CIRCULAR THERMAL℠

HOW TO PUT WASTE HEAT BACK INTO INDUSTRIAL PROCESSES AND BEYOND

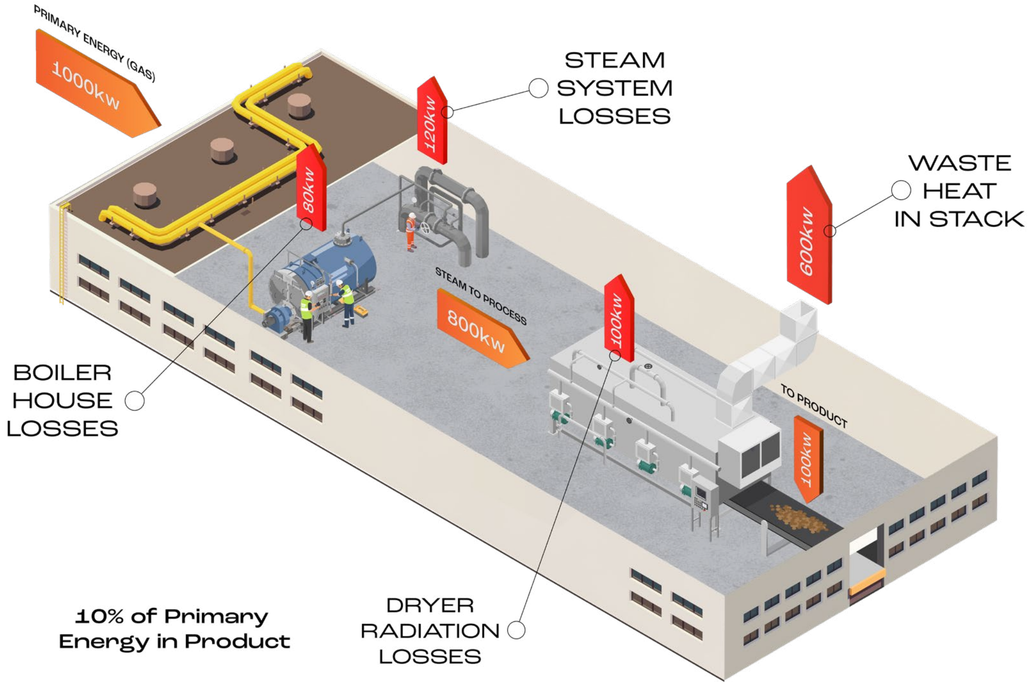
Armstrong®
EXPERIENCE MATTERS™

WHERE DOES THE ENERGY GO?

Simply stated, the first law of thermodynamics tells us that energy cannot be destroyed or created—its quantity within a system remains stable. When energy is put to work, sometimes by converting it from one form to another, it is degraded to a lower quality of energy. So, if energy in an industrial plant is degraded but not destroyed, how does it leave the plant?

Currently, primary energy is brought into a plant in the form of electricity and fossil fuels—which are increasingly being replaced by renewables. These sources are measurable, so we know the quantity of incoming primary energy. In a typical factory, less than 20% of incoming energy is used for moving things (motors converting electricity into mechanical energy) or lighting the facilities. Due to energy efficiency, part of this energy eventually ends up as waste heat that increases the building's interior air temperature. Does that mean that the remaining 80% of the primary energy used for thermal is going into the products being manufactured? In most industries, only a small portion of the primary energy is converted into chemical energy contained in the final product. Furthermore, the input materials used in manufacturing are usually at the same (often ambient) temperature as output products are when leaving the plant. In fact, the majority of primary energy ends up as waste heat that is still frequently lost through stacks, cooling towers, and sewage.

Standard One-way Thermal System—Single Process User



HEATING AND COOLING IN INDUSTRY

The heating and cooling sequence is the basis of industrial processes. Plants are designed to facilitate the flow of products—and heating and cooling at different stages of the process often just compensate each other from an energy perspective.

COOLING

Cooling is achieved by removing heat from a fluid. Once extracted, that energy is typically wasted through cooling towers that release heat and water vapor into the atmosphere. The amount of energy extracted as part of the cooling process can represent as much as 1/3 of a plant's heating needs—or even more.

An air compressor is a good example: Up to 90% of an air compressor's electrical input becomes waste heat as part of the compressor cooling. Depending on the air's humidity, its condensation will add waste heat that is the equivalent of 5% to 20% of the compressor's electrical input. The sum of these two can sometimes represent more than 100% of the electricity used by the compressor.

The highest potential for waste heat from cooling is found in factories that use deep freezing processes for ice cream, frozen food, and other products that are colder when leaving the plant than raw materials are when entering. By taking heat out of the product, they generate a significant excess of waste heat from cooling. This energy can fulfill not only their own heating needs, but some of their neighbors' thermal demand, as well.

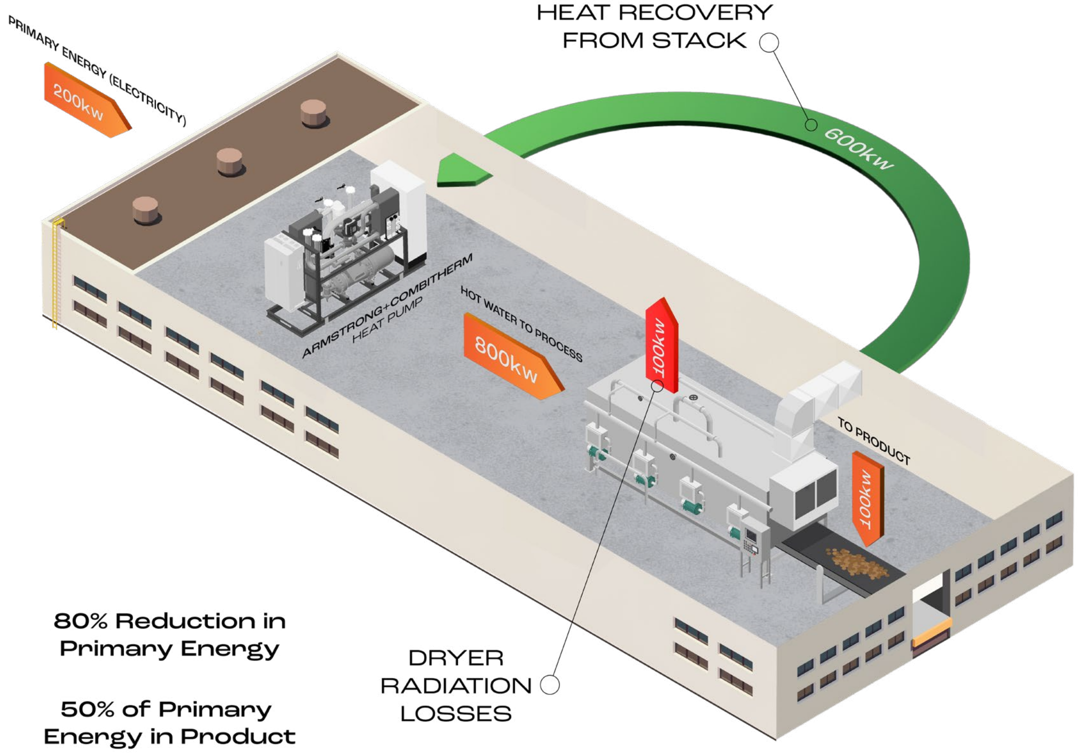
HEATING

Heating loses energy to the atmosphere through inefficiencies in utilities generation and distribution. The efficiency of a typical steam system generally ranges from no more than 60% to a maximum of 80%. The remaining energy is used for important tasks, such as drying products through water evaporation, heating products to trigger a chemical reaction, heating/humidifying/dehumidifying air, heating water for cleaning, and more. But what happens to the energy after that? In a dryer, which is one of the largest heating applications in industry, as much as 80% of the energy is released into the atmosphere through stacks in the form of very humid, low-temperature air (< 175°F/< 80°C). This is also true for most other industrial applications—and in certain cases, such as distillation columns and evaporators, the process output often has to be cooled.

TAKING A CIRCULAR APPROACH

While the quality of energy contained in waste heat has been degraded, the quantity of energy it contains is still very significant. Based on our studies, from 50% to 80% of the primary energy used in light industries leaves the plant as waste heat at medium temperatures (< 400°F/200°C) or even low temperatures (< 200°F/< 90°C). This means that 50% to 80% of this energy can be reused and therefore, the related Scope 1 emissions could be avoided. By applying a circular approach to industrial thermal, we can recover that energy and put it back to work in the process.

Circular Thermal℠ System—Single Process User



For more than 40 years, heavy industry has used Process Integration (PI), or Pinch, to maximize plant thermal efficiency—mainly through direct heat recovery. This method consists of mapping and overlapping cold and hot streams in a plant to calculate maximum theoretical heat recovery and minimum energy requirements for the plant. The result is an ideal design that can be adapted to the practical realities of the site based on educated trade-offs. In light industries, an additional "heat exchanger network" is needed for recovering low-grade heat from sources, storing it, upgrading it if necessary, and moving it to heat sinks. Through this methodology, industrial plants can recover their waste heat and significantly reduce their primary energy use and CO2 emissions. We call this process Circular Thermal^{SM}.

CIRCULAR THERMAL^{SM} IS AT THE HEART OF ARMSTRONG'S DECARBONIZATION METHODOLOGY

Armstrong's methodology for thermal decarbonization includes three steps: optimize thermal system efficiency, minimize energy demand from process, and decarbonize the facility's primary energy sources. As part of system optimization, Circular Thermal^{SM} often delivers the greatest impact with positive return on investment.

Step One: Optimize Thermal System Efficiency Through Waste Heat Recovery

Although the theory behind Circular Thermal^{SM} has long been recognized, it was frequently ignored in new construction of industrial plants due to economics. In the past, fossil fuels were considered cheap and abundant, and few were concerned about CO2 emissions, so it was easy and convenient to design and operate one-way thermal systems. However, this is no longer true. In today's world, energy is a geopolitical and business risk, fossil fuels are increasingly expensive and sometimes unavailable, renewable electricity is becoming cheaper, CO2 emissions have a price—and the payback for Circular Thermal^{SM} is significantly improving. Once fossil fuels are taken off the table, recovering waste heat will be the most economical way to decarbonize thermal systems.

Desteaming

Steam systems typically generate and distribute heat at 365°F/185°C (which is 150 psig/10 barg saturated steam)—even when the process requires a much lower heating temperature. Recovering waste heat to generate low pressure steam—which can then be compressed to higher pressure—is technically feasible. However, if the final goal is to heat a product at a much lower temperature, this will result in excessive energy use, partially due to the minimum 20% losses inherent to steam systems.

That is why we consider hot water to be the best heating fluid up to 250°F/120°C. Desteaming is about replacing steam systems with hot water or glycol ones for optimized waste heat recovery. By allowing a closer match between heat generation and heat use within the process, desteaming optimizes system efficiency. Armstrong International has more than a century of in-depth steam system expertise, and we recommend desteaming for low-grade heating.

In theory, using hot water requires larger heat exchange surfaces—as sensible heat contains 4 to 5 times less energy than latent heat. However, in practice, existing steam heat exchangers are frequently oversized—that is why doubling the heat exchange surface is often sufficient. Desteaming also eliminates the condensate drainage issues inherent to applications using steam for heating < 212°F/100°C—which can create a vacuum in heat exchangers.

Finally, to avoid excessive lengths of larger water pipes, heat sources should be linked to nearby heat sinks. This decentralized system design is inherent to Circular Thermal^{SM} systems—as opposed to the historical "central steam boiler room and distribution network" approach.

Heat Pumps

High-grade waste heat can often be recovered using only a heat exchanger—although this can sometimes be technically challenging due to contamination of process air discharged through stacks. However, waste heat is often available at lower temperatures than the process demands, so low-grade heat must be upgraded to medium-grade heat. This requires additional high-grade energy (electricity) to run the heat pump compressors that increase waste heat temperatures to needed levels.

The technology used in heat pumps has existed for 170 years. It is the same technology that runs the refrigerators in our homes and the air conditioning in our offices. Efficiency is the most significant advantage heat pumps provide. The electricity required to run a heat pump typically represents only 1/4 to 1/3 of the total heat output—and almost all of that electricity is eventually converted into useful heat. However, the majority of the output energy comes from the low-grade waste heat that has been recovered. Heat pumps are often considered thermal electrification technology, but in industrial applications they are primarily a waste heat upgrade technology.

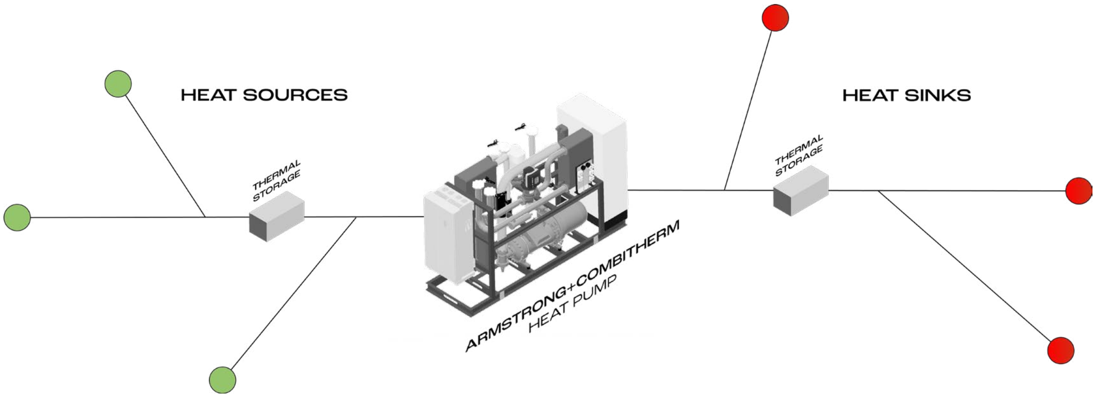
Closed-circuit heat pumps are now available for medium capacities (between 1.7 to 7 million BTU per hour per unit / 0.5 MW to 2 MW per unit). These heat pumps use a new generation of working fluids that are safer for users, reliable (due to relatively low pressure in the circuit) and have a limited environmental impact (GWP < 10 and TFA degradation < 2%). They can deliver temperatures in the medium range—recovering low-grade waste heat < 176°F/80°C (as a side effect, sometimes producing useful cooling); and upgrading that heat to 250°F/120°C, which allows for the generation of low-pressure steam, if necessary.

This steam can be used for direct injection, or its pressure and temperature can be increased using a steam compressor as part of Mechanical Vapor Recompression (MVR) system. These compressors require about 10% water injection. The additional steam compensates for radiation losses and leaks in the downstream steam system. By recovering condensate and flash steam beyond heat exchangers and sending them back as input to the high-temperature heat pump, the loop can be closed and balanced.

Storage

Waste heat is not always available when and where it is needed. Once recovered, it must be relocated and stored—typically as hot water or using solid materials—until it can be used in the process. Although space can be an issue in certain plant configurations, reliable technologies to overcome this problem do exist.

Circular Thermal^{SM} System—Multiple Process Users



Through Circular Thermal^{SM}, as heat flows in multiple directions across plants, a more dynamic thermal system is created. Recovered heat is stored and then upgraded from lower to higher temperatures whenever it is most convenient or when electricity in the grid is cheapest—thus contributing to its demand management. These systems are more automated and use real-time data to decide when heat should be moved or stored. And they are available as a service, which decreases the need for capital, allows the outsourcing of risks, and provides flexibility of assets needed to adapt to a constantly changing world.

Step Two: Minimize Energy Demand From Process

The ratio between electricity and useful heat output of a heat pump is called Coefficient of Performance (COP), and it depends on the temperature increase. Optimizing the COP is the primary reason to match heat source and heat sink temperatures as closely as possible. Whenever a heat pump performs useful work by both cooling the source and heating the sink (for example, in a distillation process), while not using more electricity to do so, it has a much higher Combined COP (CCOP).

The design of many processes was based on higher utility temperatures that are relatively easy to obtain with steam. However, analyzing the actual steam temperature in the heat exchanger (following pressure reduction produced by a control valve) or identifying the exact temperature requirements of the process, often reveals that the needed heat sink temperature is much lower than expected. Consequently, COP is improved without impacting plant process conditions or product quality.

Heat pumps producing lower output temperatures require less electricity, so COP is higher. The resulting permanent decrease of Opex costs is worth the effort, even in cases where additional Capex is required (mainly for desteaming). In the long term, Opex can be further decreased by replacing aging or end-of-life process equipment with modern equipment that offers higher energy efficiency or requires lower heating temperatures.

In certain cases, the same useful work can be performed without using heat at all. For example, steam has been used for humidifying air in healthcare or industries such as pharma, while the same increase in air humidity can be achieved using adiabatic or electric humidifiers. These humidifiers do not use less energy to evaporate water at atmospheric pressure, but they do allow desteaming of Air Handling Units (AHUs). This eliminates the need to generate medium-temperature steam using heat pumps with the resulting lower COP, as well as the need to distribute it afterwards, with the inherent steam system losses.

Step Three: Decarbonize Your Facility's Primary Energy Sources

The primary energy needed to run Circular Thermal^{SM} systems is electricity, which can be decarbonized by using renewable power. The remainder of thermal decarbonization can be achieved by switching to renewables, such as biogas, biomass, solar thermal, hydrogen, or direct electrification. This is the final phase of Armstrong's three-step thermal decarbonization methodology.

However, it is critical that decarbonization be implemented only after the potential of optimizing and minimizing has been exhausted. Switching one-way thermal systems—that result in 50% to 80% of primary energy being released into the atmosphere as waste heat—to renewables is a mistake. It leads to significant wastage of scarce renewable energy that is essential for decarbonizing hard-to-abate applications in heavy industry, transportation, or building sectors.

THE ADVANTAGES OF CIRCULAR THERMAL^{SM} ARE SUBSTANTIAL

A very large percentage of the thermal energy currently used in industry can be recovered by applying Circular Thermal^{SM}. Furthermore, this methodology should not be limited to the boundaries of a single factory. While a growing number of industrial areas are applying a circular approach to materials and energy generation, the sharing and upgrading of waste heat across neighboring industrial plants, hydrogen electrolyzers, data centers, office areas, and cities is still too rare. The development of transportable solid-material thermal storage containers is expanding opportunities for the physical movement of waste heat over medium-range distances (ideally, using decarbonized transportation). Heavy industrial plants having an excess of high-grade waste heat can share it with light industrial plants or a district heating located tens of miles / kilometers away.

The Potential For Heating And Cooling In Buildings

Waste heat recovery and reuse can also be envisioned for building heating and cooling. However, applying Circular Thermal^{SM} presents more of a challenge in buildings than it does in industry due to one significant difference—timing. Industrial applications demand regular heating and cooling, at least weekly, which limits size requirements for thermal storage. Circular Thermal^{SM} for building heating and cooling would require seasonal thermal storage that maintains heat at approximately the same temperature for as long as six months. If, one day, affordable, small-volume seasonal thermal storage becomes commercially available, it will significantly increase the average yearly COP of heat pumps used for building heating and cooling, thus greatly reducing their yearly primary electrical consumption.

Building cooling can already be used as a heat source for nearby industries, which need heat all year long. Such "district cooling" systems might make sense primarily in warmer climates, where cooling is needed most of the year. In colder climates, a more valuable heat source from buildings might be the sewage system, collecting "once-through" heated sanitary water from showers and taps.

Another source for building heat pumps is geothermal—either shallow, or from lakes and rivers. Compared to the ambient air, geothermal offers a higher temperature that remains relatively stable throughout the year. During summer, this source is often cold enough to bypass the heat pump's compressor, making it possible to run in a "free cooling" mode.

CIRCULAR THERMAL^{SM} LOWERS THE BAR FOR THERMAL DECARBONIZATION

Heating and cooling in industry and buildings represent approximately 70% of current global final energy consumption. By recovering, upgrading, and reusing the heat wasted in industrial plants, we can significantly lower the bar for thermal decarbonization and reduce the amount of renewable energy required to run these plants in the future. Throughout the world, transformation of existing sites is already underway, and an increasing number of new systems are being designed using the Circular Thermal^{SM} methodology.

Applying this concept beyond the boundaries of a single plant and into buildings will decrease the need for primary energy and help with the decarbonization of global energy systems even further.

Armstrong®

EXPERIENCE MATTERS™

INTELLIGENT THERMAL UTILITIES SOLUTIONS FROM A GLOBAL
LEADER IN ENERGY MANAGEMENT AND ENJOYABLE EXPERIENCES

Armstrong International
The Americas | Asia | Europe, Middle East, Africa
armstronginternational.com