# Industrial Heat Pumps for Steam and Fuel Savings

Industrial heat pumps are a class of active heat-recovery equipment that allows the temperature of a waste-heat stream to be increased to a higher, more useful temperature. Consequently, heat pumps can facilitate energy savings when conventional passive-heat recovery is not possible. The purpose of this Steam Technical Brief is to introduce heat-pump technology and its application in industrial processes. The focus is on the most common applications, with guidelines for initial identification and evaluation of the opportunities being provided.

## Introduction to Heat Pumps

A heat pump is a device that can increase the temperature of a waste-heat source to a temperature where the waste heat becomes useful. The waste heat can then replace purchased energy and reduce energy costs.

However, the increase in temperature is not achieved without cost. A heat pump requires an external mechanical- or thermal-energy source. The goal is to design a system in which the benefits of using the heat-pumped waste heat exceed the cost of driving the heat pump.

Several heat-pump types exist; some require external mechanical work and some require external thermal energy. For the purpose of discussing basic heat-pump characteristics, this brief will first introduce the mechanical variety, and then address the thermal types.

## Why can a heat pump save money?

Heat pumps use waste heat that would otherwise be rejected to the environment; they increase air temperature to a more effective level. Heat pumps can deliver heat for less money than the cost of fuel.

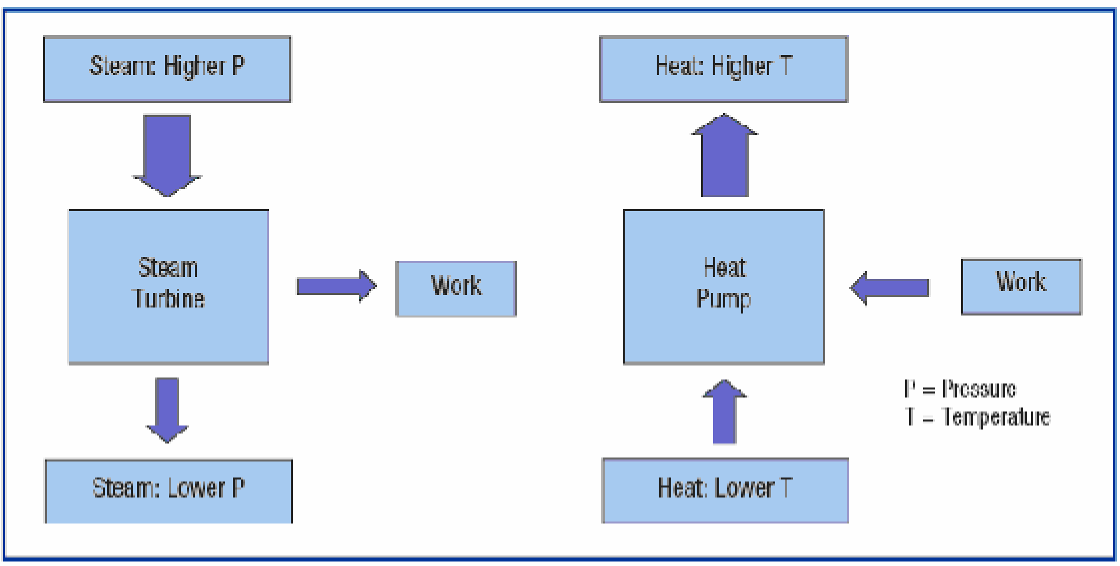
Heat pumps operate on a thermodynamic principle known as the Carnot Cycle. To aid understanding of this cycle, it is helpful to contrast the Carnot Cycle with the more familiar thermodynamic cycle that underlies the operation of steam turbines, the Rankine Cycle.

Degrading high-grade thermal energy into lower-grade thermal energy creates shaft work, or power, in the Rankine Cycle. In a steam turbine, this is accomplished by supplying high-pressure steam and exhausting lower-pressure steam.

In contrast, mechanical heat pumps operate in the opposite manner. They convert lower temperature waste heat into useful, higher-temperature heat, while consuming shaft work.

The work required to drive a heat pump depends on how much the temperature of the waste heat is increased; in contrast, a steam turbine produces increasing amounts of work as the pressure range over which it operates increases.

Heat pumps consume energy to increase the temperature of waste heat and ultimately reduce the use of purchased steam or fuel. Consequently, the economic value of purchasing a heat pump depends on the relative costs of the energy types that are consumed and saved.




Comparison of Steam-Turbine and Heat-Pump Operating Principles

### How does a heat pump work, and how much energy can it save?

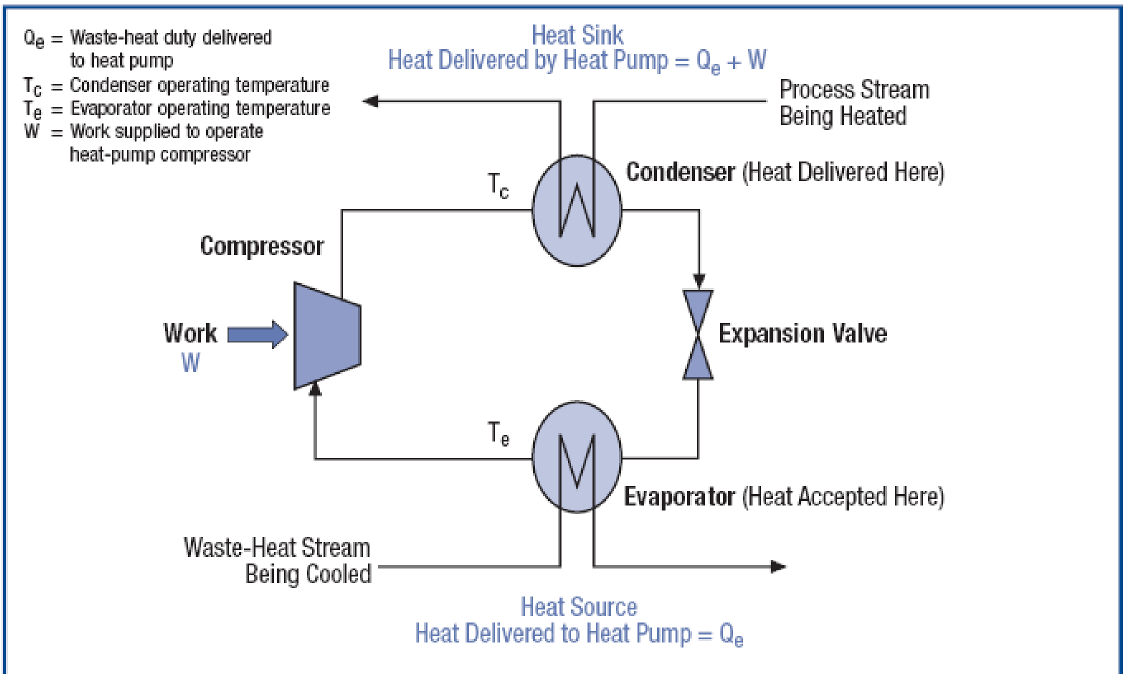
Several types of heat pumps exist, but all heat pumps perform the same three basic functions:

- Receipt of heat from the waste-heat source
- Increase of the waste-heat temperature
- Delivery of the useful heat at the elevated temperature.

One of the more common heat pump types, the mechanical heat pump, will be used to show how these functions work.

Waste heat is delivered to the heat-pump evaporator in which the heat-pump working fluid is vaporized. The compressor increases the pressure of the working fluid, which in turn increases the condensing temperature. The working fluid condenses in the condenser, delivering high-temperature heat to the process stream that is being heated.
A key parameter influencing the savings that a heat pump achieves is the temperature lift realized in the heat pump. Temperature lift is the difference between the evaporator and condenser temperatures.

The following figure illustrates how the cost of heat delivered by an electric-motor-driven mechanical heat pump depends on the cost of electric power and on the temperature lift that the heat pump achieves.




1. Waste-heat stream evaporates heat-pump working fluid at low temperature and pressure
2. Compressor increases pressure of heat-pump working fluid
3. Heat-pump working fluid condenses at high temperature and pressure in the condenser, providing useful heat to a process stream
4. Condensed working fluid is expanded back to the evaporator

Under the right circumstances, a heat pump can reduce energy costs and provide an attractive cost-reduction project, particularly when:

- The heat output is at a temperature where it can replace purchased energy such as boiler steam or gas firing
- The cost of energy to operate the heat pump is less than the value of the energy saved
- The net operating cost savings (reduction in purchased energy minus operating cost) is sufficient to pay back the capital investment in an acceptable time period.

For industrial applications, simple paybacks of 2 to 5 years are typical. Different types of heat pumps accomplish the three basic heat-pump functions in different ways, but in all cases the goal is the same: recover waste heat, increase its temperature, and deliver it at a higher, more useful, temperature for a reduced cost compared to the alternative. The common variants are described below:

## Common types of industrial heat pumps

A brief description of the most common types of heat pumps and their key operating principles is provided below.

***Closed-Cycle Mechanical Heat Pumps*** use mechanical compression of a working fluid to achieve temperature lift. The working fluid is typically a common refrigerant. Most common mechanical drives are suitable for heat-pump use; examples include electric motors, steam turbines, combustion engines, and combustion turbines.

***Open-Cycle Mechanical Vapor Compression (MVC) Heat Pumps*** use a mechanical compressor to increase the pressure of waste vapor. Typically used in evaporators, the working fluid is water vapor. MVC heat pumps are considered to be open cycle because the working fluid is a process stream. Most common mechanical drives are suitable for heat-pump use; examples include electric motors, steam turbines, combustion engines, and combustion turbines.

***Open-Cycle Thermocompression Heat Pumps*** use energy in high-pressure motive steam to increase the pressure of waste vapor using a jet-ejector device. Typically used in evaporators, the working fluid is steam. As with the MVC Heat Pump, thermocompression heat pumps are open cycle.

***Closed-Cycle Absorption Heat Pumps*** use a two-component working fluid and the principles of boiling-point elevation and heat of absorption to achieve temperature lift and to deliver heat at higher temperatures. The operating principle is the same as that used in steam-heated absorption chillers that use a Lithium Bromide/water mixture as their working fluid.

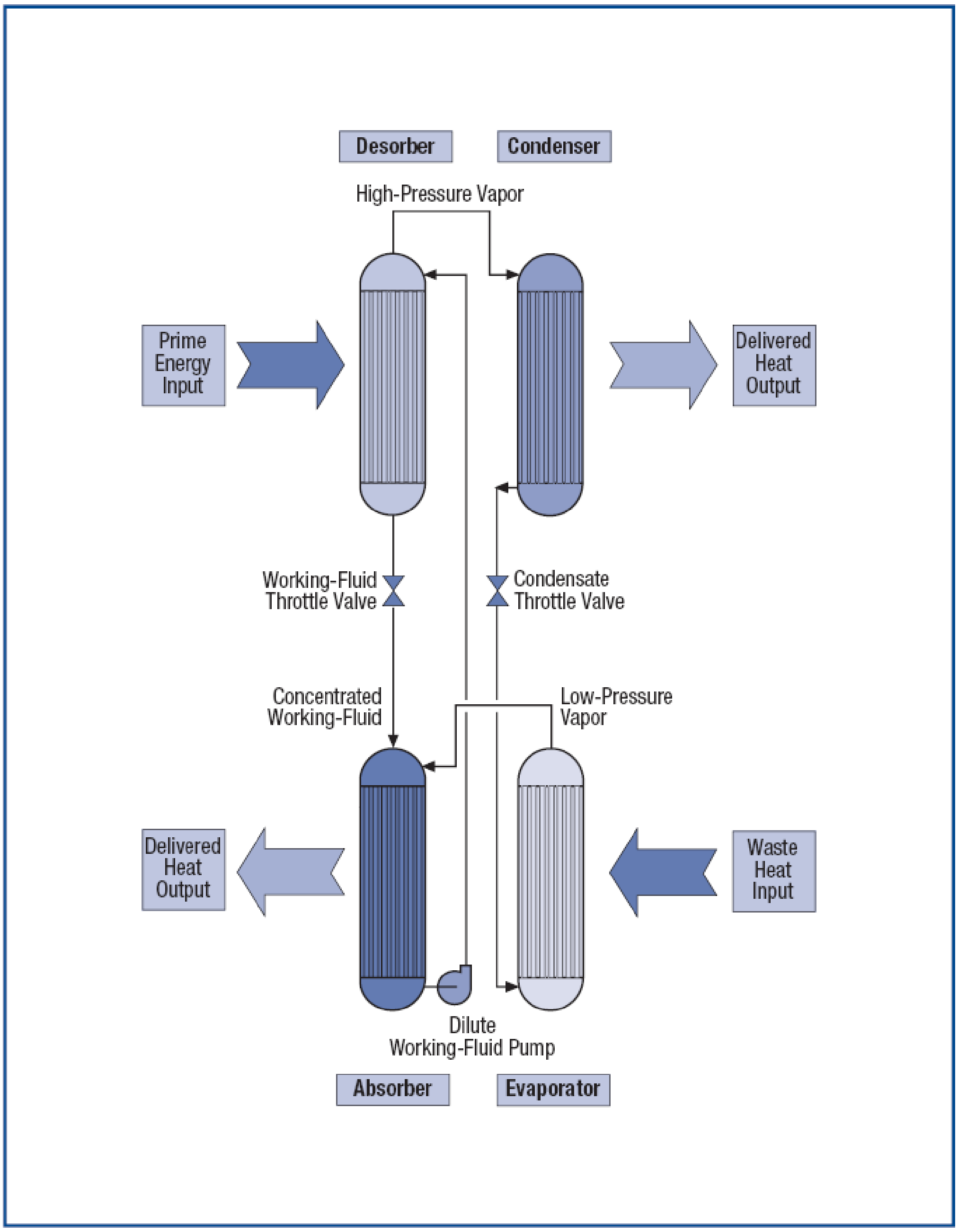
Key features of absorption systems are that they can deliver a much higher temperature lift than the other systems, their energy performance does not decline steeply at higher temperature lift, and they can be customized for combined heating and cooling applications.

Four heat exchangers—an evaporator, condenser, generator, and absorber—are found in a typical absorption heat pump. High-temperature prime energy (steam or fuel) is supplied to the desorber, where vapor is boiled out of the working fluid at high pressure. The high-pressure vapor is condensed in the condenser, where the heat is recovered into a process stream. High-pressure condensate from the condenser is throttled to a lower pressure in the evaporator, where the waste heat is recovered to vaporize the low-pressure condensate. In the absorber, concentrated working fluid from the desorber contacts low-pressure vapor from the evaporator, creating heat that is recovered into a process stream. The working fluid returns to the desorber to complete the cycle.

In a typical absorption heat-pumping application, waste heat at low temperature is delivered to the evaporator, and prime heat at high temperature is delivered to the generator. An amount of heat equivalent to the sum of the high- and low-temperature heat inputs can be recovered at an intermediate temperature via the condenser and absorber. This is analogous to the thermocompression heat pump, in which high-pressure steam is used to increase or lift low-pressure waste vapor to a higher pressure and temperature. However, in the case of the high-lift absorption heat pump, the temperature lift can be 200 to 300° F, rather than the 20 to 50° F of the thermocompression system.

The ability to provide simultaneous cooling and heating provides additional benefits over a ‘heatingonly’ heat pump and improves the economics of an installation.

An alternate configuration for an absorption heat pump allows a medium-temperature waste-heat stream to split into one higher-temperature stream and one lower-temperature stream. Adjusting the operating pressures and working-fluid concentrations accomplishes this reconfiguration.




Simplified Schematic of an Absorption Heat Pump

## Industrial Applications

### Which applications use heat pumps?

Table provides a representative overview of heat-pump applications in industrial processes. The table is not comprehensive, but highlights the most common industrial applications and heat pump types. The most common industrial application of heat pumping is dehumidification drying of lumber.

### Table 1. Representative Overview of Heat-Pump Applications in Industrial Manufacturing Activities

| Industry | Manufacturing Activity | Process | Heat-Pump Type |
|---|---|---|---|
| **Petroleum Refining and Petrochemicals** | Distillation of petroleum and petrochemical products | Separation of propane/propylene, butane/butylene and ethane/ethylene | Mechanical Vapor Compression, Open cycle |
| **Chemicals** | Inorganic salt manufacture including salt, sodium sulfate, sodium carbonate, boric acid | Concentration of product salt solutions | Mechanical Vapor Compression, Open cycle |
| | Treatment of process effluent | Concentration of waste streams to reduce hydraulic load on waste treatment facilities | Mechanical Vapor Compression, Open cycle |
| | Heat recovery | Compression of low-pressure waste steam or vapor for use as a heating medium | Mechanical Vapor Compression, Open cycle |
| | Pharmaceuticals | Process water heating | Mechanical Compression, Closed cycle |
| **Wood Products** | Pulp manufacturing | Concentration of black liquor | Mechanical Vapor Compression, Open cycle |
| | Paper manufacturing | Process water heating | Mechanical compression, Closed cycle |
| | Paper manufacturing | Flash-steam recovery | Thermocompression, Open cycle |
| | Lumber manufacturing | Product drying | Mechanical Compression, Closed cycle |
| **Food and Beverage** | Manufacturing of alcohol | Concentration of waste liquids | Mechanical Vapor Compression, Open cycle |
| | Beer brewing | Concentration of waste beer | Mechanical Vapor Compression, Open cycle |
| | Wet corn milling/corn syrup manufacturing | Concentration of steep water and syrup | Mechanical Vapor Compression, Open cycle<br>Thermocompression, Open cycle |
| | Sugar refining | Concentration of sugar solution | Mechanical Vapor Compression, Open cycle<br>Thermocompression, Open cycle |
| | Dairy products | Concentration of milk and of whey | Mechanical Vapor Compression, Open cycle<br>Thermocompression, Open cycle |
| | Juice manufacturing | Juice concentration | Mechanical Vapor Compression, Open cycle |
| | General food-product manufacturing | Heating of process and cleaning water | Mechanical Compression, Closed cycle |
| | Soft drink manufacturing | Concentration of effluent | Mechanical Compression, Closed cycle |
| **Utilities** | Nuclear power | Concentration of radioactive waste | Mechanical Vapor Compression, Open cycle |
| | | Concentration of cooling tower blowdown | Mechanical Vapor Compression, Open cycle |

In this application, warm, humid exhaust air from a lumber-drying kiln is the heat source for a closed cycle mechanical heat pump that delivers heat to the incoming air. In addition to energy benefits, the lower operating temperature of heat-pumped kilns improves product quality; the heat pump removing VOCs from the exhaust also provides an environmental benefit.

While lumber-drying applications are numerous, the size of the units is usually small in terms of the heat delivered. For example, 150,000 Btu/h heat output would be considered a large application; however, industry is developing larger systems of 3 to 5 MMBtu/h. Closed-cycle applications that are not for lumber drying range from 1 to 20 MMBtu/h heat output, and typically heat streams, such as process liquids or air. The most common large-heat-load application is vapor compression evaporation. In this application, evaporated vapor is compressed over a small pressure range and condensed to provide the energy to drive the evaporation process. Such systems deliver 20 MMBtu/h to over 100 MMBtu/h at a low cost.

Evaporators and flash-steam recovery systems frequently incorporate thermocompression systems. For example, paper dryers commonly use thermocompressors to recover flash steam from dryer condensate. Absorption systems are commonly used in chilling applications as alternatives to mechanical chillers, rather than in heat-pumping applications.

### Examples of heat-pump applications and types

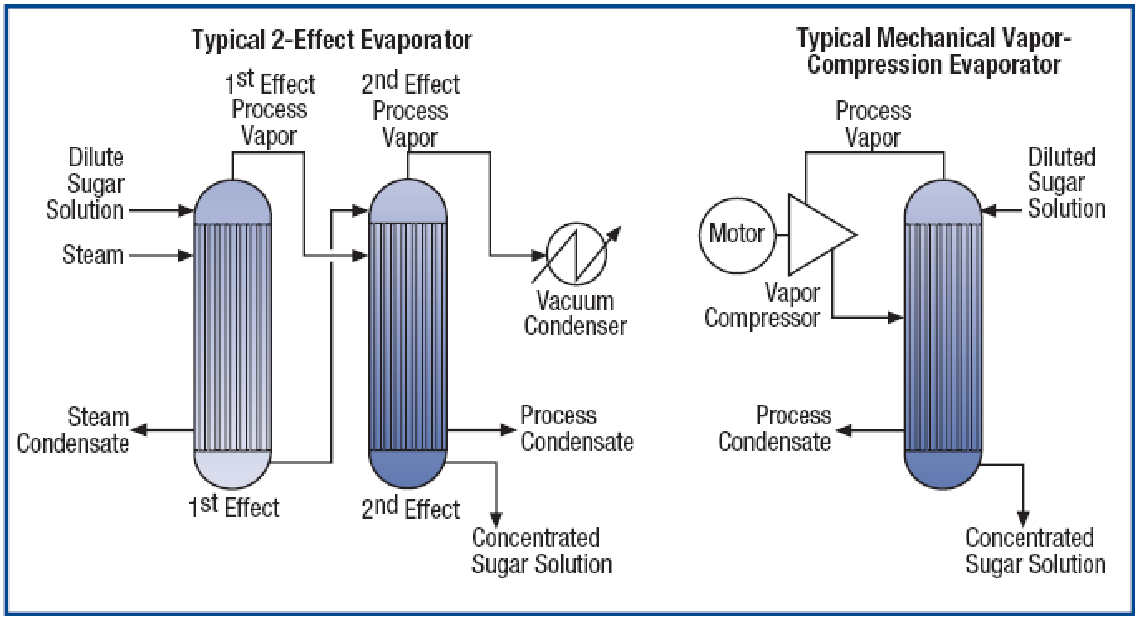
Descriptions of a few of the most common heat-pump applications can help illustrate how heat pumps are integrated into process operations.

**Lumber Drying—Closed-Cycle Mechanical**

Lumber drying is accomplished by supplying heated air to stacked lumber in an enclosed room. In a steam-heated lumber kiln, fresh air is heated and supplied to the kiln. The hot air evaporates moisture from the lumber and returns to the atmosphere. The moist kiln exhaust air is passed over the heat-pump evaporator, cooling the exhaust and producing some moisture condensation. The compressed heat-pump working fluid condenses against incoming fresh air, supplying hot air to the dryer. The cost of power to drive the heat pump is much less than the cost of using steam in the kiln without the heat pump.

**Evaporation—Open-Cycle Mechanical Vapor Compression (MVC) for Sugar Solution Concentration**

In the sugar refining process, large amounts of water must be evaporated from sugar solution before final crystallization. Figure below shows how MVC evaporation compares to multi-effect evaporation.




In multi-effect evaporation, steam is supplied to the first effect of the evaporator to boil off some water and create vapor. The vapor flows to an exchanger in the next effect, which operates at a lower pressure because a vacuum is applied. Here, additional water is evaporated; this process is repeated in each effect.

In an MVC evaporator, compressed vapor leaving the compressor condenses against the liquid being evaporated; the vapor it creates flows to the compressor inlet. The compression sufficiently increases the vapor pressure and allows vapor condensation at a temperature high enough to boil the incoming liquid.

The cost to drive the mechanical compression evaporator is less that the cost of the steam that drives the multi-effect evaporator.

However, energy cost is not the only consideration in evaporator selection. A thorough evaluation of all the benefits and drawbacks of each evaporator type would be necessary before selecting an evaporator for a specific application.

**Thermocompression—Paper-Dryer Flash-Steam Recovery**

A thermocompression heat pump is similar to the mechanical compression heat pump in that vapor is compressed so that it condenses at a higher pressure and temperature. However, instead of using mechanical work as the means of compression, a thermocompressor uses energy gained from reducing the pressure of higher-pressure steam.

In a paper machine, steam reaches each section of drying drums at the correct pressure to achieve required drying conditions. Steam condensate from higher-pressure sections is flashed to lower pressures; it is then recompressed to maximize energy recovery from the steam condensate, and to improve dryer energy efficiency.

## Heat-Pump Evaluation

Heat pump evaluation consists of four steps:

- Determining if a heat pump is a potential fit with your heat-recovery application
- Making an initial selection of heat-pump type
- Conducting preliminary cost/benefit analysis
- Performing a detailed feasibility study to define benefits and cost with sufficient confidence to move forward with the implementation.

The information below provides assistance in working through these four steps.

### When is a heat pump applicable?

Plant personnel can explore a few questions to determine if a heat pump might be applicable in their facility:

- Where is heat available from the process?
- Where is heat required in the process?
- What is the value of saved energy?
- Will the facility gain non-energy benefits such as environmental improvements or product quality?

### Initial selection of heat-pump type

Having established that a heat pump may be applicable, it is time to select a heat-pump type. Choosing a heat pump has a direct influence on capital and operating costs. The type of heat pump typically employed depends on:

- The nature of the heat source (for example, liquid, gas, condensing vapor)
- The nature of the heat sink (for example, liquid, gas, boiling fluid)
- The required temperature lift (temperature difference between the heat input and heat rejection temperatures).

### Estimating Savings

For any energy savings project, the basic goal in estimating savings in operating costs is to establish the difference in costs between current and future case-base operation. For passive-heat recovery projects, establishing this cost difference is relatively simple, because the value of steam or fuel saved is readily calculated.

In the case of heat pumps, the energy savings is equal to the value of steam or fuel saved, minus the cost of operating the heat pump. The quantity of energy saved and the cost of operating the heat pump depend on the application and the heat-pump characteristics.

## Reference:

www1.eere.energy.gov/industry/bestpractices/pdfs/heatpump.pdf