Techno-economic evaluation of industrial heat pump applications in U.S. pulp and paper, textile, and automotive industries

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Abstract:

Industrial process heat decarbonization through electrification could contribute significantly to climate change mitigation efforts. In the U.S. industry, thermal processes accounted for more than two-thirds of the total final energy demand in 2021. Cross-cutting electrification technologies like industrial heat pumps are suitable for the process heat supply to several industrial unit operations in a sustainable way while also improving overall energy efficiency. This study employs a bottom-up approach to investigate the techno-enviro-economic potentials of deploying high-temperature and steam-generating heat pumps in U.S. textile, pulp and paper, and automotive sectors in different timeframes. The results show that the annual technical potential energy and CO_2 savings by electrifying heat supply are 310 PJ (or 36% of the projected energy demand) and 28 $MtCO_2$ (or 71% of the projected CO_2 emissions) in 2050 respectively, however, these incur additional costs in each sector (ranging between 5 and 18 \$/GJ). The required heating capacity of industrial heat pumps is estimated at 15 GW, which translates roughly into a market of over 6'000 heat pump units and an investment volume of \$7 billion in the studied processes. Although there may be individual cost-effective opportunities for electrifying heat supply in specific industrial sites, the overall costs are estimated to be high in the three industrial sectors due to the large disparity between electricity and natural gas prices and low heat source temperatures. To overcome the identified techno-economic barriers, comprehensive action plans for different stakeholders are also given. This study provides novel insights that should inform policymakers' and executives' decisions about the electrification of the current and future U.S. industrial heat supply in relevant industrial sectors.

Keywords: *Industrial heat pumps, Electrification, Process heat, Specific costs, CO_2 emissions, Specific energy consumption, United States*

Highlights:

1. *Bottom-up approach to study the sectoral potentials of IHP applications.*
2. *The potential energy savings by IHP applications are 310 PJ p.a. in 2050.*
3. *The potential CO_2 savings by IHP applications are 28 Mt p.a. in 2050.*
4. *The costs are high due to the large disparity between electricity and fuel prices.*
5. *Novel insights that inform stakeholders' decisions about industrial electrification.*

1. Introduction

To fight climate change, the Paris agreement aims to limit the increase in global average temperature to less than 2°C and preferably to 1.5°C compared to the levels of the pre-industrial time [1]. The application of the historic agreement is also key for the accomplishment of the United Nations' Sustainable Development Goals (SDGs) and offers a roadmap to building climate resilience [2], [3]. Countries including the United States that contracted the historic agreement are required to develop and implement national climate action plans to cut their greenhouse gas (GHG) emissions. Climate change, in the form of heatwaves, extreme drought, calamitous wildfires, etc., has significantly impacted the U.S. The U.S. Bipartisan Infrastructure Deal aims to invest $65 billion and more in clean energy grids and transmission. The goal is to upgrade the power grid infrastructure and build new and resilient transmission lines to facilitate renewable energy deployment. The U.S. has also set an ambitious goal to decarbonize 100% of its power grids by 2035 [4], [5]. These efforts provide a great opportunity to decarbonize different U.S. economic sectors, for example, by switching 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. industry accounts for nearly 25% of the country's total energy consumption and CO_2 emissions [6]. Thermal processes in the U.S. industry are responsible for nearly 75% of the total final energy consumption [7], [8]. Given that the share of clean energy sources for power generation is expected to grow significantly in the coming years, decarbonization of the industrial process heat supply through electrification could contribute significantly to combating climate change. However, the heterogeneity of the manufacturing sector and the variety of different production techniques enable different levels of process integration. A detailed assessment to develop optimal industrial decarbonization pathways is hence needed [9]. In contrast, cross-cutting electrification technologies like electric-driven heat pumps that apply to a range of industrial processes without needing major modifications to the existing infrastructure may facilitate the green transition [9], [10].

Electric heat pumps are suitable for supplying process heat to several industrial unit operations in a sustainable way while also improving overall energy efficiency [9], [11]. 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. industry sector has been limited, unlike in Europe and Japan where substantial IHP deployment in manufacturing has occurred [12]. 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 in U.S. manufacturing. While a large number of IHP applications have already been recognized particularly in the food and beverage industry [13]–[16], the potential applications in other relevant manufacturing sectors including textile, pulp and paper, and automotive, which usually require low-to-medium temperature heat demand suitable for IHP applications, are vaguely studied in the scientific literature.

Furthermore, the optimal placement of an IHP in an industrial plant can be studied through pinch analysis (see Section 2.2 for details). Several case studies on the integration of IHPs in industrial plants using pinch techniques have been performed in the literature. Olsen et al. [14] and Becker et al. [15] studied the case of IHP applications in candy and cheese production facilities. Li et al. [17] analyzed IHP integration in a crude distillation unit. Similarly, Beck et al. [18] investigated IHP applications for steam supply in steel plants. It must be noted that waste heat resources available in an industrial plant are strictly site-specific and these case studies were performed based on plant-level process stream data. Given the different plant-specific characteristics and constraints, developing composite curves generalized for a global industrial sector possess a great level of uncertainty. On the contrary, techno-economic analysis for IHP integration in an industrial sector is performed typically based on the estimation of available waste heat at certain temperature levels that can be sourced by IHPs for process heat supply at suitable temperatures. The matching of these two heat flows in different industrial sectors, as studied by Kosmadakis [19] and Seck et al. [20], results in the technical potential for energy and emissions reduction due to IHP integration. However, the limitation of this approach is that it often fails to analyze the sector-specific unit operations that use the process heat supplied by IHPs.

To address these literature gaps, this work develops a general and conservative methodology to identify and generalize potential applications in different industrial processes where a significant amount of heat demand can be fulfilled by IHPs. More precisely, the aims and objectives of this work are:

i) To review the current state-of-the-art of IHPs and their potential applications,
ii) To analyze the technical, economic, and environmental potentials of the IHP applications in U.S. textile, pulp and paper, and automotive sectors under different energy supply and price scenarios, and
iii) To identify implementation drivers and barriers, and propose action plans to overcome these barriers.

It should be noted that this work directly builds on our previous work for the food and beverage industries [16] which have different levels of IHP integration potential than the sectors studied in this article. Furthermore, this detailed study offers recommendations for all the relevant stakeholders and provides novel insights to inform policymakers' and executives' decisions about the electrification of the current and future process heat supply in the studied manufacturing sectors.

2. Materials and methods

2.1. Industrial heat pumps: state-of-the-art

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}). Heat pumps use low-boiling point refrigerants as transitional fluids to absorb heat and vaporize in an evaporator. Despite the evaporation, the refrigerant is not hot enough to warm the process fluid, hence a compressor is used to increase the temperature and pressure of the refrigerant further 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. The temperature and pressure of the refrigerant are further reduced in the final step after passing it through an expansion valve [21].

Heat pumps are very efficient because they only transfer heat instead of combusting fossil fuels to create it, ultimately reducing GHG emissions from heating applications such as in the industry sector [21]. The performance of a heat pump is defined by the coefficient of performance (COP) which is the ratio of heat output to work (electricity) input, as shown in Eq. 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 a heat source (T_{source}) and sink (T_{sink}) having absolute temperatures. The maximum theoretical or Carnot COP is given as Eq. 2. Since thermodynamic processes undergo many losses, the real COP of a heat pump is a fraction of the Carnot COP. An efficiency term, also known as quality grade, η_{HP} that relates the actual COP (COP_{real}) to the Carnot COP (COP_{carnot}) is given as Eq. 3. The COP of a heat pump is greater than 1 as it always supplies more heat than the electricity consumed.

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

Where ΔT_{lift} is the temperature lift applied to heat sources and sinks.

$$\eta_{HP} = \left(\frac{COP_{real}}{\mathrm{COP}_{carnot}}\right) \quad (3)$$

The ranges of IHP capacities and sink temperatures have steadily grown over the years. IHPs with high-temperature heat sink temperatures of up to 165°C are commercially available at scale [22]. The heating capacities of IHP range from 20 kW to 100 MW. 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 [23], [24]. The COP values as a function of the respective temperature lift for the various IHPs on market with 140°C sink temperatures were studied by Arpagaus et al. (2018) [24] and demonstrated that the COP values could range from 1.6 to 5.8 at temperature lifts of 130 to 40 K respectively. Furthermore, the quality grade η_{HP} of an IHP typically ranges between 40 and 60% [25], and this work assumes a conservative value of 45%.

2.2. Key assumptions and limitations

The optimal placement of an IHP in an industrial plant can be investigated through pinch analysis. 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 [26]. The point where the hot and cold composite curves most closely approach each other is called the “pinch point”. There is a heat deficit above the pinch point and a heat surplus below the point [14]. 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, referred to as temperature lift. The higher the temperature lift, the lower the COP and the higher the capital and operational costs of an IHP [27]. Therefore, it is critical to evaluate the available excess heat resources prudently that can be utilized for optimal IHP integration into a process.

The excess heat resources available in an industrial plant are strictly plant-specific. The level of process integration of an industrial plant depends on a range of techno-economic variables (e.g. excess heat volume, temperature, excess heat uses that compete with each other, plant complexity, space shortage, energy prices, external contracts, etc.) that are unique to that plant. Given these plant-specific characteristics and constraints, performing pinch analysis for a generalized industrial process to estimate the pinch point offers a significant level of uncertainty. In other words, the resultant IHP integration design may not necessarily be optimal. This article’s primary objective is to identify and generalize potential applications in the aforementioned three industrial processes where a large share of process heat can be supplied by IHPs. Moreover, since the plant-level data for each industrial plant within each sector are not publicly available partly due to confidentiality issues, we are making a simplifying assumption that heat sources (such as plant water and air supply) are available at the ambient temperature of 25°C[1] and pressure of 1 bar.

For a specific IHP application in an industrial plant, there might be excess heat sources available at higher temperatures than 25°C. The use of these sources by the IHP for the same application would improve its performance. Hence, the techno-economic results (e.g. COPs, future electricity demand by IHPs, marginal costs, etc.) computed in this study must be considered conservative and could significantly change if more systematic process optimization techniques (e.g. pinch analysis) are applied to individual industrial sites. However, the sensitivity of the economic energy conservation and CO_2 abatement potentials to changes in heat source temperature has been tested and presented in Section 3.2.

Apart from heat source temperatures, there are other important assumptions and considerations made in

[1] The production in the studied manufacturing sectors is typically done in closed environments where building temperatures are maintained for thermal comfort. Hence the ambient temperature at 25°C is assumed to be reasonable for the base case scenario. However, in some cases, the ambient temperature could be lower than 25°C which could impact IHP efficiencies.

this study. The terminology for the temperature level of an IHP is not consistent in the scientific literature. This article classifies IHPs with heat sink temperatures lower than 100°C as high-temperature heat pumps (HTHP) while heat pumps with supply temperatures greater than or equal to 100°C are termed steam-generating heat pumps (SGHP). There are only a few SGHP manufacturers on the market that can provide steam at heat sink temperatures greater than 120°C, unlike HTHPs which are at an advanced stage of commercialization. The literature review also shows that there are a substantial number of HTHPs already applied in different industrial plants across the globe, however, only a few SGHP installations have been made in industrial facilities due to the technology's early stage of commercial deployment and lack of awareness. Hence the following two implementation scenarios have been developed for IHP applications in the three U.S. industrial sectors:

- *Scenario 1 - Conservative:* Only HTHP applications are considered. These applications include heat demand at temperatures less than 100ºC and boiler feedwater preheating for steam generation.
- *Scenario 2 - Ambitious:* Both HTHP and SGHP applications are considered. The maximum heat sink temperature of SGHP is cut-off at 150ºC for the following two reasons.
  - i) The existence of even fewer SGHP manufacturers who could deliver temperatures over 150ºC.
  - ii) The maximum temperature lift of 130 K was established by only a few SGHP suppliers. Because of our assumption for heat source temperature (25ºC), a temperature lift higher than 130 K is unrealistic.

It must be noted that the climate impact of electrification of process heat supply cannot be substantial (or even negative) if electricity generation remains CO_2-intensive. Therefore, it is critical to decarbonizing the electricity grid through renewables to decrease the CO_2 intensity of process heat in industry. Given the U.S. electric grid decarbonization targets at the federal and state levels (see the summary of these targets presented by [28]), this study assumes the rate of grid decarbonization in the future. Two grid decarbonization scenarios have been created that state: a) 2035 given the federal pledge[2], and b) 100% CO_2-free electricity by 2050 as assumed by several other studies in the literature. This work further assumes a linear trend for grid decarbonization in both these scenarios. The national average electricity grid emission factor in 2021 is estimated at 0.37 tCO_2/MWh based on [29].

Furthermore, there is a consensus that demand for consumer products generally increases with a country's population growth. Since the studied industrial processes are manufacturing consumer products including textiles, paper, and automobiles, this article estimates the future production volumes based on the U.S. population growth projected by U.S. Census Bureau (2020) [30]. These production volumes are used to determine the sectoral frozen efficiency energy demand for the base case. Frozen efficiency energy demand represents the amount of final energy which the industrial processes would have used if no energy efficiency improvement due to IHP applications had been implemented. It is calculated by multiplying the specific energy consumption (SEC) of each product in the base year 2021 by the production volumes in the future years. Since the estimated production volumes and SEC values possess uncertainty due to the lack of detailed statistics, the resulting final energy demand has a degree of uncertainty. However, frozen efficiency energy demand estimates offer a basis to compare final energy demand and CO_2 emissions with or without IHP integration in the studied U.S. industrial sectors.

Finally, the number of production facilities within each sector [31] and their utilization rates [32] are acquired from national statistics to estimate the required number of IHPs and capacities in the studied sectors. The specific energy demand (SEC) of each process is adapted based on [33]. The individual sources for process-specific production volumes are given in the relevant sections.

[2] The U.S. administration has set an ambitious target to produce 100% carbon-free electricity by 2035 [4]. Hence in this grid decarbonization scenario, the national average electricity grid emission factor is assumed zero in 2035.

2.3. Potential energy and CO_2 savings

Potential energy conservation *ES* due to the electrification of heat demand in the three studied industrial sectors can be estimated by Eq. 4. The difference between heat demand at a certain temperature by an industrial process (heat sinks) and the potential increase in electricity demand due to IHP applications as a replacement of current process equipment for the same energy service, is determined as energy savings.

$$ES = Q_{out} - W_{in} \tag{4}$$

Where;

Q_{out}= Current heat demand at a certain temperature by an industrial process
W_{in}= Electricity demand by IHPs for the same energy service in an industrial process

Similarly, potential CO_2 emissions reduction *CA* due to IHP applications and simultaneous electricity grid decarbonization can be estimated by the following equation:

$$CA = (Q_{out} \times f_{NG}) - (W_{in} \times f_{grid}) \tag{5}$$

Where;

f_{NG} = Natural gas emission factor, taken as 0.05 tCO_2/GJ based on [34]
f_{egrid} = National average electricity grid emission factor based on [29]

2.4. Costs of IHP applications

In this article, specific costs of energy conservation C_{ES} and CO_2 abatement C_{CA} due to IHP applications in the three industrial sectors are calculated using the following equations:

Costs of conserved energy:

$$C_{ES} = \frac{\alpha.I + O\&M - B}{ES} \tag{6}$$

Costs of CO_2 abatement:

$$C_{CA} = \frac{\alpha.I + O\&M - B}{CA} \tag{7}$$

Where;

I = Capital investment costs of IHPs
O&M = Annual operations and maintenance costs of IHPs
B = Annual cost benefits, calculated by Equation 8
α = Capital recovery factor or annuity factor, calculated by Equation 9

$$B_s = \left(Q_{out,s} \times P_{NG}\right) - \left(W_{in,s} \times P_{el}\right) \tag{8}$$

Where;

P_{NG} = National average natural gas price for the industry in 2021
P_{el} = National average electricity price for the industry in 2021

$$\alpha = \frac{(1+r)^L \times r}{(1+r)^L - 1} \tag{9}$$

Where;

r = Real discount rate, taken as 10% from the private perspective
L = Lifetime of industrial heat pumps assumed as 15 years based on [35]

It should be noted that since annual benefits in Eq. 6 and Eq. 7 are presented as negative values as a consequence of energy cost savings, all the costs associated with IHPs applicable in the studied industrial processes that fall below zero on the horizontal axis (negative costs) will be considered cost-effective.

2.5. Supporting data

A study by Zuberi et al. (2018) [36] estimated the IHP-specific capital costs based on catalog prices of necessary components given by different manufacturers. This article has adapted these capital costs for the U.S. industry as shown in Fig. 1. The range of IHP capital costs as a function of heating capacity includes equipment and installation costs (assumed approximately 20% of the total capital costs based on [36]) and are given after adjusting for the regional differences in labor and material costs and exchange rates. The specific capital costs adapted here are also in good agreement with [37].

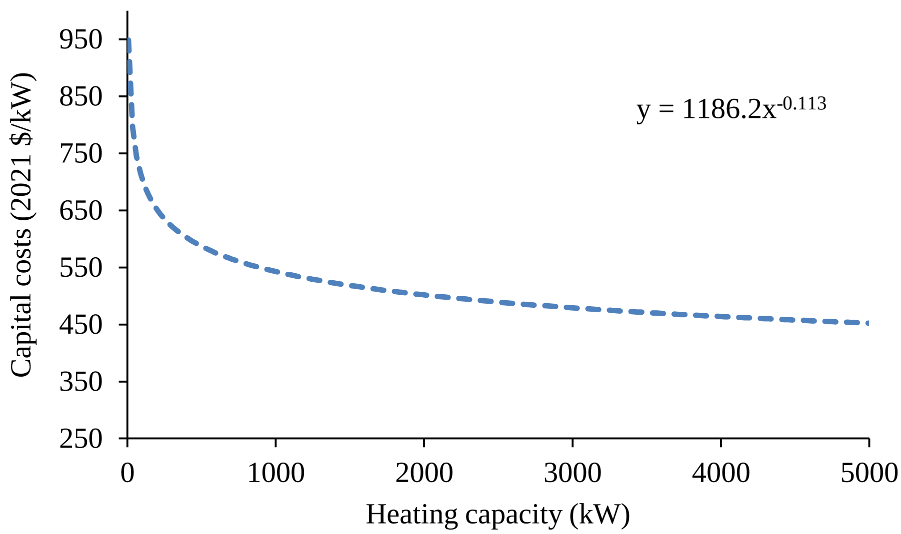

Figure 1. Capital costs of IHPs as a function of their heating capacity.

Furthermore, the IHP annual operations and maintenance (O&M) costs (excluding energy costs) are assumed to be 1% of the capital costs in this study based on [35]. However, some studies have shown that the IHP O&M costs can be significantly large i.e. up to 6% of the capital costs [38]. 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 [39] and the Annual Energy Outlook [6]. These price projections and the corresponding electricity-to-gas price ratios are presented in Fig. 2.

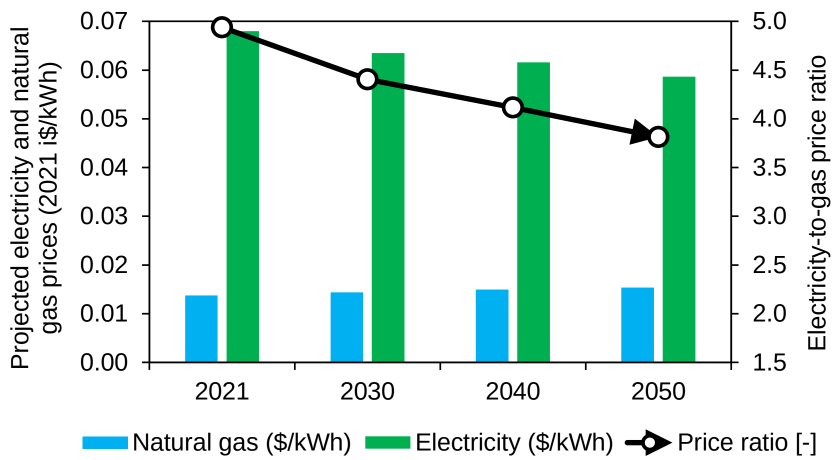

Figure 2. Projected national average electricity and natural gas prices for the U.S. industry.

3. Results and discussion

3.1. Techno-economic assessment of IHP applications

3.1.1. Textile manufacturing

Production process

The U.S. woven fabric mills weaved roughly 0.5 Mt of grey goods in 2021 (estimated based on [40]). 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 below. 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 yarn. 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 [33], [41].

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 de-sizing, 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 [33], [41]. The two subsections below discuss the IHP applications in textile spinning and weaving and wet-processing industries.

Textile spinning and weaving

<u>*IHP application*</u>

The process heat demand for textile spinning and weaving at temperatures suitable for IHP applications is highlighted in Tab. 1 (in green color). The schematic of these IHP applications and their corresponding COPs is presented in Fig. 3. 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 there is no HTHP application identified for weaving, and the conservative scenario (or Scenario 1) is not developed. In Ambitious Scenario 2, a SGHP can be employed to generate steam at 150ºC for drying and sizing. The required heating capacity of SGHPs is estimated at 150 MW in the U.S. textile spinning and weaving processes. Furthermore, the COP of the SGHP is determined to be low i.e. 1.5, mainly because the temperature lift is high.

Table 1. Specific energy consumption of conventional and modified processes in the textile spinning and weaving industry.

Conventional energy demand			Process steps	Modified process with IHP	
Fuel use in boilers	Steam or water temp.	Electricity use		Electricity use in IHP	Electricity use in other processes
GJ/t (kWh/t)	*ºC*	*kWh/t*		*kWh/t*	*kWh/t*
		161.5	Winding & Spinning		161.5
		161.5	Warping		161.5
10.5 (2907.5)	150		Slashing/Drying	1493.5	
		323.1	Weaving		323.1
10.5 (2907.5)	150	646.1	Total	1493.5	646.1

<u>*Notes:*</u>
SEC values are per tonne of gray products.
Boiler system efficiency is assumed at 80% (adapted based on [7], [8]).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

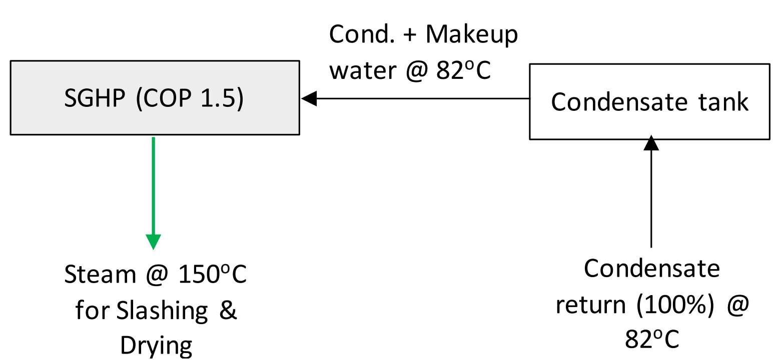

Figure 3. Industrial heat pump applications in the textile spinning and weaving industry.

It should be noted that the optimal placement of an IHP depends on the level of integration in an industrial plant and the available excess heat resources. However, since the level of integration varies by industrial plant, it gets very challenging to estimate available excess heat source temperatures. As discussed, we have assumed the available heat source at ambient conditions, for example, plant water supply at 25ºC. Hence the schematic in Fig. 3 and all other schemes later discussed may not be the ideal configuration for a specific production plant. This is the best that could have been done to generalize the applications for the studied processes regardless of their level of integration. Fig. 3 only highlights the typical process step to which IHP could potentially be applied. It is therefore advised that a more systematic analysis (or pinch analysis) must be done for an individual site, based on its detailed site-specific data, to design an optimal IHP system for a specific plant. Our assumptions are reasonable for the industry-level analysis. Given this background, the following results 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 specific costs). However, to assess the changes in the magnitude of all the computed results, a detailed sensitivity analysis is done in Section 3.2.

Energy, emissions, and cost implications

The comparison of the specific energy demand of the conventional and electrified (using IHPs) processes is also shown in Tab. 1. The change in annual final energy demand in the U.S. textile weaving industry in different IHP application scenarios and timeframes is presented in Fig. 4.[3] The figure shows that the measure suggested in Fig. 3 can reduce 40% of the total final energy demand despite the projected increase in production between 2021 and 2050. As mentioned earlier, 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 SGHPs (Scenario 2) 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, 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.

The change in annual CO_2 emissions in the U.S. weaving plants in different IHP application scenarios and timeframes is presented in Fig. 5. The figure shows negligible potential for CO_2 abatement in 2021 as a result of the 100% adoption rate of SGHPs in the sector.[4] However, it is estimated that around 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 in this scenario.

[3] It should be noted that no process 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 Fig. 3 (and in all the similar figures in Sections 3.1.2 – 3.1.3) 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.

[4] Electrification projects will be implemented at the plant level. If a given industrial plant in a specific region electrifies its process heating demand with the help of IHPs today and purchases renewable electricity through a power purchase agreement, then CO_2 emissions reductions at a large scale can be achieved immediately.

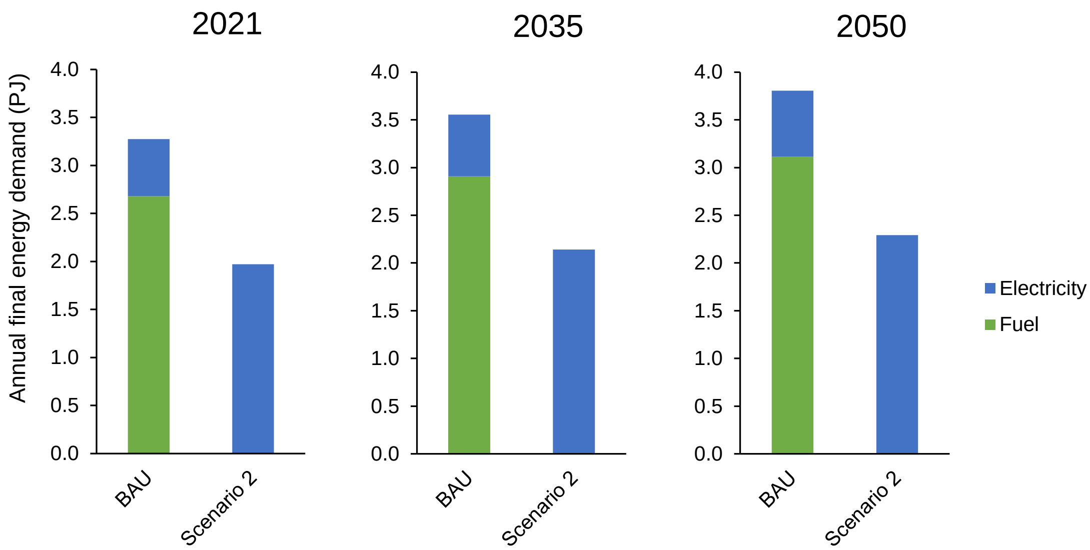

Figure 4. Annual final energy demand in the U.S. textile spinning and weaving industry up to 2050 (This is a total technical potential assuming a 100% adoption rate). Note: BAU does not consider any IHP applications while Scenario 2 considers both HTHP and SGHP applications.

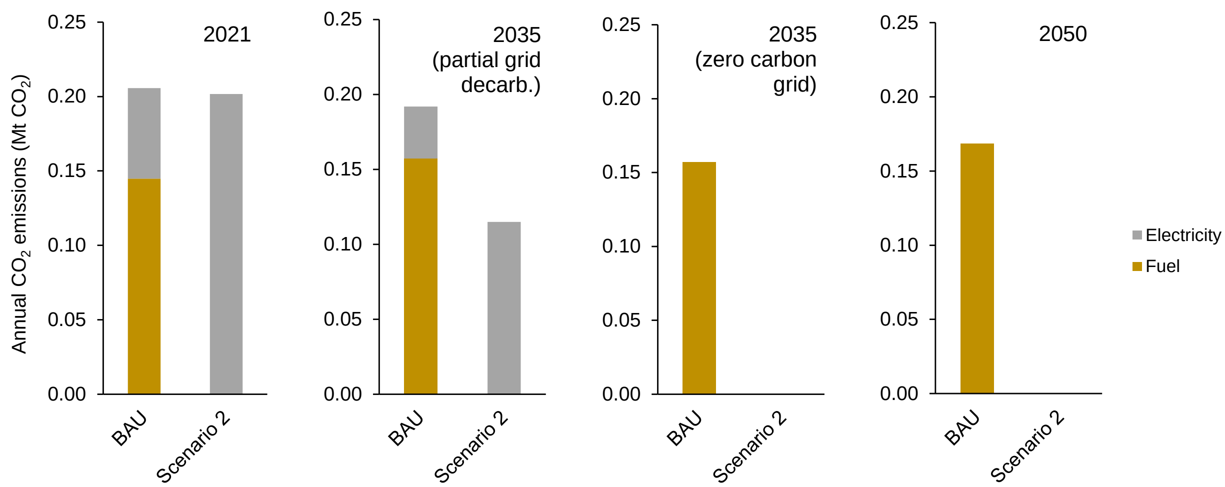

Figure 5. Annual CO_2 emissions from the U.S. textile spinning and weaving industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

According to Fig. 6, the specific costs of conserved energy and CO_2 abatement due to deploying SGHPs are estimated at 18 \$/GJ and 161 \$/t CO_2 per year respectively in 2050. 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 the higher side (see earlier discussion). It is therefore recommended to explore suitable excess heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

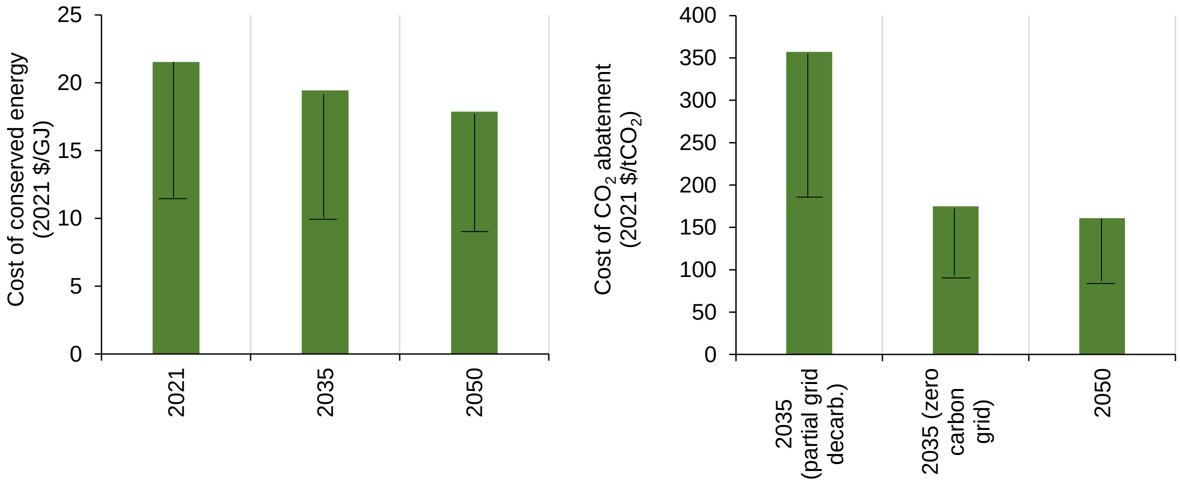

Figure 6. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. textile spinning and weaving industry under Scenario 2. Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 3.2 for more details.

Textile wet-processing

<u>IHP applications</u>

The process heat demand for textile finishing at temperatures suitable for IHP applications is highlighted in Tab. 2 (in green color). The schematic of these IHP applications and their corresponding COPs are presented in Fig. 7. The steam condensate returns from the process at around 82°C, and the mixing of makeup water and return condensate at different temperature levels destroys exergy. Hence 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 HTHPs for the U.S. textile finishing industry is estimated at 12 MW.

It must be noted that most of the processes in Tab. 2 need hot water at different temperatures which can ideally be supplied directly by HTHPs. 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 time slices. This will require multiple small-scale HTHPs 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 SGHPs.

In Ambitious Scenario 2, two separate SGHPs can be employed to generate process steam, one at 120°C for de-sizing, scouring, mercerizing, bleaching, washing, and dyeing/printing, and the second at 150°C for drying applications. The required heating capacity of SGHPs is estimated at 375 MW. Furthermore, the COP of the SGHPs is 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 (see earlier) will result in a higher COP or lower electricity demand for an IHP operation. It must be noted that the schematic shown in Fig. 7 may not be the ideal solution for a specific weaving plant for reasons already explained.

Table 2. Specific energy consumption of conventional and modified processes in textile wet-processing.

Conventional energy demand				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 IHP	Electricity use in other processes
GJ/t (kWh/t)	*GJ/t (kWh/t)*	*ºC*	*kWh/t*		*GJ/t (kWh/t)*	*kWh/t*	*kWh/t*
4.7 (1292.2)				Singeing	4.7 (1292.2)		
	0.9 (242.3)	120		Desizing			
	3.5 (969.2)	120	113.1	Scouring			113.1
	2.2 (605.7)	120	16.2	Mercerizing & Washing			16.2
	4.9 (1373.0)	120	32.3	Bleach & Wash/rinse			32.3
	4.4 (1211.5)	150	64.6	Drying		3285.5	64.6
	7.6 (2099.9)	120	161.5	Dyeing & Washing			161.5
	0.9 (242.3)	120		Printing			
7.4 (2067.6)			32.3	Drying/setting	7.4 (2067.6)		32.3
	2.5 (686.5)	120		Steaming			
	0.9 (242.3)	120	32.3	Washing			32.3
4.7 (1292.2)			32.3	Dry & frame	4.7 (1292.2)		32.3
16.7 (4652.0)	27.6 (7672.6)		484.6	Total	16.7 (4652.0)	3285.5	484.6

Notes:
SEC values are per tonne of finished products.
Boiler system efficiency is assumed at 80% (adapted based on [7], [8]).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

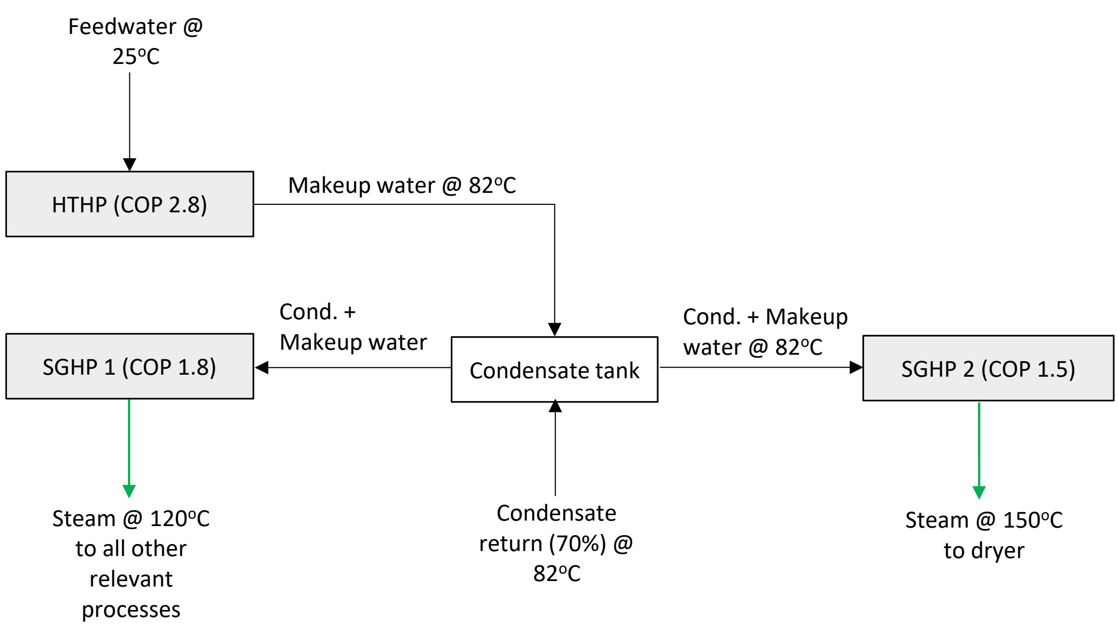

Figure 7. Industrial heat pump applications in the textile wet-processing industry.

Energy, emissions, and cost implications

The specific energy demand of the conventional and electrified IHP-based processes are compared and shown in Tab. 2. The change in annual final energy demand in the U.S. textile finishing industry in different IHP application scenarios and timeframes is presented in Fig. 8. The figure illustrates that the measures suggested in Fig. 7 can reduce 34% of the total final energy demand despite the increase in production projected from 2021 to 2050. It is quantified that approximately 0.2 PJ per year of final energy savings can be realized 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 COP of the IHPs. 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.

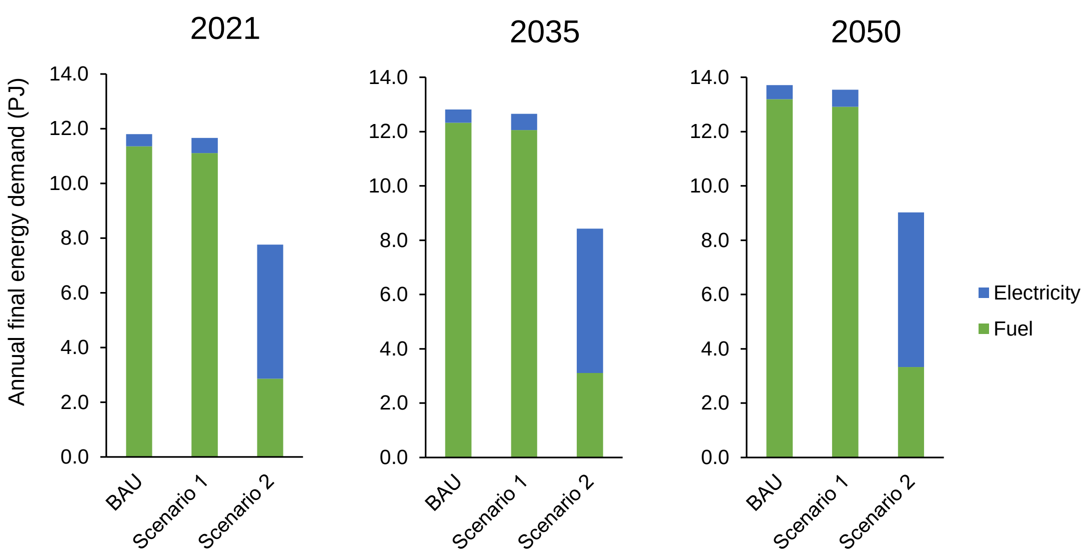

Figure 8. Annual final energy demand in the U.S. textile wet-processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate). Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The change in annual CO_2 emissions in the U.S. textile finishing industry in different IHP application scenarios and timeframes is shown in Fig. 9. The figure shows 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. Moreover, the different levels of potential CO_2 abatement in 2035 in Fig. 9 (and similar for other sectors) represent different grid decarbonization scenarios (see Section 2.2).

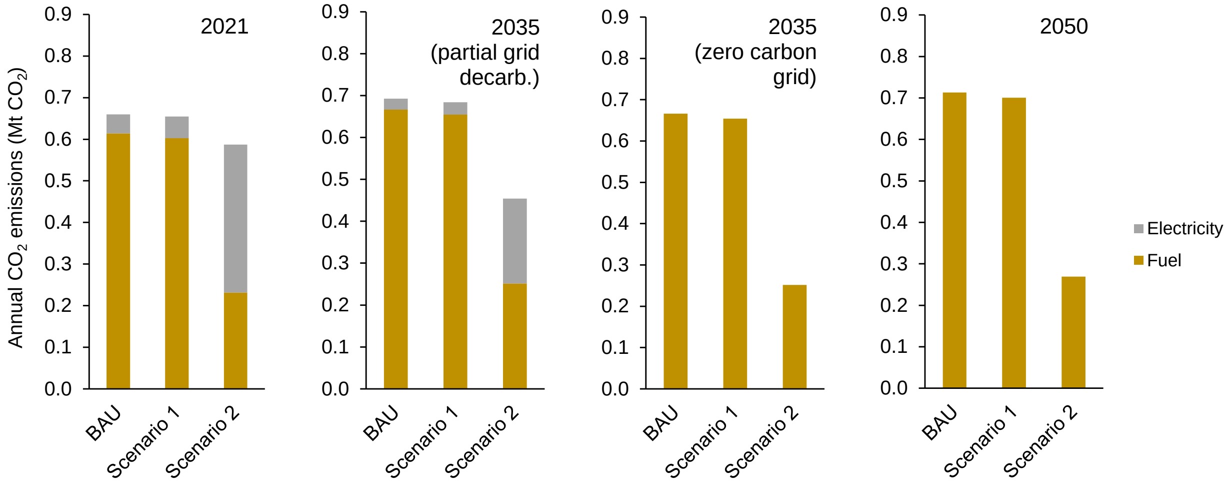

Figure 9. Annual CO_2 emissions from the U.S. textile wet-processing industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

Figure 10 presents the specific costs of conserved energy and CO_2 abatement for IHP applications in the U.S. textile finishing industry. The figure shows that the energy conservation costs range from 10 to 15 \$/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. It is evident that integration of IHPs in U.S. textile finishing 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 excess heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

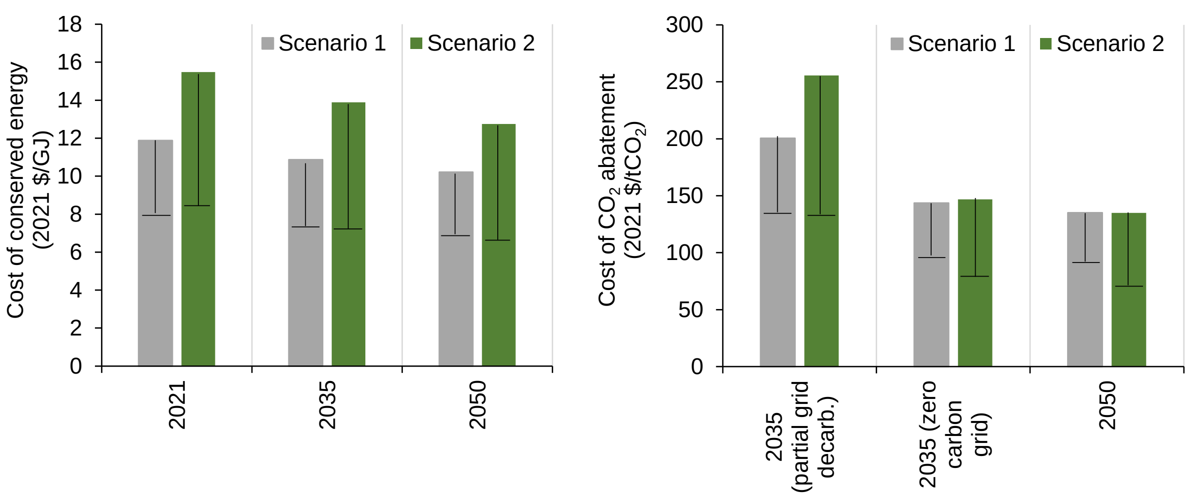

Figure 10. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. textile wet-processing industry. Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 3.2 for more details.

3.1.2. Pulp and paper manufacturing

Production process

The U.S. paper mills produced around 26 Mt in 2021 (estimated based on [42]). The production volume is estimated to grow to 30 Mt in 2050. The pulp and paper production processes are 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 [43].

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 [44].

The washed pulp is then screened, cleaned, and most of the water is removed to prepare it for papermaking. 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 [33].

IHP applications

Tab. 3 presents the typical specific final energy consumption of an integrated paper mill, disaggregated by direct and indirect fuel and electricity demand in each step. The process heat demand at a temperature suitable for IHP application is also highlighted in the same table (in green color). As stated earlier, the steam produced in the recovery furnace could be sufficient for supplying heat to the digestor, bleaching machine, and multiple evaporators. Therefore, paper drying is assumed to be the only application that requires steam from other sources including IHPs. All of the steam condensate from the paper drying process can be recovered, requiring no makeup water preheating. In other words, there is no HTHP application identified for papermaking and no conservative scenario (or Scenario 1) is hence developed. However, depending on specific cases, HTHP may have some applications in the pulp and paper industry.

Fig. 11 presents the schematic of the SGHP application and its corresponding COP. In Ambitious Scenario 2, a SGHP can be employed to generate process steam at 120^{o}C for drying after the press section. The required heating capacity of SGHP for the drying application 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 will result in a higher COP or lower electricity demand for an IHP operation.

Table 3. 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 (kWh/t)	*GJ/t (kWh/t)*	*ºC*	*kWh/t*		*GJ/t (kWh/t)*	*kWh/t*	*kWh/t*
			90.4	Barker, Shredder, Chipper			90.4
	5.9 (1641.1)	170		Digestor			
			72.4	Washing & Filtration			72.4
	6.3 (1748.8)	145		Multiple evaporators			
	-19.2 (-5328.3)	205		Recovery furnace			
2.2 (610.6)				Kiln	2.2 (610.6)		
			145.4	Screening knotting			145.4
	7.0 (1938.3)	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 (3015.2)	120	64.6	Drying		1252.1	64.6
			27.8	Calendar			27.8
			27.8	Winding cutting trim.			27.8
2.2 (610.6)	10.9 (3027.8)		989.2	Total	2.2 (610.6)	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 [7], [8]).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

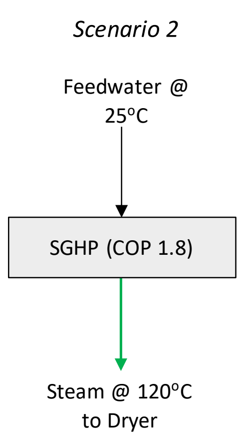

Figure 11. Industrial heat pump application in the pulp and paper industry.

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 Tab. 3. 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 Fig. 12. The figure shows that the measure suggested in Fig. 11 can save 41% of the total final energy demand due to the electrification of steam generation. 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.

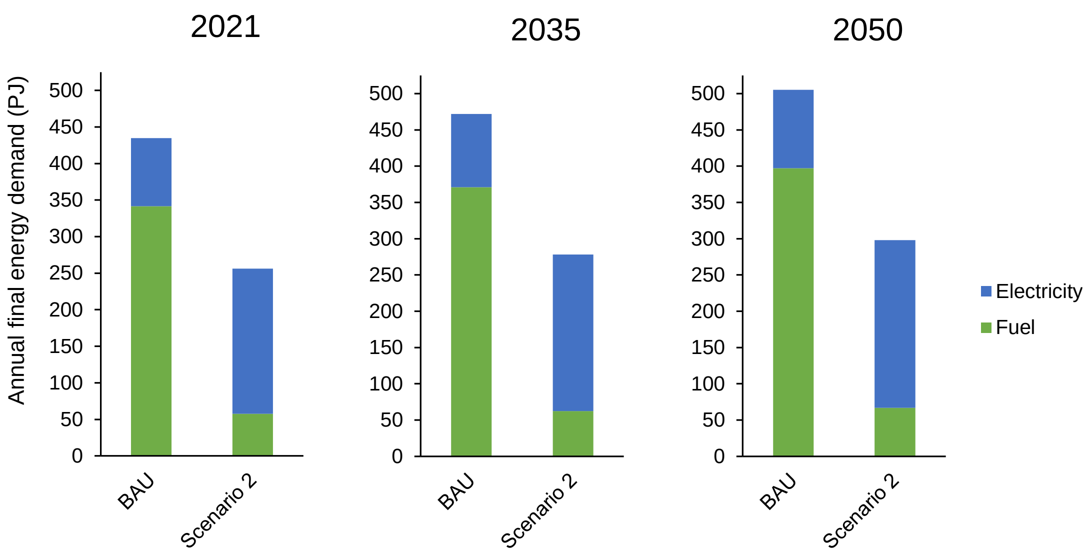

Figure 12. Annual final energy demand in the U.S. pulp and paper industry up to 2050 (This is a total technical potential assuming a 100% adoption rate). Note: BAU does not consider any IHP application, Scenario 1 considers only HTHP applications, and Scenario 2 considers both HTHP and SGHP applications.

The annual CO_2 abatement potentials in the U.S. paper mills in different IHP application scenarios and timeframes are presented in Fig. 13. The figure shows that 4.6 Mt of CO_2 emissions can be reduced already in 2021 as a result of the 100% adoption rate of the IHP application in the sector, despite the increased electricity demand which has an average emission factor greater 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. The reason for the significant potential CO_2 abatement is the projected rate of electricity grid decarbonization between 2021 and 2050.

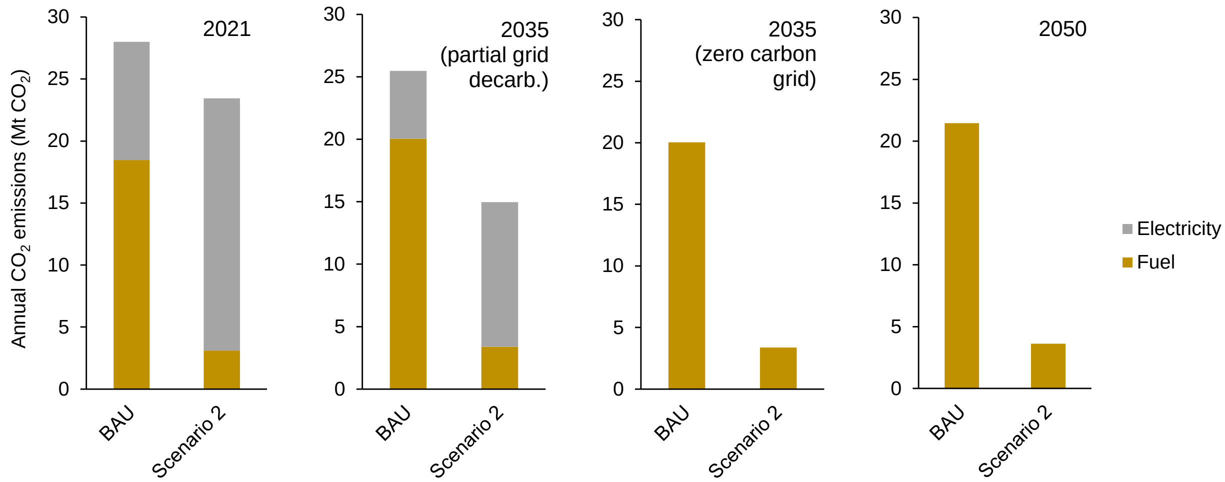

Figure 13. Annual CO_2 emissions from the U.S. pulp and paper industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

The specific energy conservation and CO_2 abatement costs due to IHP applications in U.S. paper mills are presented in Fig. 14. The figure shows that the costs of energy conservation range from 5 to 7 $/GJ in different IHP application scenarios and timeframes. The figure also shows that the CO_2 abatement costs are estimated at approximately 60 $/t CO_2 in 2050. The figure further shows that none of the scenarios have costs falling below zero which would have otherwise been considered cost savings. A large difference between the electricity and fuel prices in the U.S. industry is one of the major reasons for the specific costs to be high. The assumed heat source temperature is another reason for the high costs (see earlier explanation). It is therefore recommended to identify and utilize suitable excess heat sources at higher temperatures to minimize the temperature lifts, and consequently the electricity costs.

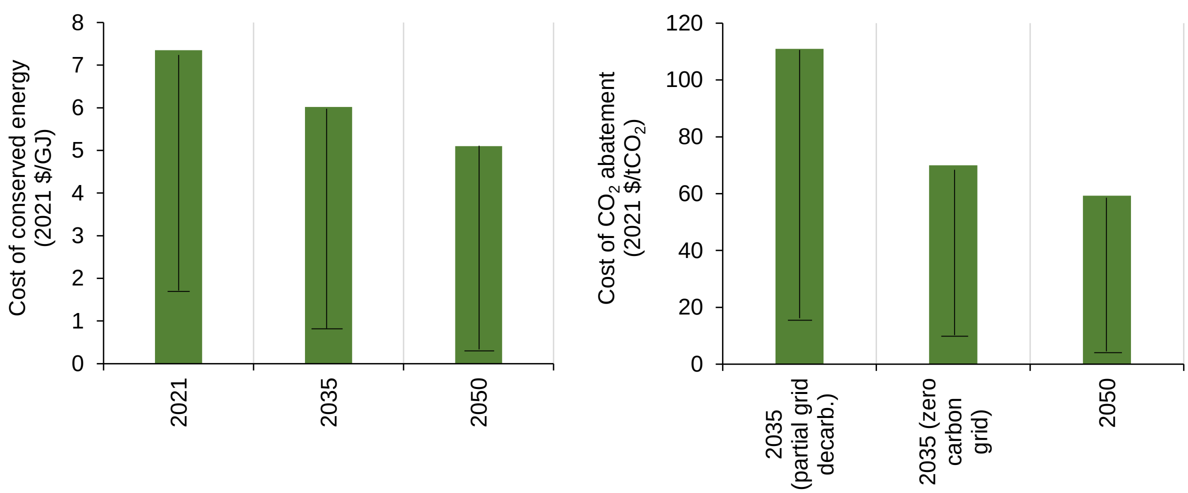

Figure 14. Cost of conserved energy and CO_2 abatement for industrial heat pump applications in the U.S. pulp and paper industry. Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 3.2 for more details.

3.1.3. Automotive manufacturing

Production process

The U.S. automotive industry manufactured around 9 million automobiles in 2021 [45]. 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 the 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 [46], [47].

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 [46], [47].

IHP applications

The typical specific final energy consumption of an automotive plant, disaggregated by direct and indirect fuel and electricity demand in each step is presented in Tab. 4. The table also highlights, in green color, the process heat demand at temperatures suitable for IHP applications. Fig. 15 presents the schematic of these IHP applications and their corresponding COPs. In Conservative Scenario 1, two separate HTHPs 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 [48], [49]. The required heating capacity of IHPs 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 4. Specific energy consumption of conventional and modified processes in the automotive industry.

Conventional energy demand				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 IHP	Electricity use in other processes
GJ/t (kWh/t)	*GJ/t (kWh/t)*	*°C*	*kWh/t*		*GJ/t (kWh/t)*	*kWh/t*	*kWh/t*
			180.9	Metal cutting			180.9
			82.1	Cut metal			82.1
0.3 (69.8)	0.3 (72.5)	27	1.3	Welding	0.3 (69.8)		1.3
			190.6	Body assembly			190.6
	1.7 (458.6)	177	3.9	Body preparation	1.7 (458.6)		3.9
1.0 (265.6)				Drying	1.0 (265.6)		
	4.8 (1339.5)	27	1.9	Painting		428.7	1.9
3.5 (977.6)				Drying	3.5 (977.6)		
			91.1	Trim assembly			91.1
	0.4 (119.0)	50		Wash & test			
			228.7	Final assembly			228.7
	0.4 (119.0)	50	57.5	Finishing & Washing			57.5
			37.5	Compressor			37.5
4.7 (1312.9)	7.6 (2108.5)		875.5	Total	6.4 (1785.1)	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 [7]).
Process steps highlighted in green color show the processes with heat demand at temperatures suitable for IHP applications.
1 GJ = 277.78 kWh

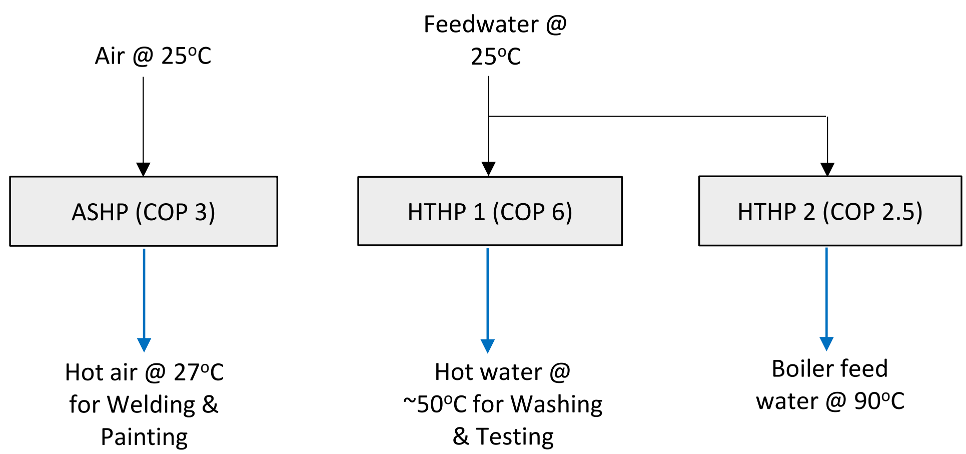

Figure 15. Industrial heat pump applications in the automotive industry.

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 Tab. 4. The change in annual final energy demand in the U.S. automotive industry in different IHP application scenarios and timeframes is illustrated in Fig. 16. The figure shows that the measures suggested in Fig. 15 can decrease the total final energy demand by 30%. It is estimated that approximately 96 PJ per year of final energy can be reduced if all HTHP applications are realized 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, 128 PJ per year of fuel demand could be decreased 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.

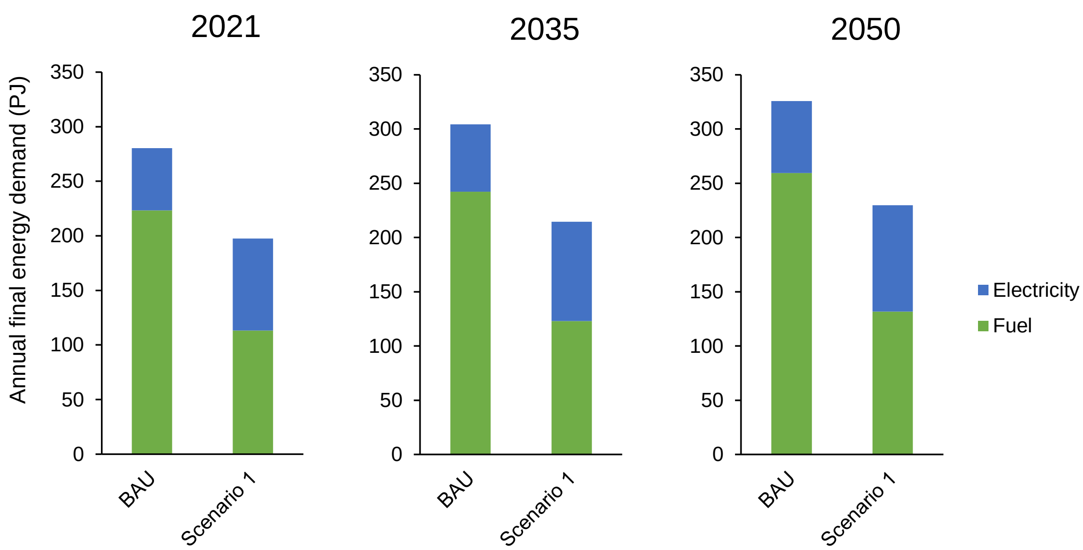

Figure 16. Annual final energy demand in the U.S. automotive industry up to 2050 (This is a total technical potential assuming a 100% adoption rate). Note: BAU does not consider any IHP applications while Scenario 1 considers HTHP and ASHP applications. Since the required steam temperature is higher than the current IHP technology can deliver, Scenario 2 has not been considered for the automotive industry.

The changes in annual CO_2 emissions in the U.S. automotive industry in different IHP application scenarios and timeframes are presented in Fig. 17. The figure displays up to 5 Mt of potential CO_2 savings already in 2021 as a result of the 100% IHP technical potential realization in the sector, despite the increased demand for electricity which has a higher U.S. average emission factor than natural gas. It is further estimated that nearly 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 until 2050.

According to Fig. 18, the specific costs of energy and CO_2 savings due to deploying IHPs in the automobile manufacturing sector are estimated at 5 $/GJ and 50 $/t CO_2 per year in 2050 respectively. The associated costs of IHP applications in U.S. automotive plants do not fall below zero which would have otherwise represented cost savings. One of the major reasons for the high specific costs is the large difference in the U.S. industry-specific electricity and fuel prices (or high electricity-to-gas price ratio, refer to Fig. 2). The assumed heat source temperature is another factor influencing the costs to be high (see earlier). It is therefore advised to look for suitable excess heat sources at higher temperatures for optimal placement of the proposed IHPs.

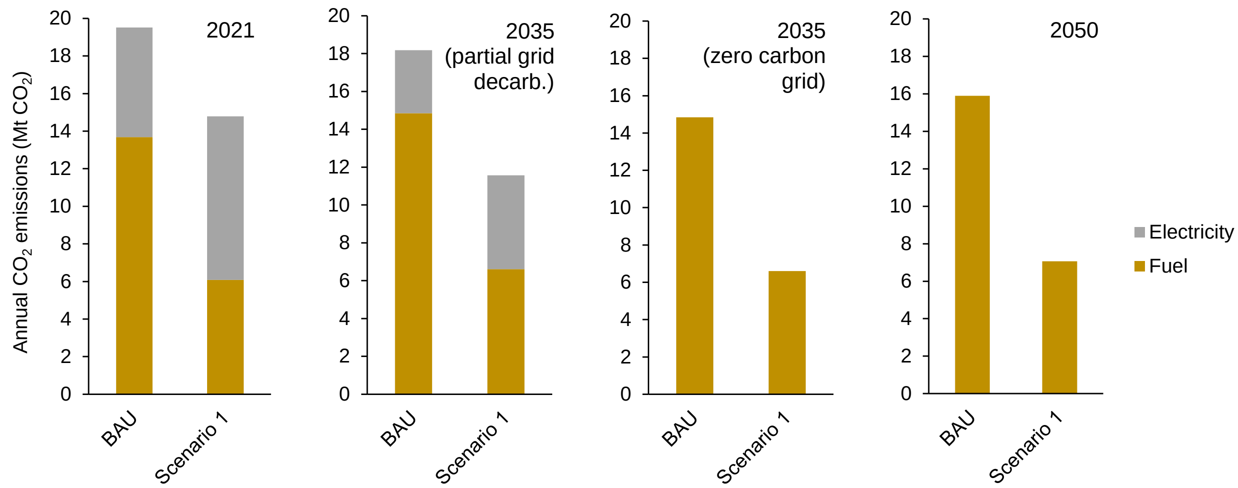

Figure 17. Annual CO_2 emissions from the U.S. automotive industry up to 2050 (This is a total technical potential assuming a 100% adoption rate).

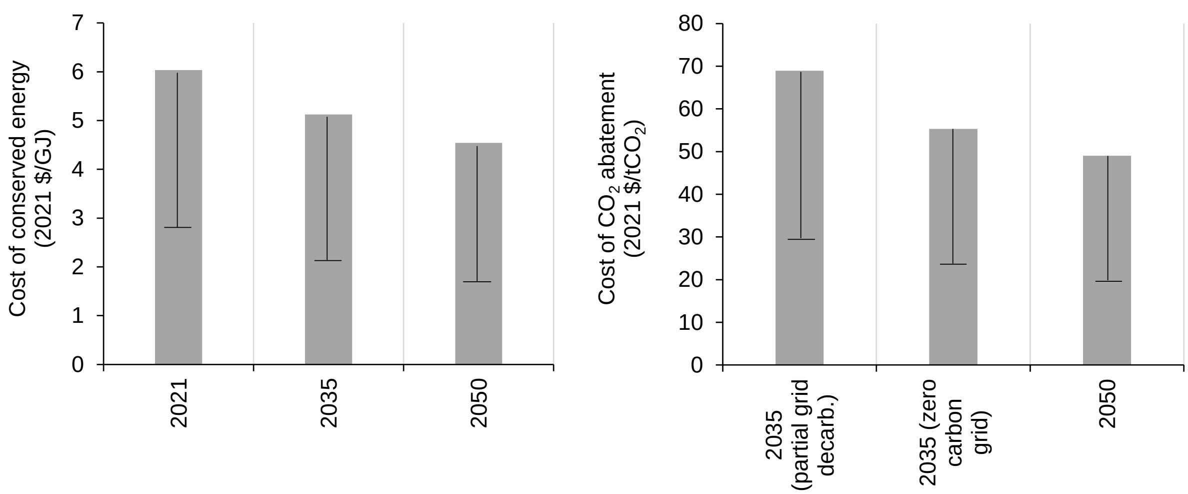

Figure 18. Cost of conserved energy and CO_2 abatement cost for industrial heat pump applications in the U.S. automotive industry under Scenario 1. Note: The marginal costs as a result of 50% lower electricity prices than those projected in the corresponding year are shown as error bars. See sensitivity analysis in Section 3.2 for more details.

3.2. Sensitivity analysis

The specific energy conservation and CO_2 abatement costs for the three industrial sectors are quite sensitive to fuel and electricity price projections and excess heat source temperatures. Therefore, it is 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 scenarios have been developed:

- *High natural gas price scenario:* Natural gas prices are taken 1.5 times higher than those projected in 2050.
- *Low electricity price scenario:* Electricity prices are taken 1.5 times lower than those projected in 2050.
- *High heat source temperature scenario:* Excess heat sources are assumed at 40°C instead of the base case assumption at 25°C.

- *Combined scenario:* Natural gas and electricity prices are taken 1.5 times higher and lower than those projected in 2050. Excess heat sources are existing at 40ºC.

Fig. 19 and Fig. 20 present the sensitivity analysis of energy conservation and CO_2 abatement costs in 2050 to the aforementioned variables. The figures show that the specific costs can be reduced significantly if excess heat sources potentially available at 40ºC are utilized by IHP configurations, consequently minimizing temperature lifts, maximizing COPs, and minimizing electricity costs. It is therefore essential to explore and utilize heat sources at high temperatures yet below the pinch point to optimize IHP operations. It is also demonstrated that the specific costs can be decreased by an order of 1.5-3 times if natural gas prices are increased by 50%. Raising natural gas prices to a level closer to the price of electricity is hence recommended to make IHPs economically competitive. Any form of a carbon tax that results in higher fossil fuel prices could make electrified processes such as IHP applications substantially more cost-effective. In addition, the figures show that the costs can be reduced by up to 18 times if electricity prices are halved from those projected in 2050.

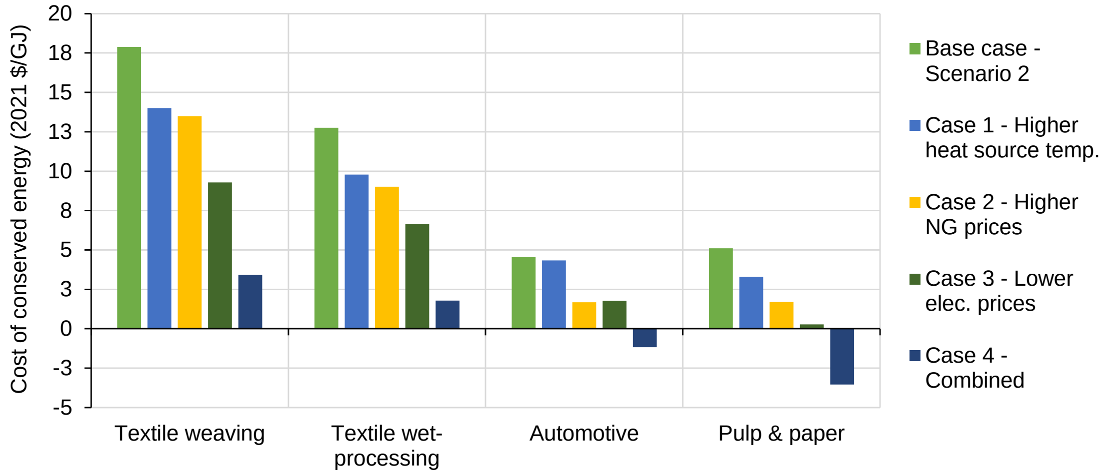

Figure 19. Sensitivity analysis of energy conservation costs in 2050 to different techno-economic variables in 2050.

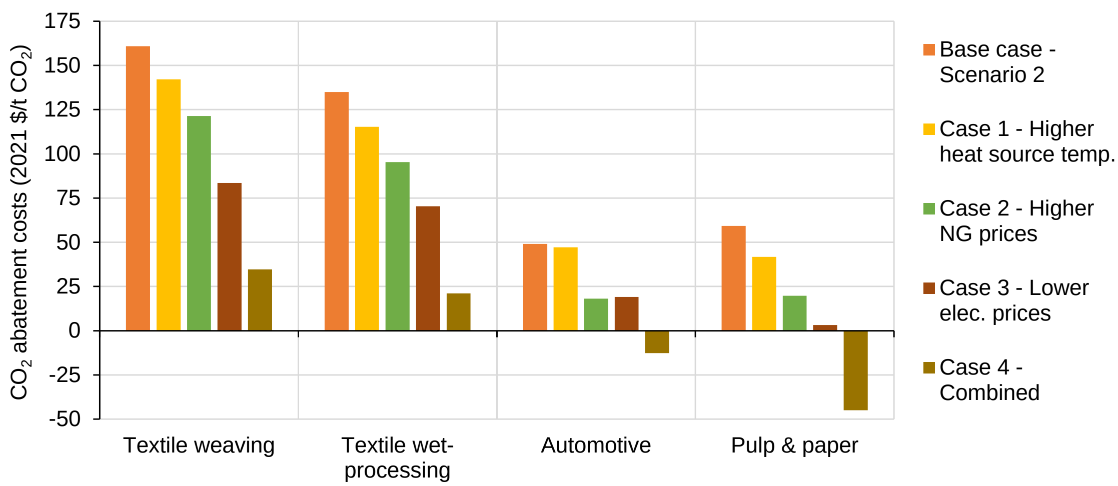

Figure 20. Sensitivity analysis of CO_2 abatement costs in 2050 to different techno-economic variables in 2050.

The results of these three scenarios show that decreasing electricity prices in the future could be the most effective measure to enable the wide-scale implementation of IHPs in the studied sectors. Alternatively, in the first phase of the IHP applications, backup combustion boilers may be employed for industrial steam generation. These boiler-IHP hybrid systems may allow choosing between fuel heating and electric heating depending on the electricity rates. Since electricity rates are projected to fall due to the increasing share of renewable electricity and growth in energy consumption, there might be time slices during the day when electricity is available at a rate lower than natural gas. An example is California where there are daily hours when excess renewable electricity is distributed to its neighboring states, and the California Independent System Operator (ISO) pays off-takers up to 25 $/MWh for this electricity [50].

Despite using high-quality excess heat, decrease in electricity prices, and increase in natural gas prices, the specific costs in Fig. 19 and Fig. 20 are not found to be cost-effective. However, in the combined scenario where all the techno-economic factors are considered, the specific costs for pulp and paper and automotive sectors are found to be economical. This shows that IHP optimization and energy price reforms alone are not enough to overcome the application barriers. Instead, a set of different measures must be applied simultaneously by all stakeholders to facilitate IHP applications. Given the specific costs for textile manufacturing are still high in the combined scenario, more efforts are needed. Since the COP of HTHPs is calculated to be higher than those of SGHPs, electrified steam generation, using IHPs in the textile industry with less to no HTHP applications, is found to be expensive in the sector. It can therefore be concluded that sufficient volumes of heat sources at temperatures higher than those assumed in the base case and combined scenarios must be identified and first utilized for SGHPs (as their impact on energy and emissions savings is higher than HTHPs) so that the temperature lifts and operational costs are minimized and COPs are maximized.

In addition, Arpagaus et al. (2022) [38] stated that the technical lifetimes of IHPs range from 15 to 25 years and evaluated the IHP costs based on discount rates ranging from 5% to 15%. Although not shown as separate scenarios in Fig. 19 and Fig. 20, this study also analyzed the effect of different lifetimes and discount rates on the marginal costs of IHPs in the studied sectors. The results show that the marginal costs decrease and increase by 16% and 18% on average as compared to that in the base case scenario for a discount rate of 5% and 15% respectively. Similarly, the marginal costs decrease up to 10% if the technical lifetime of IHPs is assumed as 25 years.

Lastly, this work only investigates the effect of changes in heat source temperatures, energy prices, discount rates, and technical lifetimes. To evaluate the impact of change in all the other parameters such as current boiler efficiencies, IHP investment costs, production volumes, etc., more information is required which is currently not available, and hence not evaluated.

4. Barriers and recommendations

4.1. Challenges and barriers

It must be noted that there are still many challenges associated with the large-scale implementation of IHPs despite the large potential for energy conservation and CO_2 abatement not only in the studied sectors but in the U.S. and global manufacturing in general. Some of the main challenges are as follows that are listed based on the information and concerns raised by [27], [37], [51]:

- A large disparity between fuel and electricity prices.
- IHP applications into existing manufacturing processes due to custom-built designs lead to longer payback periods than those for fossil-based combustion boilers.
- Lack of refrigerants in the high-temperature range with low global warming potential and ozone depletion potential.

- Lack of suitable compressors for high temperatures.
- Heat storage to compensate for the time lag between demand and supply as in batch processes.
- Competing fossil-based heat supply technologies to deliver process heat at high temperatures.
- Lack of awareness of IHP operation and its capabilities among different stakeholders.
- Lack of industrial-scale IHP demonstration in the U.S.
- Lack of training and events that disseminate knowledge about IHPs.

To address these challenges, key and targeted efforts including research, development, demonstration, and deployment (RDD&D), policy interventions, capacity building, workforce development, 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.

4.2. Recommendations

Research, development, demonstration, and deployment

While IHPs are commercially available, further advancement especially for HTHPs and SGHPs depends on further investment in research, development, demonstration, and deployment (RDD&D). Optimal IHP integration strategies are influenced by different variables, including sector, processes, and location. Industrial plants can partner with academia, national labs, and think tanks, among other stakeholders, to explore and enhance IHP applications. IHPs can also be a part of an integrated industrial system that provides both heating and cooling simultaneously. The ability to provide simultaneous heating and cooling offers additional benefits over a heating-only IHP and improves the economics of an installation. Hence IHP applications for simultaneous heating and cooling in manufacturing processes must be explored, carefully assessed, and demonstrated for wide-scale 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 global warming and no ozone depletion potentials. U.S. participation in the IEA Heat Pumping Technologies (HPT) Annex 58 HTHP program [52] may support international cooperation and knowledge exchange with many European and East Asian countries. Local governments must also step in and incentivize IHP deployments. They can provide tax credits or grants to financially incentivize large IHP pilots and demonstrations. 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.

Policy and workforce development

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 IHPs that are market-ready. Moreover, they can adopt tax policies that encourage investment in IHPs; 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 IHPs.

In addition to company knowledge, employees and contractors at individual plant facilities may require additional training on IHP integration, installation, and maintenance. 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. 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.

Capacity building

Due to a lack of awareness, industrial consumers may be risk-averse and avoid applying new technologies altogether. Subsequently, IHP must compete with familiar fossil fuel-fired boilers that have been in use for decades and are well established. Companies can seek information about the types of available IHPs 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 IHPs have been implemented, then disseminate information or case studies about their challenges and successes. Companies can also educate their peers about the benefits of IHPs. 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 IHPs 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. IHP suppliers 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 IHPs. They can further educate financial institutions and potential investors about their products and the advantages of IHPs.

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 the 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 IHPs and the need for additional investment and support can improve policy and investment decisions.

5. Conclusions

This article presents the energy savings and CO_2 abatement potentials and their associated costs for IHPs in the U.S. textile weaving and wet-processing, pulp and paper, and automotive manufacturing sectors. It is a comprehensive analysis of the effects of electrification of heat and steam demand in the studied sectors in the period 2021-2050 and investigates cases for the wide-scale IHP applications under different price and emission scenarios. The technical potential energy savings by electrifying relevant process heat supply are estimated at 270 PJ and 310 PJ per year in 2021 and 2050 respectively. Furthermore, IHP applications can initially abate 10 Mt of CO_2 emissions per year in 2021. However, since the electricity grids are aimed to be fully decarbonized in 2050, CO_2 abatement is projected to be 28 $MtCO_2$ per year in 2050. In addition, the required heating capacity of industrial heat pumps is estimated at 15 GW, which roughly translates into a market of over 6'000 heat pump units and an investment volume of approximately $7 billion in the studied manufacturing processes.

The costs of conserved energy and CO_2 abatement due to IHP applications in the three industrial sectors vary substantially. The energy conservation costs in these sectors in 2050 range between 5 and 18 $/GJ saved. Similarly, the CO_2 abatement costs in 2050 range between 50 and 160 $/tCO_2$-saved. It is observed that IHP applications in the U.S. textile, pulp and paper, and automotive sectors do not fall below zero which would have otherwise represented cost savings. The large disparity between the U.S. average electricity and fuel prices (or large electricity-to-gas price ratios) in the industry is found to be the major reason. In addition, heat source temperature is another major factor that influences the specific costs substantially. It is therefore advised to explore suitable excess heat sources at higher temperatures to optimize temperature lifts and minimize expenditure on increased electricity demand.

Given the assumptions in this study, the computed results 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 specific costs). A sensitivity analysis is hence performed to evaluate the impact of changes in source temperatures and energy prices on the results for potential energy and CO_2 emissions reduction and its associated costs. The sensitivity analysis shows that IHP optimization and energy price reforms alone are not enough to overcome the application barriers and a combined set of dedicated measures must be implemented simultaneously by all stakeholders to encourage IHP applications.

It is further concluded that the economic opportunities to install IHPs may continue to expand as electricity prices drop in the future. To exploit these opportunities, industrial companies must start factoring process heat electrification into their plans for capital spending. Utilities and policymakers could take advantage of analyzing how IHP applications on a wide scale may influence the rate at which renewables are added to the electricity generation system. Utilities must also ensure upgrading electricity grid infrastructure to supply uninterrupted electricity to electrified processes. Policymakers must act by incentivizing IHP deployment through tax credits and/or grants. Since wide-scale electrification of industrial steam generation will entail major changes to the current U.S. electricity system and individual plants, it is vital to accelerate the coordination efforts to plan these changes as early as possible.

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