Stop the Waste: Using Industrial Heat Pumps to Rethink Thermal Loads

February 2024

Hellen Chen, Neal Elliott, Andrew Hoffmeister

Summary

Engineering design of thermal systems focuses on providing the highest-quality heat needed for industrial processes, leading to over-designed equipment that uses more energy than is needed. Industrial heat pump (IHP) technology flips this approach, designing for the lowest-quality heat needed, then boosting to meet higher-quality needs. This right-sizing approach reduces electricity requirements and energy use compared to the equivalent energy input into a boiler system, resulting in lower emissions and operating costs. Because IHPs are not a drop-in replacement for boilers, engineers must adopt a new mindset for thermal system design. This topic brief presents an alternative engineering approach for the design of IHP systems and is intended to inform industrial engineers, manufacturing end users interested in IHPs, and energy efficiency program managers.

Introduction

Over the past four years ACEEE has renewed its commitment to supporting the expansion of industrial heat pumps (IHPs), a readily available yet underutilized decarbonization technology that enables right-sizing heat sources to heat sinks in thermal system design. While the technology has been available for over four decades, its application in U.S. industry has been limited to some niche applications, such as lumber drying.

The reasons for slow uptake of this technology are complex and include low natural gas prices, limited product availability, and limited awareness of how to effectively apply the technology among both industrial end users and engineers who design industrial thermal process systems. Energy and greenhouse gas (GHG) savings, among other non-energy benefits, can be not only enabled by IHPs but also deepened by right-sizing IHP systems and flipping the current thermal system design approach.

IHPs for GHG reductions and industrial decarbonization

The past few years have seen a surge in interest in IHPs among industrial end users. This change has been largely motivated by commitments to sustainability and increased concerns about climate change regulation. By displacing fossil fuels, IHPs have the potential to reduce industrial energy use by about 33% and, in turn, GHG and other criteria pollutant emissions.

High efficiency coupled with waste heat recovery make IHP systems an attractive solution for many industrial subsectors. Policymakers and IHP suppliers have responded by including IHPs in new policy and programs (e.g., Department of Energy's Onsite Energy Technical Assistance Program,[1] 48C tax credits) and expanding domestic production of equipment. Efforts to address end-user and design engineering knowledge and awareness gaps are still in their early stages. To overcome slow adoption of IHPs, a change to the engineering approach when analyzing and designing thermal systems should be the default starting point.

The current approach to thermal system design

Over the past two centuries, many industrial thermal processes have been powered by steam. Engineering design approaches have been developed to take advantage of the unique nature of steam and the systems that produce (e.g., boilers) and deliver it. Boilers and their associated thermal system design approach are now ubiquitous in various thermal processes, including space heating for buildings and process equipment in industrial plants, as well as in other applications throughout the economy.

The current engineering approach can be summarized as:

1. Identify the highest thermal quality (i.e., temperature and pressure) load in the facility/plant.
2. Sum all maximum thermal loads throughout the plant.
3. Select a boiler and steam distribution system to deliver the summed thermal output (plus a margin of safety) at the highest quality required in the plant.

For those applications that require lower thermal quality, pressure reducing valves (PRV) and thermostatic mixing valves are used to match quality to individual process needs. This design approach has proven reliable and effective in thermal system design, ensuring that there is capacity to meet future and potentially higher-quality thermal needs.

Unfortunately, the flexibility of the system and uncertainty of process requirements creates potentially large inefficiencies. Often, a good portion of the thermal loads are provided with higher-quality steam than is required, resulting in significant wasted energy and water. With many legacy steam systems, the mismatch has become even worse in recent years as thermal process requirements have reduced the need for very high-temperature process heat. In many cases, thermal systems have shifted to pressurized hot water, leaving legacy steam systems even more mismatched and oversized. Additionally, boilers are often natural gas-fired, causing harmful emissions and additional energy losses in flue gases. While electric boilers with high efficiencies are becoming more prevalent, the legacy design approach results in oversized systems where poorly utilized boilers are not only more inefficient but typically also have higher maintenance costs due to variable operation.

A new design approach for thermal systems with IHPs

IHP manufacturers/suppliers and engineers familiar with IHP system design are now advocating a different thermal system approach that reduces both wasted energy and costs of the system. This approach turns the historic, steam-system approach on its head (see figure 1):

[1] The Department of Energy's Onsite Energy Technical Assistance Program provides technical assistance, economic analysis, strategies, and other resources to help industrial and large commercial facilities explore and adopt clean energy technologies. https://www.energy.gov/eere/iedo/onsite-energy-program

1. Identify the lowest thermal-quality load in the facility/plant.
2. Identify higher thermal loads for individual processes throughout the plant.
3. Select thermal-quality boosting technologies, including higher-temperature IHPs or electric boilers for each higher-quality load, to upgrade the thermal quality from the lowest plant level.
4. Size a baseload IHP system to deliver the lower thermal quality, usually in the form of pressurized water, to meet the balance of plant requirements.

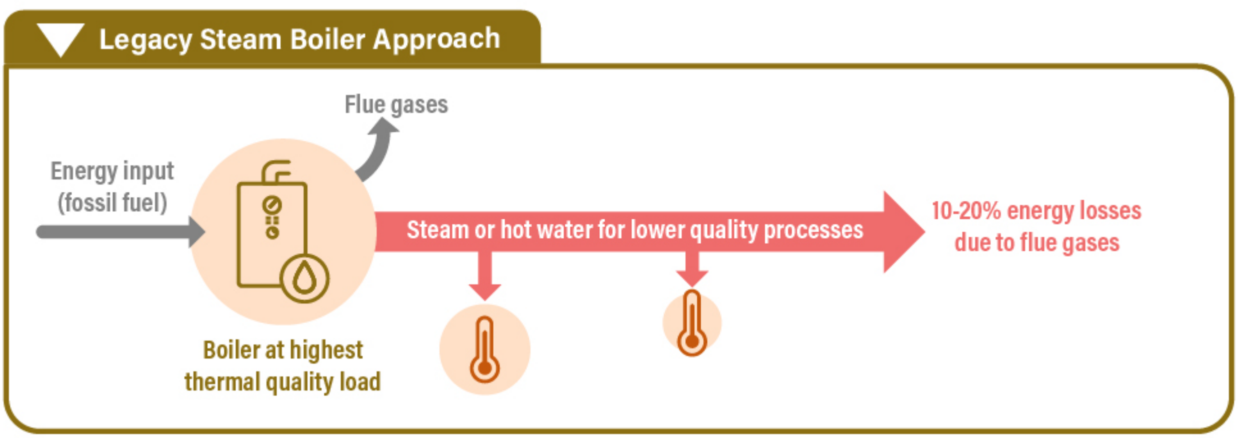
A different thermal system design approach for IHPs turns the legacy approach on its head

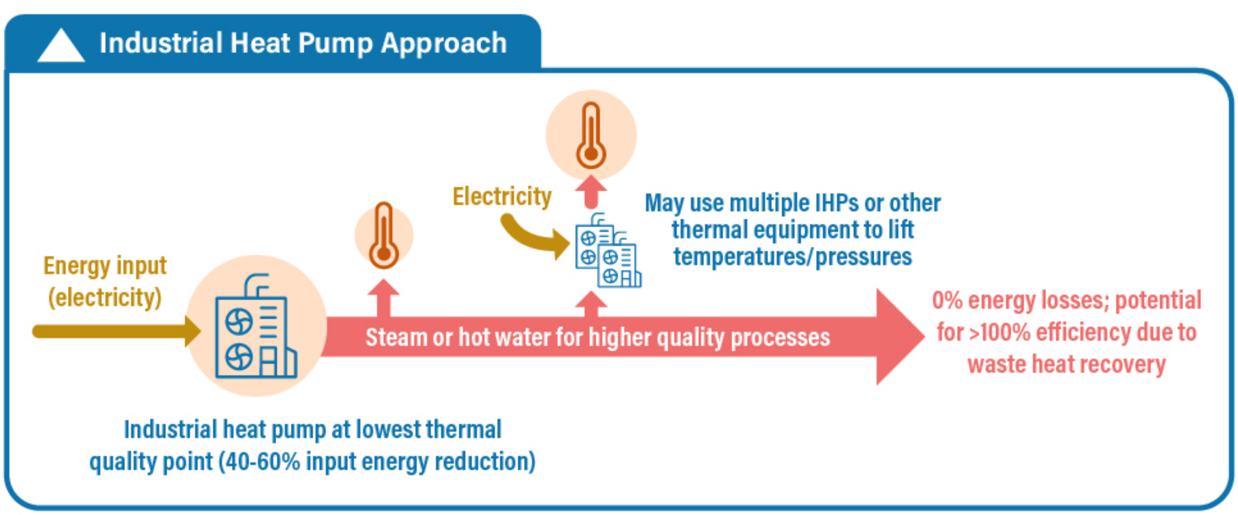
▼ Legacy Steam Boiler Approach

1. Identify the **highest thermal quality** (i.e., temperature and pressure) load in the facility/plant.
2. Sum all maximum thermal loads throughout the plant.
3. Select a boiler and steam distribution system to deliver that thermal output (plus margin of safety) at the highest quality required in the plant.

▲ Industrial Heat Pump Approach

1. Identify the **lowest thermal quality** load in the facility/plant.
2. Identify higher thermal loads for individual processes throughout the plant.
3. Select thermal quality boosting technologies, including higher-temperature IHPs or electric boilers for each higher-quality load, to upgrade the thermal quality from the lowest plant level.
4. Size a baseload IHP system to deliver the lower thermal quality, usually in the form of pressurized water, to meet the balance of plant requirements.





Orange circles show "size" or level of thermal quality of thermal load (large = high thermal quality load, small = low thermal quality load)

Figure 1. Comparison of legacy engineering design approach and new approach for designing thermal systems with IHPs

Global experience with this approach suggests that overall energy use can be reduced by 40–60% when replacing steam boiler systems with optimized IHP systems, reducing capital cost and the electricity service required for the facility. IHPs[2] essentially lift or boost heat from ambient air or waste heat temperature to be used for higher-temperature processes. This design approach takes advantage of the unique nature of IHPs to both right-size systems and in many cases shift from central to more modular systems. Modularization allows for better process control through advanced strategies that can enable grid responsiveness. With modules, portions of the thermal system can be shut down when they are not essential, shedding load during grid events and outages without shutting down the entire plant.

Reducing the need for overall energy strengthens facility resilience, while the inherent efficiency of heat pumps in most applications can further reduce electricity service requirements (and operational carbon). Right-sizing systems can also allow for smaller equipment and components such as pipes and valves due to the modular design, mitigating concerns about space constraints within a plant and eliminating losses from large extended steam pipe systems.

This engineering approach is similar to the approach used by industrial refrigeration engineers. In fact, some of these firms are entering the IHP design marketplace by applying their experience to high-temperature applications. Bridging the knowledge gap of how to design for IHPs entails comprehensive assessment of the thermal demands and loads on a granular level, where the engineer understands the real temperature levels, hot-water needs, and energy balances of a particular plant or process.

Engineers must unlearn the idea that overshooting thermal needs is necessary and recognize that IHPs are not a drop-in replacement for conventional boilers, all the while considering the efficiency of their current systems and potential for future build out as they review designs. IHP suppliers will need to train and help develop a workforce who can design and maintain IHP systems to optimize performance.

Start with new builds or expansions to build design experience

The current surge in investments in new industrial facilities provide an opportunity for engineers to apply this new approach to growing customer demand while diversifying and improving their design skills. While thermal redesign of existing boiler systems will be important to decarbonize current processes, initial application of this new engineering approach should be applied to greenfield plants. Greenfields do not face many of the design challenges of legacy infrastructure, where retrofits of existing legacy steam systems are complex, needing potential overhaul of an oversized system and upgrades to electricity infrastructure.

New builds especially can take advantage of the funding resources recently dedicated to rebuilding the U.S. manufacturing base because they are less costly than retrofits. They also represent an opportunity to lock in more efficient, next-generation technologies; replace legacy fossil fuel technologies; and demonstrate the optimized performance and decarbonization potential of IHPs through this bottom-up design approach. For example, in Norway, TINE SA built a greenfield dairy facility with an integrated IHP system and added rooftop solar to supplement electricity peak demands. The new IHP system had a

[2] An IHP is an electrically or mechanically driven system that moves heat using the same cycle as a refrigerator or domestic HP, that is, evaporation of a working fluid to draw in heat, compression of vapor for transfer, condensation to release heat, and expansion to prepare for the next round of evaporation.

coefficient of performance[3] of 4.1, achieved an energy savings of 37%, and reduced GHG emissions by up to 91% compared to fossil fuel boiler systems.[4] As illustrated through this example, the thermal system designed for IHPs not only performs better than a legacy steam system but also offers the opportunity to install onsite clean energy as the resource input for the IHP, further reducing emissions.

Use pinch analysis in conjunction with new design approach to maximize efficiency and savings

Engineers are achieving further efficiency and cost saving through the application of thermal system optimization techniques, known as pinch analysis, to larger and more complex plants. Pinch analysis, developed in the 1970s, has been applied widely in complex industries such as petroleum refining and organic chemicals.

For IHP systems, pinch analysis provides detailed estimates of different thermal loads to identify pinch points where heat availability overlaps with heat demands. Pinch analysis integrates the thermal boosting capacity of heat pumps to recover waste heat and consolidate heating and cooling demands, improving efficiency and thermal process capacity while reducing bottleneck processes. Energy and water consumption could be reduced by about 10-40% when preceding design of a right-sized system with pinch analysis.[5]

Paying the upfront cost for this pre-engineering analysis is critical not only to achieve maximum efficiency in the plant but also to ultimately reduce overall costs (the initial investment in pinch analysis reduces both lifecycle operational expenses and capital expenses due to right-sized equipment).

Conclusion

As the U.S. economy decarbonizes, industrial subsectors, especially those with low-to-medium heat processes, should take advantage of the benefits enabled by IHP technology. With historic funding being dedicated to decarbonized, domestic manufacturing, greenfield plants can lead a transformation of the market for IHPs. To start, end users, energy program managers, and engineers need to design from the lowest thermal quality of a plant rather than the highest thermal need. Flipping the legacy thermal design process on its head is important for IHP implementation because the new approach

- Avoids lock-in of less efficient fossil fuel technologies of the past
- Can deepen IHP savings through right-sizing systems, reducing energy, emissions, and costs and, in turn, mitigating barriers to slow uptake
- Allows for reduced system temperature or thermal-quality requirements, extending the reach of IHPs to more applications

[3] The coefficient of performance refers to the ratio of process heat delivered to input energy required. While efficiency (ratio of useful heat or electricity to input energy) is less than 1 (e.g., steam boiler efficiencies are typically 0.7–0.85), the coefficient of performance of an IHP can be greater than 1 due to a heat pump's ability to move and upgrade heat with little input energy.

[4] Read more about the integrated IHP system for the new dairy in Norway: https://iifiir.org/en/news/an-award-winning-industrial-dairy-using-an-integrated-heat-pump-system.

[5] Read more from ACEEE's report "Industrial Heat Pumps: Electrifying Industry's Process Heat Supply": https://www.aceee.org/research-report/ie2201.

- Increases the value proposition of IHPs, especially for greenfield plants that can be highly optimized.