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Electrification of U.S. Manufacturing With Industrial Heat Pumps

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Executive Summary

Thermal processes in U.S. manufacturing are responsible for approximately two-thirds of the total final energy demand. Decarbonization of industrial heat demand through electrification could contribute significantly to climate change mitigation efforts. Cross-cutting electrification technologies that are applicable to a range of industrial processes without needing major modifications to the existing infrastructure may facilitate the clean energy transition in the industry. Electric-driven heat pumps are among those technologies that are suitable for process heat supply to several industrial unit operations in a sustainable manner, while also improving the overall energy efficiency. However, despite a promising alternative for an efficient and emission-free supply of process heat at technically feasible temperatures in industrial processes, the industrial heat pump (IHP) deployment in the U.S. has been limited.

Presently, there is a lack of studies in the literature that focus on wide-scale applications of IHP in U.S. manufacturing. To address these literature gaps, the objectives of this work are i) to review the current state-of-the-art and real-life applications of IHP globally, ii) to analyze the technical, economic, and energy-saving and CO_2 reduction potentials of the IHP technology's wide-scale deployment in several U.S. manufacturing sectors under different energy supply and price scenarios, and iii) to identify the drivers and barriers to implementation and provide action plans to overcome the barriers. We conducted the closed-loop IHP application analysis for the following industrial subsectors: meat processing, dairy, beer, canned vegetable and fruit processing, cane sugar refining, beet sugar, corn wet-milling, soybean oil, textile spinning, and weaving, textile wet processing, pulp and paper, and automotive industries.

CO_2 abatement cost curves and energy conservation cost curves are developed to estimate the marginal costs and the technical potentials for CO_2 emissions reduction and energy savings from IHP applications respectively. The results show that despite the current average U.S. electricity grid emission factor being higher than the emission factor of natural gas, electrifying hot water and steam generation systems in the thirteen industrial processes studied can already decrease the annual CO_2 emissions by around 17 Mt CO_2 per year in the base year 2021, assuming a 100% adoption rate of IHP applications. However, given the fact that electricity grids will be further decarbonized and potentially fully decarbonized in 2050, the magnitude of total CO_2 abatement potential is projected to be 58 Mt CO_2 per year in 2050 (equivalent to 5% of the total greenhouse gas emissions from U.S. manufacturing), as shown in Figure ES-1. The figure also shows that the CO_2 abatement costs in different industrial processes range between 49 and 160 $/t$CO_2$ in 2050. Since the coefficient of performance (COP) of an IHP application with a high-temperature lift (i.e. difference between heat source and heat sink temperatures) is typically low, the CO_2 abatement costs in industrial sectors with few or no applications requiring high-temperature lifts (i.e. greater than 100 K) are found to be relatively less expensive (e.g. in the automotive industry as shown in Figure ES-1). This means that high-temperature heat sources must be first utilized for heat sinks with the highest temperatures, to minimize the temperature lifts and operational costs, and maximize heat pump COPs.

As far as the rankings of the CO_2 abatement costs for each sector are concerned, multiple factors including current process-specific boiler efficiencies, IHP's COPs, required IHP capacities, and the corresponding investment and operational costs affect the marginal costs of IHP applications in U.S. manufacturing sectors. One of the major reasons for the high abatement costs is the disparity between the electricity and fuel prices in the U.S. industry. For example, the average electricity price in the U.S. industry (i.e. 70 $/MWh) is almost 5 times higher than the average price of natural gas (i.e. 14 $/MWh) in 2021. The assumed heat source temperature i.e. 25°C is another factor influencing the costs to be high and it is recommended to explore and utilize suitable waste heat sources at higher temperatures to minimize the temperature lifts and consequently reduce the electricity costs.

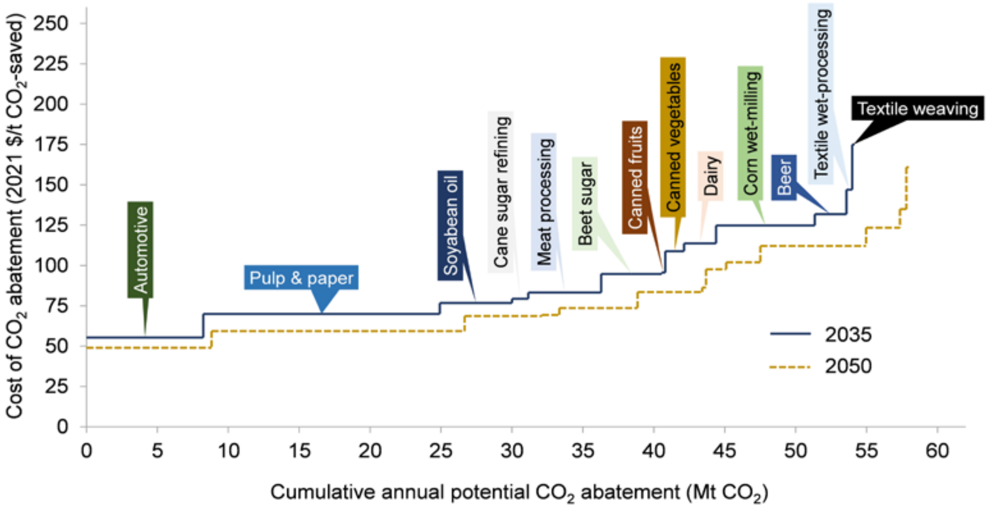

Figure ES - 1. CO_2 abatement cost curve for industrial heat pump applications in U.S. manufacturing.

The CO_2 abatement costs for each industrial process are quite sensitive to fuel and electricity price projections and waste heat source temperatures. A sensitivity analysis is performed to evaluate the impact of changes in energy prices and source temperatures on the CO_2 abatement costs. The analysis shows that the costs can be significantly reduced if waste heat sources at 40°C (if available) are utilized by IHP, consequently minimizing temperature lifts and maximizing COPs. Hence it is essential to explore and utilize heat sources at high temperatures to optimize IHP operation. It is further observed that the abatement costs can be reduced by an order of 2 to 3 times if natural gas prices are increased by 50%. Natural gas prices must be raised to a level closer to the price of electricity to make IHP economically competitive. Any form of a carbon price scheme (e.g. carbon tax or levy or cap and trade system, etc.) that results in higher fossil fuel prices could make the electrified process heat supply substantially more cost-effective. It is further realized that the costs can be decreased by up to 6 times if electricity prices are halved from those projected in 2050. These scenario results show that reducing electricity rates in the future could be the most impactful measure to facilitate the wide-scale applications of IHP in the relevant industrial facilities.

Despite the increase in natural gas prices, decrease in electricity prices, and utilization of high-quality waste heat sources, the marginal costs are not found economical. However, in the combined scenario where all the aforementioned factors are considered simultaneously, the marginal costs for most industrial processes are found to be cost-effective. This concludes that optimizing IHPs or revising energy prices alone will not make wide-scale implementation attractive, instead, a combination of different techno-economic measures must be applied by different stakeholders to encourage wide-scale IHP deployment in U.S. manufacturing. Despite the large potential for energy and CO_2 emissions reduction in U.S. manufacturing, there are several barriers associated with the wide-scale applications of IHP. To address these challenges, key and targeted actions including further research, development, demonstration, and deployment (RDD&D), policy interventions, workforce development, and capacity building, are needed. Detailed action plans are provided by the authors that different stakeholders could take to facilitate the applications of IHP in industrial processes where suitable in U.S. manufacturing.

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1 Introduction

The United States has set an ambitious goal to reach 100% carbon-free electricity by 2035 (The White House, 2021, n.d.). These efforts provide a significant opportunity to decarbonize different U.S. economic sectors, for example, by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used. The U.S. manufacturing industry accounts for approximately 25% of the country's total energy use and greenhouse gas (GHG) emissions (U.S. EIA, 2021a). Thermal processes in U.S. manufacturing are responsible for approximately two-thirds of the total final energy demand (U.S. DOE/Energetics, 2022; U.S. EIA, 2021b). Hence decarbonization of industrial heat demand through electrification could contribute significantly to climate change mitigation efforts. However, the heterogeneity of the manufacturing sector and the variety of different production methods on a process level enable different levels of process integration. It also requires a detailed assessment to develop optimal industrial decarbonization pathways.

In contrast, cross-cutting electrification technologies that are applicable to a range of industrial processes without needing major modifications to the existing infrastructure may facilitate the clean energy transition (Zühlsdorf et al., 2019). Electric-driven heat pumps are among those technologies that are suitable for process heat supply to several industrial unit operations in a sustainable manner, while also improving the overall energy efficiency (Zühlsdorf et al., 2019) see Section 2 for details. Despite a promising alternative for an efficient and emission-free supply of process heat at technically feasible temperatures in industrial processes, the industrial heat pump (IHP) deployment in the U.S. industry sector has been limited, unlike in Europe and Japan where substantial IHP deployment in manufacturing has occurred.

To increase the awareness of technical possibilities and to choose between the alternatives, a high level of expertise in process design, integration and planning must be developed. Presently, there is a lack of studies in the literature that focus on wide-scale applications of IHP for high-temperature heat supply (i.e. greater than 40-60°C by most conventional heat pumps) in U.S. manufacturing. A recent study by ACEEE (Rightor et al., 2022) is one of the few in this direction for the U.S. where a limited number of unit operations in three industrial groups were analyzed for potential IHP integration.

To address the aforementioned literature gaps, the aims and objectives of this work are:

i) To review the current state-of-the-art and real-life applications of IHP in a variety of manufacturing sectors,

ii) To analyze the technical, economic, and environmental potentials of the closed-loop IHP technology's wide-scale deployment in suitable U.S. manufacturing sectors under different energy supply and price scenarios, and

iii) to identify the drivers and barriers to implementation and provide action plans to overcome the barriers.

This study offers recommendations for various stakeholders and provides novel insights to inform policymakers' and executives' decisions about electrification of the current and future process heat supply in U.S manufacturing.

2 Industrial Heat Pump Basics and Market Overview

Heat pumps drive heat from one or more heat sources (Q_{in}) at low temperatures (T_{source}) to one or more heat sinks (Q_{out}) at high temperatures (T_{sink}) with the assistance of an external energy source (electricity; W_{in}). The thermodynamic working principle of an electric heat pump is illustrated in Figure 1a. In other words, heat pumps are designed to transfer thermal energy opposite to the direction of natural heat flow by absorbing heat from a cold reservoir and discharging it to a hot one (U.S. DOE, 2003). The external energy or work required to drive a heat pump depends on how much the temperature of the low-quality heat is to be raised.

Heat pumps employ refrigerants as transitional fluids to absorb heat and vaporize in an evaporator. Refrigerants have low boiling points and evaporate even at sub-zero temperatures. Despite the evaporation, the refrigerant is not hot enough to warm the process fluid. Hence a compressor is used to further raise the temperature and pressure of the refrigerant through volume reduction and forces the high temperature and pressure gas to a condenser. The absorbed heat is released where the refrigerant condenses in a condenser. Finally, the temperature and pressure of the refrigerant are further reduced after passing through an expansion valve (Gagneja and Pundhir, 2016). Figure 1b presents the heat pump cycle. The most common examples of heat pumps are refrigerators and air conditioners.

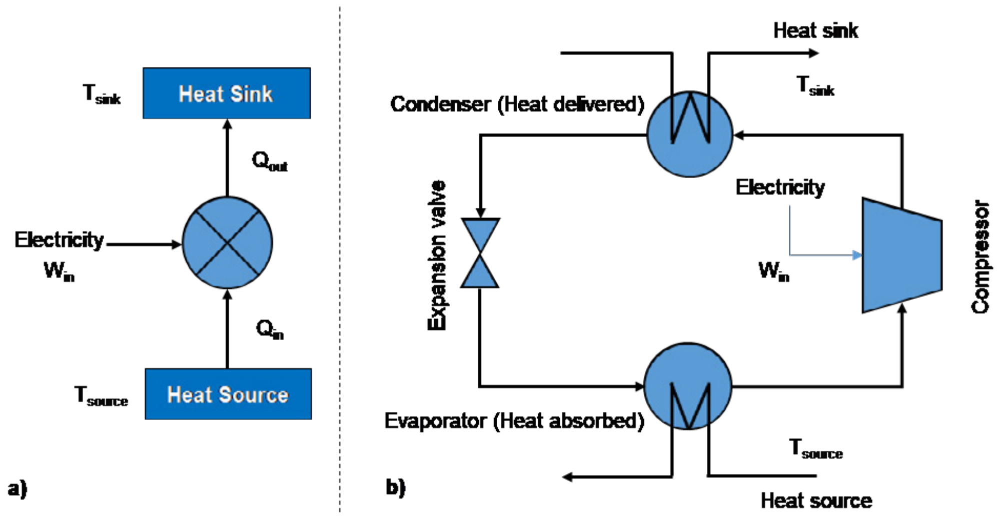

Figure 1. Thermodynamic representation and cycle of a heat pump.

Heat pumps are very efficient because they only transfer heat instead of combusting fuels to create it, ultimately reducing GHG emissions from heating applications such as in the manufacturing industry (Gagneja and Pundhir, 2016). The performance of a heat pump is defined by the coefficient of performance (COP) which is the ratio of heat output to energy input as shown in Equation 1.

$$COP_{real} = \left(\frac{Q_{out}}{W_{in}}\right) \quad (1)$$

In the heating mode, heat pumps based on the ideal Carnot cycle, operate between two heat reservoirs having absolute temperatures $T_{source} \approx T_{evap}$ (heat source) and $T_{sink} \approx T_{cond}$ (heat sink or process temperature). The maximum theoretical COP is given as Equation 2.[1] Since thermodynamic processes undergo many losses, the real COP of a heat pump is a fraction of the maximum theoretical COP. An efficiency term, also known as quality grade or 2nd law efficiency, η_{HP} that relates the actual COP (COP_{real}) to the maximum theoretical COP (COP_{carnot}) is given in Equation 3. The COP of a heat pump is greater than 1 as it always supplies more heat than the electricity consumed.

$$COP_{carnot} = \left(\frac{T_{sink}}{T_{sink} - T_{source}}\right) = \left(\frac{T_{sink}}{\Delta T_{lift}}\right) \tag{2}$$

Where ΔT_{lift} is the temperature lift applied to the process streams i.e. heat sources and sinks.

$$\eta_{HP} = \left(\frac{COP_{real}}{COP_{carnot}}\right) \tag{3}$$

The ranges of IHP capacities and sink temperatures have steadily grown over the years. Industrial heat pumps with high-temperature heat sink temperatures of up to 165°C are commercially available at scale (Marina et al., 2021). The terminology for the temperature level of an IHP is not consistent in the literature, refer to the literature review in Arpagaus et al. (2018) for more details. This work classifies IHP with heat sink temperatures lower than 100°C as high-temperature heat pumps (HTHP). While IHP with steam delivery temperatures greater than or equal to 100°C are termed steam-generating heat pumps (SGHP).

There are several HTHP manufacturers on the market that can provide heat sink temperatures of up to 90°C, however, a limited number of SGHP suppliers including Kobelco (Japan), Mitsubishi (Germany), Siemens (Germany), MAN Energy (Switzerland), Heaten (Norway), Ochsner (Austria), Mayekawa (Japan), Combitherm (Germany), etc. have commercial success in exceeding 120°C (steam supply). It is evident that the market capabilities for IHP are most developed in Europe and Japan due to strong economic and policy incentives (Arpagaus et al., 2018). Moreover, the heating capacities of IHP range from 20 kW to 100 MW (for example, MAN Energy and Siemens Energy have SGHP units with heating capacities of up to 100 MW and 70 MW respectively). Some of the commonly used refrigerants in IHP are R134a, R245fa, R717, R744, and R1234ze(E). For more technical details on the heat pump circuits, refrigerants used, and compressor types, refer to Arpagaus (2018) and Arpagaus et al. (2018).

Furthermore, the COP values range as a function of the respective temperature lift for the various IHP on market with 140°C sink temperature are presented in Figure 2 (with the permission of Arpagaus et al., 2018). Figure 2 shows that the COP values range from 1.6 to 5.8 at temperature lifts of 130 to 40 K respectively. The quality grade η_{HP} of an IHP typically ranges between 40 and 60% (Schlosser et al., 2019), as also shown in the figure, however, this work assumes a rather conservative value of 45%. Several research groups in Europe and East Asian countries are working on research projects to push the limits and achieve higher levels of COPs and heat sink temperatures (Arpagaus et al., 2018).

1. T_{evap} and T_{cond} are the evaporating and condensing temperatures that are assumed approximately equal to T_{source} and T_{sink} temperatures respectively. Although we are making the simplifying assumption, it must be noted that, typically, there exists a small temperature difference between the process streams and the heat pump working fluid. The actual temperature lift internal to the heat pump is slightly greater than the temperature lift applied to the process streams (U.S. DOE, 2003).

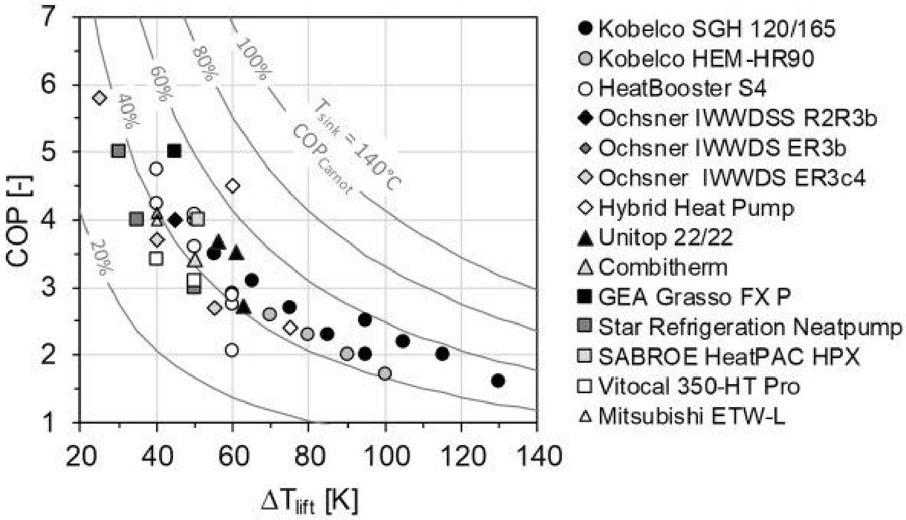

Figure 2. COP of various industrial heat pumps as a function of temperature lift (Arpagaus et al., 2018).

There is also a wide range of industrial sectors that requires process heat in the low to moderate temperature ranges that are suitable for IHP applications. A large number of IHP applications have been acknowledged particularly in food and beverage, textile, paper, metal processing, and chemical sectors, especially for drying, evaporation, pasteurizing, and distillation processes. The recent Annex 48 of the IEA Technology Collaboration Programme on Heat Pumping Technologies (IEA, 2020) presents several case studies on IHP applications (including SGHP installations) in European and Japanese plants and demonstrates real-life experiences that other regions might learn from. This work has also made use of these real examples as a reference to build the case for U.S. manufacturing.

3 Assumptions, Limitations, and Application Scenarios

The optimal placement and integration of an IHP in an industrial plant can be investigated through pinch analysis. Pinch analysis is a technique to minimize the energy demand of industrial processes by identifying the potential heat recovery between hot and cold streams and optimizing unit operations (Becker et al., 2011) . Pinch analysis includes the development of composite curves where the profiles of available heat sources (hot composite curve) are combined with heat sinks (cold composite curve) and the magnitude of overlap between the curves is determined as the potential heat integration. The point where the hot and cold composite curves most closely approach each other is referred to as the “pinch point”. There is a heat deficit above the pinch point and a heat surplus below the point (Olsen et al., 2017). Generally, the optimal placement of an IHP in a process is where heat is driven from below the pinch point to above it at a higher temperature (also called temperature lift).

The higher the temperature lift, the lower the COP and the higher the capital and operational costs of an IHP (Rightor et al., 2022). It is, therefore, crucial to carefully assess the available waste heat resources that can be utilized for optimal IHP integration into a process. However, the amount of waste heat resources available in an industrial plant is strictly site-specific. The level of process heat integration of an industrial plant depends on a range of techno-economic variables (including waste heat volume and temperature, competing opportunities for waste heat utilization, plant complexity, space available, energy prices, external agreements, etc.) that are unique to that plant. Given these site-specific characteristics and constraints, developing generalized composite curves for an industrial process and estimating the pinch temperature based on these curves possess a significant level of uncertainty. In other words, the resultant IHP integration design may not necessarily be optimal.

The prime objective of this study is to identify and generalize potential applications of IHP in different industrial processes where heat can be supplied by IHP. In addition, since the plant-level process data for each industrial site within each sector are not publicly available, we are making a simplifying assumption that heat sources (such as water and air) are available at ambient conditions i.e. at a temperature and pressure of 25°C and 1 bar, respectively. For a specific IHP application in a plant, there might be waste heat sources available at temperatures higher than 25°C, utilization of which for the same application would enhance the IHP performance. Hence, the techno-economic results (e.g. COPs, future electricity demand by IHPs, marginal costs, etc.) computed in this study are rather conservative and could significantly change if systematic process optimization and heat integration techniques (pinch analysis) are applied to individual U.S. industrial processes. However, the sensitivity of the economic energy conservation and CO_2 abatement potentials to changes in heat source temperature has been tested and shown in Section 5.2. Moreover, real-life case studies for the relevant IHP applications (as studied in this report) are also discussed where possible, to highlight potential waste heat sources and their temperature levels in similar industrial plants around the world.

Apart from heat source temperatures, there are other important considerations made in this study as discussed below. There are a limited number of SGHP manufacturers on the market that can provide heat sink temperatures of over 120°C (steam), unlike HTHP which are at an advanced stage of commercial maturity. The literature review for this work further suggests that there are a substantial number of HTHP already implemented in different industrial plants in different countries, however, only a few SGHP installations have been made in the industry sector due to the technology’s early stage of commercial deployment and lack of awareness. In this context, the following two implementation scenarios have been developed for IHP applications in U.S. manufacturing:

- *Scenario 1 - Conservative*: In the conservative scenario, only HTHP applications are considered. These applications include suitable heat demand at temperatures less than 100°C and boiler feedwater preheating for steam generation.

- *Scenario 2 - Ambitious*: In the ambitious scenario, both HTHP and SGHP applications are studied. The maximum heat sink temperature of SGHP is cut-off at 150°C for two reasons. The first is the existence of even fewer SGHP manufacturers who could deliver temperatures over 150°C. The second is the maximum temperature lift of 130 K (refer to Figure 2) demonstrated by only a few SGHP suppliers. Given our assumption for heat source temperature (25°C), a temperature lift higher than 130 K is techno-economically not favorable.

Moreover, the abatement cost curve is a tool frequently used to analyze the techno-economic perspectives of energy and/or CO_2 reduction. The curves show the marginal costs of energy efficiency and CO_2 abatement measures as a function of the energy or CO_2 reduction potentials. In this study, abatement cost curves are developed to estimate the marginal costs and the technical potential for energy and CO_2 savings for IHP applications in the studied U.S. manufacturing sectors. The method to build these curves is described in detail in Appendix A. To estimate the marginal costs of IHP, capital costs and operations and maintenance (O&M) costs are acquired from literature sources and adjusted for the U.S. where necessary, refer to Appendix B. A real discount rate of 10% from the private perspective is assumed for the economic analysis and the technical lifetime of IHP is assumed as 15 years (Panos and Kannan, 2016).

The key components of IHP lifetime costs are electricity and fuel prices. The average natural gas and electricity prices for the U.S. industry in constant 2021 dollars are projected for the study period 2021-2050 based on the national statistics (U.S. EIA, 2021a), see Appendix C. It must be noted that the climate impact of electrification of process heat supply cannot be significant and can be negative in some cases if electricity generation remains CO_2-intensive. Therefore, it is indispensable to decarbonize the electricity grid via low-carbon energy sources to reduce the CO_2 intensity of industrial process heating. Given the specific electricity grid targets in the U.S., both at the federal and the state level (refer to the summary of these targets presented in our previous work i.e. Zuberi et al. (2021), this study assumes the rate of electricity grid decarbonization in the future. Two grid decarbonization scenarios have been developed i.e. 100% CO_2-free electricity by a) 2035 (given the federal pledge[2]) and b) 2050 (as assumed by several other studies in the literature). This work further assumes a linear trend for grid decarbonization in both scenarios. The emission factor for natural gas is taken as 0.05 tCO_2/GJ based on (U.S. EPA, 2014) while the national average electricity grid emission factor in 2021 is estimated at 0.37 tCO_2/MWh based on (U.S. EIA, 2022a).

2. The U.S. administration has set an ambitious target to produce 100% carbon-free electricity by 2035 (The White House, 2021, n.d.).

4 Industrial Heat Pump Applications

Based on the methods and assumptions described in Appendices A-C and Section 3 respectively, this study analyzes IHP applications in the following eleven U.S. manufacturing sectors and thirteen processes. The sectors are selected based on a) initial screening for process temperatures and operations suitable for IHP applications and b) data availability. The specific energy consumption (SEC) of each industrial process is adapted based on Brown et al. (1996). The individual sources for process-specific production volumes are given in the relevant sections.

4.1 Meat Processing Industry

Production process

The U.S. red meat processing plants produced approximately 25 million tonnes (Mt) in 2021 (estimated based on (USDA ERS, 2022a). The production volume is estimated to grow to 30 Mt in 2050. The red meat production process is briefly described as follows. The first step in red meat production is the slaughtering of livestock and letting it bleed to prevent decay while blood is processed in the next step. The blood is heated to coagulate the albumin and separate albumin and fibrin from blood water (serum). After bleeding, the hide is removed and the animal is eviscerated. The internal organs (heart, liver, kidneys, etc.) are removed from the viscera along with waste products such as intestines and washed, followed by trimming, cutting, and deboning of the carcass (U.S. EPA, 2004).

Edibles from the cutting process that do not go into products like sausages and canned meat are directed to rendering. The rendering process separates fats and water from the tissue. Dry batch rendering is the widely used rendering process, particularly for edible rendering. These edibles are processed in a variety of ways including sausages, canned and pickled meat, portioned cuts, etc. The inedibles are processed in a separate area mainly for producing animal feed. Part of the wastewater from the meat processing plants runs through grease traps to recover grease which is also sent to inedible rendering. After packaging, processed meat is refrigerated to inhibit bacterial growth (U.S. EPA, 2004).

Table 1 presents the typical specific final energy consumption of a meat processing plant, disaggregated by fuel and electricity demand in each process step.

IHP applications

Table 1 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 3 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to heat process water to 60°C for evisceration and viscera handling. The same heat pump is also supposed to preheat the makeup feed water to 60°C. Since the steam condensate returns from the process at around 82°C, the mixing of makeup water and return condensate at different temperatures is not good from an exergy point of view. Hence the makeup water may be further heated from 60°C to 82°C using another HTHP before it enters the condensate tank for steam generation. The total required heating capacity of HTHP for the U.S. red meat processing industry is estimated at 850 MW.

To support the discussion on HTHP applications identified for the U.S. meat processing plants, a real-life example is presented. A HTHP system (comprised of three CO_2 heat pumps) with a heating capacity of 800 kW and COP of 3.4 was installed in a slaughterhouse in Switzerland (Arpagaus and Bertsch, 2020). The system uses waste heat at 20 to 30°C from multiple sources including refrigeration and air compressor plants and fan-coil units to heat process water to 90°C. The heated water is used for different purposes including slaughtering and cleaning, boiler feedwater, and space heating. The HTHP system reduced 30% of the plant's annual CO_2 emissions.

Table 1. Specific energy consumption of conventional and modified processes in the meat processing industry.

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

In our Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for drying, scalding, rendering, and other processes. The total required heating capacity of SGHP is estimated at 2620 MW. Furthermore, the COP of the SGHP is determined to be low i.e. 1.8 (calculated using Equations 2 and 3), mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (25°C) will result in a higher COP or lower electricity demand for an IHP operation.

It should be noted that the level of an industrial plant's process integration and the available nearby heat resources determine where an IHP must optimally be placed. However, since the level of integration varies by industrial plant, it gets very difficult to estimate available waste heat source temperatures. As discussed in Section 3, we have assumed the available heat source (e.g. plant water supply) at 25°C. Hence the schematic shown in Figure 3 and all other schemes discussed in Sections 4.2 – 4.11 may not be the ideal configuration for a specific production plant. The figure only highlights the typical process steps to which IHP could potentially be applied. It is therefore recommended that a more systematic analysis (or pinch analysis) must be done for a plant, based on its detailed site-specific data, to design an optimal IHP system for that specific plant. Our assumptions are reasonable for the industry-level analysis. In the same context, the results presented below are rather conservative i.e. the energy and CO_2 savings could be considered close to the lower bound (minimum net savings) and specific costs close to the upper bound (maximum costs). However, to evaluate the change in the magnitude of all the computed results, a detailed sensitivity analysis is done in Section 5.2.

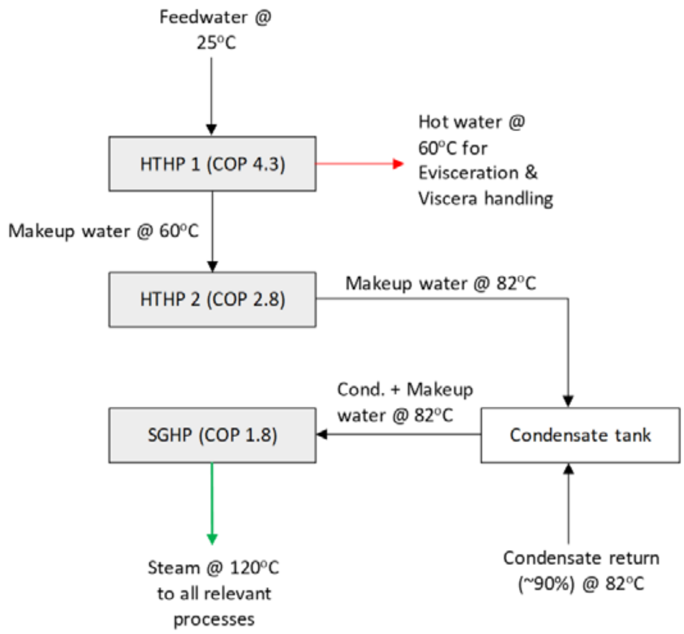

Figure 3. Industrial heat pump applications in the meat processing industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified processes using IHP is also presented in Table 1. The change in annual final energy demand in the U.S. meat processing industry in different IHP application scenarios and timeframes is presented in Figure 4.[3] The figure shows that the measures suggested in Figure 3 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that nearly 18 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential

3. It should be noted that no heat integration measures except for the IHP applications and condensate recovery are considered as they are site-specific and difficult to generalize. Hence the final energy demand in business-as-usual (BAU) in Figure 4 (and in all the similar figures in Sections 4.2 – 4.11) is the maximum required by the individual process without heat integration. Depending on what a plant currently does with its waste heat, the demand might be slightly lower.

increases to approximately 69 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 23 and 102 PJ per year of fuel demand could be reduced while 4 and 33 PJ per year (or 1.1 and 9.2 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

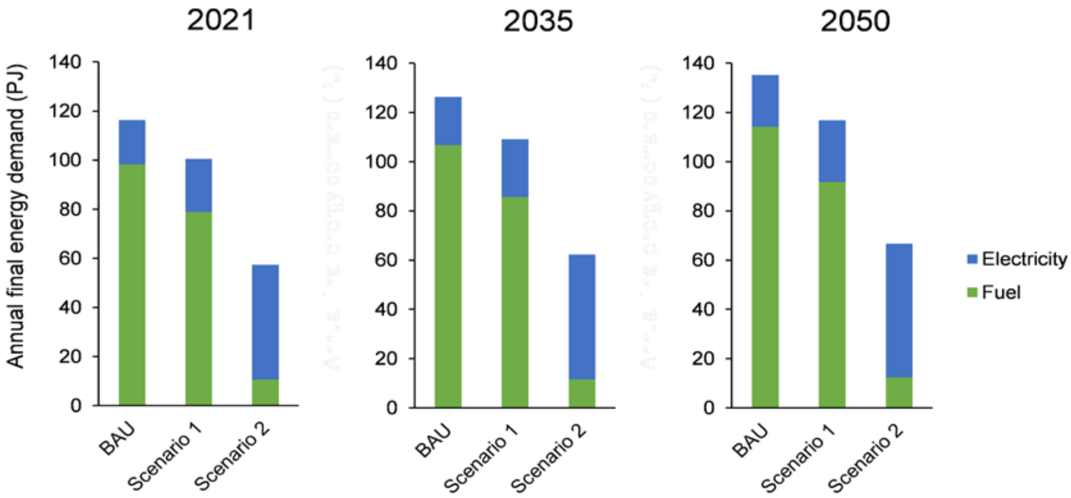

Figure 4. Annual final energy demand in the U.S. meat processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. meat processing industry in different IHP application scenarios and timeframes is presented in Figure 5. The figure shows up to 1.8 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption/diffusion of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 1.3 and 5.5 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid's CO_2 emissions factor (grid decarbonization) between 2021 and 2050. It must be noted that the different levels of potential CO_2 emissions reduction in 2035 represent two different grid decarbonization scenarios i.e. zero-carbon grid and partial grid decarbonization by 2035, see Section 3.

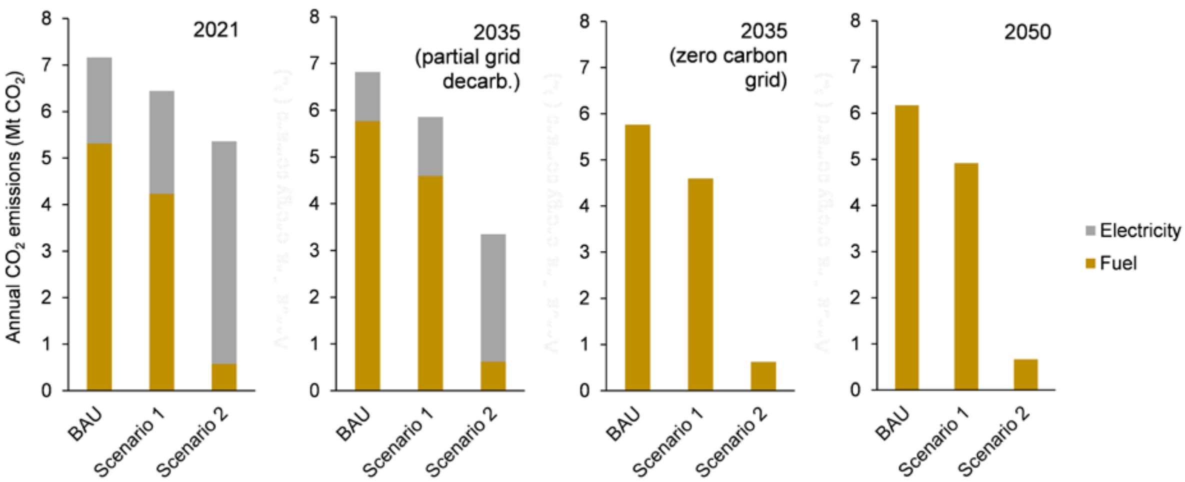

Figure 5. Annual CO_2 emissions from the U.S. meat processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 6 presents the costs of conserved energy and CO_2 abatement costs for IHP applications in the U.S. meat processing industry. The figure shows that the energy conservation costs range from 3 to 8 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 40 and 74 $/t CO_2 in Scenarios 1 and 2, respectively. The abatement costs for 2021 are found to be very high due to no effective grid decarbonization in the base year, hence not shown in Figure 6. It is evident that IHP integration in U.S. meat processing plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high costs is the disparity between the electricity and fuel prices in the U.S. industry.

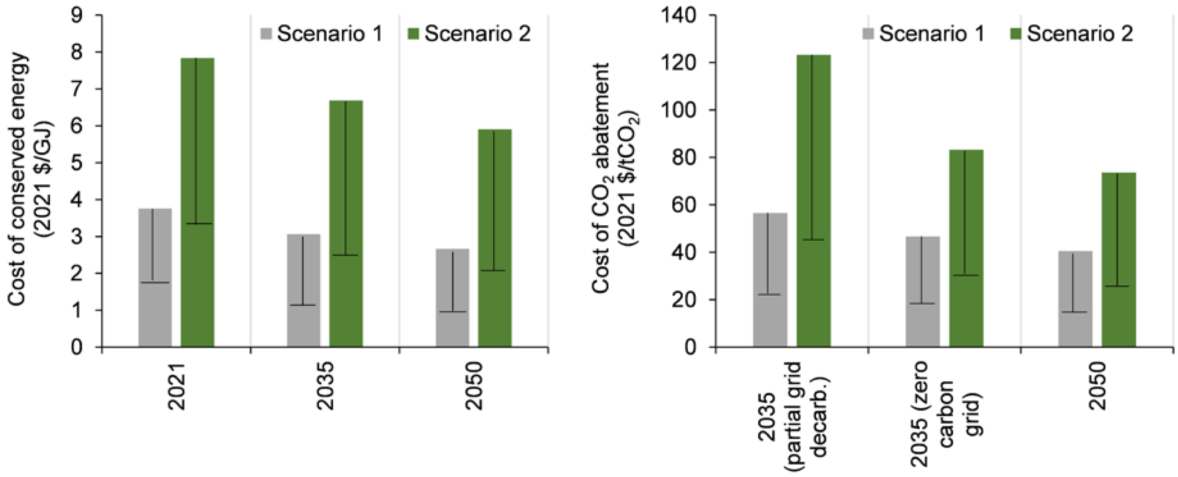

Figure 6. Costs of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. meat processing industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

The assumed heat source temperature i.e. 25°C is another factor influencing the costs to be high (see earlier discussion). Given our assumptions, since the SGHP has a higher temperature lift than the HTHPs, the amount of electricity required per unit of energy savings is also higher for SGHP. Consequently, the costs in Scenario 2, which considers the SGHP application, are found to be greater than in Scenario 1. It is therefore advised to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts and the electricity costs. It should however be noted that a moderate carbon price of around $50/t$CO_2$ can make IHP integration in the U.S. meat processing industry cost-competitive in 2035 and beyond. Furthermore, the electricity to natural gas price ratio varies substantially across states in the U.S. Different price ratios among different states may influence the costs of energy conservation and CO_2 abatement substantially, however, state-level analysis is outside the scope of this study, hence not done.

4.2 Dairy Industry

Production process

The U.S. dairy industry produced around 103 Mt of milk in 2021 (USDA ERS, 2022b). The production volume is estimated to grow to 118 Mt in 2050. Some of the common dairy production processes are briefly described below. In the first step, raw milk entering a dairy plant undergoes preliminary analytical tests to check the quality of milk and stored. After having passed the quality control, raw milk proceeds to a clarifier where dirt particles are removed followed by the separation of globular milk from the serum (skim milk). Skim milk is directed for cheesemaking while the rest including creme is sent for fluid milk production. The fluid milk is pasteurized using steam to destroy pathogens by passing it through a heat exchanger (Díaz and García-Gimeno, 2018). The milk is later homogenized to disperse fat globules. Raw milk containing fat easily absorbs substances that give a foreign smell and taste. The next step is deodorization where steam distillation of odorizing materials from the milk is performed. The fluid milk is packaged and stored in the final step (Popov and Terechuk, 2016).

Skim milk for cheese production is first pasteurized before pumping into cheese vats. In cheese vats, skim milk is slowly cooked by jacketed steam using mild agitation. The cooked curd and whey are then moved to a vertical silo where the whey is removed and dried in the first step. On the other hand, the curd grains are washed with water and cooled, followed by mixing with cream or dressing to produce cottage cheese (Tetra Pak, 2015; Kealey and Kosikowski, 1986).

Table 2 presents the typical specific final energy consumption of an integrated milk and cheese (cottage) production plant, disaggregated by fuel and electricity demand in each process step.

Table 2. Specific energy consumption of conventional and modified processes in the dairy industry.

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

IHP applications

Table 2 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 7 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to preheat the makeup feed water to 82°C before it enters the return condensate tank for steam generation. The total required heating capacity of this HTHP in the sector is estimated at 43 MW.

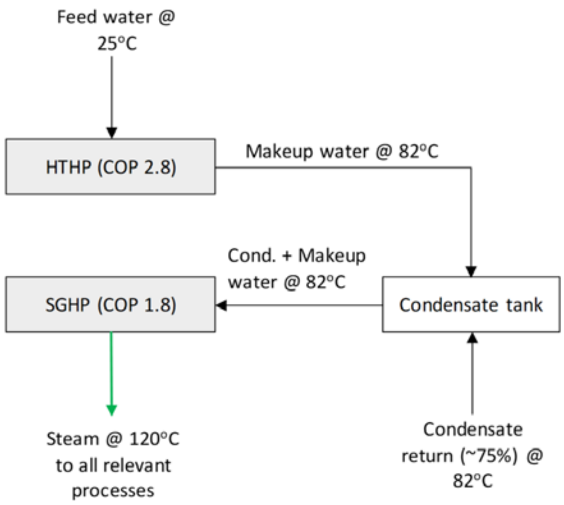

Figure 7. Industrial heat pump applications in the dairy industry.

In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for pasteurization and deodorization in fluid milk production and pasteurization, and settling and cooking in cottage cheese production. The total required heating capacity of SGHP is esti-mated at 1656 MW. Furthermore, the COP of the SGHP is determined to be low i.e. 1.8, mainly because the temperature lift is high (heat source at ambient). The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic shown in Figure 7 may not be the ideal solution for a specific dairy plant for reasons explained in Sections 3 and 4.1.

To support the discussion on IHP applications identified for U.S. dairy plants, a couple of real-life examples are presented. A Norwegian dairy integrated an IHP for combined heating and cooling for all processes in their facility. In other words, the dairy plant does not consume any fossil fuels for heating anymore, thereby reducing CO_2 emissions to zero. The IHP has a heating capacity of 940 kW and a COP of 5. The final energy consumption was reduced by 40% per year (de Boer et al., 2020). In another example, a Swiss cheese factory used waste heat from a nearby data center as a heat source for a HTHP to supply process hot water, and heat for buildings at >90°C. The IHP installation saves the factory around 5.4 TJ of natural gas per year (de Boer et al., 2020).

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (using IHP) processes is also presented in Table 2. The change in annual final energy demand in the U.S. dairy industry in different IHP application scenarios and timeframes is presented in Figure 8. The figure shows that the measures suggested in Figure 7 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that only a slight decrease of approximately 0.8 PJ per year of final energy can be achieved if only the HTHP application (Scenario 1) is realized in 2050. However, the technical potential increases to nearly 26 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 1.1 and 45 PJ per year of fuel demand could be reduced while 0.3 and 19 PJ per year (or 0.1 and 5.1 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050, respectively.

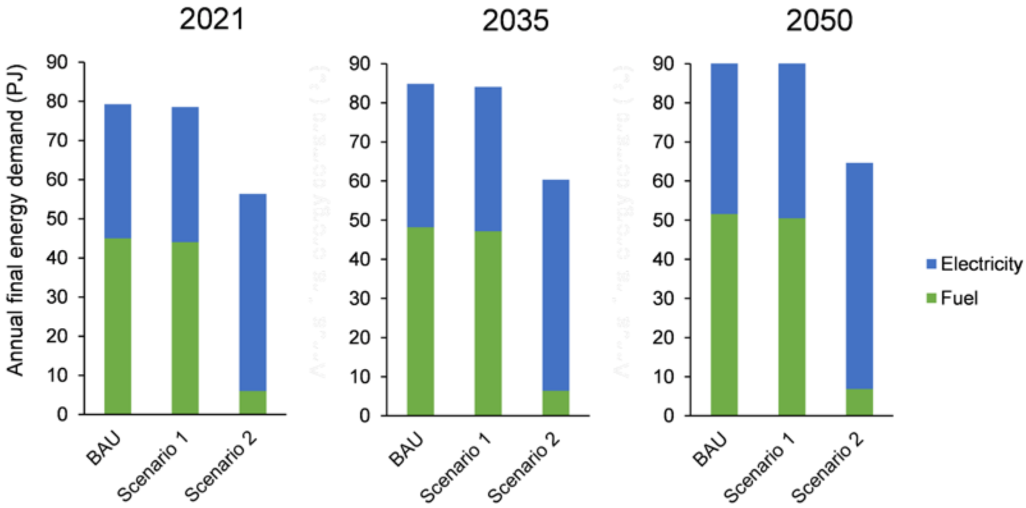

Figure 8. Annual final energy demand in the U.S. dairy industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. dairy industry in different IHP application scenarios and timeframes is presented in Figure 9. The figure shows up to 0.5 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.1 and 2.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emissions factor (grid decarbonization) between 2021 and 2050. The different levels of CO_2 emissions reduction potential in 2035 represent different grid decarbonization scenarios (refer to Section 3).

Figure 10 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. dairy industry. The figure shows that the energy conservation costs range from 7 to 12 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 90 and 102 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. dairy plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high specific costs is the disparity between the electricity and fuel prices in the U.S. industry. The assumed heat source temperature is another factor influencing the costs to be high (see earlier discussion). It is therefore advised to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

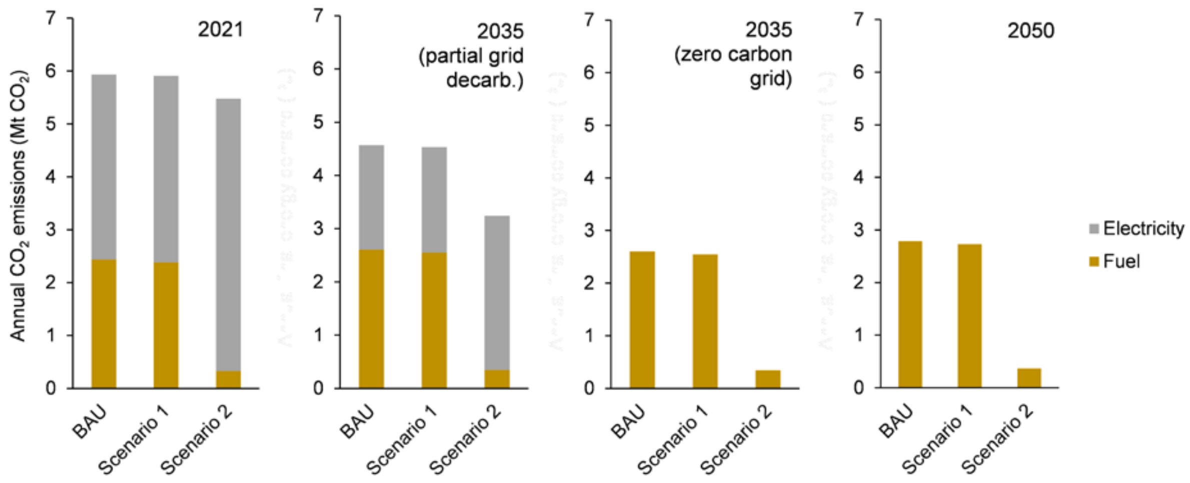

Figure 9. Annual CO_2 emissions from the U.S. dairy industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

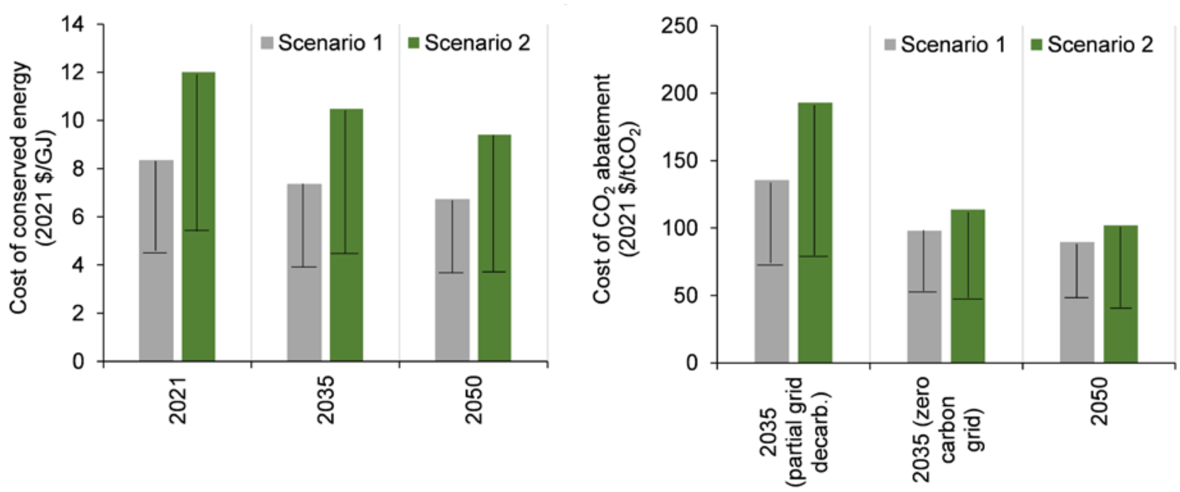

Figure 10. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. dairy industry.
Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.3 Beer Industry

Production process

The U.S. breweries produced around 180 million barrels of beer in 2020 (Statistica, 2021). The production volume is estimated to grow to 210 million barrels in 2050. The beer production process is briefly described as follows. The brewing process uses several ingredients such as malted barley, cereals, etc. for the production of beer. The first production step involves the modification of barley to malt called malting followed by milling to produce coarse powder called grist. In the next step, the grist is mixed with warm water in a tank and constantly agitated for an hour. Hot water is added to the grist to help the conversion of starch to sugar by enzymes. The mash is heated in stages with the help of steam jackets. The liquid obtained from mashing is called wort which is separated from the residual grain in a filter (also called lautering) (Hasanbeigi et al., 2021). The residual/spent grain is screened and dried to produce animal feed.

The wort is sterilized through a boiling process in a kettle which halts enzyme activity and condenses the liquid. On the completion of the boiling process, the wort is cooled down to around 20°C. The fermentation process involves adding yeast to the wort. The yeast helps ferment the wort and converts it into beer. The beer is chilled and stored in a tank for maturation (Hasanbeigi et al., 2021). The beer is then filtered to remove yeast, resulting in clear beer stored in a bright beer tank. The beer must be kegged or bottled and carbonated, either naturally or by force. Typically, force carbonation is performed by adding high-pressure CO_2 to a container, forcing it to get absorbed into the beer. Some facilities also pasteurize their beer to improve clarity and shelf life (The Beer Connoisseur, 2016).

Table 3 presents the specific final energy consumption of a typical brewery, disaggregated by direct and indirect fuel and electricity demand in each process step.

Table 3. Specific energy consumption of conventional and modified processes in the beer industry.

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		133.7	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			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/m^3.
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

IHP applications

Table 3 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 11 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a series of HTHPs can be employed to provide hot water at temperatures ranging from 54°C to 82°C to processes including mash tun, cleaning, filtration, and pasteurization. The same heat pumps are also supposed to preheat the makeup feed water to 82°C in different stages before it enters the condensate tank for steam generation. The required heating capacity of HTHP for the U.S. beer industry is estimated at around 2 GW.

To support the discussion on HTHP applications identified for U.S. breweries, a real-life example is presented. A HTHP system with a heating capacity of 370 kW and a COP of 4.4 was installed in an Austrian brewery (IEA, 2014). The heat pump utilizes waste heat from its chillers to heat process water to 77°C. The HTHP system reduced 6.6 TJ per year of natural gas demand and consumed only 1.5 TJ per year of electricity for the HTHP operation.

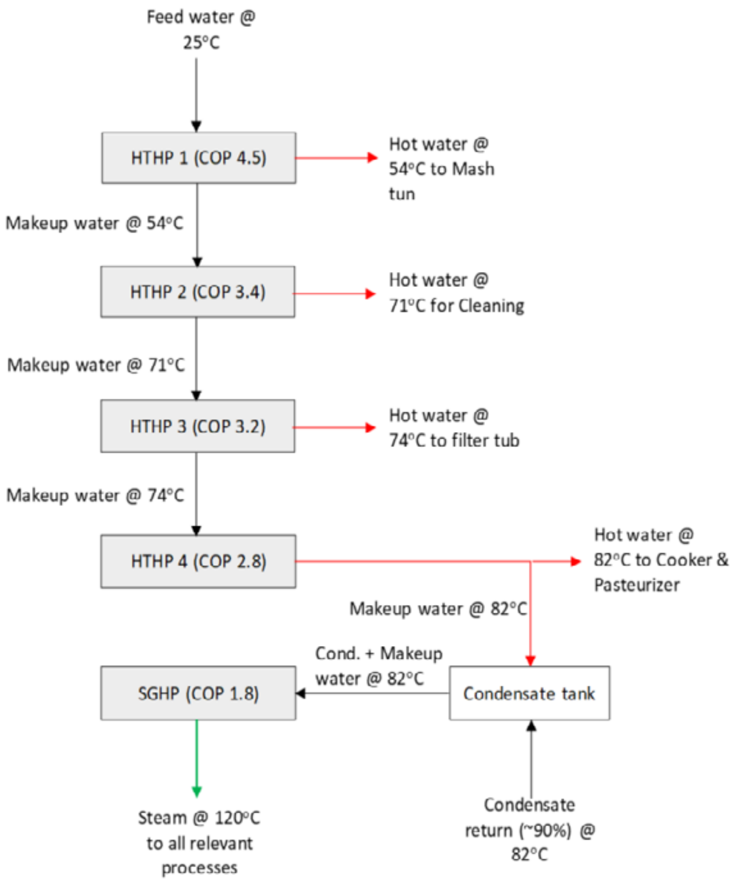

Figure 11. Industrial heat pump applications in the beer industry.

In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for cooking, mashing, and brewing. The total required heating capacity of SGHP is estimated at 880 MW. Furthermore, the COP of the SGHP is estimated to be low i.e. 1.8, mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic in Figure 11 may not be an ideal configuration for a specific brewery for the reasons explained in Sections 3 and 4.1.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 3. The change in annual final energy demand in the U.S. beer industry in different IHP application scenarios and timeframes is presented in Figure 12. The figure shows that the measures suggested in Figure 11 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 26 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 32 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COP of the IHPs. More precisely, 33 and 44 PJ per year of fuel demand could be reduced while 6 and 12 PJ per year (or 1.8 and 3.4 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

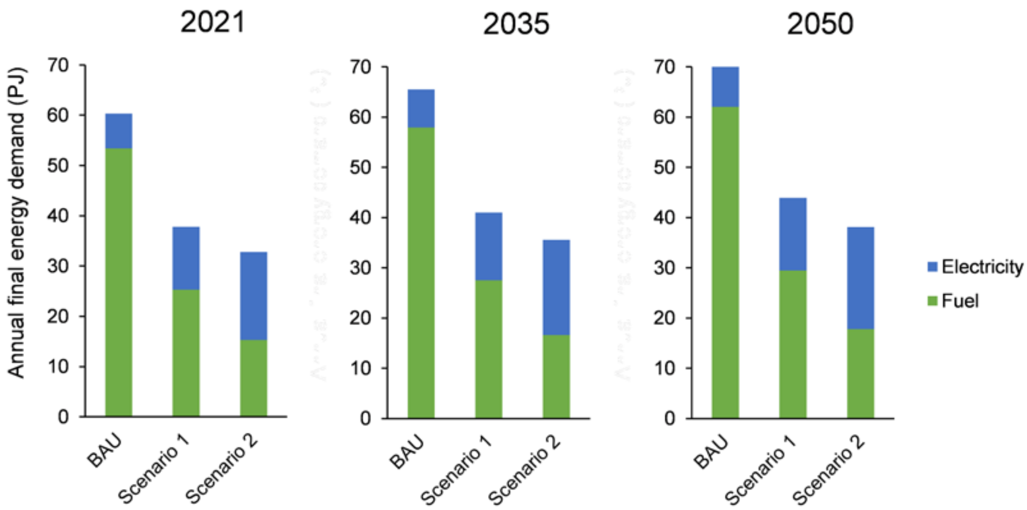

Figure 12. Annual final energy demand in the U.S. beer industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. beer industry in different IHP application scenarios and timeframes is presented in Figure 13. The figure shows up to 1 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 1.8 and 2.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 abatement in 2035 represent different grid decarbonization scenarios, refer to Section 3.

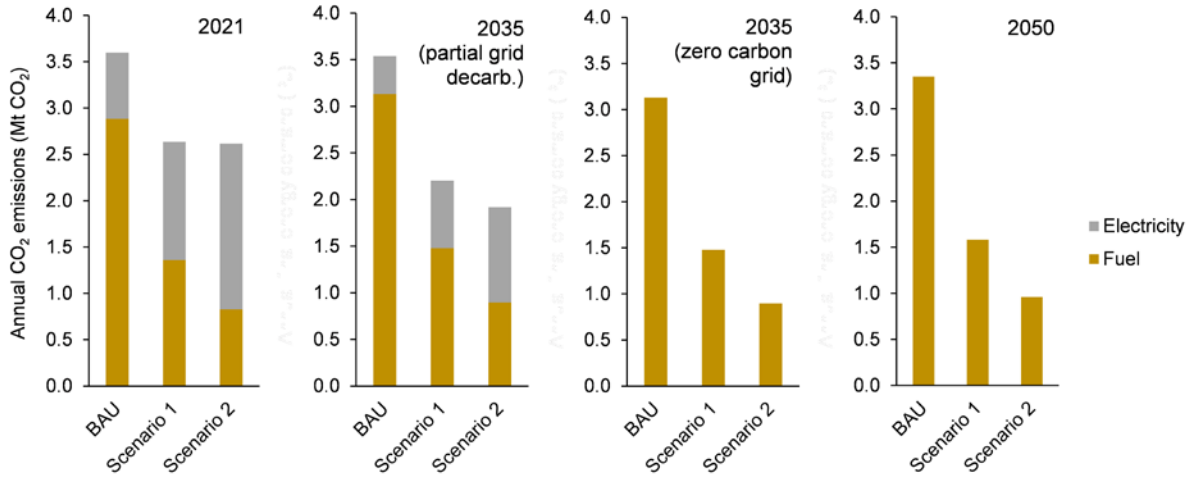

Figure 13. Annual CO_2 emissions from the U.S. beer industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 14 presents the specific costs of conserved energy and CO_2 abatement for IHP applications in the U.S. beer industry. The figure shows that the energy conservation costs range from 6 to 11 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 88 and 123 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. beer plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. The two major reasons for the high marginal costs are the large difference between the U.S. average electricity and fuel prices and the low heat source temperature (25°C) as assumed in this study. It is therefore recommended to explore relevant waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

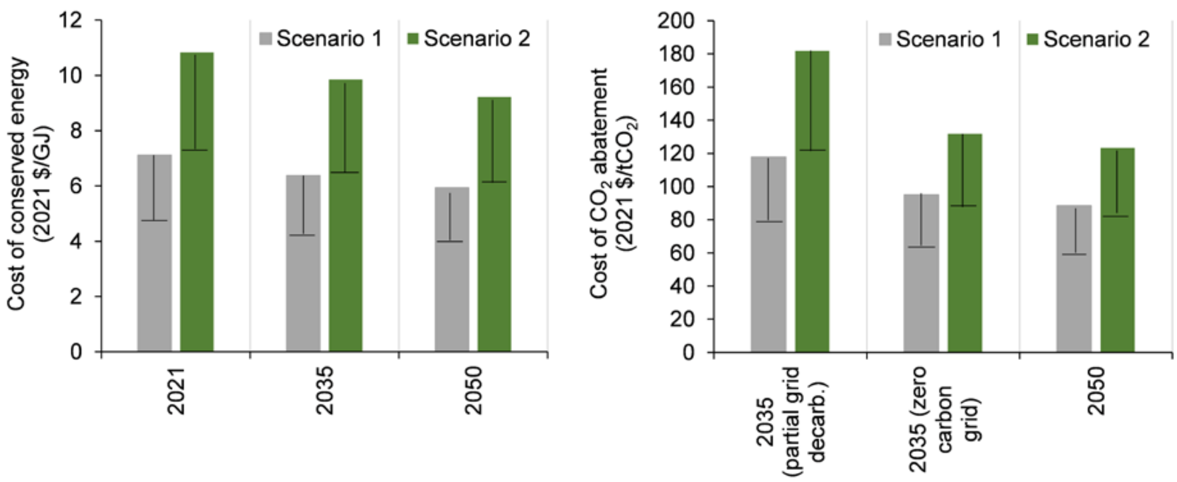

Figure 14. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. beer industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.4 Canned Vegetable and Fruit Processing Industry

Production process

The production of U.S. canned vegetable and fruit processing plants was around 8 Mt in 2021 estimated based on U.S. DOE/AMO (2017). The production volume is estimated to reach 10 Mt in 2050. The canned vegetable and fruit production processes are briefly described as follows. The basic process steps in the conventional canning of fruits and vegetables are similar for both product types, however, the sequencing of these processes may differ. There is also a great diversity among plant operations processing the same commodity. Typically, the production process begins with the washing and grading of fruits and vegetables. The raw produce is graded for size and maturity followed by cutting/slicing where relevant. Most of the fruits are not blanched before filling into cans, while many of the vegetables undergo this process step. Canned vegetables generally require more processing than fruits because the vegetables have much lower acidity and contain more heat-resistant soil organisms. Moreover, many vegetables require more cooking than fruits to advance their desirable flavor and texture (U.S. EPA, n.d.).

For both vegetables and fruits, peeling is done either by mechanical, steam, or lye peeling and the choice mainly depends on the type of product. Furthermore, in the case of vegetable products, salt is added for palatability. Cans or containers are first washed with hot water followed by product filling by a machine. Exhausting is done in the next step to remove air so that the pressure inside the container following the downstream processes will be less than atmospheric, ultimately extending the shelf life of canned food products. In the sealing process, a double seam is made by interlocking the curl of the lid and flange of the can. Sealing machines are often equipped to create a vacuum in the headspace by steam flow before lids are sealed. In retorting, microorganisms that can cause decay during processing are sterilized using steam. The retort temperature and processing time vary with the nature of the product and the size of the container. After heat retorting, containers are immediately cooled to prevent overcooking. In the last step, cans or jars are labeled and packed into shipping cartons (U.S. EPA, n.d.).

4.4.1. Canned vegetables

IHP applications

Table 4 presents the typical specific final energy consumption of a canned vegetable production plant and highlights (in green color) the process heat demand at temperatures suitable for IHP applications.

Table 4. Specific energy consumption of conventional and modified processes in the canned vegetable industry.

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	336.6	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		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 15 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to heat process water to 60°C for washing vegetables and cans. The same heat pump is also supposed to preheat the makeup feed water to 60°C followed by another HTHP raising the water temperature from 60°C to 82°C before it enters the condensate tank for steam generation. The required heating capacity of HTHP applications for the U.S. canned vegetable industry is estimated at 225 MW.

In a real-life example, a Swiss vegetable production plant installed a multi-purpose heat pump that serves both heating and cooling (Arpagaus and Bertsch, 2020). In winter, groundwater is used as the heat source to provide hot air at approximately 60°C to the plant greenhouses. The capacity of the heat pump is 1 MW while the COP in heating mode is 3.6. The coupling of the refrigeration with their heat pump system enables the plant to significantly reduce the costs of refrigeration and heat generation. The heat pump generates 14.4 - 18 TJ of thermal energy per year, saving the plant around 500,000 m^3 of natural gas for heating the greenhouses.

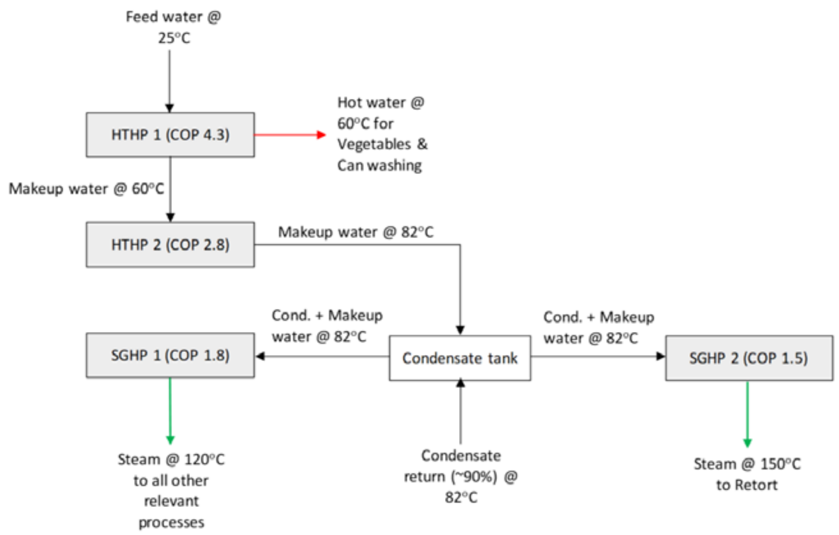

Figure 15. Industrial heat pump applications in the canned vegetable industry.

In Ambitious Scenario 2, two separate SGHP can be employed to generate process steam, one at 120°C for scalding, cooking, brine heating, exhausting, and sealing, and the second at 150°C for the retort. The total required heating capacity of SGHP is estimated at 740 MW. Furthermore, the COPs of the SGHP are determined to be low mainly because the temperature lift is high, especially for delivering steam at 150°C. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic shown in Figure 15 may not be the ideal configuration for a specific canned vegetable production plant for reasons explained in Sections 3 and 4.1.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 4. The change in annual final energy demand in the U.S. canned vegetable industry in different IHP application scenarios and timeframes is presented in Figure 16. The figure shows that the measures suggested in Figure 15 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 5 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 16 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 6 and 26 PJ per year of fuel demand could be reduced while 1 and 10 PJ per year (or 0.3 and 2.8 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

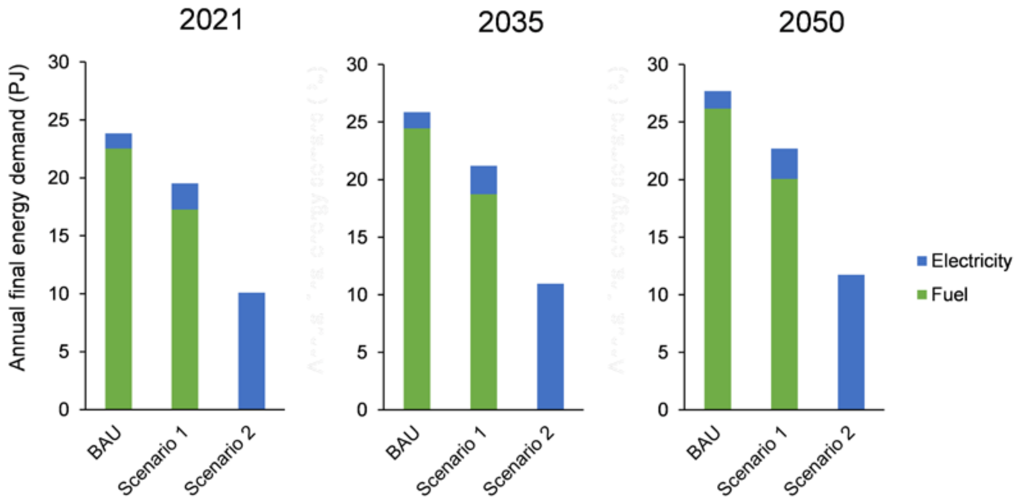

Figure 16. Annual final energy demand in the U.S. canned vegetable industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. canned vegetable industry in different IHP application scenarios and timeframes is presented in Figure 17. The figure shows up to 0.3 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.3 and 1.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emissions factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

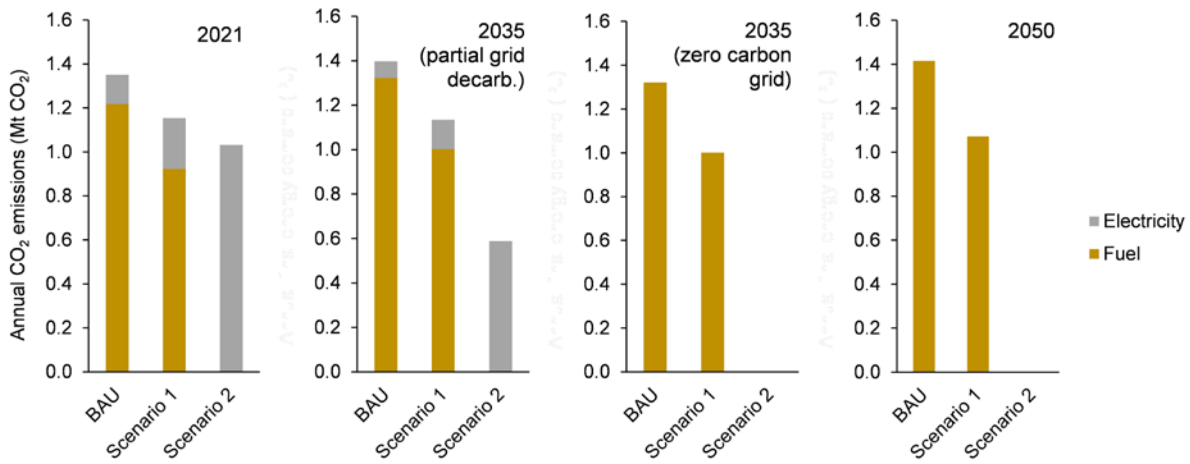

Figure 17. Annual CO_2 emissions from the U.S. canned vegetable industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 18 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. canned vegetable industry. The figure shows that the energy conservation costs range from 3 to 11 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 40 and 98 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S.

canned vegetable plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high marginal costs is the disparity between the electricity and fuel prices in the U.S. industry. The other major factor is the assumed heat source temperature that influences the costs to be high. Hence it is advised to explore waste heat sources at higher temperatures to minimize the temperature lifts and maximize the COPs.

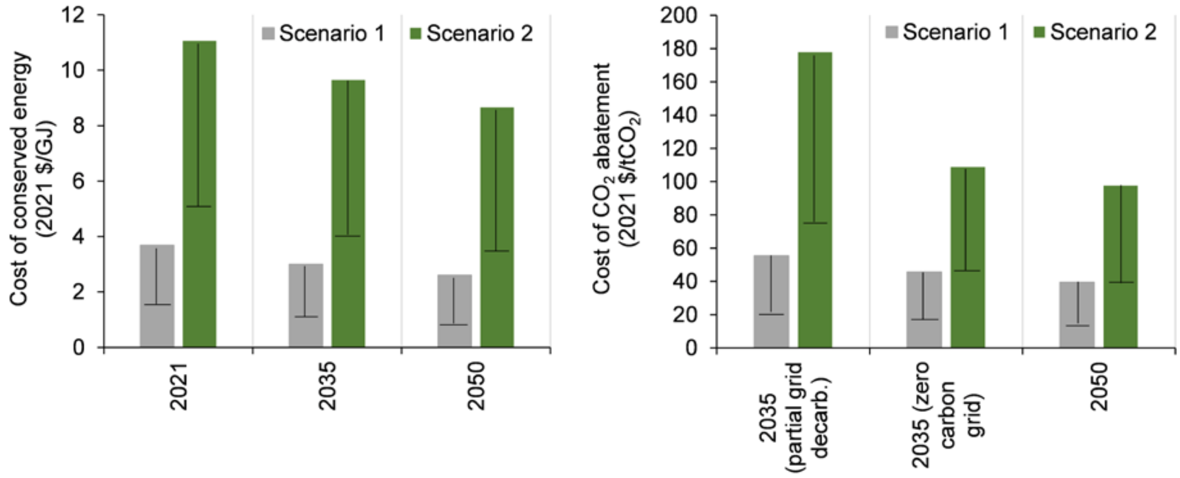

Figure 18. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. canned vegetable industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.4.2. Canned Fruits

IHP applications

Table 5 presents the typical specific final energy consumption of a canned fruit production facility and highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 19 presents the schematic of these IHP applications and their corresponding COPs. Since the production processes for canned vegetables and fruits are very similar, the potential HTHP applications are also very similar. The required heating capacity of HTHP for the U.S. canned fruit industry is estimated at 80 MW.

The SGHP application in Ambitious Scenario 2 is similar to that in the canned vegetable industry, however, since retort also requires steam at 120°C, one SGHP is sufficient to supply steam to all processes. The total required heating capacity of SGHP is estimated at 100 MW.

Table 5. Specific energy consumption of conventional and modified processes in the canned fruit industry.

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

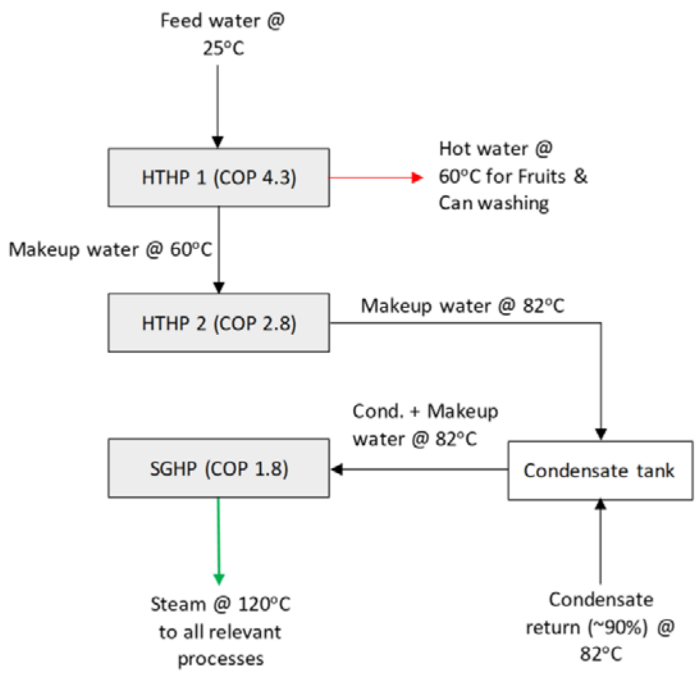

Figure 19. Industrial heat pump applications in the canned fruit industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 5. The change in annual final energy demand in the U.S. canned fruit industry in different IHP application scenarios and timeframes is presented in Figure 20. The figure shows that the measures suggested in Figure 19 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 2 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 3.5 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COP of the IHPs. More precisely, 2 and 5 PJ per year of fuel demand could be reduced while 0.4 and 1.6 PJ per year (or 0.1 and 0.4 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

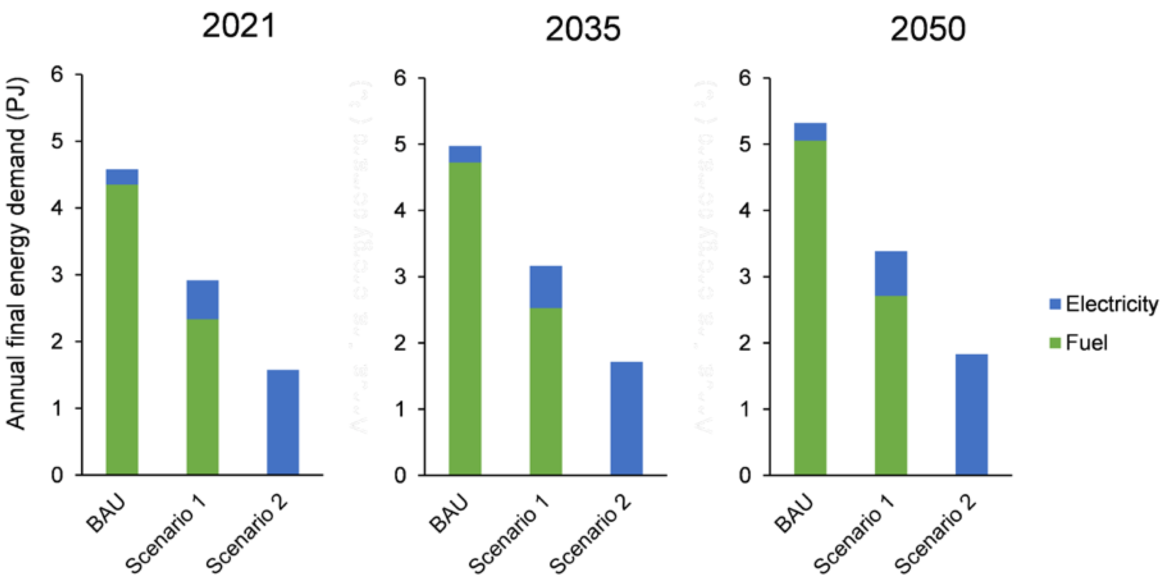

Figure 20. Annual final energy demand in the U.S. canned fruit industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. canned fruit industry in different IHP application scenarios and timeframes is presented in Figure 21. The figure shows up to 0.1 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.1 and 1.3 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

Figure 22 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. canned fruit industry. The figure shows that the energy conservation costs range from 3 to 9 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 45 and 86 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. canned fruit plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. The reasons for the high marginal costs are no different than in the canned vegetable processing industry. It is hence recommended to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

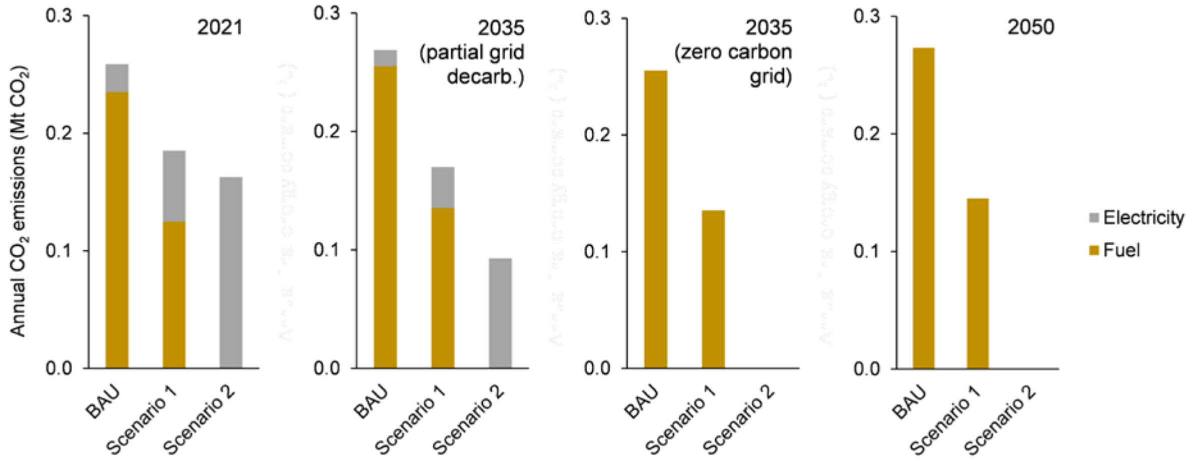

Figure 21. Annual CO_2 emissions from the U.S. canned fruit industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

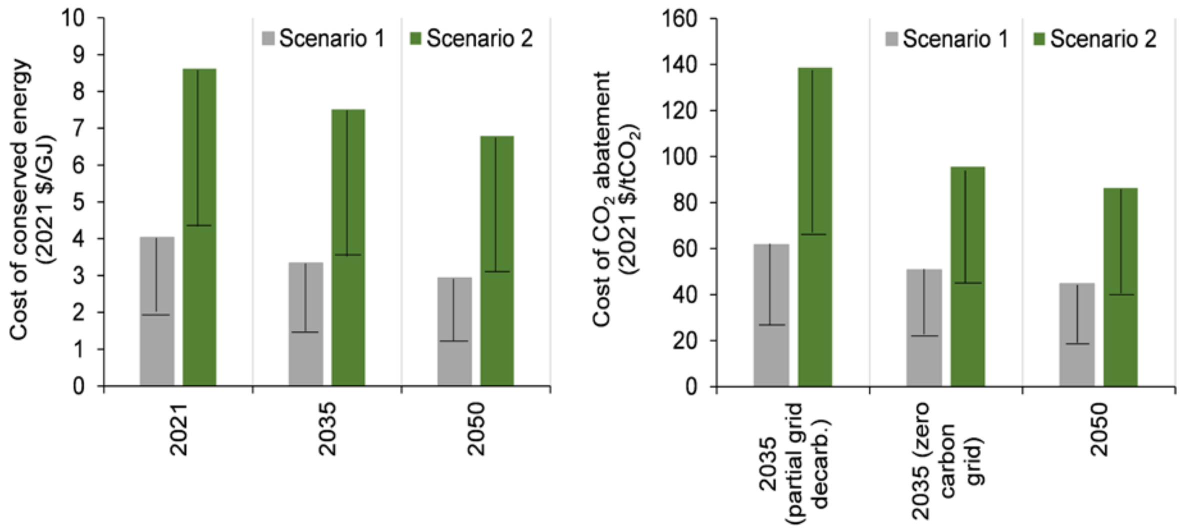

Figure 22. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. canned fruit industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.5 Cane Sugar Refining Industry

Production process

The cane sugar production plants in the U.S. manufactured around 3.6 Mt in 2021 (USDA ERS, 2022c). The production volume is estimated to reach 4.2 Mt in 2050. The cane sugar refining process is briefly described as follows. In the first step, a mingler is used to start transforming raw sugar extracted from sugarcane into a refined granulated product. Retention time and intense mixing are critical in this step. Raw sugar is blended with hot water (affination syrup) to loosen molasses. In the next step, sugar crystals are separated from the syrup in a centrifuge and washed with warm water. The sugar crystals are then directed to a melter where they are mixed with hot water. The mixture undergoes clarification where sludge is removed using steam followed by pressure filtration (U.S. EPA, n.d.).

Decolorization is done in the next step to remove soluble impurities by adsorption. Spent adsorbent (activated charcoal) is then removed from the bed, regenerated, cooled, and reused. The decolorized sugar solution is sent to multiple-effect evaporators to concentrate the juice, and then to the vacuum pans to crystallize the sugar. The sugar crystals are separated from the liquor and washed in the centrifuge. The sugar crystals are shredded to form soft (brown) sugar. The sugar solution from the centrifuge is sent to a granulator where it is dried using steam. In addition to white granulated sugar and brown sugar, liquid sugar is processed in the final step (Brown et al., 1996; U.S. EPA, n.d.)

Table 6 presents the typical specific final energy consumption of a cane sugar refining plant, disaggregated by direct and indirect fuel and electricity demand in each process step.

Table 6. Specific energy consumption of conventional and modified processes in the cane sugar refining industry.

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*	*°C*	*kWh/t*		*GJ/t*	*kWh/t*	*kWh/t*
	0.1	63	16.2	Mingler		513.7	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			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

IHP applications

Table 6 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 23 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a series of HTHP can be employed to provide hot water at temperatures ranging from 63°C to 90°C to process equipment including mingler, centrifuge, filter, and melter. The required heating capacity of HTHP for the U.S. cane sugar refining industry is estimated at 285 MW.

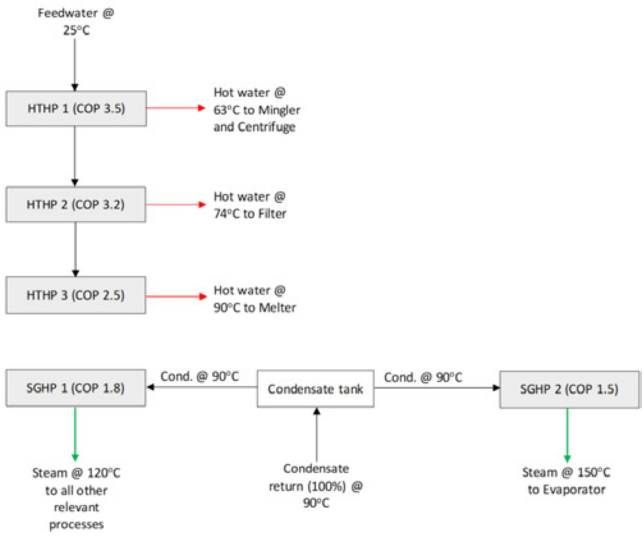

Figure 23. Industrial heat pump applications in cane sugar refining.

In Ambitious Scenario 2, two separate SGHP can be employed to generate process steam, one at 120°C for clarification, granulation, drying, and vacuum pans, and the second at 150°C for the evaporator. The required heating capacity of SGHP is estimated at 485 MW. Furthermore, the COPs of the SGHP are determined to be low mainly because the temperature lift is high, especially for delivering steam at 150°C. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic shown in Figure 23 may not be the ideal solution for a specific cane sugar refining plant for reasons explained in Sections 3 and 4.1.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 6. The change in annual final energy demand in the U.S. cane sugar industry in different IHP application scenarios and timeframes is presented in Figure 24. The figure shows that the measures suggested in Figure 23 can significantly reduce the sector's total final energy demand. It is estimated that approximately 6 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 15 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 8 and 23 PJ per year of fuel demand could be reduced while 2 and 8 PJ per year (or 0.5 and 2.2 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

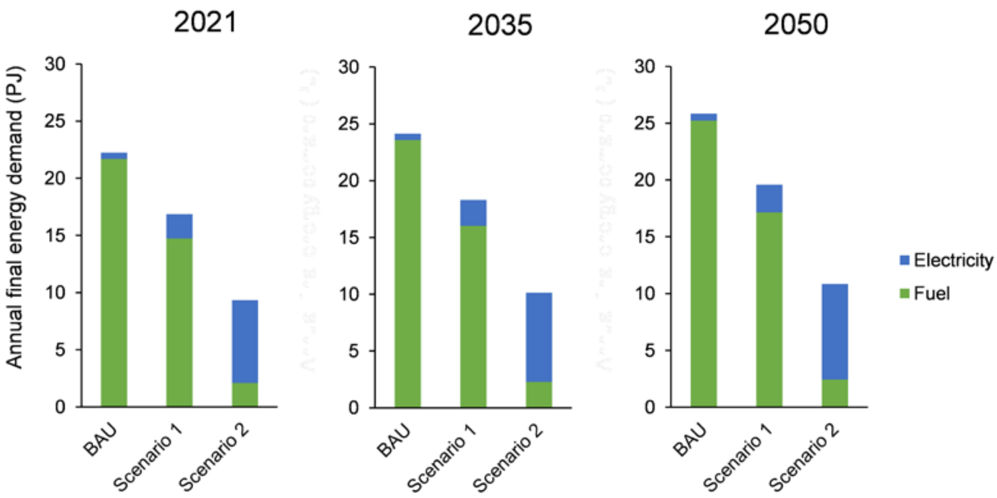

Figure 24. Annual final energy demand in the U.S. cane sugar refining industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

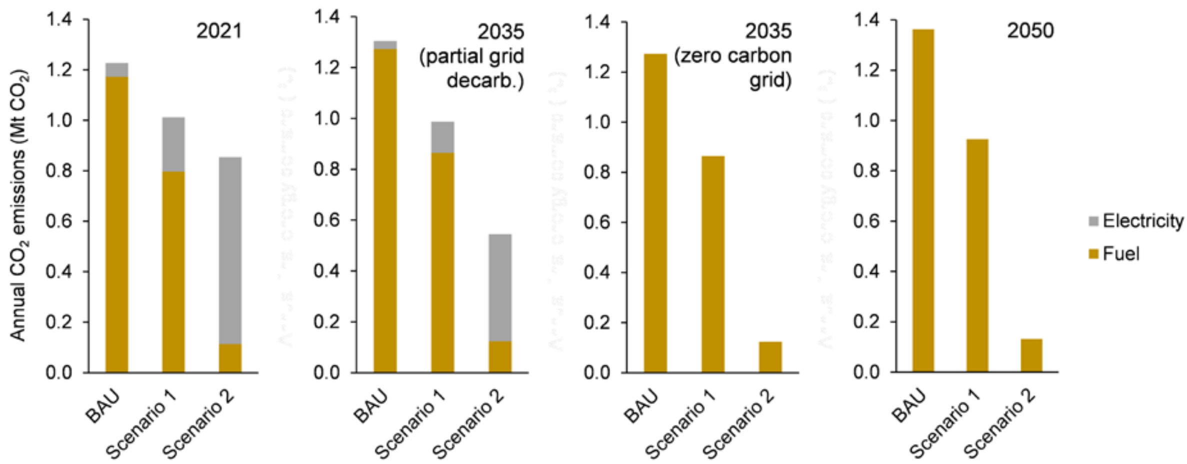

Figure 25. Annual CO_2 emissions from the U.S. cane sugar industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

The change in annual CO_2 emissions in the U.S. cane sugar refining industry in different IHP application scenarios and timeframes is presented in Figure 25. The figure shows up to 0.4 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.4 and 1.2 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emissions factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

Figure 26 presents the specific costs of conserved energy and CO_2 abatement for IHP applications in the U.S. cane sugar refining industry. The figure shows that the energy conservation costs range from 3 to 8 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 38 and 69 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. cane sugar refining facilities incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. The disparity between the average industrial electricity and fuel prices in the U.S. is the major reason for the high marginal costs. The assumed heat source temperature is another factor impacting the costs. Hence suitable waste heat sources at higher temperatures must be explored to minimize the temperature lifts that ultimately also minimize the electricity costs.

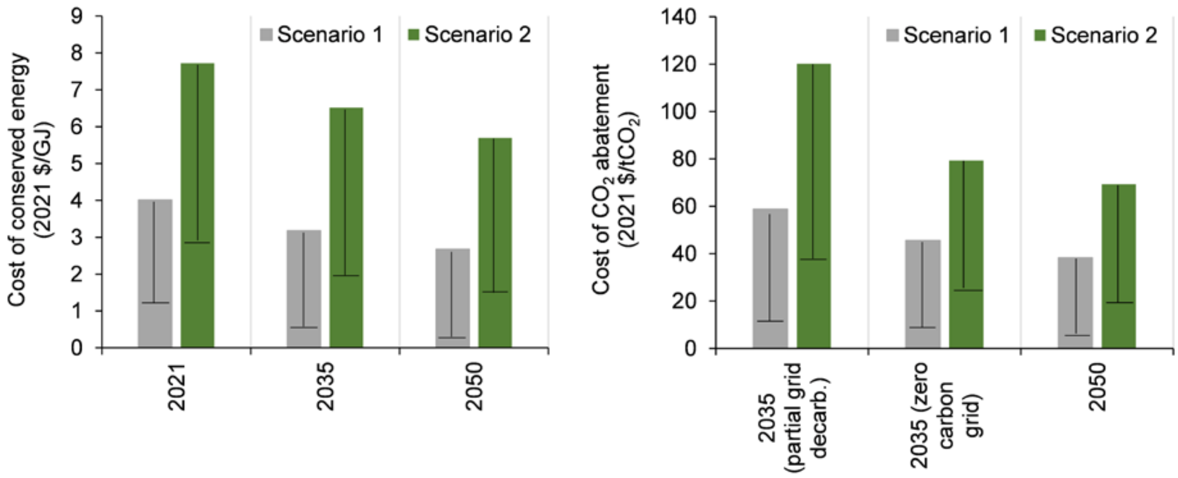

Figure 26. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. cane sugar refining industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.6 Beet Sugar Industry

Production process

The U.S. beet sugar plants manufactured approximately 33 Mt of sugar in 2021 (USDA ERS, 2022c). The production volume is estimated to grow to 38 Mt in 2050. The beet sugar production process is briefly described as follows. The production process starts with the washing and slicing of sugar beet into thin slices called cossettes. In the second step, cossettes are exposed to hot water in a diffuser for the extraction of sucrose in the form of the resulting diffusion juice (Hasanbeigi et al., 2021). The residual pulp is compressed, dried, and processed as animal feed. Milk of lime is used to chemically react with different soluble non-sugars in the juice. The juice is then directed to carbonation tanks where it is carbonated to form a calcium carbonate precipitate, allowing filtration of the impurities (U.S. EPA, n.d.).

In the next step, the resulting purified juice is sent to the evaporation section. The major steam requirements in the diffuser and purification sections are for heating the juice. The evaporation process in a multiple-effect evaporator reduces the water content in the juice, consequently increasing the sugar content of the juice and producing syrup. Evaporation is responsible for more than half of the steam demand in the entire production process. The syrup feeds the sugar end, where sucrose is crystallized to obtain granulated refined sugar and molasses. The granulated sugar is separated and dried in the final step (Brown et al., 1996; U.S. EPA, n.d.)

Table 7 presents the typical specific final energy consumption of a beet sugar plant, disaggregated by direct and indirect fuel and electricity demand in each process step.

Table 7. Specific energy consumption of conventional and modified processes in the beet sugar industry.

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		242.2	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		
			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

IHP applications

Table 7 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 27 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to heat process water to 60°C for diffusion. The same heat pump is also supposed to preheat the makeup feed water to 60°C. Since the steam condensate returns from the process at around 82°C, the mixing of makeup water and return condensate at different temperatures is not appropriate from an exergy point of view. Hence the makeup water may be further heated from 60°C to 82°C using another HTHP before it enters the condensate tank for steam generation. The required heating capacity of HTHP for the U.S. beet sugar industry is estimated at 235 MW.

In Ambitious Scenario 2, two separate SGHP can be employed to generate process steam, one at 120°C for the diffuser, juice heaters, evaporators, and dryers, and the second at 138°C for the vacuum pans. The required heating capacity of SGHP is estimated at 2.7 GW. Furthermore, the COPs of the SGHP are determined to be low mainly because the temperature lift is high especially for delivering steam at 138°C. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic presented in Figure 27 may not be the ideal configuration for a specific beet sugar manufacturing plant for reasons explained in Sections 3 and 4.1.

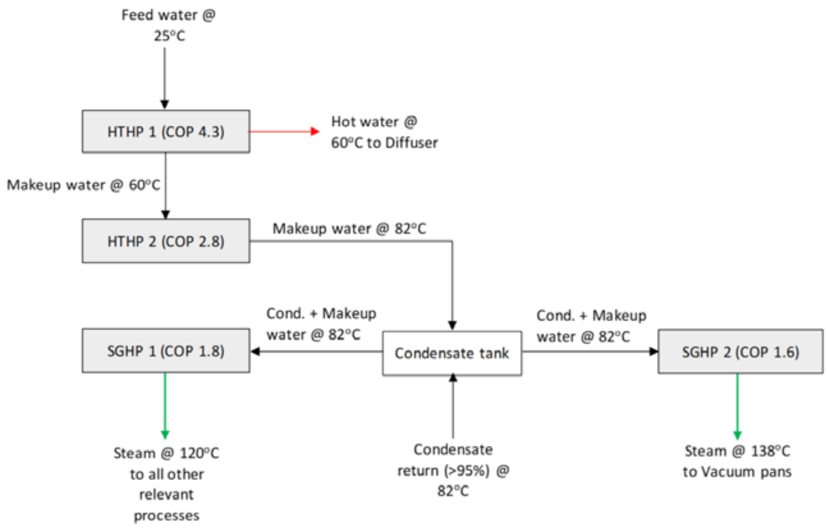

Figure 27. Industrial heat pump applications in the beet sugar industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 7. The change in annual final energy demand in the U.S. beet sugar industry in different IHP application scenarios and timeframes is presented in Figure 28. The figure shows that the measures suggested in Figure 27 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 5 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 51 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 7 PJ and 84 PJ per year of fuel demand could be reduced while 1.2 PJ and 33 PJ per year (or 0.3 and 9.2 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

The change in annual CO_2 emissions in the U.S. beet sugar industry in different IHP application scenarios and timeframes is presented in Figure 29. The figure shows up to 1 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.4 and 4.6 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050, respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

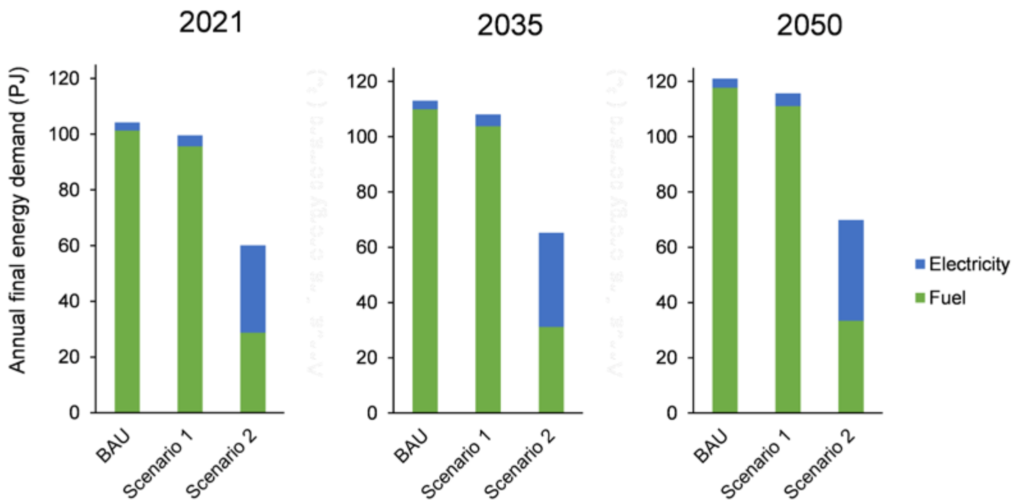

Figure 28. Annual final energy demand in the U.S. beet sugar industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

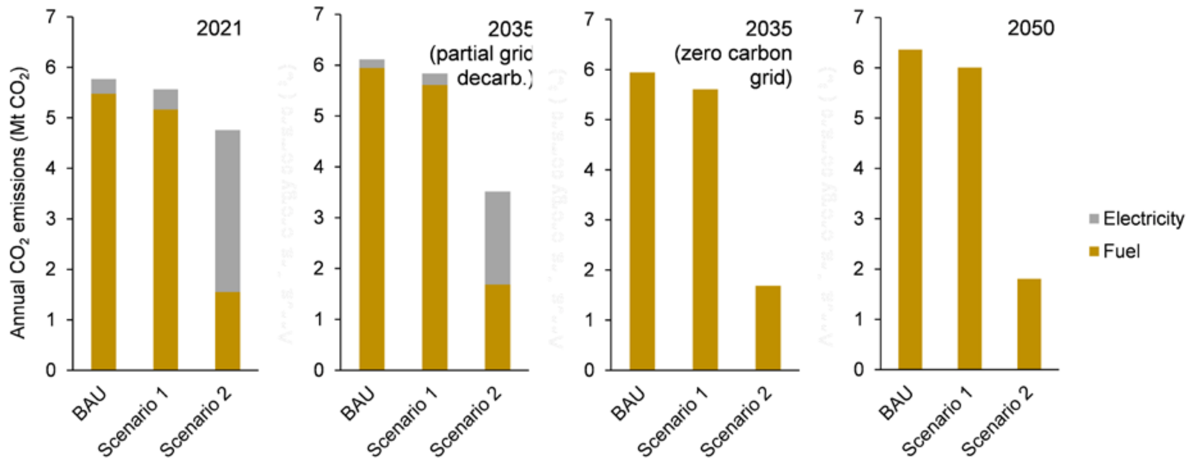

Figure 29. Annual CO_2 emissions from the U.S. beet sugar industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 30 presents the costs of conserved energy and CO_2 abatement cost for IHP applications in the U.S. beet sugar industry. The figure shows that the energy conservation costs range from 2 to 10 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 22 and 84 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. beet sugar plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. Likewise earlier discussion, the major reason for the high marginal costs is the large difference between U.S. industrial electricity and fuel prices. The heat source temperature assumed at 25°C is another factor influencing the costs to be high. It is therefore recommended to find and utilize suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

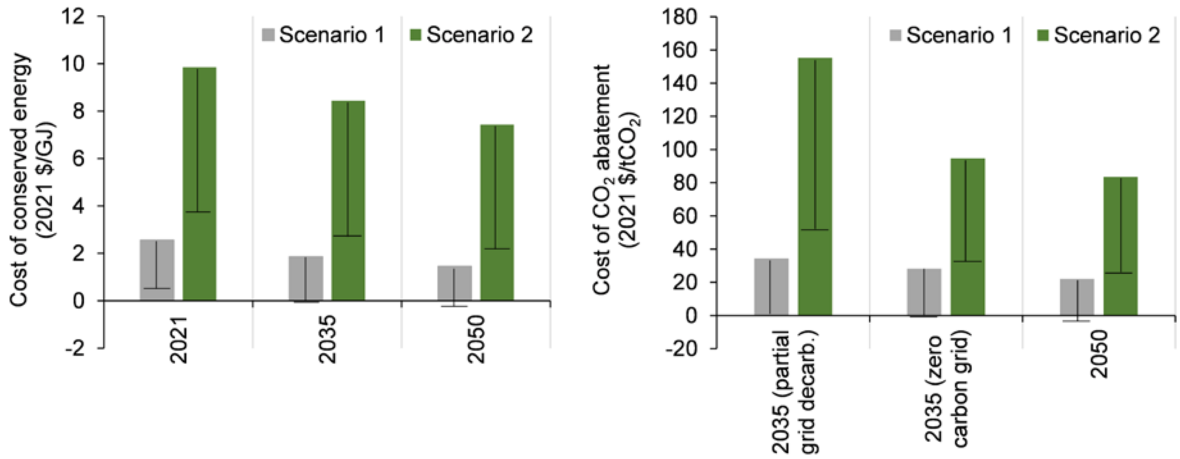

Figure 30. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. beet sugar industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.7 Corn Wet-milling Industry

Production process

The U.S. corn wet mills processed a total of around 26 Mt of corn input in 2021 (USDA ERS, 2022c). The processing is estimated to grow to 30 Mt in 2050. The corn wet-milling process is briefly described as follows. In the first step, corn is removed from the cobs and cleared of all foreign materials. The corn kernels then undergo steeping, where they are soaked in large tanks in mildly acidic warm water normally for 20-36 hours. During steeping, the kernels absorb water, gluten bonds are loosened and starch is released followed by coarse grinding to release the germ from the kernels. To maximize efficiency, steep water is evaporated using steam in multiple effect evaporators. In the degermination process, the germ is separated from the other components since it contains most of the oil present in the corn kernel. The germ is dewatered using a screw press requiring electricity. The resultant consists of 50-60% water content. To achieve a moister content of 2-4%, rotary steam driers are used to dry the germ. After germ drying, corn oil is extracted through a combination of mechanical and chemical processes. In the next step, all impurities are removed from the extracted oil in a series of steps, and the oil is prepared for the market (Galitsky et al., 2003; Hasanbeigi et al., 2021).

The corn-water slurry after oil extraction undergoes fine grinding and screening to separate all starch and gluten from the fiber. The fiber is also washed with water to recover starch and gluten as much as possible. The fiber is dewatered in a centrifuge, dried, and prepared as animal feed while a filtering system or set of hydro-cyclones is used to separate the starch from the gluten. For the starch to be sold directly (instead of being converted into syrups and/or ethanol), the starch is completely dried to powder using steam. Part of the starch can also be physically modified to produce a range of products with varying functionality, such as dextrin. Dextrin is made from the starch that is roasted and then hydrolyzed by amylase (an enzyme that digests starch taken in as food) (Galitsky et al., 2003; U.S. EPA, n.d.).

The starch that is not dried undergoes saccharification to convert the solution to sugar syrups. The syrups are further refined to make a variety of final products, including high fructose corn syrup (HFCS). Evaporation is a key step in syrup refining and consumes a significant amount of energy (mainly steam). The liquor after refining is transferred to crystallizing vessels where it is held for days. After about 60 percent of the dextrose is crystallized, they are separated from the liquid by centrifuges, dried, and packaged (Brown and Hamel, 1996; Galitsky et al., 2003; U.S. EPA, n.d.)

Table 8 presents the specific final energy consumption of a typical corn wet-milling facility, disaggregated by direct and indirect fuel and electricity demand in each process step.

Table 8. Specific energy consumption of conventional and modified processes in the corn wet-milling industry.

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		577.2	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		
			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

IHP applications

Table 8 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 31 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to preheat the makeup feed water to 82°C. The required heating capacity of HTHP for the U.S. corn wet-milling industry is estimated at 60 MW.

In Ambitious Scenario 2, two separate SGHP can be employed to generate process steam, one at 107°C for steeping, and the second at 120°C for the evaporators, dryers, oil extractors, refiners, and starch conversion. The required heating capacity of SGHP is estimated at 5.7 GW. Furthermore, the COPs of the SGHP are determined to be low, mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation.

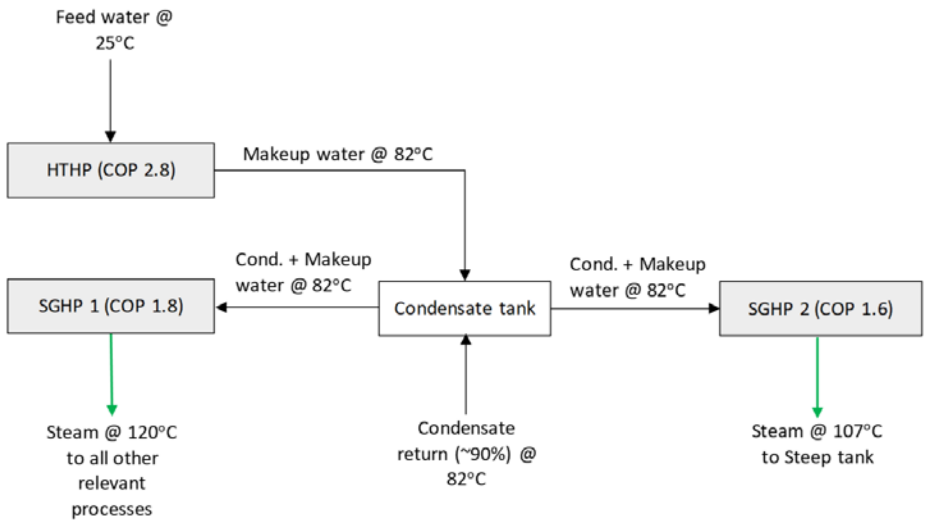

Figure 31. Industrial heat pump applications in the corn wet-milling industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 8. The change in annual final energy demand in the U.S. corn wet-milling industry in different IHP application scenarios and timeframes is presented in Figure 32. The figure shows that the measures suggested in Figure 31 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 1.1 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 75 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 2 and 138 PJ per year of fuel demand could be reduced while 0.4 and 63 PJ per year (or 0.1 and 17.6 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

The change in annual CO_2 emissions in the U.S. wet corn-milling industry in different IHP application scenarios and timeframes is presented in Figure 33. The figure shows up to 0.9 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.1 and 7.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

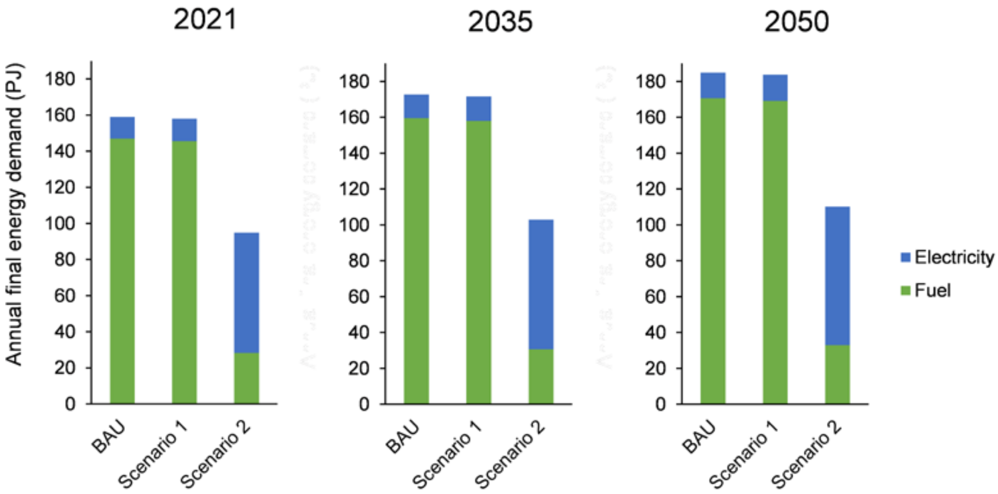

Figure 32. Annual final energy demand in the U.S. corn wet-milling industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

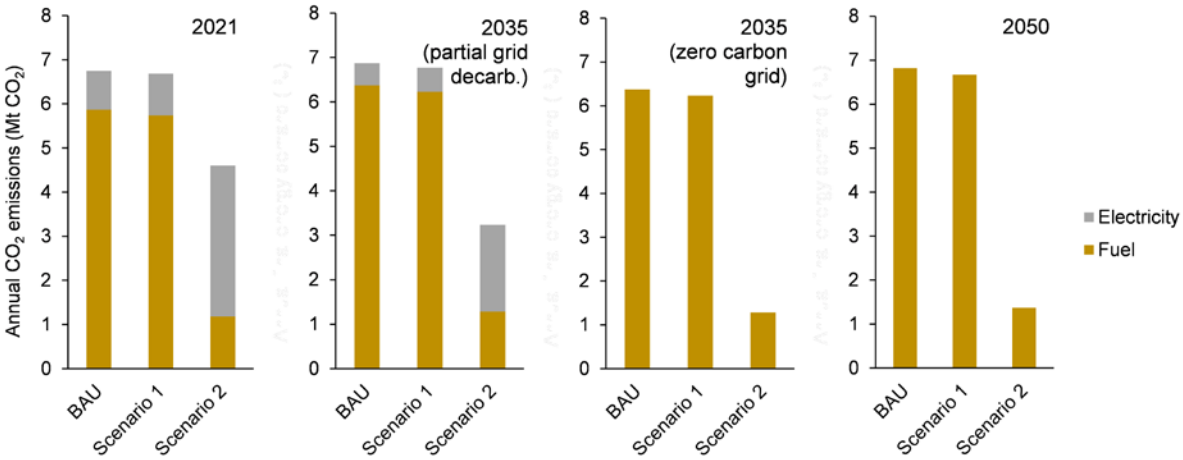

Figure 33. Annual CO_2 emissions from the U.S. corn wet-milling industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 34 presents the specific costs of conserved energy and CO_2 abatement cost for IHP applications in the U.S. corn wet-milling industry. The figure shows that the energy conservation costs range from 5 to 14 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 69 and 112 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. corn wet-milling plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high marginal costs is the large disparity between the electricity and fuel prices in the U.S. industry. The assumed heat source temperature is another factor impacting the costs to be high (see earlier discussion). Thus, it is advised to explore plant-specific waste heat sources at higher temperatures to minimize the temperature lifts and the electricity costs.

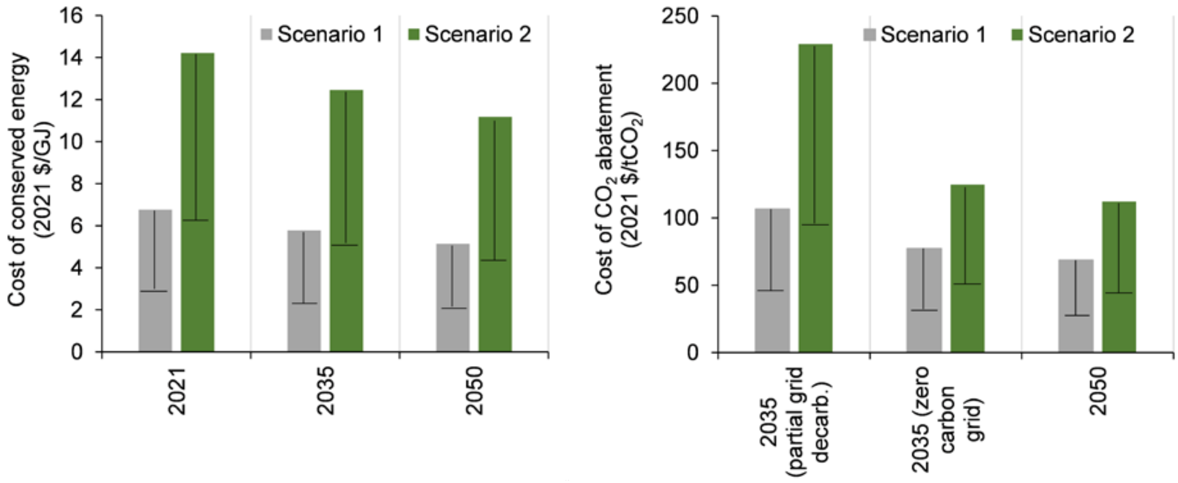

Figure 34. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. corn wet-milling industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.8 Soybean Oil Industry

Production process

The U.S. soybean oil plants manufactured approximately 12 Mt of oil in 2021 (USDA ERS, n.d.). The production volume is estimated to grow to 14 Mt in 2050. The soybean oil production process is briefly described as follows. The first step is the cleaning of the soybeans on a screen to remove foreign materials such as stems, pods, sand, dirt, etc. The beans are then dried to reduce their moisture content to approximately 10-11% by weight. Cracking mills break soybeans into smaller pieces followed by mechanical separation of the hulls. The cracked beans are then put into a rotary steam tube or a stacked cooker and heated using steam to make them pliable and keep them hydrated (also referred to as conditioning). The heated cracked beans are later fed to smooth cylindrical rolls that press them into smooth flakes. The flaking process exposes the soybean oil cells and facilitates oil extraction (U.S. EPA, n.d.).

In the next step, soybean flakes are directed to an oil extractor, where they are first washed counter currently with various hexane/oil mixtures and then with pure hexane. In the desolventizer, hexane solvent is evaporated using steam. The solvent is condensed, separated from the steam condensate, and reused. The desolventized flakes then pass a steam dryer to remove extra moisture followed by grinding and cooling for use as animal feed. Crude soybean oil from the extractor contains a small amount of naturally occurring substances including proteinaceous materials, free fatty acids, and phosphatides which are removed to produce refined oil. Volatile substances which may cause undesirable flavors and odors are removed in a stripper, which employs the use of steam injection under a high vacuum and temperature. The refined oil is then filtered and stored until transported (U.S. EPA, n.d.).

Table 9 presents the typical specific final energy consumption of a soybean oil production plant, disaggregated by direct and indirect fuel and electricity demand in each process step.

Table 9. Specific energy consumption of conventional and modified processes in the soybean oil industry.

Conventional process				Process steps	Modified process with IHP		
Direct fuel use	Fuel use in boilers	Steam 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
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

IHP applications

Table 9 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 35 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to preheat the makeup feed water to 82°C. The required heating capacity of HTHPs for the U.S. soybean oil industry is estimated at 105 MW.

In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for the conditioner, desolventizer, and evaporator. For meal drying and vacuum stripping, the required steam temperature is higher (i.e. 177°C) than the current state of the art, hence not considered. The required heating capacity of the SGHP is estimated at 2520 MW. Furthermore, the COP of the SGHP is determined to be low i.e. 1.8, mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation.

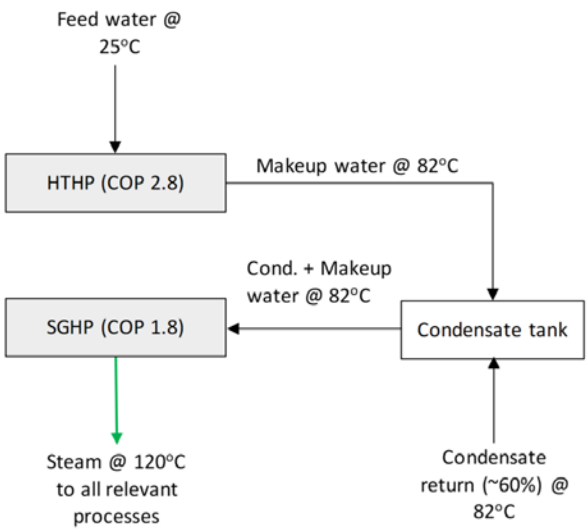

Figure 35. Industrial heat pump applications in the soybean oil industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 9. The change in annual final energy demand in the U.S. soybean oil industry in different IHP application scenarios and timeframes is presented in Figure 36. The figure shows that the measures suggested in Figure 35 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 2 PJ per year of final energy can be saved if only the HTHP application (Scenario 1) is realized in 2050. However, the technical potential increases to nearly 37 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 3 and 66 PJ per year of fuel demand could be reduced while 0.8 and 29 PJ per year (or 0.2 and 8 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

The change in annual CO_2 emissions in the U.S. soybean oil industry in different IHP application scenarios and timeframes is presented in Figure 37. The figure shows up to 2 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.2 and 5.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

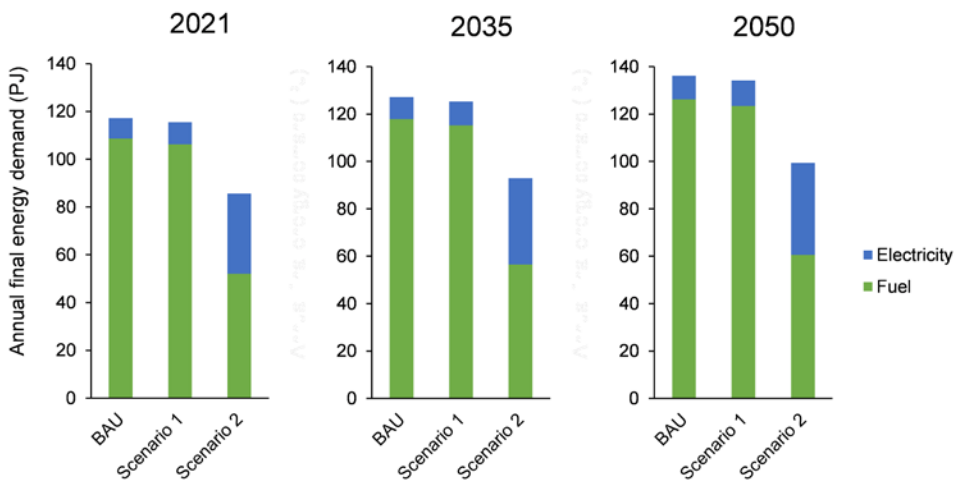

Figure 36. Annual final energy demand in the U.S. soybean oil industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

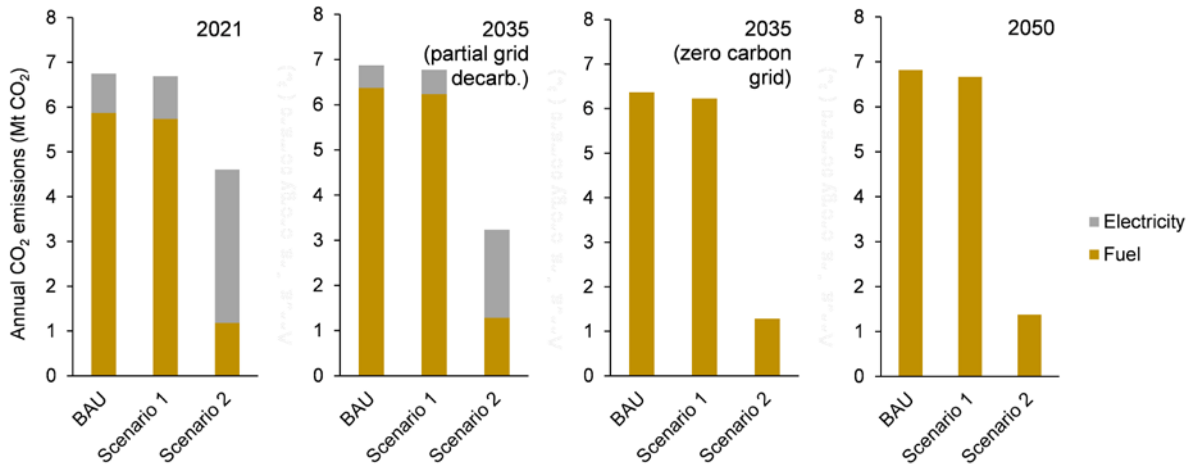

Figure 37. Annual CO_2 emissions from the U.S. soybean oil industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 38 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. soybean oil industry. The figure shows that the energy conservation costs range from 5 to 13 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at 72 and 69 $/t CO_2 in Scenarios 1 and 2 respectively. It is evident that IHP integration in U.S. soybean oil plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high specific costs is the disparity between the electricity and fuel prices in the U.S. industry. The assumed heat source temperature is another factor influencing the costs to be high (see earlier discussion). It is therefore advised to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

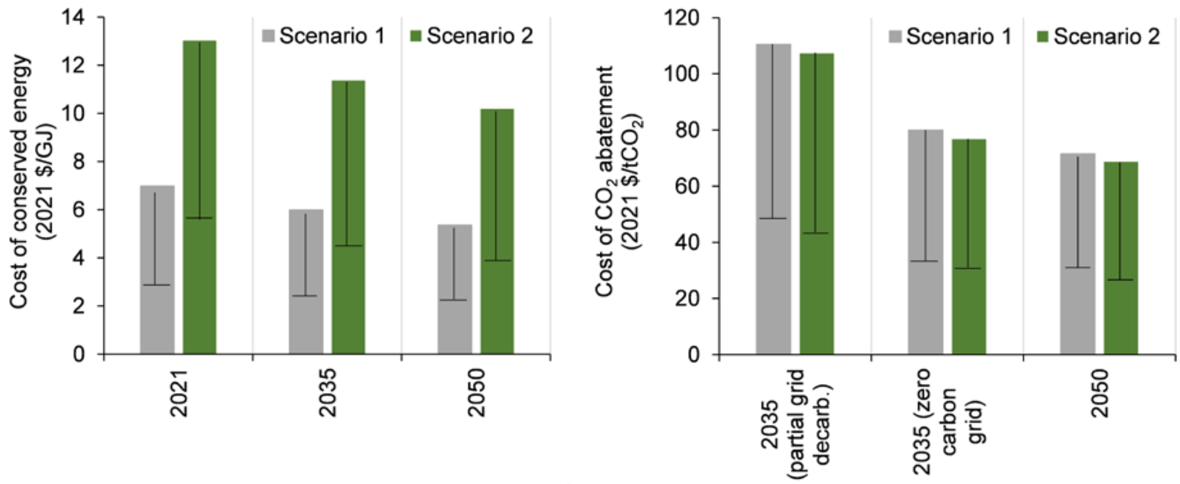

Figure 38. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. soybean oil industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.9 Textile industry

Production process

The U.S. woven fabric mills weaved roughly 0.5 Mt of grey goods in 2021 (estimated based on Groz-Beckert, 2017). Almost half of these woven fabrics (i.e. 0.25 Mt) are assumed to be made of synthetic fibers which undergo finishing (or wet-processing) in different U.S. textile mills. The production volume of finished synthetic goods is estimated to grow to 0.3 Mt in 2050. The textile weaving and finishing processes are briefly described as follows. In the first step, spinning is done using machines with bobbins that have been wound with fiber or spinning material called roving. The machine winds the roving around a bobbin and pulls it between two rollers that turn at different speeds to make yarn. The yarn is used as input for warping. Warping combines yarns from different cones together to form a sheet of yarns. The process also preserves the yarn elongation and maintains it at a uniform level to ensure better performance during weaving in terms of low-end breakage rate. Moreover, the short protruding hairs on the yarn may entangle during weaving. Hence it is made flat by adding starch to the surface of the yarn in a process called sizing (or slashing) followed by drying using steam rollers. This step makes the yarn smoother and stronger. In the weaving process, two yarns of similar materials are interlaced at right angles to manufacture grey woven fabrics (Brown et al., 1996; Hasanbeigi, 2010).

Textile wet-processing involves different unit operations most of which require steam for process heat supply. Singeing is a pre-treatment process to remove loosened, hairy, and projecting fiber by burnout. In desizing, starch and sizing compounds are removed that were applied to yarns to ensure tensile strength. In scouring, natural impurities such as non-cellulose materials, oil, fat, and wax are removed. Mercerizing is an additional treatment to increase the strength and luster of the materials and is only performed when the end consumer requires it. The bleaching process reduces the natural color of raw materials. Dyeing is the process of applying different colors to white or grey fabrics and its performance depends on the bleaching process. Printing gives a special appearance on colored or white fabrics. After dyeing and/or printing, woven fabrics are heated (curing) in large ovens to dry and set the dyes. Fabrics are further stretched onto a moving frame (Brown et al., 1996; Hasanbeigi, 2010).The two subsections below discuss the IHP applications in textile spinning and weaving and wet-processing industries.

4.9.1. Textile Spinning and Weaving

IHP applications

Table 10 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 39 presents the schematic of these IHP applications and their corresponding COPs. There is no HTHP application identified for weaving. Only steam is required in steam rollers for sizing and drying. The steam condensate can be recovered in its entirety requiring no makeup water preheating. Hence conservative scenario is not developed. In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for drying. The required heating capacity of SGHP is estimated at 150 MW. Furthermore, the COP of the SGHP is determined to be low i.e. 1.8, mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation.

Table 10. Specific energy consumption of conventional and modified processes in the textile spinning and weaving industry.

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

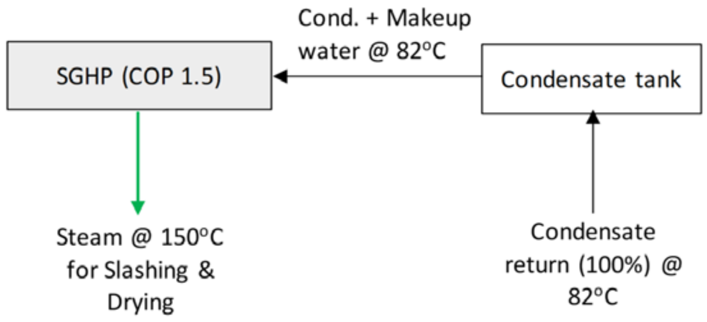

Figure 39. Industrial heat pump applications in the textile spinning and weaving industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 10. The change in annual final energy demand in the U.S. textile weaving industry in different IHP application scenarios and timeframes is presented in Figure 40. The figure shows that the measure suggested in Figure 39 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. There is no HTHP application identified for weaving (as described in the previous section), however, it is estimated that approximately 1.5 PJ per year of final energy can be saved if the conventional boilers are replaced with SGHP (Scenario 2) in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 3.1 PJ per year of fuel demand could be reduced while 1.6 PJ per year (or 0.4 TWh per year) of electricity demand would be increased in Scenario 2 in 2050 respectively.

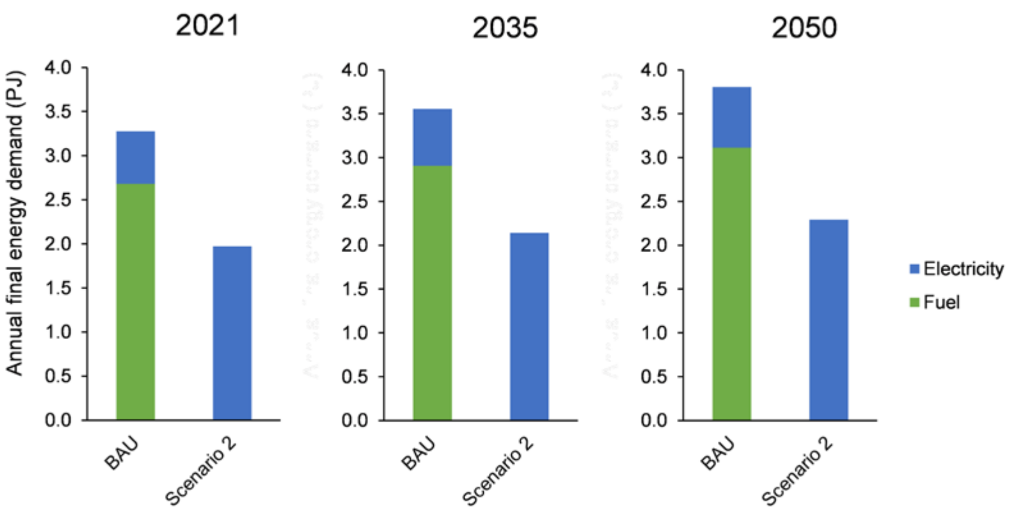

Figure 40. Annual final energy demand in the U.S. textile spinning and weaving industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP applications while Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. weaving plants in different IHP application scenarios and timeframes is presented in Figure 41. The figure shows negligible potential for CO_2 abatement in 2021 as a result of the 100% adoption rate of SGHP in the sector. However, it is estimated that approximately 0.16 and 0.17 Mt per year of CO_2 emissions can be avoided in the second scenario in 2035 and 2050, respectively. The annual CO_2 emissions in 2035 and 2050 under Scenario 2 are zero because of the 100% adoption of SGHP and the zero-carbon grid assumed in 2035 and 2050.

According to Figure 42, the specific costs of conserved energy and CO_2 abatement due to deploying SGHP are estimated at 18 $/GJ and 161 $/t CO_2 per year respectively in 2050. Likewise, in several other sectors, the associated costs of SGHP installations in U.S. weaving plants do not fall below zero which would have otherwise represented cost savings. Apart from the disparity between the electricity and fuel prices in the U.S. industry, the assumed heat source temperature is a major factor influencing the costs to be on a higher side (see earlier discussion). It is therefore recommended to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

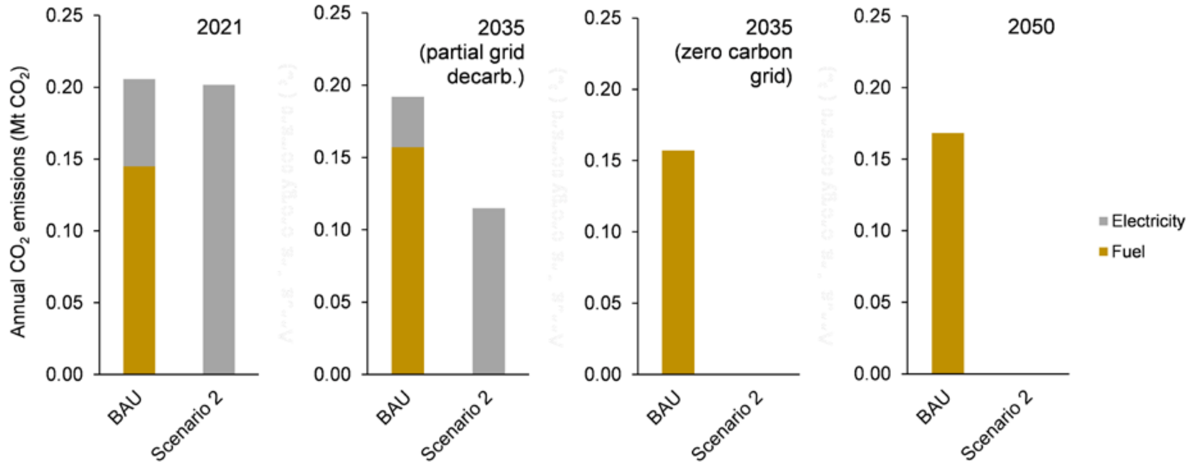

Figure 41. Annual CO_2 emissions from the U.S. textile spinning and weaving industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

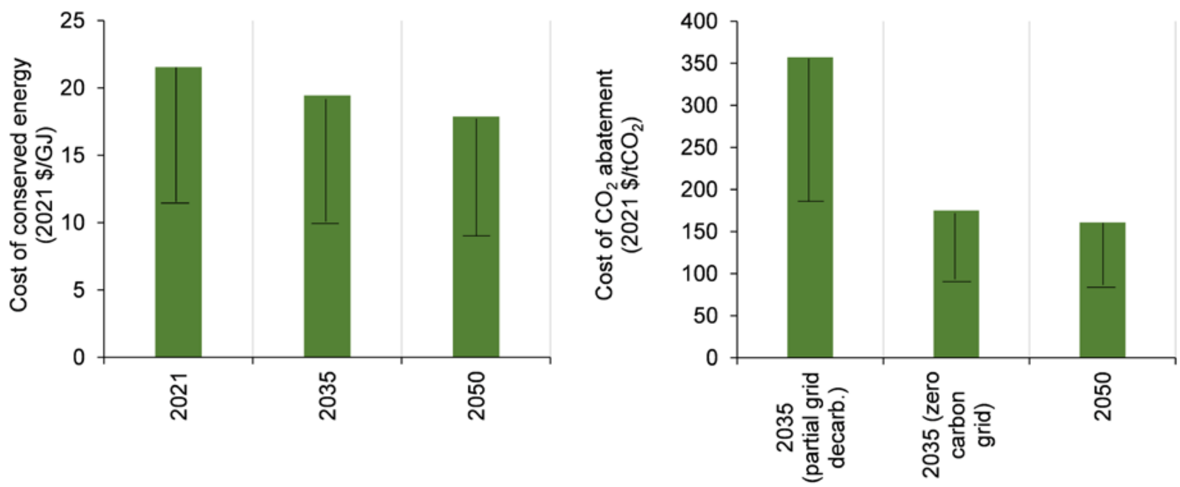

Figure 42. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. textile spinning and weaving industry under Scenario 2.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

4.9.2. Textile Wet-Processing

IHP applications

Table 11 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 43 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, a HTHP can be employed to preheat the makeup feed water to 82°C before it enters the condensate tank for steam generation. The required heating capacity of HTHP for the U.S. textile wet-processing industry is estimated at 12 MW. In a real-life example, a HTHP with a heating capacity of 137 kW and COP of 5.1 was installed in a German textile plant producing dyed fabrics. The system uses waste heat at 30-40°C from the dyeing machine exhaust to produce hot water for space heating at 50°C (IEA, 2020).

Table 11. Specific energy consumption of conventional and modified processes in textile wet-processing.

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	3285.5	
	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			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

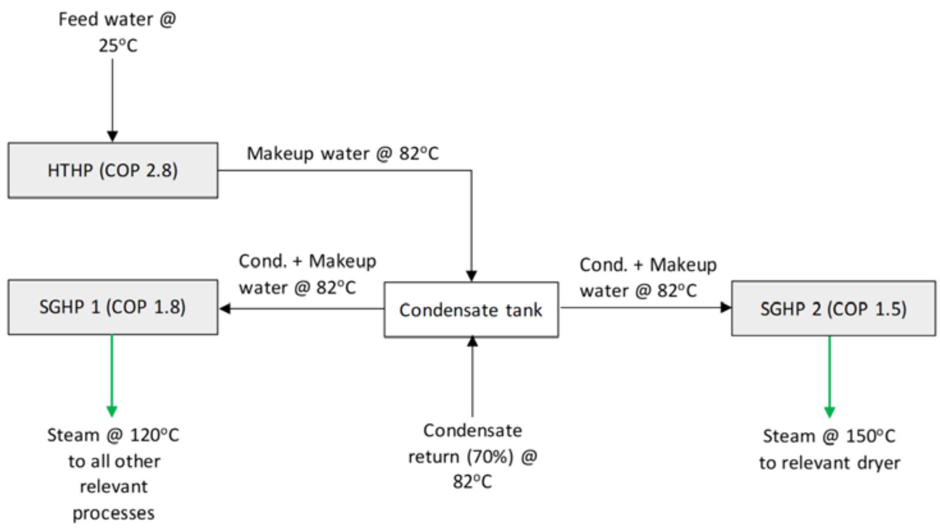

Figure 43. Industrial heat pump applications in the textile wet-processing industry.

It must be noted that most of the processes in Table 11 need hot water at different temperatures which can ideally be supplied directly by HTHP. However, textile plant equipment often has different water retention rates. For example, a washing machine may have 4-5 different compartments requiring hot water at different temperatures in different timeframes. This will require multiple small-scale HTHP only for one-unit operation, hence it is not feasible. Therefore, the process heat to all these processes is supplied in the form of steam which can be generated by SGHP.

In Ambitious Scenario 2, two separate SGHP can be employed to generate process steam, one at 120°C for desizing, scouring, mercerizing, bleaching, washing, and dyeing, and the second at 150°C for drying. The total required heating capacity of SGHP is estimated at 375 MW. Furthermore, the COPs of the SGHP are determined to be low mainly because the temperature lift is high especially for delivering steam at 150°C. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic shown in Figure 43 may not be the ideal configuration for a specific textile wet-processing plant for reasons explained in Sections 3 and 4.1.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (using IHPs) processes is also presented in Table 11. The change in annual final energy demand in the U.S. synthetic textile wet-processing industry in different IHP application scenarios and timeframes is presented in Figure 44. The figure shows that the measures suggested in Figure 43 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 0.2 PJ per year of final energy can be saved if only HTHP applications (Scenario 1) are realized in 2050. However, the technical potential increases to nearly 5 PJ per year if both the HTHP and SGHP applications (Scenario 2) are adopted in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 0.3 and 10 PJ per year of fuel demand could be reduced while 0.1 and 5.2 PJ per year (or 0.03 and 1.4 TWh per year) of electricity demand would be increased in Scenarios 1 and 2 in 2050 respectively.

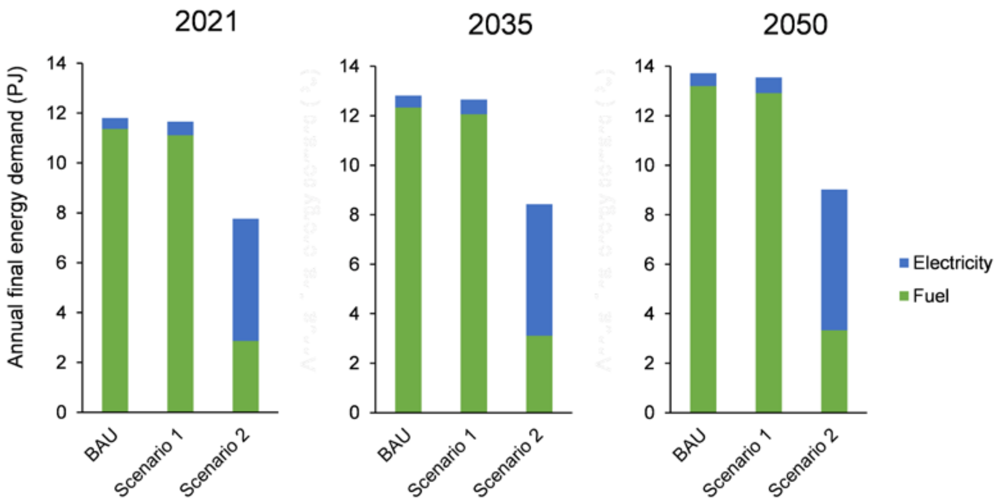

Figure 44. Annual final energy demand in the U.S. textile wet-processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. textile wet-processing industry in different IHP application scenarios and timeframes is presented in Figure 45. The figure demonstrates up to 0.07 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 0.01 and 0.4 Mt per year of CO_2 emissions can be avoided in Scenarios 1 and 2 in 2050 respectively. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

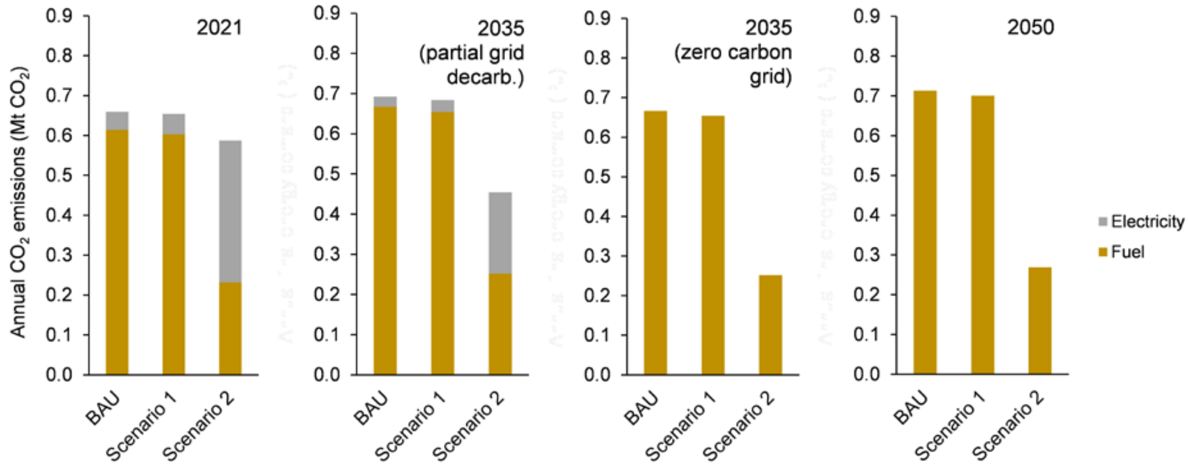

Figure 45. Annual CO_2 emissions from the U.S. textile wet-processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 46 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. synthetic textile wet-processing industry. The figure shows that the energy conservation costs range from 10 to 16 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs in 2050 are estimated at around 135 $/t CO_2 in both the IHP application scenarios.

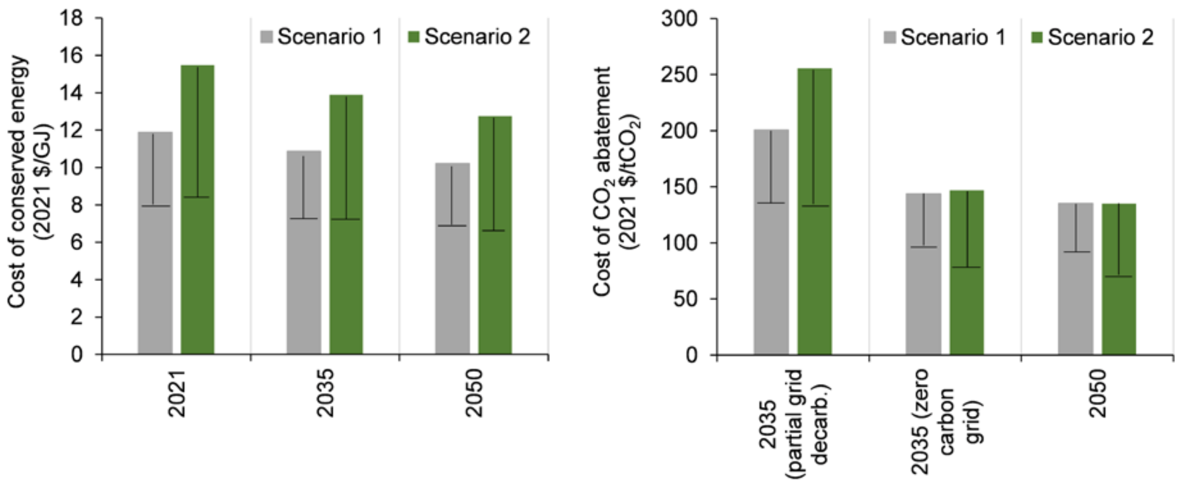

Figure 46. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. textile wet-processing industry.
Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

It is evident that IHP integration in U.S. textile wet-processing plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. One of the major reasons for the high marginal costs is the disparity between the electricity and fuel prices in the U.S. industry. The assumed heat source temperature is another factor influencing the costs to be high (see earlier discussion). It is therefore recommended to explore and utilize suitable waste heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

4.10 Pulp and Paper industry

Production process

The U.S. paper mills produced around 26 Mt in 2021 (estimated based on Statistica, 2022). The production volume is estimated to grow to 30 Mt in 2050. The paper production process is briefly described as follows. In an integrated pulp and paper mill, wood is received at a pulp mill often in the form of short logs or bolts of round wood with the bark still attached to them. The round wood is first debarked and then chipped if the pulping process requires chemical digestion. The bark is shredded and discarded while the chips are screened, cleaned, and stored for further processing. In Kraft chemical pulping, chips are sent to a large pressure vessel or digester where other chemicals are added. The chips are digested with steam to separate fibers and partially dissolve the lignin and other extractives. The resulting pulp mix is first filtered to remove large shives, knots, dirt, and other debris and then washed in multiple stages (Pulp and Paper Technology, 2022).

Black liquor is the by-product of the Kraft process and is concentrated in a multiple-effect evaporator using steam. After this step, the black liquor has about 20–30% solids. The black liquor is further evaporated to 65-80% solids and burned in a recovery furnace to produce steam (which is often supplied as process heat to various production steps) and to increase plant energy efficiency. The green liquor from the recovery furnace is sent to a causticizer where it is reacted with lime to convert sodium carbonate to sodium hydroxide. The causticized green liquor, called white liquor, is returned to the digester for reuse in the pulping process while the precipitated calcium carbonate is washed and sent to a lime kiln where it is heated to produce calcium oxide (Tran and Vakkilainen, 2016).

The washed pulp is then screened, cleaned, and most of the water is removed to prepare it for paper making. Since the pulp mix contains a significant amount of lignin and other discoloration materials, the pulp is bleached using water, steam, and chemicals to produce light-colored or white papers at a later stage. In the refining process, the fibers are brought under compression and shear forces which cause several changes in the specifications of fibers and improve their quality. Water is added to the pulp slurry to make a thin mixture containing <1% fiber. The slurry is cleaned and screened before being fed into the wet end of the paper-forming machine. In the forming section, the fibers present in the slurry form a paper web through drainage by gravity and applied suction below the forming fabric. In the press section, the remaining water is removed by mechanical pressure applied through the nips of a series of presses while the wet web is consolidated. The remaining water content is later dried using steam. Calendaring process smoothens and compresses the paper material by passing a single continuous sheet through a series of heated rolls. The final step involves winding and cutting the traveling sheet into paper reels (Brown et al., 1996).

Table 12 presents the typical specific final energy consumption of an integrated paper mill, disaggregated by direct and indirect fuel and electricity demand in each process step.

IHP applications

Table 12 highlights (in green color) the process heat demand at a suitable temperature for IHP application. It must be noted that there is no HTHP application identified for paper making. All of the steam condensate from the paper drying process can be recovered, requiring no make-up water preheating. Hence conservative scenario is not developed. However, depending on specific cases, HTHP may have some applications in the pulp and paper industry. For example, a HTHP with a heating capacity of 4 MW was installed in a Danish paper mill (IEA, 2020). The system uses waste heat at 50-55°C from the dryer to heat water to 70°C for district heating. The HTHP system reduced 130 TJ of the plant's annual heat demand which equals 60% of the energy demand of the 3000 households in the Danish city of Skjern.

Table 12. Specific energy consumption of conventional and modified processes in the pulp and paper industry.

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

In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120°C for paper drying after the press section. The required heating capacity of SGHP for the drying application in the U.S. pulp and paper industry is estimated at 6.8 GW. Furthermore, the COP of the SGHP is determined to be low i.e. 1.8, mainly because the temperature lift is high. The utilization of an available heat source at a temperature higher than what is currently assumed (refer to Section 3) will result in a higher COP or lower electricity demand for an IHP operation.

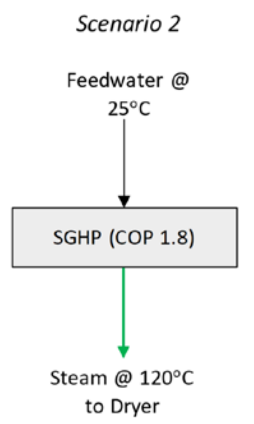

Figure 47. Industrial heat pump application in the pulp and paper industry.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 12. The change in annual final energy demand in the U.S. pulp and paper industry in different IHP application scenarios and timeframes is presented in Figure 48. The figure shows that the measure suggested in Figure 47 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 207 PJ per year of final energy can be saved in 2050 if SGHP is used to generate steam for paper drying (Scenario 2). The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COP of the IHP. More precisely, 330 PJ per year of fuel demand could be reduced while 123 PJ per year (or 34 TWh per year) of electricity demand would be increased in 2050.

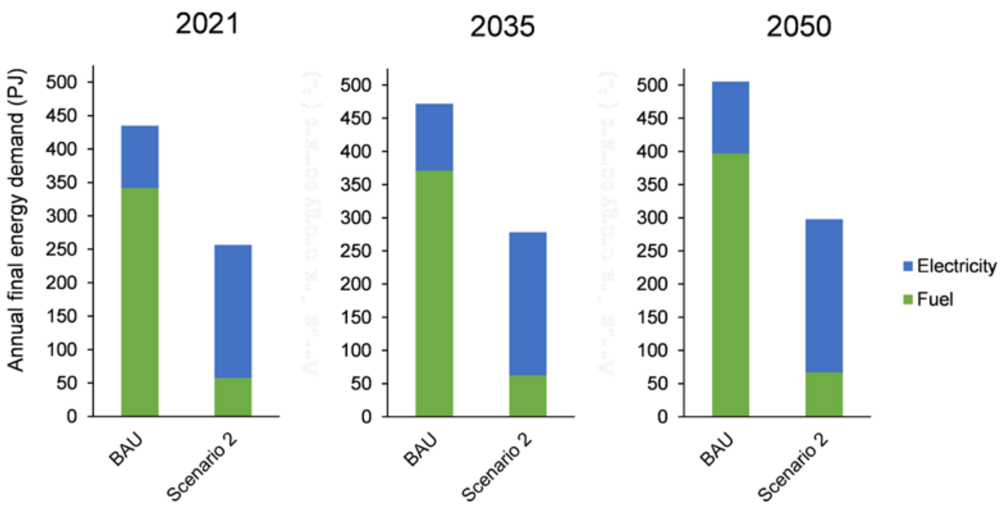

Figure 48. Annual final energy demand in the U.S. pulp and paper industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. pulp and paper industry in different IHP application scenarios and timeframes is presented in Figure 49. The figure shows up to 4.6 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of the IHP application in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. Furthermore, it is estimated that approximately 17.8 Mt per year of CO_2 emissions can be avoided in 2050. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

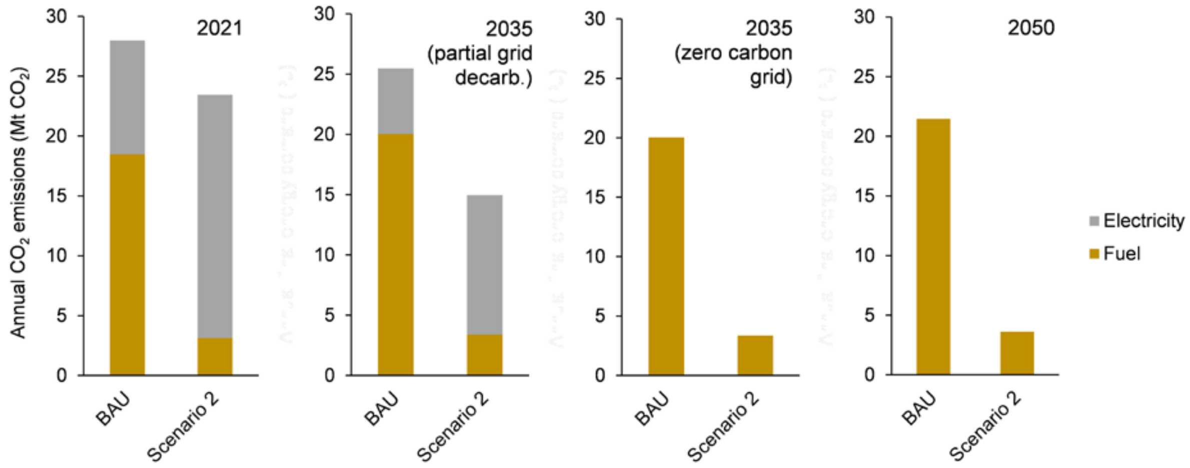

Figure 49. Annual CO_2 emissions from the U.S. pulp and paper industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 50 presents the specific costs of conserved energy and CO_2 abatement for IHPs applications in the U.S. paper industry. The figure shows that the energy conservation costs range from 5 to 7 $/GJ in different timeframes. The figure also shows that the CO_2 abatement costs are estimated at approximately 60 $/t CO_2 in 2050.

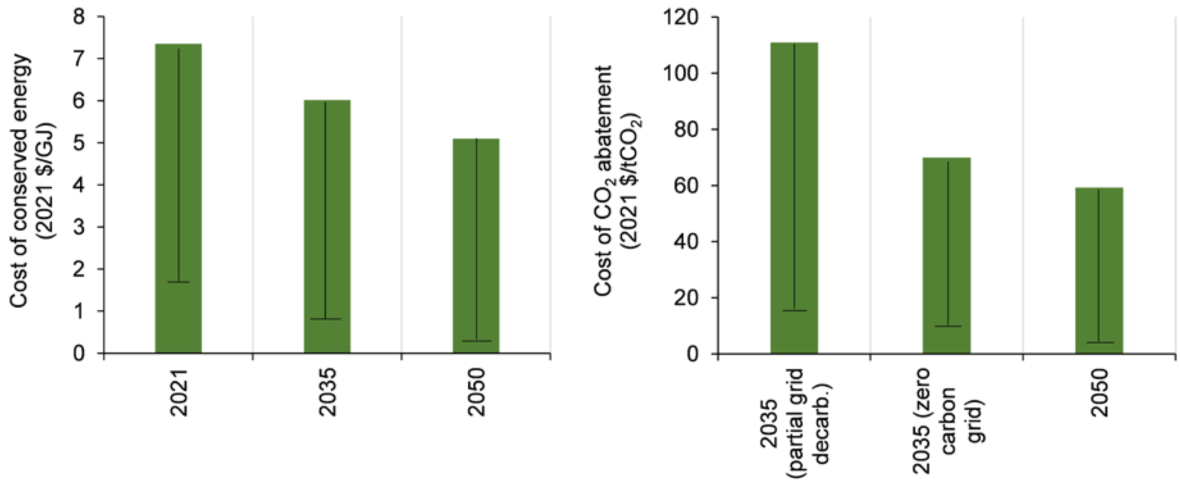

Figure 50. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. pulp and paper industry.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

It is clear that IHP integration in U.S. paper plants incurs additional costs and none of the scenarios have costs falling below zero which would have otherwise represented cost savings. The large difference between the U.S. average industrial electricity and fuel prices is the major reason why the costs are found to be high. The heat source temperature assumed at 25°C is another reason causing high marginal costs. Exploring and utilizing suitable waste heat sources at higher temperatures to minimize the temperature lifts is strongly recommended.

4.11 Automotive industry

Production process

The U.S. automotive industry manufactured around 9 million automobiles in 2021 (Statistica, 2022b). The production volume is estimated to grow to 10 million in 2050. A typical automobile production process is briefly described as follows. In the first step, strips or metal sheets are cut (or bent) into a shape needed. Next is mechanical pressing to drive a punch against sheet metal to cause a permanent change in the shape of the metal. Welding is done to sculpt materials using heat and permanently join them together, followed by body assembling. Before painting, the body undergoes a rigorous inspection. An assembly conveyor transports it through a cleaning station where it is immersed and cleaned of all oil, dirt, and contaminants. The body leaving the cleaning station is then dried. Painting is the next manufacturing process that is performed in multiple stages and aims to protect the body against corrosion and give a vehicle body its final appearance (Gekatex Group, 2019; Groover and Kolchin, 1997).

Once the body has been fully covered with paint, a conveyor carries it to baking ovens where the paint is cured at temperatures over 100°C. After the body leaves the paint area, it is ready for interior or trim assembly where the remaining parts and sub-assemblies including engine and transmission, dashboard, seats, tires, and so on are assembled into the body. The vehicle then undergoes quality check and testing before the final components including batteries are installed. The vehicle is washed in the final step (Gekatex Group, 2019; Groover and Kolchin, 1997).

Table 13 presents the typical specific final energy consumption of an automotive manufacturing plant, disaggregated by direct and indirect fuel and electricity demand in each process step.

IHP applications

Table 13 highlights (in green color) the process heat demand at temperatures suitable for IHP applications. Figure 51 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, two separate high-temperature heat pumps can be employed to heat water to 50°C and 90°C. Process water at 50°C is used for washing and finishing while the makeup water at 90°C is utilized for steam generation. Air can be heated and delivered at 27°C for welding and painting processes using an air source heat pump (ASHP) system. The COP of the ASHP system is assumed as 3, based on Zuberi et al. (2021). The required heating capacity of IHP for the U.S. automotive industry is estimated at 5.8 GW. For body preparation, the required steam temperature is higher (i.e. 177°C) than the current state of the art, hence not considered.

Table 13. Specific energy consumption of conventional and modified processes in the automotive industry.

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

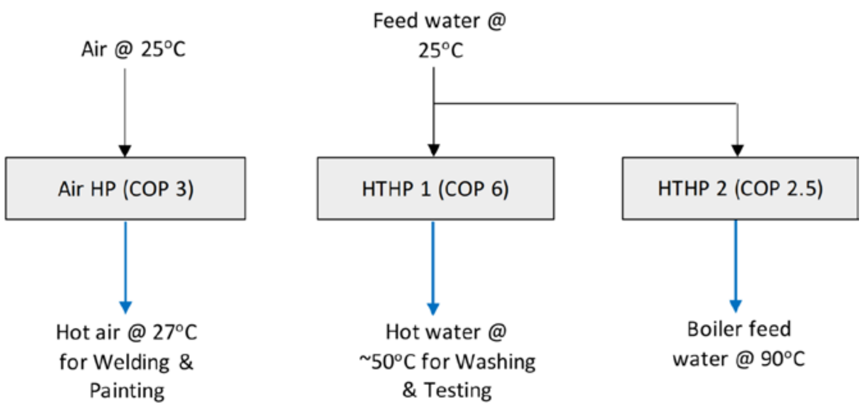

Figure 51. Industrial heat pump applications in the automotive industry.

To support the discussion on HTHP applications identified for the U.S. automobile production plants, a real-life example is presented. A HTHP system with a heating capacity of approximately 1.7 MW and COP of 5.6 was installed in a German car manufacturing plant owned by Volkswagen (IEA, 2020). The system uses waste heat at 26-29°C from the plant's cathodic dip-coating process in the paint shop to heat process water to 65-75°C. The heated water is used for various purposes.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (due to IHP integration) processes is also presented in Table 13. The change in annual final energy demand in the U.S. automotive industry in different IHP application scenarios and timeframes is presented in Figure 52. The figure shows that the measures suggested in Figure 51 can significantly reduce the total final energy demand despite the projected increase in production between 2021 and 2050. It is estimated that approximately 96 PJ per year of final energy can be saved if all IHP applications are realized in 2050. The substantial reduction in final energy demand is due to the increase in efficiency measured in terms of COPs of the IHP. More precisely, 128 PJ per year of fuel demand could be reduced while 32 PJ per year (or 8.8 TWh per year) of electricity demand would be increased in 2050 respectively. As mentioned earlier, since the required steam temperature is higher than the current IHP technology can deliver, Scenario 2 has not been considered for the automotive sector.

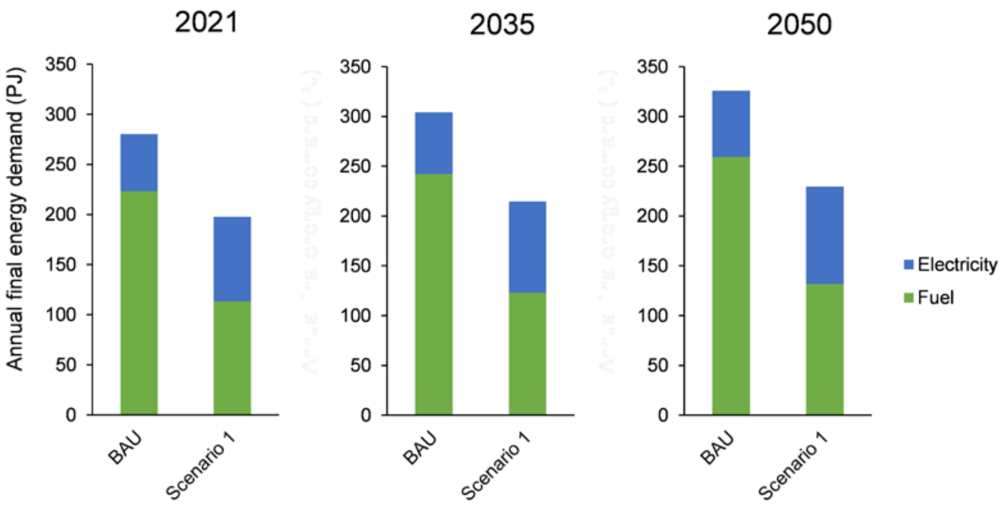

Figure 52. Annual final energy demand in the U.S. automotive industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).
Note: BAU does not consider any IHP applications while Scenario 1 considers HTHP and ASHP applications. Since the required steam temperature is higher than the current IHP technology can deliver, Scenario 2 has not been considered for the automotive industry.

The change in annual CO_2 emissions in the U.S. automotive industry in different IHP application scenarios and timeframes is presented in Figure 53. The figure shows up to 5 Mt of potential CO_2 abatement already in 2021 as a result of the 100% adoption rate of all IHP applications in the sector, despite the increased demand for electricity which has a higher average emission factor than natural gas in the U.S. It is further estimated that approximately 9 Mt per year of CO_2 emissions can be avoided in 2050. This substantial reduction in CO_2 emissions is the consequence of a projected decline in the electricity grid emission factor (grid decarbonization) between 2021 and 2050. The different levels of potential CO_2 emissions reduction in 2035 represent different grid decarbonization scenarios, refer to Section 3.

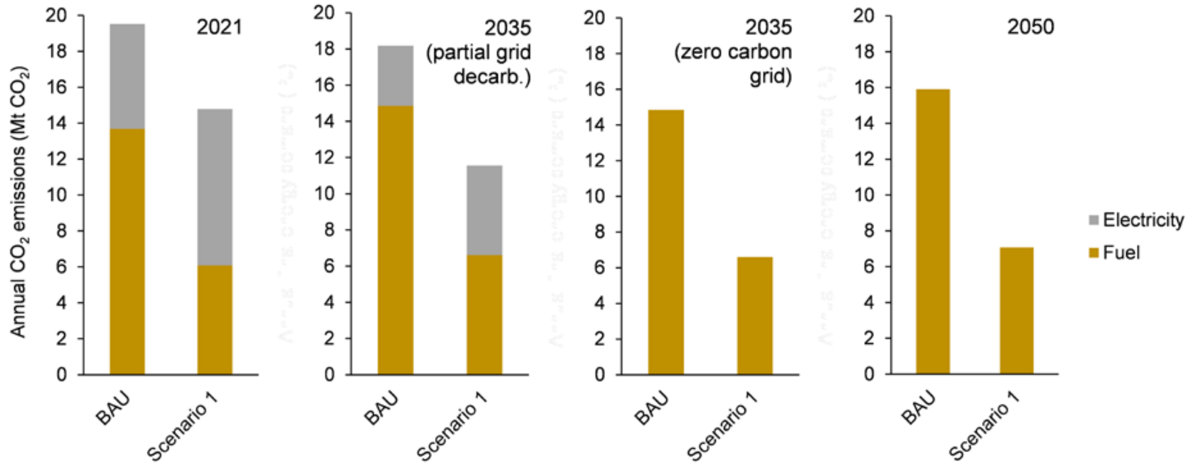

Figure 53. Annual CO_2 emissions from the U.S. automotive industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

According to Figure 54, the specific costs of conserved energy and CO_2 abatement for IHP applications are estimated at 5 $/GJ and 49 $/t CO_2 per year respectively in 2050. The associated costs of IHP applications in U.S. automotive plants do not fall below zero which would have otherwise represented cost savings. The major factor that is influencing the marginal costs to be high is the disparity between the U.S. average industrial electricity and fuel prices. The assumed heat source temperature is another major reason why the costs are not economical (see earlier discussion). Therefore, it is recommended to explore suitable waste heat sources at higher temperatures and utilize them for maximizing the IHP COPs, and minimizing the temperature lifts and consequently the electricity costs.

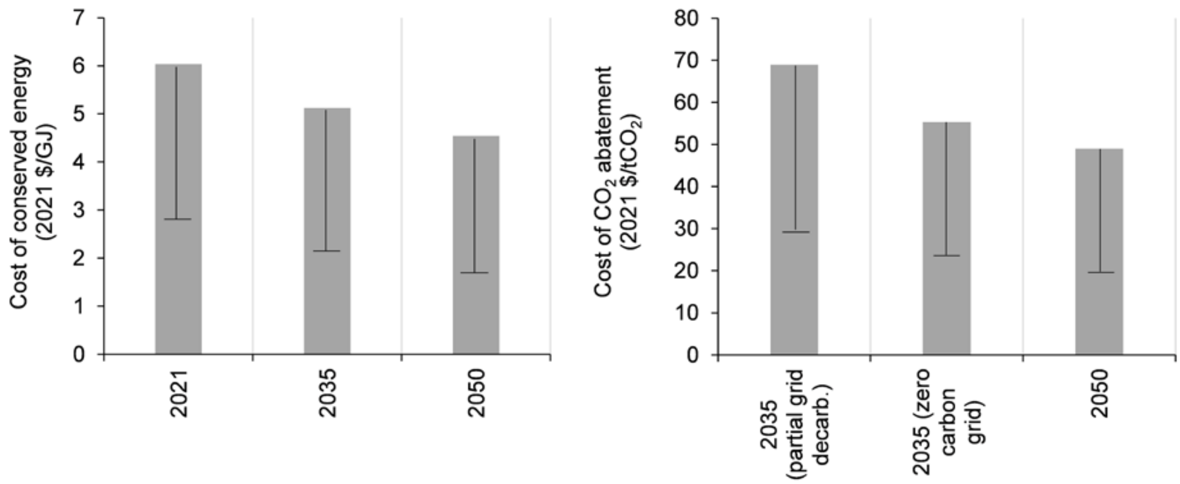

Figure 54. Cost of conserved energy and CO_2 abatement cost for industrial heat pump applications in the U.S. automotive industry under Scenario 1.

Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 5.3 for more details.

5 Cross-sectoral Comparison of Energy Savings and costs

5.1 Relative Energy Savings

Figure 55 presents the summary of fuel savings (presented as % of total fuel used) as a result of IHP applications in the studied industrial processes in different technical scenarios. The figure shows that the potential fuel energy savings in manufacturing processes like meat processing, beer, canned fruits and vegetables, cane sugar refining, automotive, etc. are significant if only HTHP are deployed (Conservative - Scenario 1). On the other hand, the impact of HTHP on the overall heat demand in the remaining processes including dairy, beet sugar, corn wet-milling, textiles, paper, etc. is low or even negligible due to high steam demand. However, the results for the Ambitious - Scenario 2 show that more than two-thirds of the fuel demand, in the majority of the studied processes, can be reduced if SGHP applications are also exploited. Moreover, all of the heat demand for canned vegetable and fruit production, and textile spinning and weaving can be fulfilled by IHP applications.

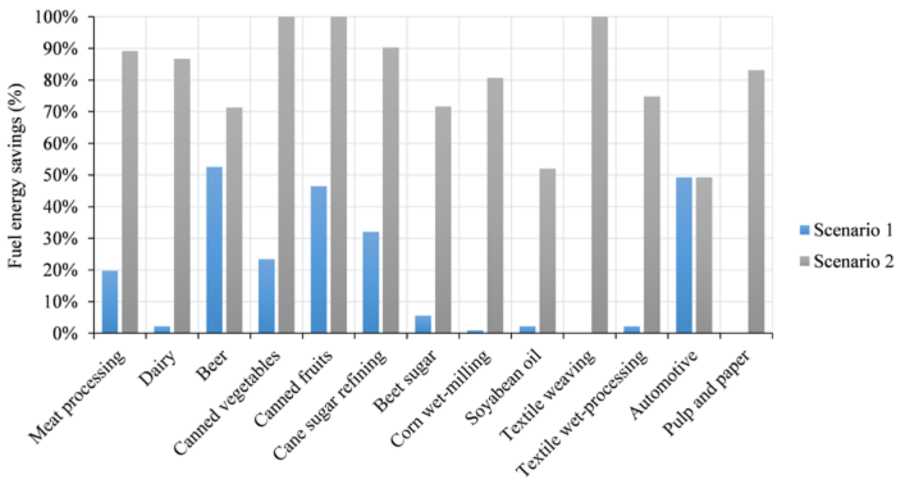

Figure 55. Sectoral fuel energy savings potential (as % of total fuel used) in different industrial heat pump application scenarios in the U.S.

Furthermore, since IHP applications increase the electricity demand of an industrial facility, total final energy savings (or net savings due to simultaneous decrease in fuel demand and increase in electricity use) are estimated for each industrial process and shown in Figure 56. The potential final energy savings in the thirteen processes range from 27% to 66%. The energy-saving trends in Figure 56 are no different than those in Figure 55. However, the enviro-economic aspects of the technical potential must also be analyzed and are discussed in the next section.

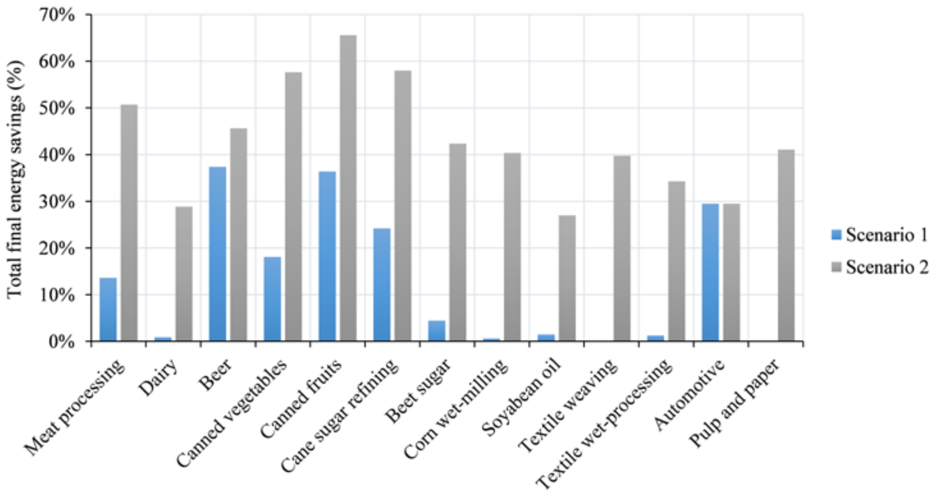

Figure 56. Sectoral final energy savings potential (as % of the total energy used) in different industrial heat pump application scenarios in the U.S.

5.2 Marginal Cost Curves

A conservation supply curve is an analytical tool, commonly used to present the techno-economic perspectives of energy and/or CO_2 conservation. The curve shows the marginal costs of climate mitigation measures as a function of the potential energy and/or CO_2 conservation. In this study, specific costs of energy conservation and CO_2 abatement for IHP applications in specific industrial processes are calculated using the methods and materials described in Appendices A-C. For plotting conservation supply curves, industrial processes are arranged in ascending order by conservation costs and presented against their annual cumulative potential energy or CO_2 savings. The height of each process on the vertical axes shows the process-specific costs of IHP applications while the width on the horizontal axes shows the annual energy or CO_2 savings. Furthermore, since annual benefits are shown as negative values as a consequence of final energy cost savings, all processes that fall below zero on the horizontal axes will be considered cost-effective.

The energy conservation cost curve in Figure 57 shows the costs of conserved energy due to the IHP applications (as described in Section 4, Ambitious Scenarios 2) in different U.S. industrial processes as a function of their corresponding process-wide potential energy savings in the base year 2021 and future years. The height of each industrial process on the y- axis shows the specific costs while the width of each sector on the x-axis shows the technical energy saving potential (in PJ). The figure shows that the technical potential energy savings as a result of IHP applications are 545 PJ per year (approximately 4% of the total final energy demand in U.S. manufacturing) in the base year 2021. The figure illustrates that IHP applications incur additional costs in each process and none of the U.S. industrial processes have energy conservation costs falling below the horizontal axis (which would have otherwise represented cost savings). In other words, the overall costs are not economical (higher than zero) and additional expenditure on IHPs is required to make the energy shift in all studied industrial sectors.

As far as the rankings are concerned, multiple factors including current process-specific efficiencies, IHP COPs, required IHP capacities, and the corresponding investment and operational costs affect the specific costs of IHP applications in U.S. manufacturing. One of the major reasons for the high specific costs is the disparity between the electricity and fuel prices in the U.S. industry. For example, the average electricity price in the U.S. industry (i.e. 70 $/MWh) is almost 5 times higher than the average price of natural gas (i.e. 14 $/MWh) in 2021 (refer to Appendix C). The assumed heat source temperature i.e. 25°C is another factor influencing the costs to be high (see Section 3) and it is recommended to explore suitable waste heat sources at higher temperatures to minimize the temperature lifts (or maximize the COPs), and consequently the electricity costs. Therefore, it is not possible to pinpoint a single factor that dictates the rankings of the industrial processes in Figure 57 the most. However, the impact of the changes in the aforementioned factors is discussed in the next section.

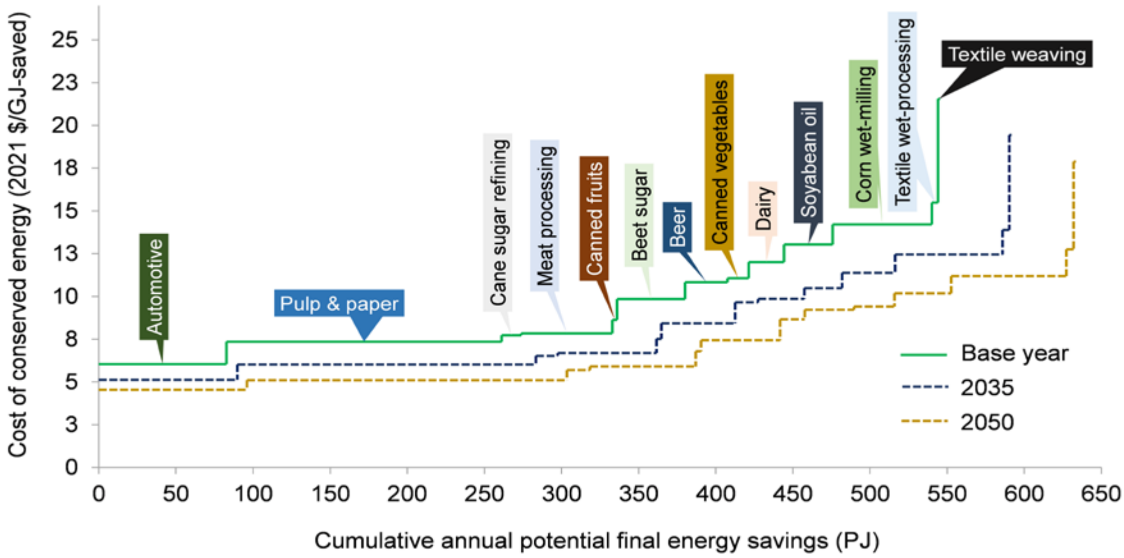

Figure 57. Energy conservation cost curve for industrial heat pump applications (in Ambitious scenario 2) in U.S. manufacturing.

Furthermore, energy demand for steam generation and natural gas prices are projected to grow in the future. However, electricity prices are expected to slightly decrease in the future (see Appendix C). All these projections will impact the costs of energy conservation. Figure 57 also presents the marginal cost curves in 2035 and 2050. The figure shows that while the potential energy savings in 2050 could increase to almost 634 PJ per year, the costs may moderately decrease i.e. from 6-22 $/GJ-saved in 2021 to 5-18 $/GJ-saved in 2050. The moderate decrease in costs of conserved energy is because electricity prices are expected to decrease in the future but as per the projections, they may still be higher on an equal unit energy basis than natural gas in 2050 (refer to Appendix C).

Despite the current average U.S. electricity grid emission factor being higher than the emission factor of natural gas, electrifying hot water, and steam generation systems in the studied industrial processes can already decrease the annual CO_2 emissions by around 17 Mt CO_2 per year in the base year 2021, assuming a 100% adoption rate of IHP applications. This outcome is in contrast with the findings of Zuberi et al. (2021), who displayed that a higher grid emission factor than natural gas could initially lead to an increase in annual CO_2 emissions as a result of electrified steam generation through electric boilers. This contrast is mainly because the high efficiencies of IHP (measured in terms of COPs, which are estimated rather conservatively in this study) as compared to combustion and electric boilers are dominating the other factors. However, given the fact that electricity grids will be further decarbonized and potentially fully decarbonized in 2035 or 2050, the magnitude of CO_2 abatement is projected to be 54 or 58 Mt CO_2 per year respectively (i.e. reaching net-zero emissions), as presented in Figure 58.

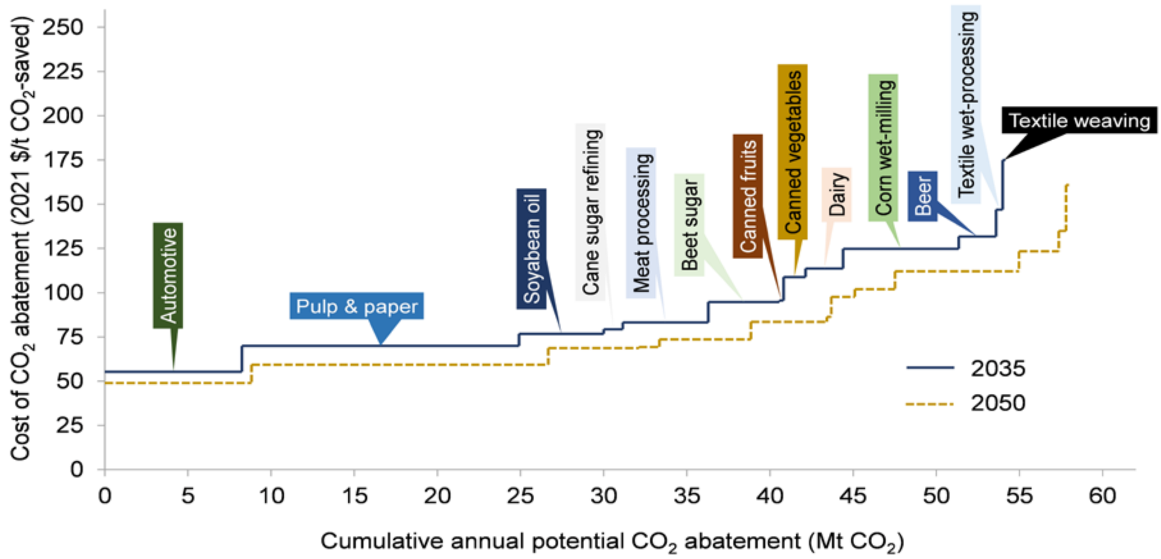

Figure 58. CO_2 abatement cost curve for industrial heat pump applications (in Ambitious scenario 2) in U.S. manufacturing.

Figure 58 further shows that the CO_2 abatement costs in different industrial processes range between 49 and 161 $/t$CO_2$ in 2050. Since the COPs of SGHP are estimated lower than those of HTHP given the technical assumptions in Section 3, the CO_2 abatement costs in industrial sectors with less to no SGHP applications are found to be relatively less expensive (e.g. automotive industry as shown in Figure 58). This means high-temperature heat sources must ideally be exploited first for SGHP (as they are more impactful than HTHP) to minimize temperature lifts and operational costs. Since the COP of an IHP application with a high-temperature lift is typically low, the CO_2 abatement costs in industrial sectors with few or no applications requiring high-temperature lifts (i.e. greater than 100 K) are found to be relatively less expensive (e.g. in the automotive industry as shown in Figures 57 and 58). This means that high-temperature heat sources must be first utilized for heat sinks with the highest temperatures, to minimize the temperature lifts and operational costs, and maximize heat pump COPs.

5.3 Sensitivity Analysis

As mentioned earlier, the marginal costs for each industrial process are quite sensitive to fuel and electricity price projections and waste heat source temperatures. It is therefore important to perform a sensitivity analysis to evaluate the impact of changes in energy prices and source temperatures on the marginal costs. In this context, the following four hypothetical case scenarios have been developed and summarized in Table 14:

- *Case 1 - Higher heat source temperature*: Substantial waste heat sources are available at temperatures of 40°C instead of 25°C (as assumed in the base case scenario).

- *Case 2 - Higher natural gas prices*: Natural gas prices are assumed 50% higher than those projected in 2050.

- *Case 3 - Lower electricity prices*: Electricity prices are assumed 50% lower than those projected in 2050.

- Case 4 - Combined: Natural gas prices are assumed 50% higher and electricity prices are 50% lower than those projected in 2050 in our base case. Also, waste heat sources are available at 40°C.

Table 14. Assumed values for different variables in different case scenarios for the sensitivity analysis.

Variable	Base case – Scenario 2	Case 1	Case 2	Case 3	Case 4
Projected U.S. avg. natural gas price in 2050 *(2021 $/MWh)*	15	15	23	15	23
Projected U.S. avg. Electricity price in 2050 *(2021 $/MWh)*	59	59	59	29	29
Heat source temperature *(°C)*	25°C	40°C	25°C	25°C	40°C

Figures 59 and 60 present the sensitivity analysis of energy conservation and CO_2 abatement costs in 2050 to different techno-economic variables. The figures show that in Case 1, the marginal costs can be reduced significantly if available waste heat sources at 40°C are utilized by IHPs, consequently minimizing temperature lifts and maximizing COPs. Hence, it is essential to explore and utilize heat sources at high temperatures yet below the pinch point to optimize IHP operation. It is further shown that in Case 2, the marginal costs can be reduced by an order of 2-3 times if natural gas prices are increased by 50%. Natural gas prices must be raised to a level closer to the price of electricity to make IHP economically competitive. Any form of a carbon tax scheme (e.g. CO_2 tax or levy or cap and trade system, etc.) that results in higher fossil fuel prices could make the electrified process heat supply substantially more cost-effective.

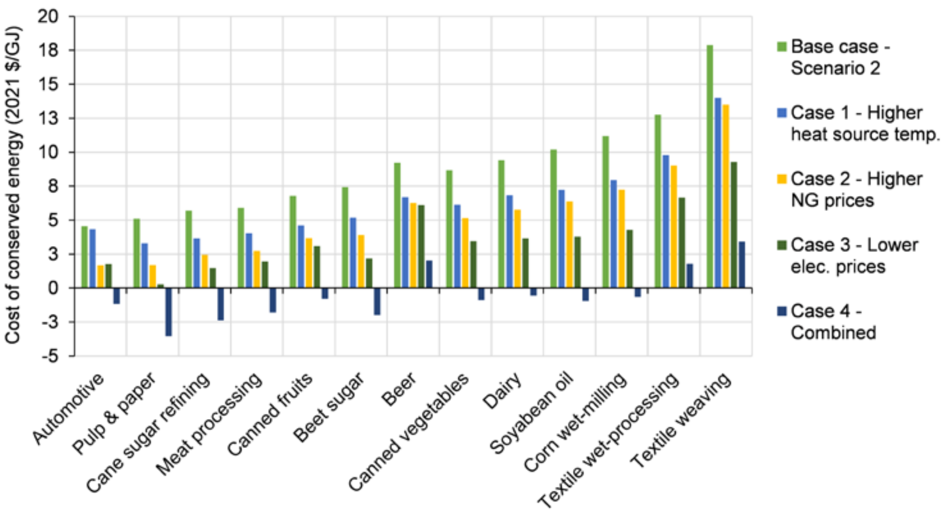

Figure 59. Sensitivity analysis of energy conservation costs in 2050 to different techno-economic variables.

The figure also shows that the costs can be decreased by up to 6 times if electricity prices are halved from those projected in 2050. The three scenario results show that reducing electricity rates in the future could be the most impactful measure to facilitate the wide-scale applications of IHP in relevant industrial facilities. Considering the influence of the electricity price and the uncertainties of economic return, an option to consider would be backup gas boilers. In the first phase of the IHP applications, backup gas boilers may be used for industrial steam generation. These combinations allow choosing between electric heating and fuel heating depending on the prices of electricity. Since electricity prices are anticipated to fall due to large volumes of renewable electricity coming online and increasing energy consumption, there may be times during the day when electricity is available at a price lower than natural gas. For example, in California, there are hours of the day when excess renewable electricity is exported to its neighboring states, and the California Independent System Operator (ISO) pays off-takers a maximum of 25 $/MWh for this electricity (Deason et al., 2018).

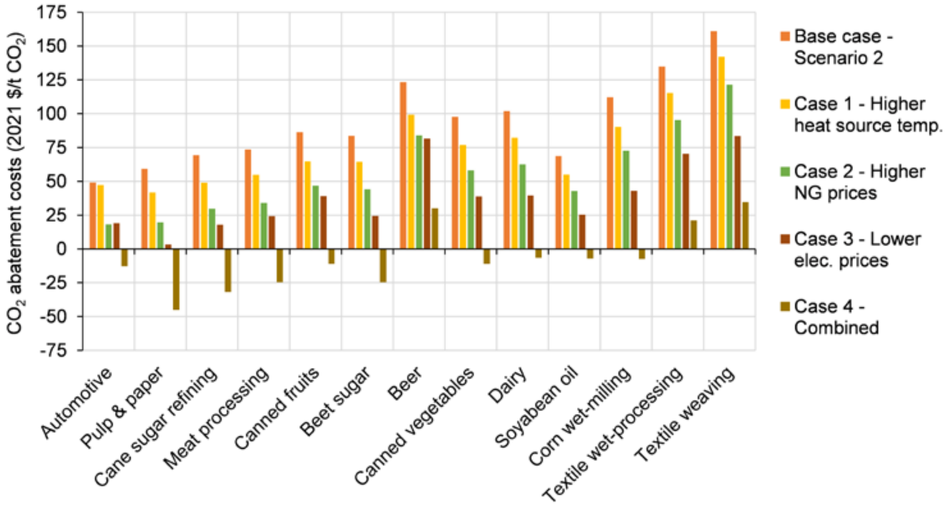

Figure 60. Sensitivity analysis of CO_2 abatement costs in 2050 to different techno-economic variables.

Despite the increase in natural gas prices, decrease in electricity prices, and utilization of high-quality waste heat sources, the marginal costs in Figures 59 and 60 do not fall below zero (costs less than zero represent cost savings, refer to the methodology in Appendix A). However, in the combined scenario where all the aforementioned factors are considered simultaneously, the marginal costs for most industrial processes are found to be cost-effective (negative costs). This concludes that optimizing IHPs or revising energy prices alone will not solve the problem, instead, a combination of different techno-economic measures must be implemented by different stakeholders to encourage wide-scale IHP deployment in U.S. manufacturing. The results can also be seen from the perspective that for cases where higher source temperatures are available, and where the electricity to natural gas price ratio is favorable (as in some regions of the U.S.), it can be worth investing in IHP to aid the transition to lower-carbon electricity and GHG emissions reduction.

Furthermore, it must be noted that the cost of energy per unit of production is generally higher for IHP compared to combustion boilers. However, energy costs are only a small fraction of the total manufacturing costs for many industrial sectors. In sectors where energy cost is only a small portion of the total production cost, a small or even moderate increase in energy cost per unit of product, resulting from the IHP applications, will not have a major impact on the price of the final product. In other words, it will have a minimal impact on the price that final consumers will pay for the product or the products that are made from those materials. Moreover, energy prices vary significantly from state to state and even county to county within the U.S. Therefore, the costs of energy conservation and CO_2 abatement for IHP applications in different sectors are highly sensitive to the price of natural gas and electricity in different states).[4]

4. Another study is being planned to investigate sector-specific IHP applications at the level of each U.S. state.

Finally, this work only studies the effect of change in heat source temperatures and energy prices. To forecast change in all the relevant parameters such as production volumes, boiler efficiencies, prices of IHPs, discount rates, etc. in the future, much more information is required which is currently unavailable, hence not done, and is planned for future work. In addition, IHP applications possess several co-benefits including simultaneous cooling, elimination of combustion-related pollutants, less frequent maintenance, better safety, etc., however, techno-economic quantifications of these co-benefits are outside the scope of this work.

6 Barriers and Recommendations

6.1 Challenges and Barriers

Despite the large potential for energy and CO_2 emissions reduction in U.S. manufacturing, there are still some barriers associated with the wide-scale applications of IHP. Some of the major barriers are listed below based on the information given by Arpagaus and Bertsch (2020), Jakobs and Stadtländer (2021), Rightor et al. (2022):

- The economic feasibility of IHP integration into existing processes due to tailor-made designs often leads to long payback times.
- Low fuel (gas) to electricity price ratios (or large differences between fuel and electricity prices).
- Limited availability of suitable compressors for high temperatures.
- Lack of available refrigerants in the high-temperature range with low global warming potentials (GWP) and no ozone depletion potentials (ODP).
- Competing heat supply technologies that use fossil fuels to deliver heat at high temperatures.
- Heat storage requirements to compensate for the time lag between demand and supply e.g. in the case of industrial batch processes.
- Lack of large-scale IHP demonstration systems in the U.S.
- Lack of awareness and understanding of IHP technology and its technical possibilities among different end-users, plant designers, consultants, investors, installers, etc.
- Lack of knowledge about IHP integration in suitable manufacturing processes.
- Lack of training of the stakeholders of the whole value chain including planners, IHP manufacturers, installers, consultants, etc., and events that support the spread of IHP knowledge.

To address the aforementioned challenges, key and targeted action plans including further research, development, demonstration, and deployment (RDD&D), policy interventions, workforce development, capacity building, etc. are needed. Below we provide detailed action plans that different stakeholders could take to facilitate the electrification of the industrial process heat supply where suitable.

6.2 Recommendations

Research, development, demonstration, and deployment

While IHP technologies are commercially available, further advancement especially for HTHP and SGHP depends on further investment in research, development, and deployment (RD-D&D). Optimal IHP integration strategies are influenced by different variables, including sector, processes, and location. Several RDD&D activities are discussed as follows.

Industrial plants can partner with academia, national laboratories, and think tanks, among other stakeholders, to explore and enhance IHP applications. IHP can be a part of an integrated system that provides both heating and cooling, hence such applications must be explored and carefully assessed for implementation. It is also not always easy to implement an IHP into an existing plant as it requires well-thought-out integration on the sides of the heat source and sinks. To overcome this hurdle, successful integrations need to be demonstrated and published. These plants can also develop business cases for the electrified heat supply by mapping out their energy and non-energy benefits.

Research efforts must ramp up to develop and demonstrate suitable compressors for high temperatures, and test refrigerants in the high-temperature range with low GWP and no ODP. Federal, state, and local governments must step in and incentivize IHP deployments. They can provide tax credits or grants to financially incentivize large IHP pilots and demonstrations. They can also help make advancements by using the exceptional capacity of the U.S. DOE's national laboratories.

Utilities can collaborate with industry and government to support RDD&D activities for electrified process heat supply. They can also partner with industry and research institutes to evaluate the grid implication of wide-scale IHP applications in their service area.

Suppliers can collaborate with industry, service and engineering firms, academia, national labs, think tanks, and other stakeholders to scale the electrification of process heat supply through IHPs. Moreover, they can also contribute to devising business cases for IHP applications by including both energy and non-energy benefits. They can further collaborate with the industry to demonstrate new IHP technologies and disseminate the results. Moreover, manufacturing larger lots than today may increase productivity and decrease capital costs due to economies of scale.

Capacity building

Due to a lack of awareness, industrial consumers may be risk-averse and avoid implementing new technologies altogether. Subsequently, IHP must compete with familiar fossil fuel-fired combustion boilers that have been in use for decades and are well established. Companies and plant operators need more information about the availability, applicability, and integration of IHPs in existing systems. Employees and contractors may require training on IHPs, especially on installation, operation, troubleshooting, and maintenance.

Companies can seek information about the types of available IHP and their potential applications. They can participate in technical assistance programs and engage with the facility's electric utility to learn about electricity rates and whether additional infrastructure for connection is required. They can also learn about where IHP has been implemented, then disseminate information or case studies about its challenges and successes. Companies can also educate their peers about the benefits of IHP. They can further inform policymakers about their interest in industrial electrification and the benefits that could be realized by adopting IHPs, including CO_2 abatement. In addition, they can also educate utilities, policymakers, and the public, about the increased demand for renewable electricity due to growth in process electrification.

Governments can support demonstrations and deployments of IHP that have already been commercially developed. Moreover, they can offer and/or support technical assistance programs for wide-scale IHP deployment. They can create or support an IHP information dissemination platform, which would include the development and distribution of real case studies. They can conduct or support research and analysis on the economic development potential of IHP applications. They can also support grants that create fellowships to provide dedicated staffing support to industries to help their IHP deployment efforts. Furthermore, governments can educate the public about the benefits that could be realized by adopting IHP, including CO_2 emissions reduction, improved air quality and health, and economic development opportunities.

Utilities can evaluate the potential demand response (including its financial impacts) that the advancement of IHP applications can cause. They can provide information to industrial customers about the utility side implications of IHP applications and potential economic gains from demand response to each industrial plant where possible. Moreover, they can provide information about their electricity rates and market structures, and required connection upgrades. Utilities can also educate policymakers and the public about increased demand for renewable electricity, energy storage, demand response, transmission system expansion needs, distribution system hardening, and grid modernization as a result of an increase in the electrified process heat supply. A better understanding of the capabilities of IHP and the need for additional investment and support can improve policy and investment decisions.

Suppliers of IHP can engage with industrial companies to learn about their electrification needs. They can provide information about available technologies and those under development to industrial companies, governments, and utilities. They can educate policymakers and the industry about their technologies and the benefits that could be realized by adopting IHP. They can further educate financial institutions and potential investors about their products and the advantages of IHP.

Policy and workforce development

To accelerate the deployment of IHP in the manufacturing sector, a wide range of policy options could be pursued. Industrial plants can collaborate with policymakers to discuss their interest in the electrification of process heat supply and the benefits that could be realized due to IHP applications.

Governments can adopt policies to support the demonstration and deployment of IHP that are market-ready. Moreover, they can adopt tax policies that encourage investment in IHP; policies that price carbon emissions at a level that supports electrified technologies; adopt electricity rate designs that encourage electrification, and adopt renewable portfolio requirements for thermal energy. Governments can also offer or support education and training programs for those that will install, operate, and maintain IHP.

Companies can provide training for employees and contractors on IHP operations. They can engage with trade groups, educational institutions, and utilities to discuss education and training needs and develop IHP application programs. In addition to company knowledge, employees and contractors at individual plant facilities may require additional training on IHP integration, installation, and maintenance. Furthermore, companies, governments, and utilities can work together with trade groups and educational institutions to ensure that current and future workers are prepared to meet the new demands of an increasingly electrified manufacturing sector. Companies can further engage with utilities about their plans for electrification and the corresponding viable solutions.

Utilities can adopt electricity rate designs that encourage IHP applications. Additionally, they can support policies that permit more on-site generation, storage, and microgrid deployment, to help address reliability concerns and to mitigate costs to all ratepayers of increased industrial load. Utilities can engage with the manufacturing sector, trade groups, and training institutes to discuss education and training needs and develop appropriate programs. Suppliers can provide training on their IHP technologies.

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Appendices

A. Methodology: Potential and costs of industrial heat pump applications

There is a general understanding that demand for consumer products typically increases with the population growth of a country. Since the industrial processes considered in this study are all producing consumer products including food items, beverages, textiles, automobiles, etc., this study estimates the future production volumes based on the U.S. population growth projected by U.S. Census Bureau (2020). These production volumes are later used to estimate the sectoral frozen efficiency energy demand for the reference case. Frozen efficiency energy demand represents the amount of final energy which the industry sector would have used if no energy efficiency improvement (e.g. IHP applications in this case) had been implemented. In this work, it is calculated by multiplying the specific energy consumption (SEC) of each product in the reference year 2021 by the production volumes in the future years. Since the production volumes and SEC values possess uncertainty due to the lack of detailed statistics, the resulting energy demand has a degree of uncertainty. However, frozen efficiency energy demand estimates provide the basis to compare the energy demand and CO_2 emissions with or without IHP integration in studied U.S. manufacturing sectors.

Potential energy savings/conservation *ES* due to the electrification of heat demand in the industrial processes (as discussed in Sections 4 and 5) can be estimated by Equation A.1. The difference between temperature-specific heat demand by current industrial processes (heat sink) and potential electricity demand due to IHP application as a replacement of current process equipment for the same energy service, is referred to as energy savings.

$$ES = Q_{out} - W_{in} \tag{A.1}$$

Where;

Q_{out} = Current heat demand at a certain temperature by industrial processes in a sector

W_{in} = Electricity demand by an IHP for the same energy service in a sector

Similarly, potential CO_2 abatement *CA* due to IHP application and simultaneous decarbonization of the electricity grid can be estimated by the following equation:

$$CA = (Q_{out} \times f_{NG}) - (W_{in} \times f_{grid}) \tag{A.2}$$

Where;

f_{NG} = Natural gas emission factor, taken as 0.05 tCO_2/GJ based on U.S. EPA (2014)

f_{egrid} = National average electricity grid emission factor based on U.S. EIA (2022a)

A conservation supply curve is an analytical tool, commonly used to present the techno-economic perspectives of energy and/or CO_2 conservation. The curve shows the marginal costs of climate mitigation measures as a function of the potential energy and/or CO_2 conservation. In this study, specific costs of energy conservation C_{ES} and CO_2 abatement C_{CA} for IHP applications in specific industrial sectors are calculated using the following equations.

Costs of conserved energy:

$$C_{ES} = \frac{\alpha.I_S + O\&M_S - B_S}{\mathrm{ES}_S} \tag{A.3}$$

Costs of CO_2 abatement:

$$C_{CA} = \frac{\alpha.I_S + O\&M_S - B_S}{\mathrm{CA}_S} \tag{A.4}$$

Where;

I_s = Capital investment costs of IHP in a sector *s*

$O\&M_s$ = Annual operations and maintenance costs of IHP in a sector *s*

B_s = Annual cost benefits in a sector *s*, calculated by Equation A.5

α = Capital recovery factor or annuity factor, calculated by Equation A.6

$$B_S = \left(Q_{out,S} \times P_{NG}\right) - \left(W_{in,S} \times P_{el}\right) \tag{A.5}$$

Where;

P_{NG} = National average natural gas price for industry

P_{el} = National average electricity price for industry

$$\alpha = \frac{(1+r)^L \times r}{(1+r)^L - 1} \tag{A.6}$$

Where;

r = Real discount rate, taken as 10% from the private perspective

L = Lifetime of industrial heat pumps assumed as 15 years

When plotting the marginal cost curve, industrial sectors are arranged in ascending order by conservation costs and displayed against their annual cumulative potential energy or CO_2 savings. The height of each industrial sector on the vertical axes displays the sector-specific costs of IHP applications while the width of each sector on the horizontal axes shows the annual energy or CO_2 savings. Finally, since annual benefits in Equations A.3 and A.4 are presented as negative values as a consequence of energy cost savings, all sectors that fall below zero on the horizontal axis will be considered cost-effective.

B. Methodology: Industrial Heat Pump Capital and O&M Costs

Zuberi et al. (2018) estimated the IHP capital costs based on catalog prices of necessary components given by different manufacturers. This study has adapted these capital costs for the U.S. industry as shown in Figure B.1. The range of capital costs of an IHP as a function of heating capacity includes equipment and installation costs and are presented in the figure after adjustments to correct for the regional differences in material and labor costs and exchange rates where necessary. The estimated specific capital costs are also in good agreement with Arpagaus and Bertsch (2020). The annual operations and maintenance (O&M) costs of IHP applications are assumed to be 1% of the capital costs.

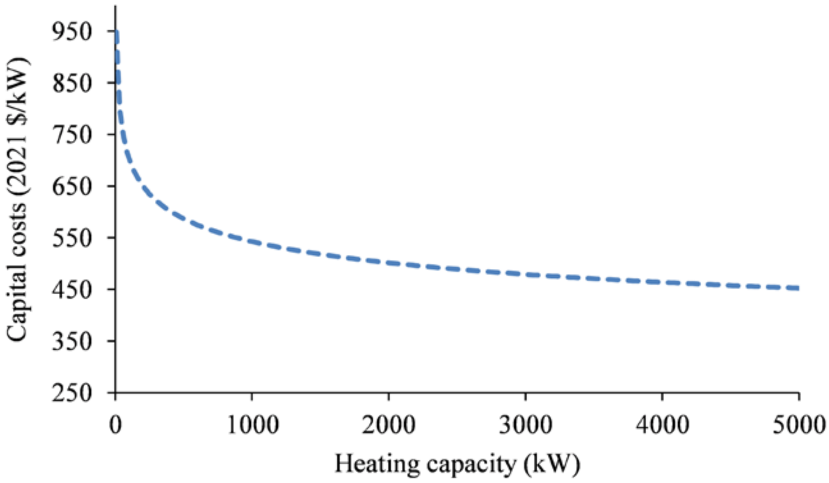

Figure B.1. Capital costs of an IHP as a function of its heating capacity.

C. Methodology: Projected Industrial Energy Prices

The current and projected national average prices of electricity and natural gas for U.S. manufacturing are acquired from the EIA's State Energy Data System (U.S. EIA, 2022b) and the Annual Energy Outlook (U.S. EIA, 2021a). These price projections are presented in Figure C.1.

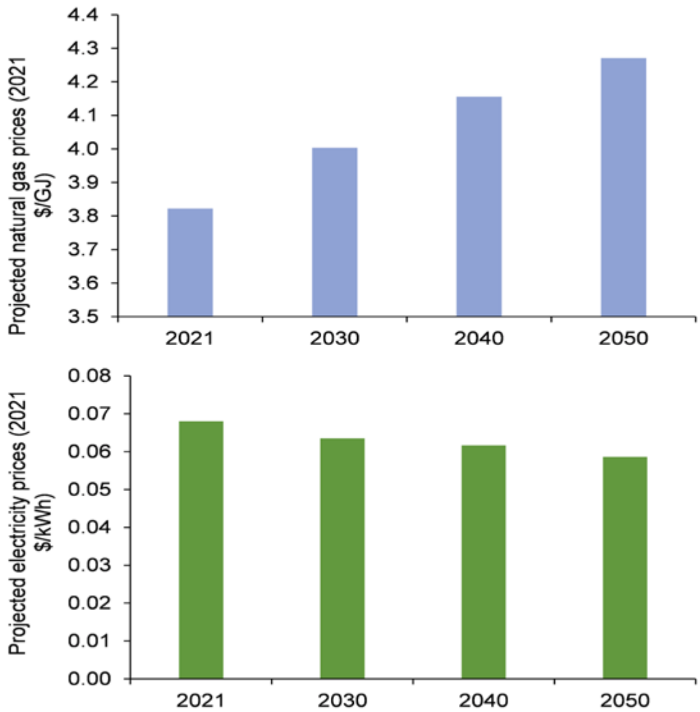

Figure C.1. Projected natural gas (top) and electricity (bottom) prices for the U.S. industry.

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Acronyms and Abbreviations

AEO	Annual Energy Outlook
AMO	Advanced Manufacturing Office
BAU	Business-As-Usual
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse Gases
GWP	Global Warming Potential
HFCS	High Fructose Corn Syrup
HTHP	High-Temperature Heat Pump
IEA	International Energy Agency
IHP	Industrial Heat Pump
NG	Natural Gas
O&M	Operations & Maintenance Costs
ODP	Ozone Depletion Potential
RDD&D	Research, Development, Demonstration, and Deployment
SDG	Sustainable Development Goals
SEC	Specific Energy Consumption
SEDS	State Energy Data System
SGHP	Steam Generating Heat Pump
USDA	United States Department of Agriculture