Applications, Economics and Scalability of Heat Pumps in Waste Water Treatment Plants and Energy Intensive Industries

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ABSTRACT

This paper investigates applications, economics and scalability of heat pumps for utilization of waste heat in industry. Examples are taken from waste water treatment facilities.

Our research identified 22 facilities with heat pump projects in multiple states. The capacities ranged from 6 to 550 tons, with coefficient of performance averaging around 3.5. Each case was compared on the basis of annual cost savings and initial investment and it was found that simple paybacks of less than 5 years were possible. In addition to their promising economic returns, the heat pumps also showed high scalability with sizes ranging from 3/4 tons capacity to well over several hundred tons. This combination of factors makes electric heat pumps a viable option for waste water treatment plants as well as other industries that have abundant waste heat streams. Additionally, heat pump applications in industries such as food processing, alcohol distillery and wood products are explored in this paper. It is found that the applications are mainly focused on energy intensive drying processes where precise control of drying is crucial due to heat sensitive characteristics of the final product. The payback times for the heat pump installations in these cases were found to range from 1.8 to 3.4 years.

The main questions considered are the actual benefits of heat pumps with the less energy efficient electrical energy source and the impact of new gas-fired heat pumps.

Introduction

Low temperature waste heat streams with large flow rates represent huge sums of energy being lost in many industries. However, effective recapture of this energy is often not possible with traditional means such as heat exchangers, because they cannot provide the sufficient temperature lift that is required for space conditioning or process purposes. Heat pumps are an effective way to recapture these low quality waste energy streams and boost the temperature of air or water to a usable level. Since these waste streams have virtually constant temperature, they can act as the necessary heat source for a heat pump. If these waste streams were otherwise unavailable, other methods to obtain a constant temperature heat source and sink can be cost prohibitive.

The chief advantage of using heat pumps is not obvious. At first look, COPs of heat pumps are typically 3 or higher, but with system electrical efficiencies at 30%, the total energy needed for heating is about the same as burning a fossil fuel. This is not exactly true, and as shown below, when typical boiler and furnace efficiencies are used (whether the heat pump replaces or simply assists a boiler or furnace system), the energy cost savings stemming from the heat pump's COP is positive. In other words, using a heat pump can be a better investment than using a furnace. However, when waste heat which is otherwise discarded is used, the benefits become significant.

A second class of applications is where both heating and cooling is needed. In this case a compressor or absorber are already required for the cooling part of the cycle, lowering implementation costs and decreasing payback.

While difficult to purchase in the US, the development of gas-fired heat pumps is likely to increase the impact of this type of technology and the utilization of low quality waste heat. The primary advantage of the gas-fired technologies (which include both engine driven and absorbers) is that the heat lost due to inefficiencies of compressors, engines etc. can be added in and contribute when a positive lift temperature is needed.

Heat Pumps in Waste Water Facilities

Waste water treatment plants are typically one of the largest energy consumers in a community and are often the focus of energy efficiency projects. While the method of treatment varies by plant, invariably large amounts of thermal and electrical energy are required. Typical treatment processes include aerobic and/or anaerobic digestion, sludge removal, dewatering as well as UV disinfection. Once the water has been treated, it is discharged as effluent, typically into a local body of water. This water is usually 50 to 60 °F and since the operation of the plant never ceases, this water is available year round. Figure 1 shows the typical heat pump setup that takes advantage of this waste water.

While the waste water has been treated and is mainly clean at this point, most systems installed in waste water facilities are of the closed loop type. This is to avoid direct interface of the effluent with the heat pump, as fouling could occur. The heat exchanger itself is submerged in the effluent and only in one instance did our survey of waste water plants uncover a complaint of fouling.

The installation of heat pumps in North American facilities is prolific; our research identified 22 facilities with heat pump projects. The typical use for these heat pumps is space conditioning, however some special applications exist. For instance, one system in Washington was used to produce hot water to heat anaerobic digesters, while another in Colorado was used to heat a local swimming pool. Of these 22 plants, only 6 provided project cost data. The range of paybacks was from 4 to 18 years as illustrated in Table 1[1], with some of these projects being included as part of new building construction while

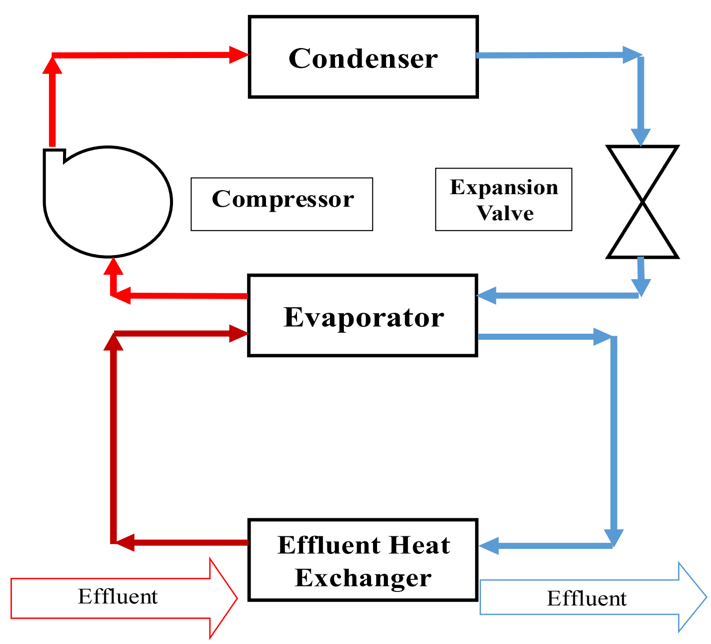


Figure 1. Typical Waste Water Effluent Heat Pump in Heating Mode

[1] Energy Information Administration, eia.gov 2011 industrial energy prices.

others are retrofits, The dataset shows reverse economies of scale as shown in Figure 2; with increasing tons the payback increases. Due to the fact that the details of the specific project costs are unknown, we will only present the data as it stands and will infer that paybacks under 5 years are possible for these systems. The list of the remaining plants that were surveyed is given in Table 2. Information about the economics of these plants were not available.

Table 1. Plant Survey Data

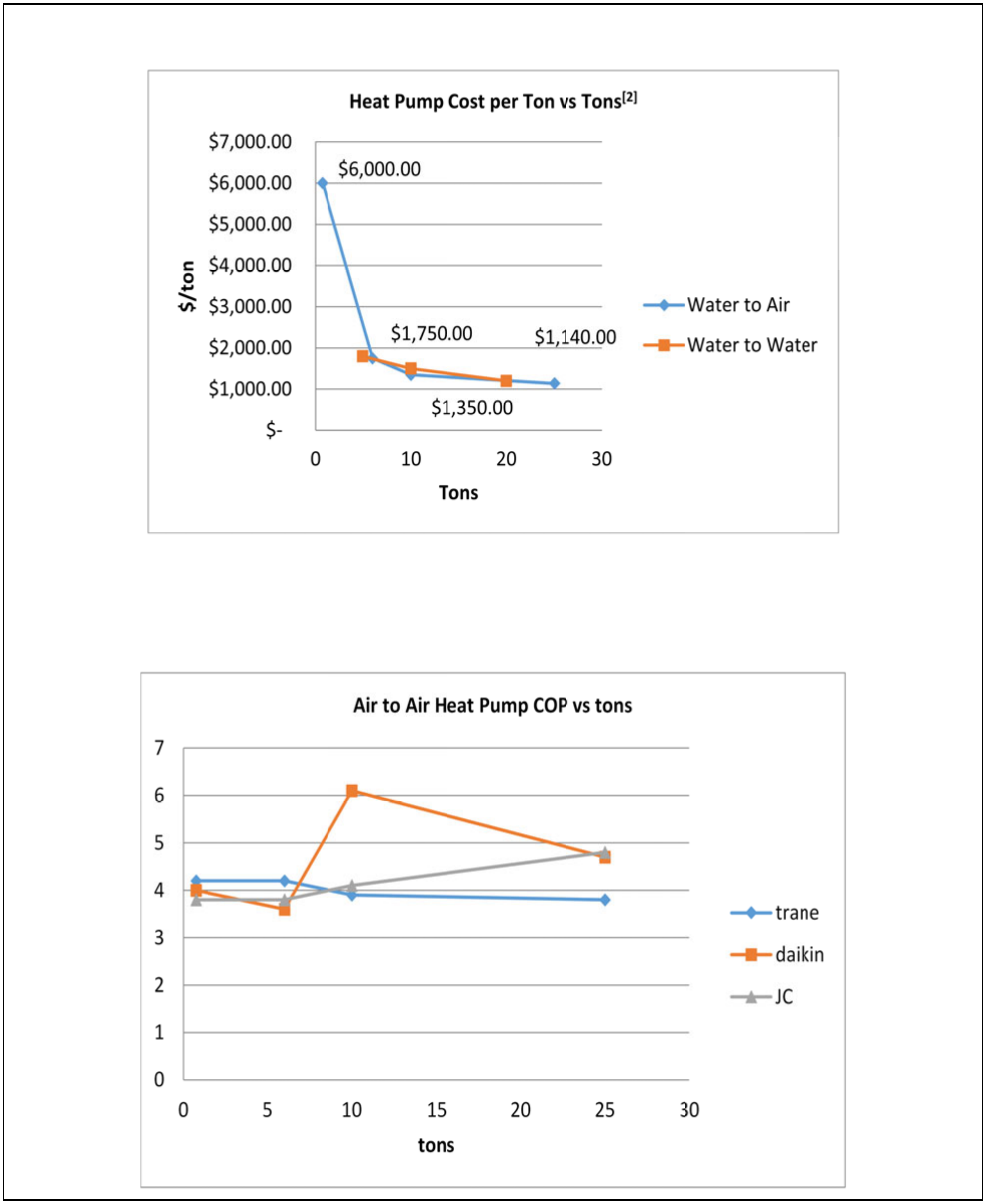
Facility	System Total Cost	Annual Savings	Simple Payback	Tons
Washington County, NY	$7,000.00	$1,750	4	6
Waterville, ME	$88,200	$7,519	4.4	20
McMinnville, OR	$217,000	$26,927	8.06	35
Chicago, IL	$75,000	$8,900	8.43	31
Philadelphia, PA	$250,000	$18,100	13.81	81.5
Saco, ME	$334,000	$18,640	17.92	30

Table 2. Facilities with Heat Pumps

Medina, NY	Silverton, OR	Sitka, AK	Whistler, BC	Williamsport, PA
Renton, WA	Moscow, ID	Stevens Point, WI	NAS Ocean, VA	Janesville, WI
Avon, CO	Dekalb Co., GA	Abingdon, VA	Kent Co., DE	

According to the survey, heat pump installations are deployed in various climates throughout US. The virtually constant temperature of the effluent enables feasibility of heat pumps in climates that are traditionally too cold for air source heat pumps. This shifts the focus to the other significant barrier to heat pump implementation: the annual dollar savings. In order for electrical heat pumps to have a lower operating cost than traditional systems such as furnaces and boilers, the COP must exceed the price ratio of electricity and natural gas. This will be even more challenging with inexpensive natural gas. In most areas of the country, the typical heat pump COP of 3-4 can easily overcome this barrier and provide significant savings, as shown in Table 3. Natural gas-fired heat pumps can circumvent this obstacle and provide positive cost savings at the cost of low COP.

Figure 2. Cost Data for Heat Pump

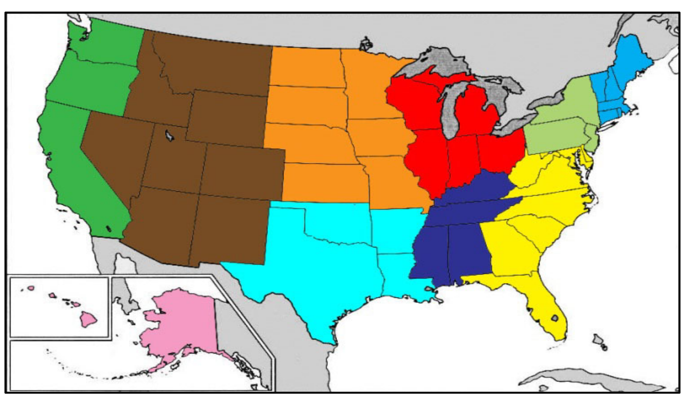


Commercially available heat pumps show excellent scalability, both in terms of available sizes and economies of scale. Sizes for water to air heat pumps ranged from ¾ to 25 tons, while water to water ranged from 5 to 20 tons. Larger capacities are available with custom systems or by modularly combining multiple systems. The price per ton of the smallest available size of 3/4 ton is very high at $6000; however installed cost per ton dramatically decreases with increasing capacity. Both water to air and water to water heat pumps exhibit this behavior. For heat pumps between 5 and 25 tons, the system cost can range from $1140 to $1750. In comparing 3 major manufacturers, it was found that the COP of heat pumps for sizes of 0.75, 6, 10 and 25 tons did not follow any clear trend despite the fact that COPs were all determined using the same ISO standard 13256.

In our preceding analysis of wastewater treatment plants, we found that the magnitude of waste heat available has provided incentive for many plants to undertake heat pump projects. The paybacks ranged from 4 to 18 years, with no clear relationship between system size and payback. Many waste water treatment plants are municipally owned and can absorb longer paybacks; however other industries may not have this luxury. Heat pumps have seen deployment in the food and wood products industries where they have enjoyed much shorter paybacks often on the order of 3 years or less. Like the waste water treatment industry, these

Table 3. Regional Industrial Energy Prices[1]

	Electricity $/MMBtu	Natural Gas $/MMBtu	Price Ratio EC/NG	Color
New England	$ 35.20	$ 9.58	3.67	
Middle Atlantic	$ 22.30	$ 8.86	2.52	
East North Central	$ 18.90	$ 6.93	2.73	
West North Central	$ 16.91	$ 5.88	2.88	
South Atlantic	$ 18.61	$ 7.20	2.59	
East South Central	$ 17.17	$ 5.55	3.10	
West South Central	$ 15.91	$ 5.68	2.80	
Mountain	$ 16.15	$ 6.61	2.44	
Pacific Contiguous	$ 20.75	$ 7.61	2.73	
Pacific Non-Contiguous	$ 77.99	$ 16.44	4.74	



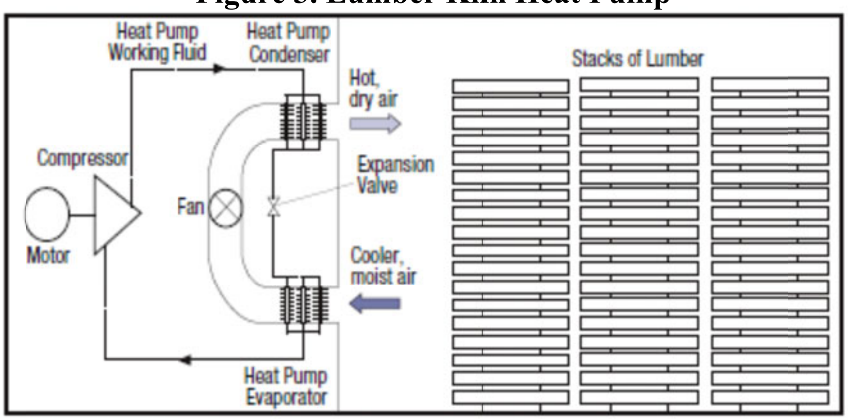
industries have processes that produce large amounts of low grade waste heat that is otherwise of too low a quality to be captured without heat pumps. The current state of heat pump usage in several industries is covered in the following narrative.

Industrial Case Studies

One major energy consuming process in industry is drying. Often this waste heat is of a low quality but it has large flow rate, a common trait this industry shares with waste water treatment plants. Normally discarded, a heat pump is required to provide the necessary temperature lift and increase the quality of the waste stream so it can be used.

A successful example is kiln drying, used to control the moisture content of lumber. Kiln drying has traditionally been accomplished through the use of steam heat exchangers in order to provide hot, dry air to evaporate moisture from wood stacked in an enclosed space such as a shed. The warm, moist exhaust air is vented to the atmosphere and represents a significant unutilized waste heat stream. A heat pump can be used to capture some of this energy, condense undesired moisture on the cold, evaporator, side and provide air at the desired drying temperature after the air crosses the condenser. A typical setup for a heat pump in a lumber drying heat pump is illustrated in Figure 3. The high COP of heat pumps allows for this process to occur with significant fuel savings. In a study conducted by Minea (2008), a 130 kW system was retrofitted to an existing 354 m^3 lumber kiln heated by steam. The system COP of 3.9 allowed them to realize between 27% to 56% savings in energy costs. This directly translated to a 47% drop in specific drying costs.

Figure 3. Lumber Kiln Heat Pump



As a second example in the pulp and paper business, Bakhtiari et al.(2010) looked to utilize the bleaching effluents from a Kraft process as a heat source for a heat pump system. One key step in this process involves the bleaching of the pulp, the purpose of which is to produce the white color required for paper. The bleaching process uses heated alkaline and acidic solutions to attain the desired whitening effect and often there is significant residual heat content in these streams after usage and disposal. These warm waste streams present a prime opportunity for heat recovery with a heat pump. In this case, an absorption heat pump was installed to provide hot water for use in the facility's boiler. Bleach effluents at 56 °C provided a heat source for the absorption heat pump, which in turn allowed an 18 °C temperature lift for hot water. An annual savings of $970k realized resulting in a simple payback period of 1.7 years.

A large proportion of the energy required within the food industry is used to remove water from food products. Since drying processes are energy intensive, their efficiency and optimum operating conditions is crucial for the economical operation of dryers. Drying uses one or a combination of convection, conduction or radiation to transfer heat to the product that is to be dried. Much work has been done to increase the drying efficiency of convection drying, particularly by the application of heat pump dehumidifiers (HPDs). HPD dryers are finding increasing applications in the food industry for drying of nuts, fruit, vegetables, herbs and fish products. The retrofit of an industrial heat pump to a direct-fired natural gas conveyor dryer for apples was implemented in Washington. The existing natural gas burners will remain as auxiliary and back-up heat. The estimated energy savings for this project was 89,400 million BTU of natural gas per year, while increasing annual electricity use by 8,580,000 kilowatt hours.

With net energy savings of $463,000 per year and an installed cost of $1.25 million, the heat pump retrofit had an estimated payback of approximately 2.7 years. The estimated carbon dioxide emissions were more than 2.4 million pounds per year, which represents a 10% reduction in greenhouse gas emissions associated in the drying operations. According to Paul Scheihing of the U.S. Department of Energy's Industrial Technologies Program "There are dozens of food processors throughout the Northwest that can benefit from the technology[2]."

A thermally driven heat pump that delivers hot water and chilling simultaneously was developed and demonstrated at a California poultry processing plant. It is driven by heat at 300 F^0, delivers hot water at 140 F^0 and provides chilling at 35 F^0. It provides 160 units of heating and 60 units of chilling per 100 units of thermal energy input. Electrical energy use is minimal at approximately 6 units of thermal energy equivalent. Rejection of the heat extracted from the chilling load at a temperature high enough to be useful in industrial application is the main concept in this technology [10].

The heat pump is a unique ammonia-water cycle, developed by Energy Concepts Company (ECC). The heat pump also uses proprietary heat and mass exchangers, which allow the delivery of the two useful energy products: hot water and chilled water.. The heat pump was originally designed, fabricated, and tested at Energy Concepts Company, shipped to and installed at the facility in Modesto the week of March 2000.

ThermoSorber™ supplies 100-tons of chilling and 3.2 million BTU per hour of hot water simultaneously, from 2 million BTU/hour of 80 psig steam. It operates on a 20/5 basis automatically and completely unattended.

The savings in both natural gas and electricity add up to over $276,120 per year. Based upon the typical installed cost for a 250 ton unit of $500K, the payback is 1.8 years. There is a corresponding large reduction in CO2 emissions which is 1,800 tons per year less[11].

As a final example, a research project on a **Gas Engine Heat Pump (GEHP)** has been implemented in 2007 by Hepbasli Kuzgunkaya and Colak of Turkey (TUBITAK). The design was a gas engine driven solar assisted band conveyor HP drying system, as shown in Figure 4 the system was applied to food drying.

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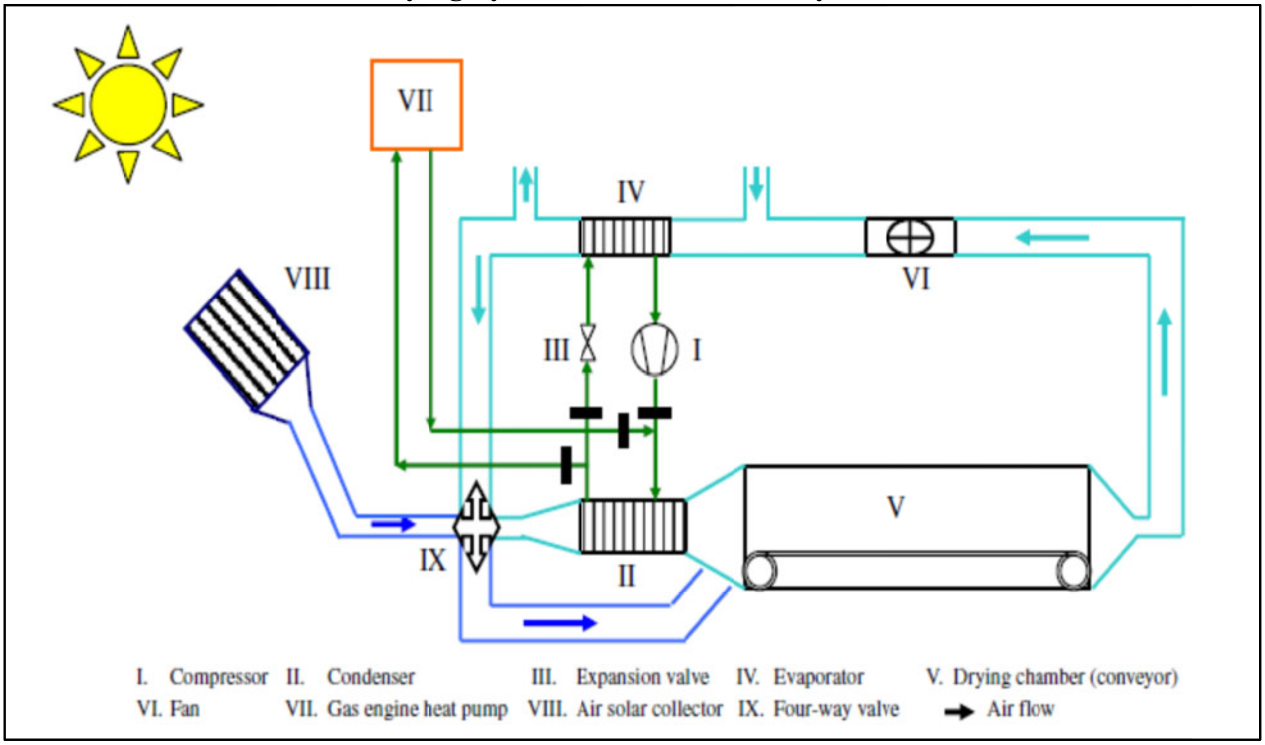
[2] *Industrial Services Factsheet*, Washington State University, 2009

Figure 4. The Schematic View of a Solar Assisted, Gas Engine Driven Heat Pump Drying System with Band Conveyor [12]



Conclusions

Heat pumps can be used effectively in industry when two key criteria are met; an abundance of waste heat is available and the COP of the heat pump is high enough to overcome the operation cost of traditional equipment such as furnaces and boilers. When electrically powered heat pumps are unable to provide sufficient savings, use of absorption heat pumps is possible, especially with natural gas prices at record lows. As a result of the survey, we found that heat pumps in the wastewater industry can deliver paybacks in the range of 4 to 18 years. However, paybacks of 3 years or less are common in the food and wood products industries. Drying and process heating applications are prime candidates for heat pump usage due their energy intensive nature and there are many installations that currently take advantage of the benefits of heat pumps such as precise control of the drying process which is crucial for heat sensitive products.

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