 MW[8] for HTHPs and 81 MW[9] for SGHPs. By 2050, approximately 2.4 PJ and 2.9 PJ can be saved in Scenarios 1 and 2, respectively, across California. This equates to approximately 3.0 and 4.0 PJ of fuel demand being reduced with a 0.55 and 1.1 PJ per year (0.15 and 0.31 TWh per year) electricity use increase for Scenarios 1 and 2, respectively.

Canned Vegetables and Fruits

The canned vegetable and fruit processing plants within the U.S. were estimated to produce 8 Mt in 2021 and are expected to grow to 10 Mt in 2050 (U.S. DOE/AMO, 2017). The conventional canning process of fruits and vegetables is similar across product types, however specific details of these processes may differ depending on the specific fruit or vegetable and processing plant. Generally, the production process begins with washing and grading of fruits and vegetables where raw produce is graded based on size and maturity. Depending on the product, the produce may be cut or sliced. Some products may also be blanched before filling into cans. Usually, vegetables require more processing due to their lower acidity and origin in soil containing heat-resistant organisms. Vegetables are usually more desirable after cooking as well. Both fruits and vegetables can go through a peeling process performed by mechanical, steam or lye peeling. Salt may also be added depending on the product type. Cans or containers are washed with hot water and are filled with product. Air is then exhausted from the containers and kept under a vacuum to be sealed, extending

[8] 2000 MW (Total U.S. Capacity) * 9.2% (California Production) = 184 MW

[9] 880 MW (Total U.S. Capacity) * 9.2% (California Production) = 81 MW

the shelf life of the food products. Sealing machines may also use steam flow to create a vacuum in the headspace before sealing. Next, retorting is a process done to sterilize microorganisms that may cause decay. The products are then cooled and labeled for distribution (U.S. EPA, n.d.).

The energy consumption of conventional canned vegetable production was compared to IHP modified processes in Figure 20 with the green highlighted process steps indicating that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to provide process hot water to temperatures around 60°C for washing vegetables and cans. The same HTHP can also be used to preheat makeup feed water to 60°C and another one can be used to raise the water temperature from 60°C to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHPs for the U.S. canned vegetable industry was estimated to be 225 MW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for scalding, cooking, brine heating, exhausting, and sealing. Another SGHP can be used at 150°C for the retort process. The required heating capacity for SGHPs was estimated to be 740 MW. It should be noted that the COP of the SGHPs used was assumed to be low due to the high temperature lift, especially for 150°C temperatures (Zuberi et al., 2022)

Conventional process			Process steps	Modified process with IHP	
Fuel use in boilers	Steam or water temp.	Electricity use		Electricity use in IHPs	Electricity use in other processes
GJ/t	*°C*	*kWh/t*		*kWh/t*	*kWh/t*
		3.3	Inspection & grading		3.3
0.6	60	4.0	Washing		4.0
		7.1	Cutting slices		7.1
0.6	120		Scalding / Blanching		
		4.0	Peeler		4.0
		4.0	Pulper		4.0
0.6	120		Cooker		
		4.0	Cooling washing	336.6	4.0
0.3	120		Brine heater		
		6.1	Can filling		6.1
0.3	120		Exhausting		
0.1	120	4.0	Sealing		4.0
0.6	150		Retort		
		4.0	Cooling		4.0
		9.1	Packaging		9.1
0.1	60		Can washing		
3.1		49.7	Total	33.6.6	49.7

Notes:
SEC values are per tonne of canned vegetables.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 20 – Specific energy consumption of conventional and modified vegetable canning process

Source: Zuberi et al., 2022

The specific energy consumption of conventional canned fruit production versus an IHP modified process can be seen in Figure 21 with the green highlighted process steps meeting heat demand temperatures suitable for IHP applications. Since the process is similar to vegetable canning, the total heating capacity of HTHPs for the U.S. canned fruit industry is estimated to be 80 MW in the conservative scenario (Zuberi et al., 2022)

In an ambitious scenario, SGHPs can be used similarly to the vegetable canning process with the retort process requiring steam at 120°C instead of 150°C. With this, the total required heating capacity of SGHPs is estimated to be 100 MW (Zuberi et al., 2022)

Conventional process			Process steps	Modified process with IHP	
Fuel use in boilers	Steam or water temp.	Electricity use		Electricity use in IHPs	Electricity use in other processes
GJ/t	°C	kWh/t		kWh/t	kWh/t
		4.3	Inspection & grading	266.6	4.3
0.6	60	4.3	Washing		4.3
0.2	120	4.3	Peeling		4.3
0.6	60		Washing & grading		
		7.5	Slicing		7.5
0.4	120		Cooking		
0.3	120		Syrup heater		
		6.5	Filling		6.5
0.2	120		Exhausting		
0.1	120	4.3	Sealing		4.3
0.4	120		Retort		
		4.3	Cooling		4.3
		9.7	Packaging		9.7
0.1	60		Can washing		
3.1		45.2	Total	266.6	45.2

Notes:
SEC values are per tonne of canned fruits.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 21 – Specific energy consumption of conventional and modified fruit canning process

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. vegetable canning industry up to 2050 are shown in Figure 22. LBNL estimated that 5 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 16 PJ if both HTHP and SGHP applications were adopted by 2050 (Scenario 2). Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 6 and 16 PJ of fuel demand could be reduced while electricity demand increases 1 PJ and 10 PJ per year (0.3 TWh and 2.8 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

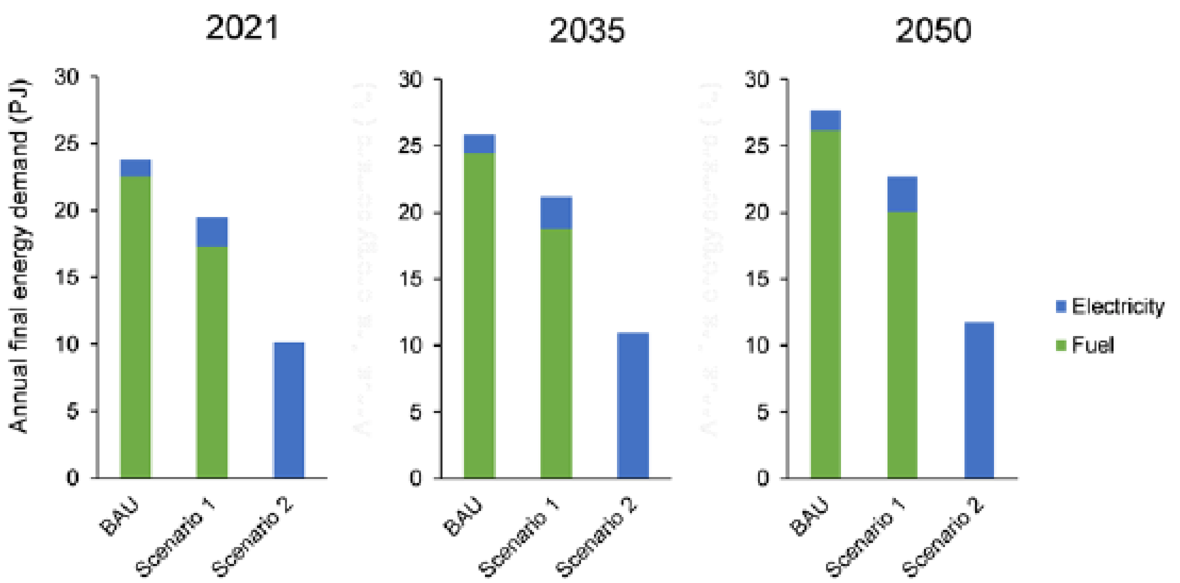

Figure 22 – Annual final energy demand in the U.S. vegetable canning industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. fruit canning industry up to 2050 are shown in Figure 23. LBNL estimated that 2 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 3.5 PJ if both HTHP and SGHP applications were adopted by 2050 (Scenario 2). Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 2 and 5 PJ of fuel demand could be reduced while electricity demand increases 0.4 PJ and 1.6 PJ per year (0.1 TWh and 0.4 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

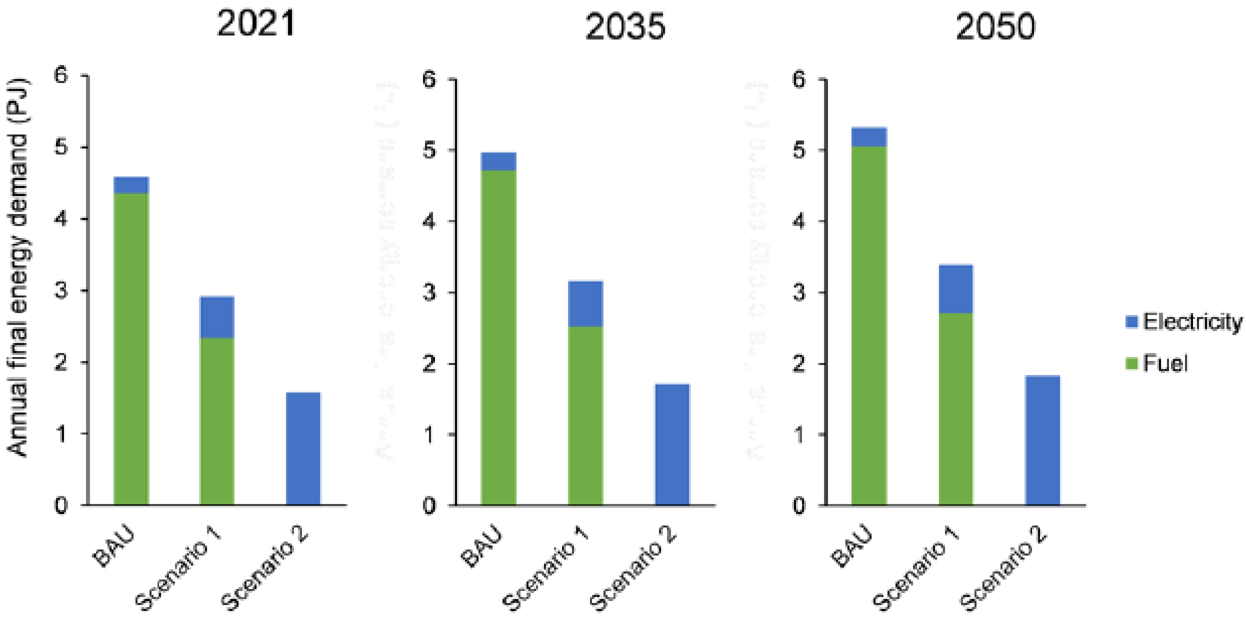

Figure 23 – Annual final energy demand in the U.S. fruit canning industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the fruit and vegetable canning industry in California, 2020 census data released on March 31,2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to fruit and vegetable canning[10] (U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total fruit and vegetable canning in California.

An estimated 22 percent of total canned fruit and vegetable production within the U.S. comes from California, meaning approximately 2 million tons of canned fruit and vegetable product was processed in 2021. With this, the total heating capacity for the California fruit and vegetable canning industry is estimated to be 68 MW (50 MW for canned vegetables and 18 MW for canned fruits)[11] for HTHPs and 186 MW (164 MW for canned vegetables and 22 MW for canned fruits)[12] for SGHPs. By 2050, approximately 1.5 PJ (1.1 PJ for canned vegetables and 0.4 PJ for canned fruits) and 4.4 PJ (3.6 PJ for canned vegetables and 0.8 for canned fruits) can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 1.7 (1.3 PJ for canned vegetables and 0.4 PJ for canned fruits) and 4.7 PJ (3.6 PJ for canned vegetables and 1.1 PJ for canned fruits) of fuel demand being reduced with a 0.3 (0.2 PJ for canned vegetables and 0.1 PJ for canned fruits)

[10] NAICS Code 311421 (Fruit and Vegetable Canning)

[11] Vegetable Canning: 225 MW (Total U.S. Capacity) * 22.2% (California Industry Employment) = 50 MW;
Fruit Canning: 80 MW (Total U.S. Capacity) * 22.2% (California Industry Employment) = 17.8 MW

[12] Vegetable Canning: 740 MW (Total U.S. Capacity) * 22.2% (California Industry Employment) = 164.4 MW;
Fruit Canning: 100 MW (Total U.S. Capacity) * 22.2% (California Industry Employment) = 22.2 MW

and 2.6 PJ (2.2 PJ for canned vegetables and 0.4 PJ for canned fruits) per year (0.09 and 0.72 TWh per year) electricity use increase for Scenarios 1 and 2 respectively.

Cane Sugar

The cane sugar industry in the U.S. produced approximately 3.6 Mt of cane sugar in 2020 and is expected to grow to 4.2 Mt by 2050 (USDA ERS, 2022c). The general refining process starts with a mingler that transforms raw sugar extracted from sugarcane into a refined granulated product. This step requires intense mixing and time to process. The raw sugar is then mixed with hot water to loosen the molasses. From the sugar mixture, sugar crystals are separated from the syrup in a centrifuge and then washed with warm water. Sugar crystals are then melted and mixed with hot water to undergo a clarification process. By using steam, the process removes sludge, and the final product is pressure filtrated. Next, adsorption is used to remove soluble impurities for decolorization. Activated charcoal is used as the adsorbent and is removed from the bed after being spent. The spent adsorbent can be regenerated, cooled, and reused while processing. The decolorized sugar solution is then concentrated through multiple evaporators and is sent to vacuum pans for crystallization. Sugar crystals are then separated and washed in a centrifuge. The sugar crystals are then shredded to form soft brown sugar. The remaining solution from the centrifuge is then sent to a granulator to dry using steam. This end-product is then further processed to form white granulated sugar, brown sugar, as well as liquid sugar (Brown et al., 1996; U.S. EPA, n.d.)

The energy consumptions of conventional cane sugar refining were compared to IHP modified processes in Figure 24. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to provide process hot water at temperatures from 63 - 90°C for applications such as mixing in the mingler, centrifugation, filtration, and melting. The total heating capacity of HTHP for the U.S. cane sugar refining industry is estimated to be 285 MW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for clarification, granulation, drying, and vacuum pans. Another SGHP may be used for process steam at 150°C for the evaporator. The required heating capacity for SGHP was estimated to be 485 MW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use for IHPs	Electricity use in other processes
GJ/t	GJ/t	ºC	kWh/t		GJ/t	kWh/t	kWh/t
	0.1	63	16.2	Mingler			16.2
	0.1	63	4.8	Centrifuge			4.8
	0.3	90		Melter			
	0.1	120	2.6	Clarification			2.6
	1.4	74	4.8	Filter			4.8
0.6				Charcoal regeneration	0.6		
			1.9	Cooling		513.7	1.9
	0.9	150		Evaporator			
	2.4	120		Vacuum pans			
			6.1	Mixer/Centrifuge			6.1
			1.3	Shredder			1.3
	0.1	120	1.6	Granulator & Dryer			1.6
			1.9	Liquid sugar process			1.9
0.6	5.4		41.4	Total	0.6	513.7	41.4

Notes:
SEC values are per tonne of cane sugar products.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 24 – Specific energy consumption of conventional and modified cane sugar refining

Source: Zuberi et al., 2022

The projected annual final energy demand of the U.S. cane sugar refining industry up to 2050 are shown in Figure 25. LBNL estimated that 6 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 15 PJ if both HTHP and SGHP applications were adopted in 2050. Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 8 and 23 PJ of fuel demand could be reduced while electricity demand increases 2 PJ and 8 PJ per year (0.5 TWh and 2.2 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022).

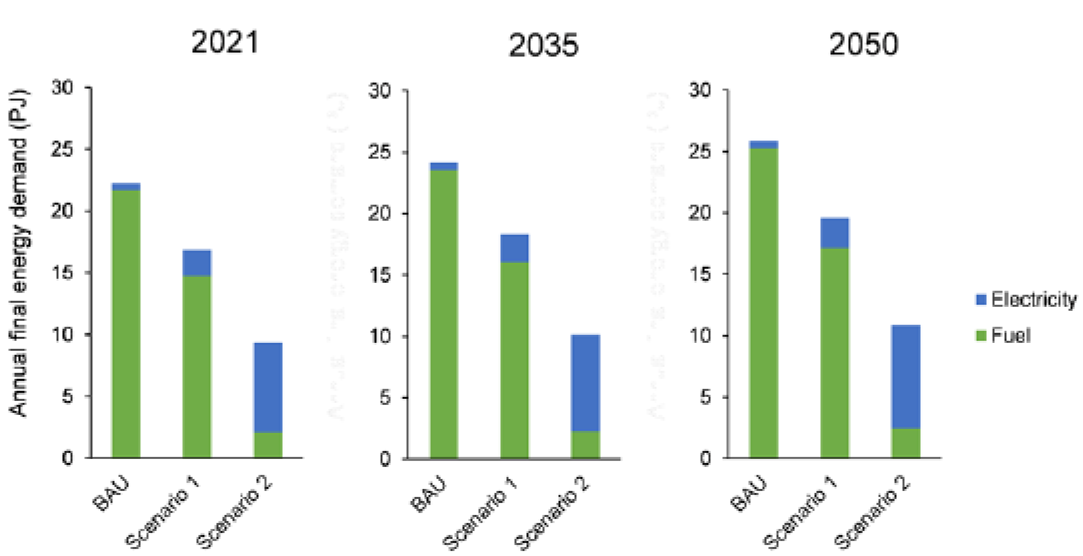

Figure 25 – Annual final energy demand in the U.S. cane refining industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the sugar cane refining industry in California, 2020 census data released on March 31,2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to cane sugar manufacturing[13] (U.S. Census Bureau, 2023). Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total cane sugar production in California.

An estimated 0.6 Mt of cane sugar was produced in 2020 or 18 percent of cane sugar production within the U.S. comes from California. With this, the total heating capacity for the California cane sugar industry is estimated to be 50.7 MW[14] for HTHP and 86.2 MW[15] for SGHP. By 2050, approximately 1.1 PJ and 2.7 PJ can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 1.4 and 4.1 PJ of fuel demand being reduced with a 0.36 and 1.4 PJ per year (0.10 and 0.40 TWh per year) electricity use increase for scenarios 1 and 2, respectively.

Beet Sugar

The beet sugar industry within the U.S. produced approximately 33 Mt of sugar in 2021 and is expected to grow to 38 Mt in 2050 (USDA ERS, 2022c). The general refining process starts with washing and slicing of sugar beets. Then, the beets are placed in a diffuser with hot water to extract sucrose resulting in a diffusion juice. The residual pulp is then compressed, dried, and processed as animal feed. The diffusion juice is then mixed with milk of lime to react with a variety of soluble non-

[13] NAICS Code 311314 (Cane Sugar Manufacturing)

[14] 285 MW (Total U.S. Capacity) * 17.8% (California Industry Employment) = 50.7 MW

[15] 485 MW (Total U.S. Capacity) * 17.8 % (California Industry Employment) = 86.2 MW

sugars in the juice. Next, the juice is processed in carbonation tanks to produce calcium carbonate precipitate, allowing filtration of impurities (U.S. EPA, n.d.). The purified juice is then sent to the evaporator to reduce the water content int the juice to produce syrup. This process is highly demanding of steam and is responsible for more than half of the entire demand throughout the refining process. The resulting syrup is then crystallized to obtain sugar and molasses that is then separated and dried (Brown et al., 1996; U.S. EPA, n.d.).

The energy consumptions of conventional beet sugar production were compared to IHP modified processes in Figure 26. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to provide process hot water at temperatures of 60°C for the diffusion process. The same HTHP can also be used to preheat makeup feed water to 60°C, while another HTHP can assist in preheating makeup water from 60°C to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHPs for the U.S. beet sugar industry was estimated to be 235 MW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for the diffuser, juice heaters, evaporators, and dryers. A second SGHP can be used to produce steam at 138°C for the vacuum pans. The required heating capacity for SGHP was estimated to be 2.7 GW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	*GJ/t*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
			1.3	Fluming & washing			2.6
			3.9	Slicing			0.3
	0.2 & 0.1	60 & 120	1.3	Diffusion			0.3
			4.5	Pulp screens & press			2.3
0.7			1.3	Kiln drier	0.7		1.0
			2.6	Pelletizing & package			
	0.2	120		Juice heater			
0.1				Lime kiln	0.1	242.2	
			1.3	Liming & carbonation			1.0
	0.3	120		Heater			1.9
	1.2	120		Evaporators			6.1
	0.3	138		Vacuum pans			24.3
			3.2	Crystallizer & mixer			
			5.2	Centrifuge			8.1
	0.01	120		Granulator dryer			19.3
0.9	2.2		24.6	Total	0.9	242.2	36.5

Note:
SEC values are per tonne of beet input.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
I GJ = 277.78 kWh

Figure 26 – Specific energy consumption of conventional and modified beet sugar production

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. beet sugar industry up to 2050 are shown in Figure 27. LBNL estimated that 5 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered in Scenario 1. This number increases to approximately 51 PJ if both HTHP and SGHP applications were adopted in 2050 (Scenario 2). Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 7 and 84 PJ of fuel demand could be reduced while electricity demand increases 1.2 PJ and 33 PJ per year (0.3 TWh and 9.2 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

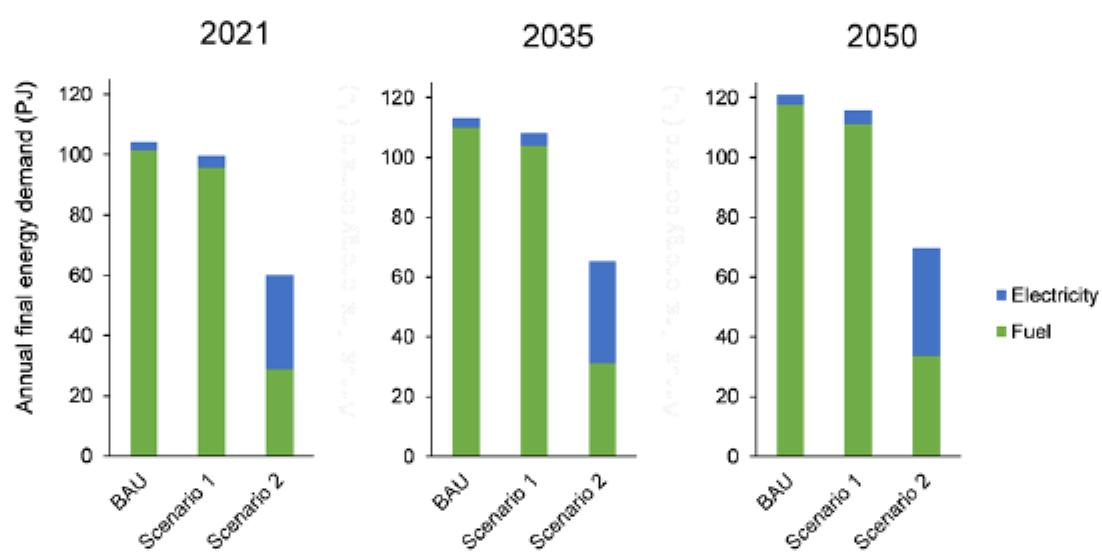

Figure 27 – Annual final energy demand in the U.S. beet sugar industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

An estimated 3.2 percent of beet sugar production within the U.S. comes from California, meaning an estimated 1.1 Mt of beet sugar was produced annually in 2021 (USDA ERS, 2022c). With this, the total heating capacity for the California beet sugar industry is estimated to be 7.6 MW[16] for HTHP and 87.6MW[17] for SGHP. By 2050, approximately 0.16 PJ and 1.7 PJ can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 0.23 and 2.7 PJ of fuel demand being reduced with a 0.039 and 1.1 PJ per year (0.011 and 0.30 TWh per year) electricity use increase for scenarios 1 and 2, respectively.

Corn Wet-Milling

The corn wet-milling industry within the U.S. processed approximately 26 Mt of corn in 2021 and is expected to grow to 30 Mt in 2050 (USDA ERS, 2022c). The general refining process starts with cobs being removed from corn and cleared of foreign materials. The kernels are then steeped in large tanks with mildly acidic warm water for 20 to 36 hours. The kernels absorb water and starch is released. Then the kernels are ground to release germ and the steep water is then evaporated using multiple effect evaporators. Throughout the degermination processes, the germ is separated from other components due to its high oil content. The germ is then dewatered using a screw press, resulting in 50 to 60 percent water content. Rotary steam driers are then used to dry the germ further. Corn oil is then extracted through a variety of chemical and mechanical processes and the impurities are removed prior to being sold as corn oil (Galitsky et al., 2003; Hasanbeigi et al., 2021).

[16] 235 MW (Total U.S. Capacity) * 3.2% (California Production) = 7.6 MW

[17] 2700 MW (Total U.S. Capacity) * 3.2% (California Production) = 87.6 MW

After oil extraction, the corn-water slurry undergoes a fine grinding and screening process to separate all starch and gluten from fiber. Fiber is then washed with water to recover as much gluten and starch as possible. Next, a centrifuge is used to dewater the fiber, which is then dried and prepared as animal feed. Another filtering system is used to separate the starch from gluten. The starch can then be sold directly as a powder after being dried with steam or converted into syrups or ethanol. Starch can be modified with varying functionality to produce other products. Dextrin is a product made by roasting starch and using amylase to for hydrolyzation (Galitsky et al., 2003; U.S. EPA, n.d.). Other starch byproducts can undergo saccharification to convert the remaining solution to sugar syrups that can be refined further to final products such as high fructose corn syrup. In refining syrups for use, evaporation is a significant process that uses a high amount of energy via steam. After refining, the liquor is held in vessels for crystallization. When about 60 percent of the dextrose is crystallized, the solids are separated by centrifugation, and are dried and packaged for distribution (Brown and Hamel, 1996; Galitsky et al., 2003; U.S. EPA, n.d.)

The energy consumption of the conventional corn wet-milling process was compared to IHP modified processes in Figure 28. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, an HTHP can be used to preheat makeup feed water to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHP for the U.S. corn wet-milling industry was estimated to be 60 MW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 107°C for steeping. A second SGHP can be used to produce steam at 120°C for the evaporators, dryers, oil extractors, refiners, and starch conversion. The required heating capacity for SGHP was estimated to be 5.7 GW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHPs		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	*GJ/t*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
			9.7	Cleaning			9.7
	0.3	107		Steep tank			
	1.0	120		Steep water evap.			
			19.4	Degerminator & Separator			19.4
	0.5	120		Germ dryer			
	0.2	120	6.5	Oil extractor			6.5
	0.1	120		Filter separator refiner			
			12.9	Grinding mills			12.9
			6.5	Washing screens			6.5
			16.2	Centrifugal separator			16.2
0.8				Feed dryer	0.8	577.2	
			16.2	Starch washing filters			16.2
	0.7	120		Starch drying			
0.2				Dextrin roaster	0.2		
	0.3	120	16.2	Starch conversion			16.2
			6.5	Filter			6.5
	0.4	120	6.5	Light refining			6.5
	0.4	120		Evaporators			
	0.2	120	6.5	Heavy refining			6.5
	0.3	120		Evaporator			
			6.5	Crystallizer & Centrifuge			6.5
0.03				Dryer	0.03		
1.1	4.5		129.2	Total	1.1	577.2	129.2

Notes:
SEC values are per tonne of corn input.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 28 – Specific energy consumption of conventional and modified corn wet-milling processes

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. corn wet-milling industry up to 2050 are shown in Figure 29. Berkeley Lab estimated that 1.1 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered in Scenario 1. This number increases to approximately 75 PJ per year if both HTHP and SGHP applications were adopted in 2050 (Scenario

2). Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 2 and 138 PJ of fuel demand could be reduced while electricity demand increases 0.4 PJ and 63 PJ per year (0.1 TWh and 17.6 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

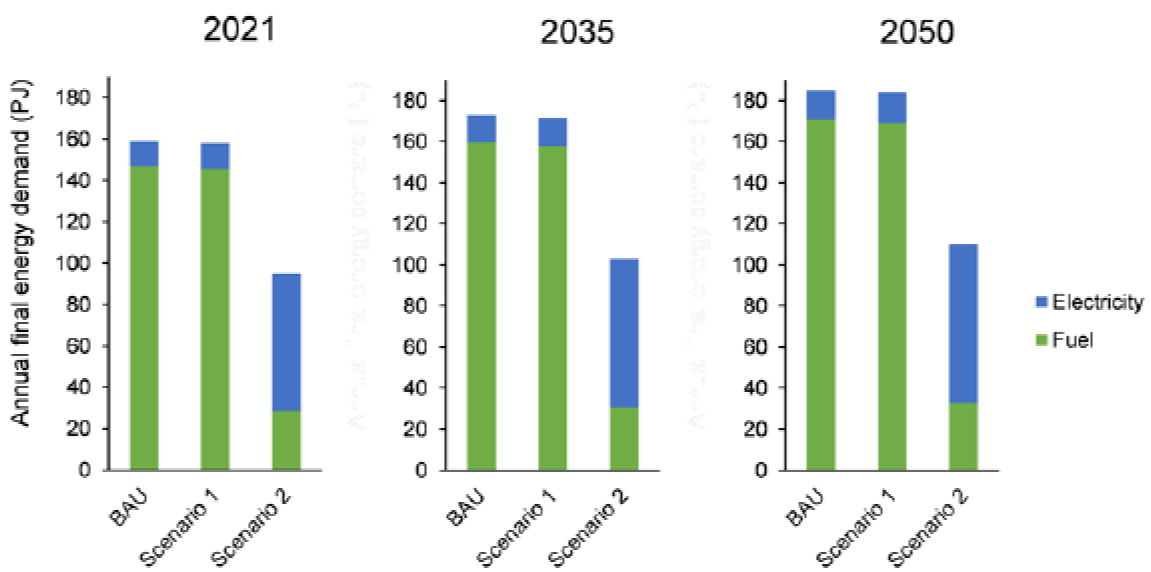

Figure 29 – Annual final energy demand in the U.S. corn wet-milling industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the corn wet-milling industry in California, 2020 census data released on March 31, 2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to wet corn milling[18] (U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total corn wet-milling production in California. In 2020, there was no employment in California for this industry meaning there is no market for these IHP applications in California.

Soybean Oil

The soybean oil industry within the U.S. processed approximately 12 Mt of oil in 2021 and is expected to grow to 14 Mt in 2050 (USDA ERS, n.d.). The general refining process starts with cleaning soybeans on a screen to remove stems, pods, sand, dirt, etc. Next the beans are taken to a drier to reduce their moisture content to approximately 10 percent by weight. A cracking mill is then used to break the soybeans into smaller pieces and separate their hulls. A rotary steam tube or stacked cooker uses steam to condition the beans and make them pliable and hydrated. The heated beans are pressed into smooth flakes that exposes the oil cells to facilitate oil extraction (U.S. EPA,

[18] NAICS Code 3112221 (Wet Corn Milling)

n.d.). The flakes are then moved to an oil extractor that uses hexane and other oil mixtures to wash the product. Next a desolventizer is used to evaporate the hexane solvent with steam. During this process, the solvent can be condensed and separated from the steam and reused. Another drying step is used to remove extra moisture from the flakes, which can then be further grinded and cooled for use in animal feed. Some of the crude soybean oils from the extractor can contain a trace amount of substances such as proteinaceous materials, fatty acids, and phosphatides that are removed in a stripper that can use steam under high vacuum and temperature to produce refined oil (U.S. EPA, n.d.).

The energy consumptions of the conventional soybean oil manufacturing process were compared to IHP modified processes in Figure 30. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to preheat makeup feed water to 82°C before it enters the return condensate tank for steam generation. The total heating capacity of HTHP for the U.S. soybean oil manufacturing industry was estimated to be 105 MW in the conservative scenario (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for the conditioner, desolventizer, and evaporator. Steam at higher temperatures around 177°C for meal drying and vacuum stripping was not considered due to the current state of IHP technology. The required heating capacity for SGHP was estimated to be 2520 MW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process					Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use	Process steps	Direct & boiler fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	*GJ/t*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
1.9			16.2	Cleaner & Dryer	1.9		16.2
			25.8	Cracking			25.8
			19.4	Dehuller			19.4
	1.7	120	19.4	Conditioner			19.4
			45.2	Flaking mill			45.2
			19.4	Extractor		588.0	19.4
	2.5	120		Desolventizer			
	2.4	177	19.4	Meal dryer	2.4		19.4
			19.4	Milling & Cooling			19.4
	0.7	120		Evaporator			
	0.2	177		Vacuum stripper	0.2		
			19.4	Separator			19.4
1.9	7.4		203.5	Total	4.4	588.0	203.5

Notes:
SEC values are per tonne of soybean oil.
Boiler system efficiency is assumed at 78% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 30 – Specific energy consumption of conventional and modified soybean oil manufacturing processes

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. soybean oil industry up to 2050 are shown in Figure 31. Berkeley Lab estimated that 2 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 37 PJ if both HTHP and SGHP applications were adopted in 2050 (Scenario 2). Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 3 PJ and 66 PJ of fuel demand could be reduced while electricity demand increases 0.8 PJ and 29 PJ per year (0.2 TWh and 8 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

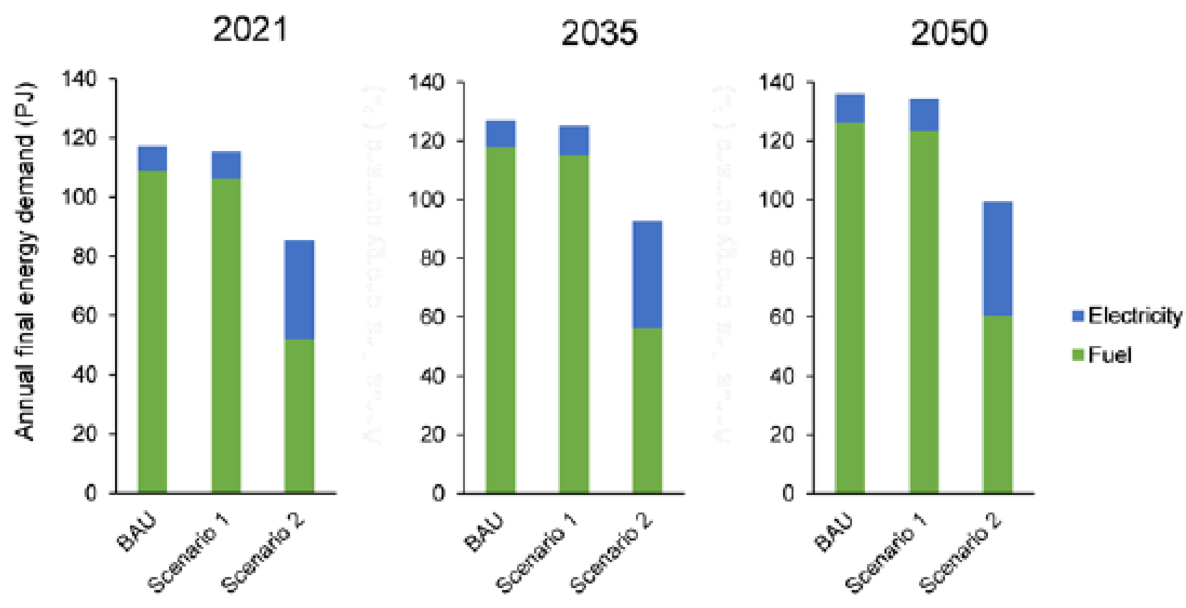

Figure 31 – Annual final energy demand in the U.S. soybean oil industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the soybean oil industry in California, 2020 census data released on March 31, 2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to soybean and other oilseed processing[19] (U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total soybean oil production in California.

An estimated 5.3 percent of soybean oil production within the U.S. comes from California, meaning an estimated 0.6 Mt of soybean oil was produced annually in 2021. With this, the total heating capacity for the California soybean oil industry is estimated to be 5.6 MW[20] for HTHP and 134 MW[21] for SGHP. By 2050, approximately 0.11 PJ and 1.97 PJ can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 0.16 and 3.5 PJ of fuel demand being reduced with a 0.04 and 1.5 PJ per year (0.012 and 0.43 TWh per year) electricity use increase for scenarios 1 and 2, respectively.

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[19] NAICS Code 311224 (Soybean and Other Oilseed Processing)

[20] 105 MW (Total U.S. Capacity) * 5.4% (California Industry Employment) = 5.6 MW

[21] 2520 MW (Total U.S. Capacity) * 5.4% (California Industry Employment) = 134 MW

Textile Industry

The textile industry within the U.S. processed approximately 0.5 Mt of grey goods in 2021 (Groz-Beckert, 2017). Approximately 0.25 Mt of these woven fabrics are assumed to undergo finishing (wet processing) in different U.S. mills. It is estimated that the production volume of finished synthetic goods will grow to 0.3 Mt in 2050. The weaving and finishing process of textiles starts with spinning done by machines to make yarn. Yarn is then used for warping, which combines yarns from different cones to form a sheet. This sheet is made flat by adding starch to the surface. Next steam rollers are used to dry the material to make the yarn stronger and smoother. Usually, two yarns of similar materials are interlaced at right angles to manufacture grey woven fabrics (Brown et. al., 1996; Hasanbeigi, 2010). For synthetic fibers, textile wet processing involves a variety of processes that require steam for heat. In order to remove loosened, hairy, and projecting fibers, singeing is done by burnout. The starch and sizing compounds are then removed when desizing. Scouring is another process where natural impurities such as oil, fat, non-cellulose materials, and wax are removed. Another treatment, known as mercerizing, increases the strength and luster of materials and is performed as required. Bleaching and dyeing of materials can also be done to alter the color of fabrics. Printing may also be done to vary fabric appearance. Once the appearance of the fabrics is altered, a large oven is used to cure the fabrics and set the dyes. The fabrics are then stretched onto a frame where they can be distributed to consumers.

The energy consumption of the conventional spinning and weaving manufacturing process were compared to IHP modified processes in Figure 32. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, there are no applications for HTHPs (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for drying. The required heating capacity for SGHP was estimated to be 150 MW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process			Process steps	Modified process with IHP	
Fuel use in boilers	Steam or water temp.	Electricity use		Electricity use in IHPs	Electricity use in other processes
GJ/t	°C	kWh/t		kWh/t	kWh/t
		161.5	Spinning & Winding		161.5
		161.5	Warping		161.5
10.5	150		Sizing/Drying	1493.5	
		323.1	Weaving		323.1
10.5	150	646.1	Total	1493.5	646.1

Notes:
SEC values are per tonne of gray products.
Boiler system efficiency is assumed at 80% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 32 – Specific energy consumption of conventional and modified spinning and weaving processes

Source: Zuberi et al., 2022

The projected annual final energy demand in the U.S. textile spinning and weaving industry up to 2050 are shown in Figure 33. Scenario 1 was not considered due to no HTHP applications. Approximately 1.5 PJ per year if SGHP applications are adopted in 2050. The final energy demand may be reduced due to increases in efficiency due to IHPs. By 2050, 3.1 PJ of fuel demand could be reduced with a 1.6 PJ per year (0.4 TWh per year) electricity demand increase for scenario 2 (Zuberi et al., 2022)

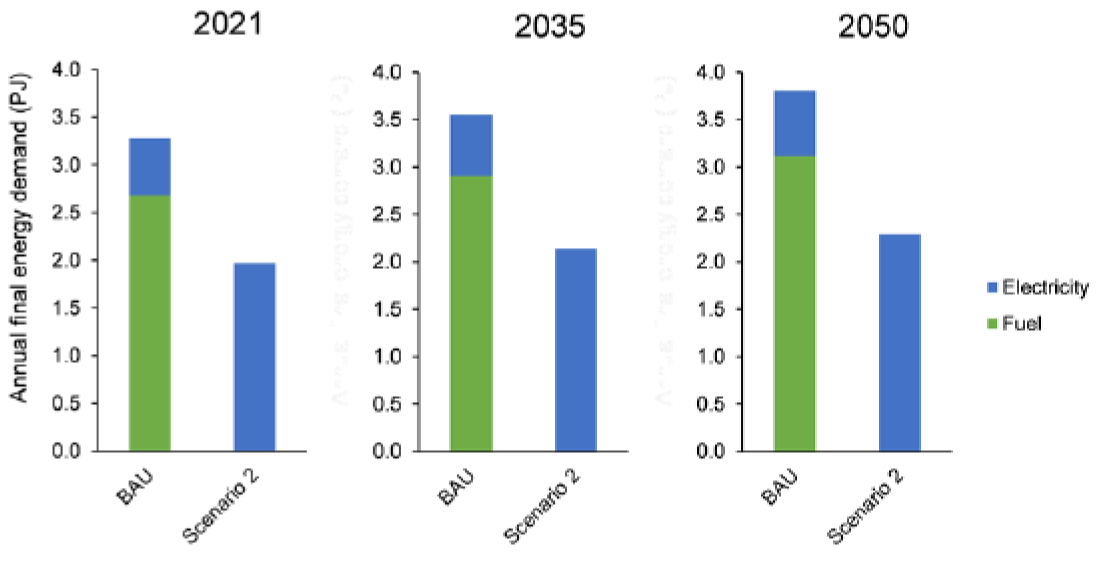

Figure 33 – Annual final energy demand in the U.S. textile spinning and weaving industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 is not considered due to no HTHP applications; Scenario 2 considers only SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the textile industry in California, 2020 census data released on March 31, 2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to textile mills[22] ((U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total textile production in California.

An estimated 5.3 percent of textile production within the U.S. comes from California, meaning an estimated 0.027 Mt of grey goods with 0.013 Mt of finished synthetic product were produced annually in 2021. With this, the total heating capacity for the California textile spinning and weaving industry is estimated to be 8 MW[23] for SGHP. By 2050, approximately 0.08 PJ can be saved in Scenario 2 across California. This equates to approximately 0.17 PJ of fuel demand being reduced with a 0.09 PJ per year (0.024 TWh per year) electricity use increase.

The energy consumption of the conventional textile wet-processing manufacturing process was compared to IHP modified processes in Figure 34.The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs may be used to preheat makeup feed water to 82°C prior to steam generation in the condensate tank. The required heating capacity for HTHP applications was estimated to be 12 MW (Zuberi et al., 2022)

[22] NAICS Code 313 (Textile Mills)

[23] 150 MW (Total U.S. Capacity) * 5.3% (California Industry Employment) = 8.0 MW

In Scenario 2, SGHPs can be used to generate process steam at 120°C for desizing, scouring, mercerizing, bleaching, washing, and dyeing. Another SGHP can also be installed at 150°C for drying. The required heating capacity for SGHP was estimated to be 375 MW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	*GJ/t*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
4.7				Singeing	4.7		
	0.9	120		Desizing			
	3.5	120	113.1	Scouring			113.1
	2.2	120	16.2	Mercerizing & Washing			16.2
	4.9	120	32.3	Bleach & Wash/rinse			32.3
	4.4	150	64.6	Drying		3285.5	64.6
	7.6	120	161.5	Dyeing & Washing			161.5
	0.9	120		Printing			
7.4			32.3	Drying/setting	7.4		32.3
	2.5	120		Steaming			
	0.9	120	32.3	Washing			32.3
4.7			32.3	Dry & frame	4.7		32.3
16.7	27.6		484.6	Total	16.7	3285.5	484.6

Notes:
SEC values are per tonne of finished products.
Boiler system efficiency is assumed at 80% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 34 – Specific energy consumption of conventional and modified textile wet-processing

Source: Zuberi et al., 2022

The projected annual final energy demand in the U.S. textile wet-processing industry up to 2050 are shown in Figure 35. Berkeley Lab estimated that 0.2 PJ of final energy could be saved by 2050 if only HTHP applications were considered (Scenario 1). This number increases to approximately 5 PJ if both HTHP and SGHP applications were adopted in 2050 (Scenario 2). The final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 0.3 PJ and 10 PJ of fuel demand could be reduced while electricity demand increases 0.1 PJ and 5.2 PJ per year (0.03 TWh and 1.4 TWh per year) for Scenarios 1 and 2 respectively (Zuberi et al., 2022)

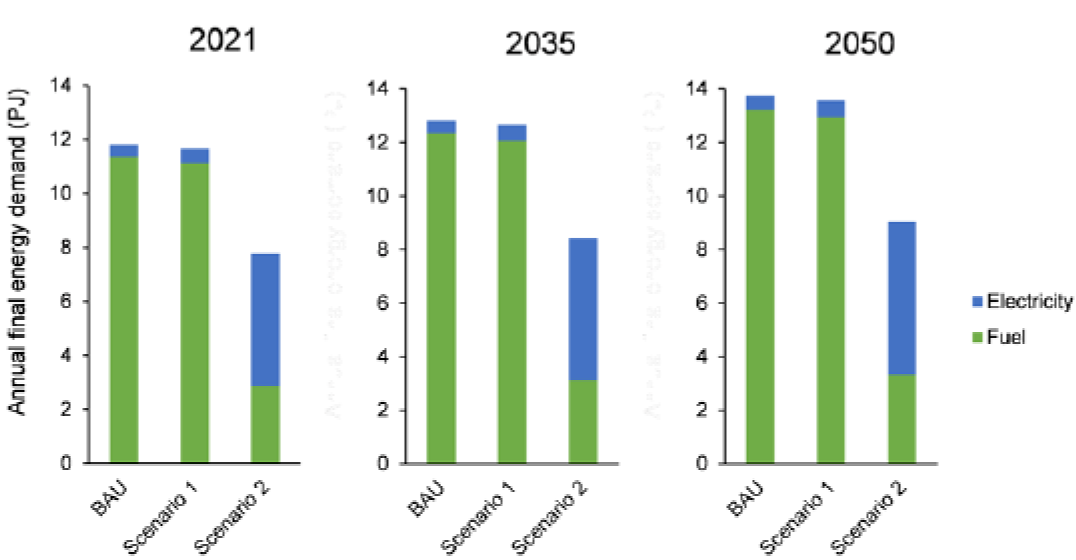

Figure 35 – Annual final energy demand in the U.S. textile wet-processing industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 is not considered due to no HTHP applications; Scenario 2 considers only SGHP applications.

Source: Zuberi et al., 2022

As mentioned above, an estimated 5.3 percent of textile production within the U.S. comes from California, meaning an estimated 0.027 Mt of grey goods with 0.013 Mt of finished synthetic product were produced annually in 2021. With this, the total heating capacity for the California textile wet-processing industry is estimated to be 0.6 MW[24] for HTHP and 20 MW[25] for SGHP. By 2050, approximately 0.01 PJ and 0.27 PJ can be saved in Scenarios 1 and 2 respectively across California. This equates to approximately 0.2 and 0.53 PJ of fuel demand being reduced with a 0.01 and 0.28 PJ per year (0.0015 and 0.077 TWh per year) electricity use increase for scenarios 1 and 2, respectively.

Pulp and Paper Industry

The pulp and paper industry within the U.S. produced approximately 26 Mt of paper in 2021 and is expected to grow to 30 Mt in 2050 (Statistica, 2022a). To produce paper, wood is first received at a pump mill in logs with bark still attached. The wood is then debarked and chipped to prepare for chemical digestion if needed. Excess bark is shredded and discarded, while chips can be further screened and processed. Chemicals may be used to digest the chips with steam in a large pressure vessel to separate fibers and dissolve other extractives. The resulting mixture is then filtered and washed in multiple stages (Pulp and Paper Technology, 2022). A byproduct of the process is a black liquor that is concentrated in an evaporator using steam. Once the liquor is 65 to 80 percent solid, it is burned in a recovery furnace to produce steam for other steps in the process. Green liquor from

[24] 12 MW (Total U.S. Capacity) * 5.3% (California Industry Employment) = 0.6 MW

[25] 375 MW (Total U.S. Capacity) * 5.3% (California Industry Employment) = 20 MW

the recovery furnace is reacted with lime in a causticizer. This converts sodium carbonate to sodium hydroxide and the liquor is returned to the digester for reuse. After being washed, the processed pulp is screened and cleaned with most of the water removed. It is then bleached with chemicals and steam to produce light-colored paper. The fibers are then compressed and fed to a calendaring process that smoothens and compresses the paper through heater rolls. Finally, winding and cutting is done to prepare the sheets of paper for distribution (Brown et al., 1996).

The energy consumption of conventional pulp and paper production were compared to IHP modified processes in Figure 36. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. Scenario 1 was not considered due to no HTHP applications (Zuberi et al., 2022)

In Scenario 2, SGHPs can be used to generate process steam at 120°C for the paper drying process after forming and pressing. The required heating capacity for SGHP was estimated to be 6.8 GW. It should be noted that the COP of SGHP used was assumed to be low due to the high temperature lift (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or water temp.	Electricity use		Direct fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	GJ/t	°C	kWh/t		GJ/t	kWh/t	kWh/t
			90.4	Barker, Shredder, Chipper			90.4
	5.9	170		Digestor			
			72.4	Washing & Filtration			72.4
	6.3	145		Multiple evaporators			
	-19.2	205		Recovery furnace			
2.2				Kiln	2.2		
			145.4	Screening knotting			145.4
	7.0	127	116.3	Bleaching			116.3
			29.1	Washing & Screening			29.1
			64.6	Thickening & Refining			64.6
			60.1	Cleaner & Screens			60.1
			290.7	Forming & Pressing			290.7
	10.9	120	64.6	Drying		1252.1	64.6
			27.8	Calendar			27.8
			27.8	Winding cutting trim.			27.8
2.2	10.9		989.2	Total	2.2	1252.1	989.2

Notes:
SEC values are per tonne of paper production (excluding paperboard).
Boiler system efficiency is assumed at 75% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 36 – Specific energy consumption of conventional and modified pulp and paper production

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. pulp and paper production industry up to 2050 are shown in Figure 37. Scenario 1 was not considered due to no HTHP applications. Approximately 207 PJ per year if SGHP applications were adopted in 2050. The final energy demand may be reduced due to increases in efficiency due to IHPs. By 2050, 330 PJ of fuel demand could be reduced with a 123 PJ per year (34 TWh per year) electricity demand increase for scenario 2 (Zuberi et al., 2022)

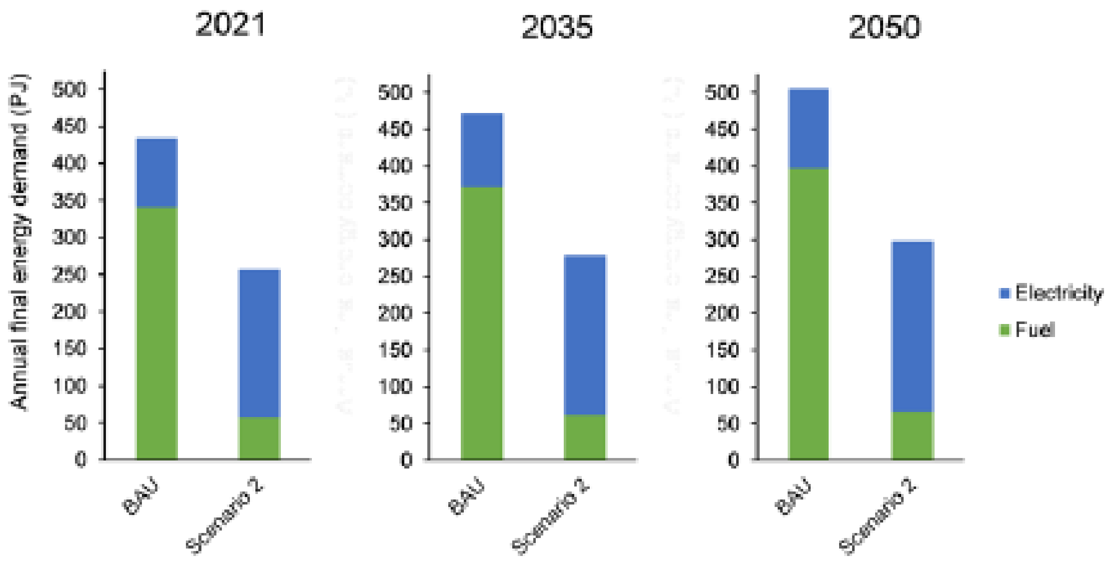

Figure 37 – Annual final energy demand in the U.S. pulp and paper industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 is not considered due to no HTHP applications; Scenario 2 considers only SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the paper and pulp industry in California, 2020 census data released on March 31, 2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to Pulp, Paper, and Paperboard Mills[26] ((U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total beet sugar production in California.

An estimated 1.1 percent of pulp and paper production within the U.S. comes from California, meaning an estimated 0.3 Mt of pulp and paper was produced annually in 2021. With this, the total heating capacity for the California pulp and paper industry is estimated to be 77.4 MW[27] for SGHP. There are no estimated applications for HTHP. By 2050, approximately 2.36 PJ can be saved in Scenario 2 respectively across California. This equates to approximately 3.76 PJ of fuel demand being reduced with a 1.4 PJ per year (0.39 TWh per year) electricity use increase for scenario 2.

Automotive Industry

The automotive industry within the U.S. produced approximately nine million automobiles in 2021 and is expected to grow to 10 million automobiles by 2050 (Statistica, 2022b). The general manufacturing process from raw materials starts with metal sheets being bent or cut into shape. Welding is also part of the procedure to sculpt and join parts together with heat. The body of the vehicle is inspected after assembly and is then cleaned from all oil, dirt, and contaminants before painting. The body is then dried and painted in multiple stages to prevent corrosion. The body is then

[26] NAICS Code 3221 (Pulp, Paper, and Paperboard Mills)

[27] 6800 MW (Total U.S. Capacity) * 1.1% (California Industry Employment) = 77.4 MW

baked in an oven to cure at temperatures over 100°C and is ready for interior or trim assembly. All remaining parts and subassemblies are then assembled into the body (Zuberi et al., 2022)

The energy consumptions of conventional automotive industry production were compared to IHP modified processes in Figure 38. The green highlighted process steps indicate that the heat demand temperatures are suitable for IHP applications. In Scenario 1, HTHPs can be used to provide process hot water at temperatures at 50°C for washing applications. Another HTHP can also be used to preheat feed water to 90°C for steam generation. An air source heat pump may also be used to heat air to 27°C for welding and painting. The total heating capacity of HTHP for the U.S. automotive industry was estimated to be 5.8 GW in the conservative scenario. There were no identifiable applications for SGHPs in the ambitious scenario since temperatures of 177°C are seen as impractical to obtain high temperature lift with current technologies (Zuberi et al., 2022)

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam or air or water temp.	Electricity use		Direct & boiler fuel use	Electricity use in IHPs	Electricity use in other processes
GJ/t	GJ/t	°C	kWh/t		GJ/t	kWh/t	kWh/t
			180.9	Metal cutting			180.9
			82.1	Cut metal			82.1
0.3	0.3	27	1.3	Welding	0.3		1.3
			190.6	Body assembly			190.6
	1.7	177	3.9	Body preparation	1.2		3.9
1.0				Drying	1.0		
	4.8	27	1.9	Painting		428.7	1.9
3.5				Drying	3.5		
			91.1	Trim assembly			91.1
	0.4	50		Wash & test			
			228.7	Final assembly			228.7
	0.4	50	57.5	Finishing & Washing			57.5
			37.5	Compressor			37.5
4.7	7.6		875.5	Total	5.9	428.7	875.5

Notes:
SEC values are per tonne of an automobile. The curb weight of an automobile is taken as 2 tonnes.
Boiler and air heater efficiencies are assumed at 82% (adapted based on U.S. DOE/Energetics, 2022).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

Figure 38 – Specific energy consumption of conventional and modified automotive production

Source: Zuberi et al., 2022

The projected annual final energy demands in the U.S. automotive industry up to 2050 are shown in Figure 39. LBNL estimated that 96 PJ of annual final energy could be saved by 2050 if only HTHP applications were considered in Scenario 1. There were no considered SGHP applications for this industry. Although production is estimated to grow, the final energy demand may still be reduced due to increases in efficiency due to IHPs. By 2050, 128 PJ of fuel demand could be reduced while electricity demand increases 32 PJ per year (8.8 TWh per year) for Scenario 1 (Zuberi et al., 2022)

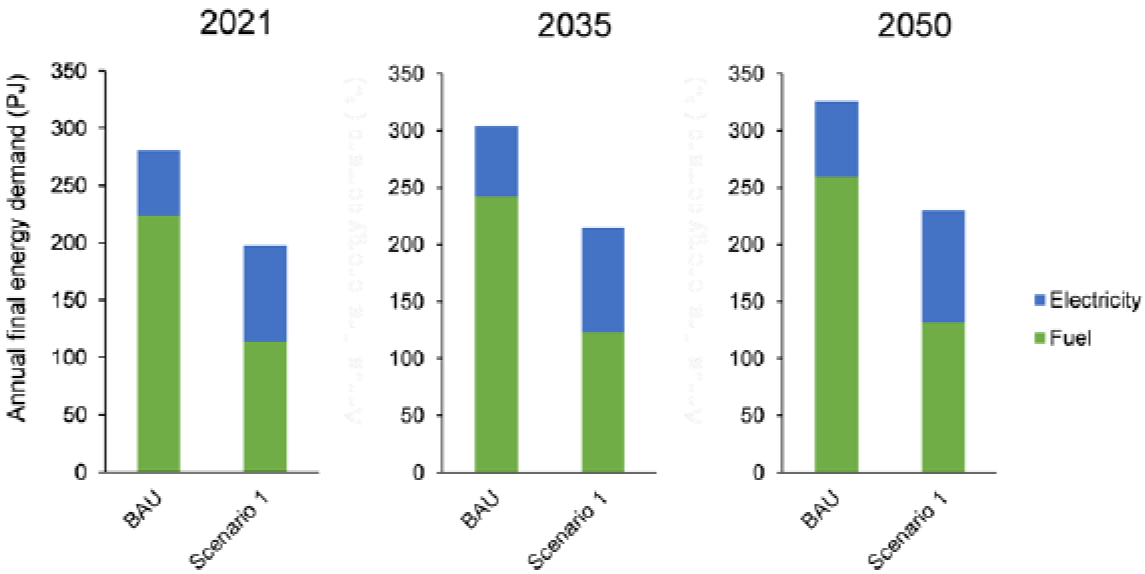

Figure 39 – Annual final energy demand in the U.S. automotive industry up to 2050

Assuming a 100% adoption rate. Business-As-Usual (BAU) case does not consider any IHP application; Scenario 1 only considers HTHP applications; Scenario 2 considers both HTHP and SGHP applications.

Source: Zuberi et al., 2022

When estimating the total potential market size for the automotive industry in California, 2020 census data released on March 31, 2023 was used to identify total employment for North American Industry Classification System (NAICS) codes relating to automobile and light duty motor vehicle manufacturing[28] ((U.S. Census Bureau, 2023) Employment within California was identified as a percentage of total U.S. employment and was used as a proxy for total automotive production in California.

An estimated 12 percent of automotive production within the U.S. comes from California, meaning an estimated 1.1 million automobiles were produced annually in 2020. With this, the total heating capacity for the California automotive industry is estimated to be 700 MW[29] for HTHP. By 2050, approximately 11.5 PJ can be saved in Scenarios 1 across California. This equates to approximately 15.4 PJ of fuel demand being reduced with a 3.8 PJ per year (1.1 TWh per year) electricity use increase for scenario 1.

[28] NAICS Code 33611 (Automobile and Light Duty Motor Vehicle Manufacturing) *Data is considered to have a high amount of noise (5% or more) based on the U.S. Census Bureau.

[29] 5.8 GW (Total U.S. Capacity) * 12% (California Industry Employment) = 0.7 GW

Appendix B: Overview of Demonstration Cases with Supply Temperatures >100°C

Table 4: Overview of demonstration cases with supply temperatures >100°C

Supplier	Industry / Process	Source in → out	Sink in → out	Refrigerant	Compressor	Capacity	COP
Mayekawa*	Electronic / Coil drying	30 °C → 25 °C	20 °C → 120 °C	R-744	Piston	0.1 MW	3.1
AMT/AIT	Minerals / Brick drying	88 °C → 84 °C	96 °C → 121 °C	R-1336mzz(Z)	Piston (8 compr.)	0.3 MW	5
SkaleUP	Dairy / Process water	20 °C → 12 °C	95 °C → 115 °C	LT-C: R-290 HT-C: R-600	Piston	0.3 MW	2.5
n. a.*	Beverage / Alcoholic distillation	78 °C → 75 °C	n. a. → 140 °C	n. a.	n. a.	0.4 MW	5.2
AMT/AIT	Food / Starch drying	76 °C → 72 °C	96 °C → 138 °C	R-1336mzz(Z)	Screw	0.4 MW	3.2
Rotrex, Epcon	Sewage / Sludge drying	n. a. → 100 °C	n. a. → 146 °C	R-718	Turbo (2 stages)	0.5 MW	4.5
MHI	Electronic / Coil drying	55 °C → 50 °C	70 °C → 130 °C	R-134a	Centrifugal	0.6 MW	3
Kobelco	Sewage / Sludge drying	93 °C → 93 °C	160 °C →160 °C	R-718	Twin-screw, Roots blower	0.7 MW	2.9
Olvondo	Pharma / Recooling	36 °C → 34 °C	178 °C →183 °C	R-704	Piston	1.5 MW	1.7
Kobelco	Refinery / Bioethanol distillation	65 °C → 60 °C	20 °C →120 °C	R-245fa	Twin-screw	1.9 MW	3.5
QPinch	Chemical / Steam prod.	120 °C →145 °C	140 °C→185 °C	H2PO4	Heat-driven	2.9 MW	0.45 ($COP_{heat,trans.}$)
Piller	Plastics / Thermal sep.	60 °C → 60 °C	126 °C →131 °C	R-718	Turbo (8 blowers)	10.0 MW	4.4
Spilling	Pulp and paper / Pulp drying	133 °C →105 °C	n. a. → 201 °C	R-718	Piston (4 LT-, 2 HT-cyl.)	11.2 MW	4.2
Spilling	Chemical / Chemical	152 °C →105 °C	n. a. → 211 °C	R-718	Piston (4 LT-, 2 HT-cyl.)	12.0 MW	5.3

Source: IEA, 2023b

Appendix C: List of IHP Manufacturers

Table 5: List of IHP Manufacturers

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
Vilter	Modular	R717 (NH3)	150* (Available 2024)	600-5000	Single Screw	Vilter Industrial Heat Pumps Lunch & Learn with Alan Simchick-20230815_120943-Meeting Recording (1).mp4
	VSH/VSSH	R744 (CO2)	70	1700	Single Screw	https://www.copeland.com/documents/next-gen-hvacr-sustainability-brochure-heat-pump-en-8574898.pdf
	VHP	R717 (NH3)	90		Single Screw	2011VM-43 R5.indd (copeland.com)
Kobelco	SGH 165	R134a+R245fa	175	624	Twin Screw	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/technologykobelcosgh165.pdf
	SGH120	R245fa	120	370	Two-stage Twin Screw	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/technologykobelcosgh120-1.pdf
	MSRC 160	R-718	175	800	Twin Screw	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/technologykobelcomsrc160l-1.pdf

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
	HEM-90A	R134a+R245fa	90	176	Semi Hermetic Two-stage Twin Screw	https://www.kobelco.co.jp/english/ktr/pdf/ktr_32/070-074.pdf
	HEM-HR-90	R134a+R245fa	90	357	Two-stage Twin Screw	https://www.chuden.co.jp/english/corporate/releases/pressreleases/__icsFiles/afieldfile/2020/04/13/20100209R2.pdf
Fuji Electric	Steam Generating Heat Pump	R245fa	120	30	Reciprocating	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/technologyfuji-electricsteam120.pdf
Mayekawa	unimo AW	R-744	90	74	Reciprocating	https://mayekawa.com/americas/mna/products/heat_pumps/
	unimo WW	R-744	90	91.9	Reciprocating	https://mayekawa.com/americas/mna/products/heat_pumps/
	unimo AWW	R-744	90	92.3	Reciprocating	https://mayekawa.com/americas/mna/products/heat_pumps/
	Ecosirocco	R-744	120	123	Reciprocating	https://mayekawa.com/americas/mna/products/heat_pumps/
	Plus+HEAT	R717 (NH3)	85	487	Reciprocating/Screw	https://mayekawa.com/americas/mna/products/heat_pumps/
	Ecocircuit	R1234ze(E)	100	100	reciprocating	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/technologymayekawaecocircuit100-1.pdf

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
Mayekawa Europe NV	HS-Compressor	R-600	120	750	Piston	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/hthpannex58mayekawahs-compressor.pdf
	FC-Compressor	R-601	145	1000	Screw	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/hthpannex58fc-compressor.pdf
Mitsubishi Heavy Industries	Q-ton ESA30EH-25	R-744	90	30	two-stage compressor (combining both rotary 1 and scroll 2 technologies)	Air to Water Heat Pump (commercial use) Q-TON | MITSUBISHI HEAVY INDUSTRIES THERMAL SYSTEMS, LTD. (mhi-mth.co.jp)
ecop	Rotation Heat Pump K7.2.4	noble gas mixture (He, Kr, Ar)	150	700	rotation heat pump	https://www.ecop.at/en/product/
GEA	RedGenium	R717 (NH3)	95	1800	Reciprocating	https://www.gea.com/en/products/refrigeration-heating/heat-pumps/compact-heatpump-small-heat-load-redgenium.jsp
	RedAstrum	R717 (NH3)	80	2900	Screw	https://www.gea.com/en/products/refrigeration-heating/heat-pumps/redastrum-ammonia-heatpump.jsp
	Open Type HP	R717 (NH3)	95	3500	Reciprocating	https://www.gea.com/en/products/refrigeration-heating/heat-pumps/open-type-heat-pump.jsp

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
Fenagy	FENAGY H-Series	R744 (CO_2)	120	300-2600	Reciprocating	https://www.fenagy.dk/en/products-heat-pumps
Rank	RANK HP	HFOs	150	500-4000	Twin-Screw	https://www.rank-orc.com/rank-hp-2/
SRM	Powerbox RBH_-WFAA	R718 (Water)	90	311-2518	Screw	https://www.srmtec.group/en/product/powerbox_srm_open_type_heat_pump_90/699d3c0449f34075a82db7b39d18df9c.html
COMBITHERM GmbH	HWW Series	R450A, R513A, R1234yf, R1234ze, R1233zd€	120	15-2071	Reciprocating/Screw	https://storage.googleapis.com/strapi-combitherm-uploads/Prospekt_V4_Englisch_220505_1d80c934d3/Prospekt_V4_Englisch_220505_1d80c934d3.pdf
SPH (Sustainable Process Heat)	ThermBooster	HFOs	165	400-1000	Piston	https://spheat.de/thermbooster/?lang=en
Johnson Controls	Sabroe HeatPAC/DualPAC/Customized	R717 (NH_3)	90	300-13000	Reciprocating/Screw	https://www.johnsoncontrols.com/en_my/heatpumps
Hybrid Energy (Johnson Controls)	HeyPAC, HeyPAC-D, HeyPAC-S	R718 (Water)+R717 (NH_3)	120	500-5000	Reciprocating/Screw	https://www.hybridenergy.no/products/

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
toCircle Industries	MVR, UHTHP, DSE	R718 (Water)+R717 (NH3)	188	1000-5000	Rotary Vane	https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/tocircle-tc-c920-rotary-vane-compressor.pdf
weel-sandvig	WS-TURBO	R718 (Water)	200	500-1000	Turbo	https://weel-sandvig.com/products/turbo
Olvondo	HighLift	Helium R-704	200	750	Double acting piston	https://www.olvondotech.no/the-technology/
Heaten	HeatBooster	HFOs	200	1000-8000	Reciprocating	https://www.heaten.com/product/
Enrin	HoegTemp UHT	Helium R-704	250	300-10,000	Piston	https://www.enerin.no/hoegtemp
Aneo Industry	SPHP	R718 (Water)+R717 (NH3)	150	1000-10,000	Reciprocating, Fast-moving centrifugal fans	https://www.aneo.com/tjenester/industry/teknologi/
enertime	Custom	R1233zdE	130	2000-15,000	Centrifugal Compressor	https://www.enertime.com/fr/solutions/pompes-a-chaleur-industrielles
Spilling Technologies GmbH	Spilling Steam Compressor	R718 (Water)	280	1000-15,000	Piston	https://www.spilling.de/about-spilling/spilling-worldwide.html
EPCON Evaporation Technology	MVR-HP	R718 (Water)	150	500-100,000	High-pressure Centrifugal fan; positive displacement blower	epcon_mvr_heatpump.pdf

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
Turboden S.p.A.	Turboden Large Heat Pumps	more than 10 different fluids between refrigerants, hydrocarbons, and siloxanes	200	3000-30,000	Turbo compressor	https://www.turboden.com/solutions/2602/large-heat-pump
MAN Energy Solutions	ETES CO2 Heat pump	R744 (CO2)	150	10,000-50,000	centrifugal turbo-compressor	https://www.man-es.com/process-industry/campaigns/heat-up-carbon-down
Piller	MVR	R718 (water), and process vapors (ethanol, methanol, IPA, mixtures, on demand)	230	1000	Turbo	https://www.piller.de/industrial-heat-pump/
Siemens Energy	MVV	R1233zd(E), R1234ze(E)	180	8,000-70,000	Centrifugal Compressor	https://www.siemens-energy.com/global/en/offerings/power-generation/heat-pumps.html
Qpinch BV	Qpinch Heat Transformer	R718 (Water), H3PO4 and derivatives	210	500-15,000	Chemical Heat Pump	https://qpinch.com/technology
OCHSNER Energietechnik GmbH	IWWHS, ISWHS, IWWHSS	R744 (CO2), ÖKO1, ÖKO2	95	60-850, 1,700	semi-hermetic compact screw compressors	High-temperature heat pumps - Ochsner Energietechnik (ochsner-energietechnik.com)

Manufacturer	Product	Refrigerant	Max. supply temperature (°C)	Heating capacity (kW)	Compressor Type	Reference
	IWWDS, ISWDS, IWWDSS	R744 (CO_2), ÖKO1, ÖKO2	130	170-750, 1,500	semi-hermetic compact screw compressors	https://ochsner-energietechnik.com/hoechsttemperatur-waermepumpen/
	IWWHC	R744 (CO_2), ÖKO1, ÖKO2	82	30-130, 390	scroll compressors	https://ochsner-energietechnik.com/hochtemperatur-kompaktbaureihe/
Friotherm	Unitop 22S, 22, 23, 28, 33, 43	halocarbon and hydrocarbon refrigerants	80	1,000-10,000	Open-type two stage centrifugal compressor	https://www.friotherm.com/products/unitop/
	Unitop 34FY, 50FY	halocarbon and hydrocarbon refrigerants	90	7,000-20,000	Open-type two stage centrifugal compressor	https://www.friotherm.com/products/unitop/
Star Refrigeration	Water Source Neatpump	R717 (NH_3)	130	700-10,000	High efficiency compressor	https://www.star-ref.co.uk/products/heat-pumps/water-source-heat-pump-neatpump/
	Air Source Neatpump	R717 (NH_3)	70	500	High efficiency compressor	https://www.star-ref.co.uk/products/heat-pumps/air-source-heat-pump-neatpump/
Viessmann	Vitocal 350-HT Pro	R1234ze	90	148-390	Piston	https://www.viessmann.hk/en/commercial-industrial/heat-pumps/vitocal-pro/vitocal-350-ht-pro.html
Skyven Technologies	Arcturus SGHP	R718 (Water)	215	37,000	Centrifugal Compressor	https://skyven.co/our-solutions/

Appendix D: Industrial Heat Pump Questionnaire

- What is the technology readiness of industrial heat pumps?
- What are the newest developments with technology and where do you see the technology heading in the future?
- What applications do you recommend targeting with industrial heat pumps?
- How feasible are retrofits/installations for the technology?
- What are the requirements for product installation? Are there any necessary technology safety standards (e.g., UL Standards, EE ratings, ETL Certification for Life Safety & Security Industry)?
- What opportunities for growth do you see?
- What are the barriers for industrial heat pumps?
- What are the estimated costs and payback for industrial heat pumps (capital expenditure + installation)?
- Do you have any recommendations for streamlining adoption and program pathways?
- Are you aware of any pilot installations of Industrial Heat Pumps for process heating in the U.S.?
- What other competing technology solutions are there?

Name: _______

Organization: ________