Industrial Waste-Heat Recovery: Benefits and Recent Advancements in Technology and Applications

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ABSTRACT

A substantial amount of energy used by industry is wasted as heat in the form of exhaust gases, air streams, and liquids leaving industrial facilities. Although it is not technically and economically feasible to recover all waste heat, a gross estimate is that waste-heat recovery could substitute for 9% of total energy used by US industry—or 1.4 quadrillion BTU—which would ultimately help improve the global competitiveness of the US (Energetics and E3M 2004). An increased use of waste-heat recovery technologies by industry would also serve to mitigate greenhouse gas (GHG) emissions. The primary sources of waste heat in industrial facilities include exhaust gases from fossil fuel-fired furnaces, boilers, and process heating equipment. These types of high-grade waste-heat sources can readily be used to preheat combustion air, boiler feedwater, and process loads. Waste-heat recovery from lower temperature sources, such as cooling water from machines and condensers, is generally somewhat more problematic, and typically involves the use of heat pumps to increase the temperature to a suitable temperature for distillation, evaporation, water heating, and space heating. This paper summarizes the results of numerous studies conducted by the authors and/or their associates to identify opportunities for waste-heat recovery in industrial facilities. It also describes recent advancements and applications in waste-heat recovery technology. Typical "energy audits" identify annual energy cost savings of about 5%. However, this paper confirms that systematic waste-heat recovery projects based on sound thermodynamic principles can yield annual energy cost savings of 10% to 20% with paybacks of 6 to 18 months for industrial facilities. Recent advancements in heat recovery technology may increase the energy savings by an additional 5% to 10%. Since only 5% of US manufacturing facilities currently use waste-heat recovery, there is tremendous potential for energy savings in the industrial sector (EIA 2002, Table 8.2).

Definition of Waste Heat for This Paper

Waste heat is the energy associated with waste streams of air, exhaust gases, and/or liquids that leave the boundaries of an industrial facility and enter the environment. In the definition of waste heat, it is implicit that the waste streams eventually mix with atmospheric air or groundwater and that the energy contained within them becomes unavailable as useful energy. The absorption of waste energy by the environment is often termed thermal pollution. In a more restricted definition, waste heat is the energy that is rejected from a process at a temperature high enough to permit the recovery of some fraction of the energy for useful purposes in an economic manner.

Usually the energy being transferred is the sensible energy (or internal thermal energy) of the fluid, but it can also include the transfer of the latent energy of the fluid. Latent heat-exchange is typically associated with a phase change between the vapor and liquid states of the fluid, such as condensation and boiling. For example, the recovery of waste heat from hot and moist air used in the lumber drying process involves the recovery of both sensible and latent heat. Moisture-laden air that would otherwise be vented to atmosphere is brought past the evaporation coil of a heat pump where it condenses, not only providing energy savings but also resulting in the capture of Volatile Organic Compounds (VOCs) in the condensate (Fouche, Ed and Heck, Greg 2006).

Quantity, Quality and Temporal Availability of Waste Heat

There are three important parameters used in the quantification of waste heat: *quantity*, *quality*, and *temporal availability*. The *quantity* of waste heat available is ordinarily expressed in terms of the enthalpy flow of the waste stream:

$H = mh$

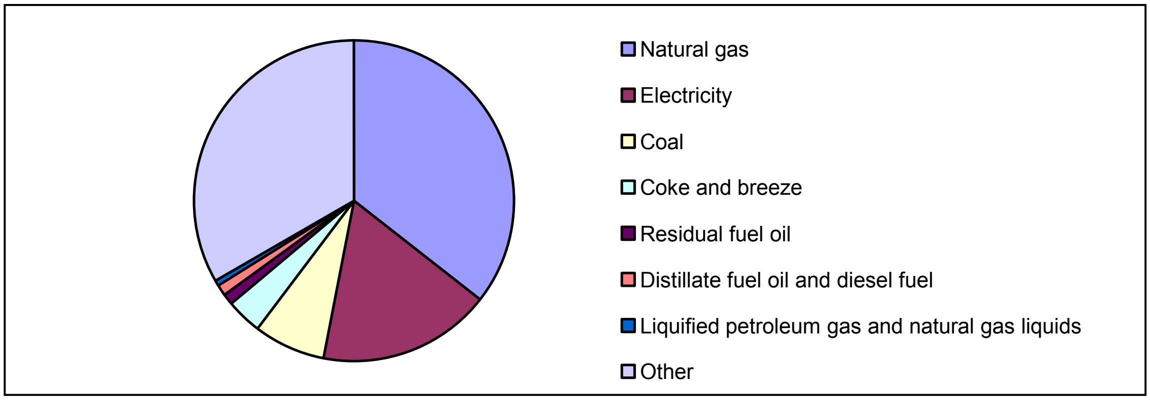
where H = total enthalpy rate of waste stream (Btu/hr); m = mass flow rate of waste stream (lb/hr); and h = specific enthalpy of waste stream, (Btu/lb.)

The *quality* can be roughly expressed in terms of the temperature of the waste stream. The higher the temperature, the more available the waste heat is for substitution of purchased energy. The use of a heat pump can improve the quality of waste heat economically over a limited range. It is immediately apparent that one cannot use a waste-heat stream at 70 °F to heat a fluid stream whose inlet temperature is 100 °F, regardless of the total quantity of waste heat available. However, a heat pump might conceivably be used to raise the temperature of the waste heat to 110 °F. Whether this is an economically feasible solution is dependent upon the final temperature required of the fluid to be heated. The *temporal availability* is a measure of the availability of waste heat at times when it is needed. Matching the availability of the waste heat to the ultimate load is an important consideration in the effectiveness of waste heat recovery. Therefore, the usefulness of waste heat does not depend as much on the *quantity* available as it does on whether its *quality* fits the requirements of the potential load and whether it is available at the times when it is required (*temporal availability*).

Heat-Recovery Potential in US Manufacturing Industry

In 2002, the US manufacturing industry used approximately 16 quadrillion BTU of energy to operate a wide variety of equipment, including boilers, machine drives, process-heating equipment, and HVAC systems (EIA 2002, Table 5.2). The majority of energy used was natural gas (36%), followed by electricity (17%), and coal (7%) (Figure 1). Because natural gas accounts for substantial amount of energy used in the US manufacturing industry and natural gas-powered power plants also generate a significant share of US electricity, the US manufacturing industry is extremely vulnerable to fluctuating natural gas prices. Additionally, the US manufacturing industry is increasingly exposed to state and federal efforts to reduce GHG emissions since industrial energy use typically accounts for close to one third of GHG emissions in advanced economies (Jolley 2006). For example, California recently implemented policy goals for the reduction of GHG emissions to 2000 levels by 2010 and to 1990 levels by 2020, while also achieving electricity and natural gas consumption cumulative savings of about 23,000 GWh and 440 MMTh by 2013, respectively (CEC 2007). The California Energy Commission (CEC) strives to save 7,800 GWh of electricity and 210 MMth of natural gas in the industrial sector by 2013 through various initiatives, including waste-heat recovery (CEC 2007).

Figure 1. US Manufacturing Industry Energy Use, Breakdown by Fuel, 2002



Total energy use: 16,273 trillion BTU. Data derived from (EIA 2002, Table 5.2)

A recent study estimates that waste heat losses account for 13% to 18% of US industrial energy use (DOE 2003a). It is estimated 1.4 quadrillion BTU of waste heat could technically and economically be recovered by industry (Energetics and E3M 2004). If realized, this translates into US industrial energy savings of almost 9% at the current energy use level.

Cost-Effective Waste-Heat Recovery and Reuse in Industry

While the US manufacturing industry primarily uses electrical-powered machine drives, it relies heavily on fossil-fuel-fired process heating equipment and boilers. Indeed, natural gas accounts for about 70% of total energy used by process heating equipment in industry, followed by coal (10%) (EIA 2002). Natural gas also accounts for 70% of total energy used by industrial boilers, followed by coal (25%) (EIA 2002). Chemicals, paper, food processing, and petroleum refining industries dominate the use of fossil fuels for boiler operation, while the primary metals, chemicals, and petroleum refining industries dominate the use of fossil fuels for process heating equipment (EIA 2002). Process heating equipment and boilers release medium-to-high temperature exhaust gases, waste steam, and effluents. For example, exhausts gases from furnaces, kilns, incinerators and other process heating equipment are typically released at temperatures above 1,000 ^{o}F (Table 1). As a result, medium-to-high temperature exhaust gases from fossil-fuel-fired boilers and process heating equipment are prime candidates for waste-heat recovery.

Cost-effective waste-heat recovery and reuse involves the identification of waste-heat sources of sufficient quality, quantity, and temporal availability, *and* heating loads that can reuse the waste heat recovered. There are numerous industrial processes available in the low-to-medium temperature range that can reuse waste heat, many of which are found in the food and beverage, textile, forest products, petrochemical, and chemicals industries (Table 1). For example, certain distillation operations in refineries and chemical plants are ideal for open-loop heat pump systems that mechanically recompress the “overhead” distillation vapor which is subsequently allowed to condense in the reboiler where it vaporizes the “bottoms” product in the distillation column. These applications typically involve small temperature differences and are often more cost-effective than using fuel combustion to heat the reboiler and a cooling tower to reject the heat in the distillate.

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Table 1. Temperatures of Industrial Heating Loads

Industrial sector	Process	Typical temperature level (°F)
All sectors	Preheating boiler feedwater	80-210
	Space conditioning of facilities and warehouses	40-210
	Heating water	100-200
	Preheating load	60-600
	Preheating combustion air	600-1,600
Food and Beverage	Drying (food processing, breweries, dairy)	85-435
	Yogurt maturation (dairy)	105-115
	Heat treating (food processing)	105-140
	Clean-in-place washing, washing bottles, clothes etc.	105-195
	Solvent extraction and distillation of vegetable oil (food processing)	140-230
	Pasteurizing (food processing, breweries, dairy)	160-250
	Boiling (food processing)	200-220
	Distilling (breweries)	205-215
	Evaporating (dairy)	140-300
	Sterilizing (food processing)	285-300
	Frying (food processing)	175-430
Textile	Rinsing after dyeing	115-125
	Washing textiles etc.	105-175
	Bleaching	140-215
	Drying	200-300
	Dyeing	210-320
Petrochemical and Chemical	Boiling	200-220
	Distilling	230-670
	Various chemical processes	250-490
Forest Products	Drying (lumber)	105-210
	Heating, drying, corrugation (pulp and paper)	230-305
Manufacturing	Spray-painting	70-85
	Galvanizing	85-195
	Dehumidification/heating of air for plastic injection molding	90-190
	Lubricating/washing	100-300
	Degreasing	120-150
	Heating plating, pickling, scouring baths	120-200
	Drying	175-195
	Steam boiler exhaust	450-900
	Reciprocating engine exhaust	450-1,100
	Exhaust gas from drying and baking ovens	450-1,100
	Gas turbine exhaust	700-1,100
	Exhaust gas from heat treating furnaces	800-1,200
	Exhaust gas from catalytic crackers	800-1,200
	Exhaust gas from cement kilns (dry process)	1,150-1,350
	Exhaust gas from open hearth furnaces	1,200-1,300
	Exhaust gas from aluminum refining furnaces	1,200-1,400
	Exhaust gas from copper refining furnaces	1,400-1,500
	Exhaust gas from hydrogen plants	1,200-1,800
	Exhaust gas from solid waste incinerators	1,200-1,800
	Exhaust gas from zinc refining furnaces	1,400-2,000
	Exhaust gas from fume incinerators	1,200-2,600
	Exhaust gas from steel heating furnaces	1,700-1,900
	Exhaust gas from copper reverberatory furnaces	1,650-2,000
	Exhaust gas from glass melting furnaces	1,800-2,800

Data derived from (Global 2006b)

Although some industrial sectors may offer greater opportunities for waste-heat recovery than others, most industrial sectors can reuse waste heat for preheating combustion air, preheating boiler feedwater, and preheating process load. For example, gas-to-gas heat exchangers can transfer heat from hot exhaust gases to the incoming combustion air. Similarly, gas-to-liquid heat exchangers can transfer waste heat from hot exhaust gases to boiler feedwater. Preheating load involves bringing high-temperature exhaust gases into direct contact with the relatively cooler load entering the process. This is a more cost-effective use of waste heat because it does not require the use of any heat exchanger.

The integration of waste-heat recovery at a local process will have overall process implications for the entire facility. Fortunately, there are strategies, tools and methods available to help identify the most promising waste-heat recovery opportunities, while simultaneously ensuring optimal process integration and energy efficiency for the *entire* industrial facility. One of the most widely used process integration methods is pinch analysis.

Pinch Analysis

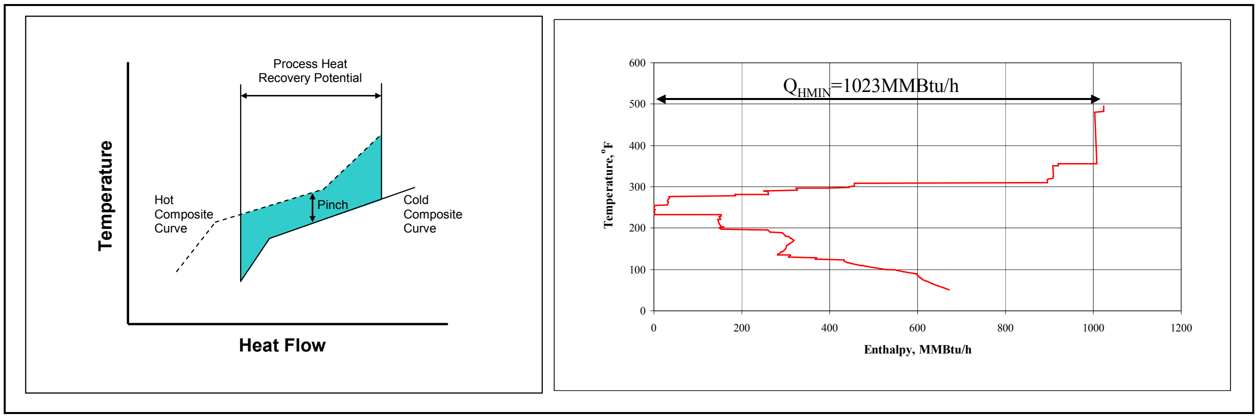
Pinch analysis was originally developed to determine optimal heat recovery between heat sources and heat loads, but is today also applied to combined heat and power systems, utility systems, distillation systems, reactor systems, hydrogen production, and even water management and wastewater treatment systems (Jolley 2006). There are four primary phases of pinch analysis in the design of waste-heat recovery systems for optimal process integration (Trivedi, Kirtan K., Fouche, Ed and Parmenter, Kelly E 2007):

- **Site survey:** Data is collected for the process and utility system, with the primary focus on heating, cooling, boiling, and condensation needs. Every energy-containing non-product flow from the facility is identified first. Thereafter, accurate data about the original source of the waste-heat stream are gathered. Simulation data may be used when measured site data is inaccurate or unavailable. Finally, a heat balance on the process or system that produces the waste heat is completed.
- **Targeting:** Targets for the minimum heating and cooling needs are established, and the maximum possible heat recovery is quantified. Practical, realistic targets are developed by taking constraints, such as difficulties in handling fluids and extended layout, into account. Comparison of practical targets with theoretically minimum values quantifies opportunities lost by the constraints.
- **Design:** An initial heat exchanger network is established using commercial software packages. The basic design method focuses on minimum energy consumption while using the fewest possible heat exchanger units or minimal total heat transfer area.
- **Optimization:** The initial heat exchanger network design is simplified and improved in terms of cost-effectiveness, and trade-offs between physical efficiency and costs are optimized.

Significance of pinch temperature. Once the “hot” and “cold” streams are identified, the whole process can be plotted on a temperature-vs.-heat flow diagram (or Composite Curves) to examine what “hot” and “cold” streams can be matched via heat recovery (Figure 2, left). The Composite Curves identify the pinch temperature (the temperature where the two curves come closest together), the minimum external heating needs (Q_{Hmin}), and the minimum external cooling needs

(Q_{Cmin}) that the process requires, assuming perfect heat recovery. The pinch temperature is valuable in determining the need for steam and how to appropriately integrate heat pumps within a process. For example, steam should not be used anywhere below the pinch temperature because the facility already has an excess of heat below this temperature. Additionally, a heat pump is appropriately placed only if it operates around the pinch, with waste heat supplied to the heat pump below the pinch and heat delivered by the heat pump above the pinch. All "hot" an "cold" process streams can be represented as a single line on a temperature-vs.-enthalpy diagram (or Grand Composite Curve), allowing for the operating temperatures and heating loads of the evaporators and condensers of the heat pumps and the heat pump placement to be determined (Figure 2, right).

Figure 2. Composite Curves



Benefits of pinch analysis. The primary benefits of using pinch analysis for waste-heat recovery are summarized below (Global 2006a).

- Pinch analysis provides a method for continuously examining energy costs and defining maximum possible energy savings;
- It provides a structured approach to identifying prime waste-heat sources and heating loads;
- It identifies clearly where changes to the process itself reduce the *overall* process energy target, rather than simply reduce energy use locally;
- It organizes waste-heat recovery projects in phases of implementation with a first order payback analysis and with cumulative savings;
- It identifies clearly what low-grade waste-heat sources can be recovered and reused;
- It accurately assesses heat pump options and placements;
- It provides rules for appropriately integrating process unit operations, such as evaporation and distillation;
- It provides insight into where changes to the utility system, such as new or alternative steam levels, may be justified;
- It identifies what type of combined heat and power system, if any, that best matches the inherent thermodynamic load

Heat Recovery Equipment

There are two primary types of heat recovery equipment used by industry: heat exchangers and heat pumps. The use of heat exchangers is more common than the use of heat pumps, especially in retrofit situations. However, heat pumps may be a more economic option in some instances. For example, heat pumps can facilitate energy savings when passive heat-exchange is not possible due to low waste-heat temperature or small temperature differences. The coefficient of performance (COP_{hp}) for a heat pump must be considerably greater than 3 to be economically attractive and greater than the breakeven COP for the prevailing energy price conditions. The vast majority of heat pumps operate with temperature lifts of less than 100 ^{o}F (DOE 2003b). There are four common types of industrial heat pumps:

- **Closed-cycle mechanical heat pumps** use mechanical compression of refrigerant. They are used for lumber drying, space heating, and heating water/process liquids.
- **Open-cycle mechanical vapor compression heat pumps** use mechanical compression to increase the pressure of waste water vapor. They are used in evaporation and distillation processes commonly found in the petroleum, chemicals, pulp, and food and beverage industries.
- **Open-cycle thermocompression heat pumps** use high-pressure steam to increase the pressure of waste water vapor. They are used in evaporators and flash-steam recovery systems, such as paper dryers. It is generally more cost-effective to select an open-cycle heat pump, as it has both higher COP and lower capital cost relative to a closed-cycle heat pump (Global 2006a).
- **Closed-cycle absorption heat pumps** use a two-component working fluid and the principles of boiling-point elevation and heat of absorption. They can deliver a much higher temperature lift than the other heat pumps and have the ability to provide simultaneous cooling and heating. They are typically used in chilling applications.

Primary Benefits of Waste-Heat Recovery

Waste-heat recovery provides numerous benefits to industry, including:

- **Reduces energy costs:** All recovered waste heat directly replaces purchased energy, thereby reducing energy costs;
- **Reduces cost of capital equipment:** Reuse of waste heat allows for the use of smaller energy conversion equipment capacity, often resulting in savings in capital expenditures offsetting the cost of the heat recovery system;
- **Reduces operating costs:** Since waste heat recovery reduces energy costs and often also reduces capital costs, it reduces operating costs;
- **Reduces environmental impact:** Because all waste-heat recovery directly replaces purchased energy, it also reduces the environmental impact on air and water;
- **Reduces GHG emissions:** Waste-heat recovery by industry reduces GHG emissions associated with industrial operation;

- **May reduce air emission treatment costs:** The cost of treatment of air pollutants may be significantly reduced by waste-heat recovery from exhaust gases in those facilities that rely on incinerators to decompose gaseous or vaporous air pollutants;
- **May improve product quality:** The use of heat pumps for lumber drying typically provides better quality dried lumber and higher yields.

Economics of Waste-Heat Recovery

The economic potential of waste-heat recovery systems depends on the capital recovery, which, in turn, depends on the annual fuel savings. Fuel savings can be difficult to predict because they depend on the time distribution of waste-heat and heat-load availability. Additionally, the rate of capital recovery of heat-recovery equipment differs substantially from production-related equipment as it is typically fixed by utility rates and current market values of fuels and cannot be as easily adjusted by manipulating product selling prices. The most appropriate type of heat-recovery equipment is determined based on technical feasibility, annual cost savings, and capital cost. It can be dangerous to only use the simple payback period. For example, industrial heat pump applications typically have longer simple payback periods (two to five years) than heat exchanger options although they usually provide better long-term solutions (DOE 2003b). Instead, proper discounted cash flow analysis should be used for accurate comparison of alternatives.

Advancements in Heat Recovery Technology and Applications

New heat recovery technology has been evolutionary and not revolutionary. However, improvements in efficiency and design of heat exchangers and heat pumps have led to new applications and improved paybacks for previous applications. Current heat recovery equipment can be constructed in special materials to withstand high temperatures, chemicals, and corrosion. For example, commonly used metallic radiation recuperators typically cannot handle inlet temperatures exceeding 2,000 ^{o}F but ceramic radiation recuperators can tolerate exhaust gas temperatures up to 2,800 ^{o}F. Additionally, condensing boiler economizers constructed in corrosion-resistant material can recover both sensible and latent energy from the exhaust gases.

Recent advancements in heat pump technology to increase COP and lower capital costs include improvements in compressor and heat exchanger efficiencies. For example, the isentropic efficiency of single-stage centrifugal steam compressors used in mechanical vapor recompression (MVR) has increased from about 70% to above 80%, resulting in operating cost savings of about 10% (Global 2006a). Turbo-blower type compressors have also been developed for steam compressor applications. They operate at lower speed, allow for large vapor volumes over pressure ratios (up to 1.3), and have lower capital costs relative to centrifugal compressors. With efficiencies greater than 80%, they help improve the economics of MRV systems further.

Selected Recent Applications of Heat Recovery Technology

Miscellaneous applications (Trivedi, Kirtan K., Fouche, Ed and Parmenter, Kelly E. 2007). Global Energy Partners, in collaboration with EPRI, has conducted about 70 waste-heat recovery analysis for a wide range of manufacturing industries in North America, including pulp and paper; petroleum; petrochemicals; inorganic chemicals; general organic chemicals; fertilizers and pesticides; synthetic fuels from coal, polymers and fibers; food; beverage; pharmaceutical; and minerals and metals industries. The analyses have resulted in annual energy savings exceeding $150 million, with paybacks typically less than two years. Table 2 summarizes selected results from these analyses conducted to identify and implement waste-heat recovery projects that met payback requirements of the industrial facility.

Table 2. Selected Results from Global Energy Partners/EPRI Waste-Heat Recovery Analyses

Project category	Type of industry	Annual savings ($)	Capital costs ($)	Simple payback (years)
Preheat boiler feedwater	Pulp and paper	3,000,000	600,000	0.2
Preheat deaerator makeup water by cooling two product streams	Refinery	383,000	67,000	0.2
Replace heat exchanger	Pulp and paper	503,600	260,000	0.5
Condensate heat recovery	Pulp and paper	700,000	400,000	0.6
MVR heat pump on distillation column	Specialty chemicals	1,153,000	1,825,000	1.1
Hot water heat recovery	Pulp and paper	3,000,000	3,750,000	1.2
Re-pipe condenser	Pulp and paper	640,000	800,000	1.2
Heat pump on refrigeration condensate to heat water	Dairy	150,000	225,000	1.5
Boiler economizer	Dairy	30,000	20,000	1.5
Heat pump in BTX unit	Refinery	1,750,000	2,760,000	1.5
Heat exchange with effluents	Pulp and paper	325,000	520,000	1.6
MVR heat pump on distillation column	Refinery	360,000	600,000	1.7
Heat exchange with effluents	Pulp and paper	1,400,000	2,450,000	1.8
Recycle press shower water	Pulp and paper	1,350,000	2,600,000	1.9
Improve/replace economizer	Paper	149,000	299,000	2.0
Heat pump on refrigeration condensate	Pharmaceutical	21,900	55,000	2.5
Preheat press shower water with exhaust air	Paper	111,000	291,000	2.6
Preheat mill water with process effluent	Newsprint	75,000	207,000	2.8
Preheat boiler feedwater	Pulp and paper	1,000,0000	3,000,0000	3.0

Data derived from (Global 2006a)

Wood drying (Fouche, Ed and Heck, Greg 2006). The single largest application of industrial heat pumps is lumber drying. Southern Company is currently evaluating a customized, heat pump-driven kiln for drying softwood lumber. Moisture-laden air that would otherwise be vented to the atmosphere is brought past the evaporation coil, where it condenses to a liquid stream containing VOCs (requires some venting). Preliminary results show that about 6 lbs. of water is removed per kWh (570 Btu/lb).

Heat pumps for an industrial building (Fouche, Ed and Heck, Greg 2006). Southern Company is currently evaluating a dehumidification system for an industrial building. The system consists of heat pumps and desiccant wheel that pre-cools the incoming air. Heat from the condenser coils provides regeneration heat to the desiccant wheel. This technology is not yet commercialized.

Heat pump/thermal storage for metal producer (Tri-State 2000a). Thermal storage can be used to transfer electric consumption off-peak. In the original system, the return cooling water was sent directly to a cooling tower and steam boilers handled the 5 million-Btu/hr heating need. The steam system was converted to a 150 °F hot water loop and a heat pump was used to reclaim waste heat from the cooling water. A 12,000-gallon storage tank enabled the heat pump to be turned off during peak electric demand hours. As a result, the 341-kW electric heat pump load does not contribute any additional peak demand and it can operate at a COP of 4.3.

Steam recompression/open-cycle heat pump (Tri-State 2000b). A manufacturing plant had 50,000 lbs/hr excess of 40 psig steam while at the same time it required 300 psig steam. To address the plant's steam needs, a steam compressor open-cycle heat pump was evaluated. A two-stage rotary screw compressor or a three-stage centrifugal compressor unit was proposed at an installed cost of $1,250,000. At an electric rate of $0.05/kWh and an annual operation of 8,000 hours, a simple payback of 2 years could be obtained.

Flue gas heat recovery (Tri-State 2000c). Economizers and/or air preheaters are the most commonly used heat exchangers for flue gases. Economizers are usually an appropriate retrofit alternative if a boiler operates at significant loads all year long. For example, a boiler that operates at 150 psig saturated steam and generates 20,000 lbs/hr can typically save 2.4 MMBtu/hr if an economizer recovers waste heat from the flue gas. At a fuel cost of $4 per million Btu, this would save approximately $52,000 a year.

Thermal oxidizer heat recovery boiler (DOE 2003c). A 3M Hutchinson plant evaluated two heat recovery applications: an oil-to-air heat exchanger to preheat supply air and makeup air, and a heat recovery boiler for low-pressure steam production. The payback period of the heat recovery boiler was much shorter than for the heat exchanger (1.2 years vs. 8.1 years). The use of a reheat boiler also mitigates the heat recovery limitations of an oil-to-air heat recovery system, as the annual energy reduction of such system is limited to the load of the specific air-handling units. Additionally, heat recovered from the thermal oxidizers for the production of low-pressure steam also can serve multiple loads throughout the plant. Annual steam production from the waste heat recovered is estimated to provide total energy savings of $772,000/year. The heat recovery boiler had a 1.2-year payback.

Heat pumps in a waste burning power plant (IEA HPC 2004a). In 2000, Umeå Energi Ltd. built a power plant combined with a municipal/ industrial wood waste burning facility. The plant uses a heat recovery system with an integrated 14 MW compression heat pump that recovers waste condensing heat in the flue gas and transfers this waste heat into the district heating system. The plant also separates ammonia slip produced as a result of thermal NO_x-reduction. Ammonia is recovered and recirculated to the boiler for reuse.

Distillation with mechanical vapor recompression (IEA HPC 2004b). As part of modernization at a chemical plant, a new propylene-propane mechanical vapor recompression (MVR) distillation column was built. The MRV system provides annual energy cost savings of 3.5 million EUR and annual CO_2 emissions reduction of 67,000 ton. The MRV system also reduces the use of cooling water. The system has a 2-year payback.

Conclusions and Recommendations

Manufacturing facilities offer great opportunities for waste-heat recovery. Medium-to-high temperature exhaust gases from fossil-fuel-fired furnaces, boilers, and other process heating equipment typically account for the greatest opportunities for passive waste-heat recovery in industry. However, the use of heat pumps to raise the temperature of low-temperature waste heat to a more suitable level for distillation, evaporation, drying, space heating, and water heating applications offers great potential too. Since less than 5% of US manufacturing facilities currently use waste-heat recovery, the potential for waste-heat recovery is tremendous in US industry. (DOE 2002, Table 8.2) Indeed, it is estimated that waste-heat recovery could substitute for 9% of total energy use by US industry—or 1.4 quadrillion BTU. (Energetics and E3M 2004) An added benefit of waste-heat recovery is the reduction in GHG emissions. Ultimately, a greater use of waste-heat recovery equipment by US industry will increase the industry's global competitiveness.

Industrial facilitates with significant energy use should conduct site-wide energy-efficiency assessments to identify opportunities to reduce energy intensity and identify waste-heat recovery and reuse opportunities. Incentive programs from utilities and federal and state agencies are available to offset all or part of the cost of a site-wide energy-efficiency assessment. The site-wide energy-efficiency assessment should:

- Start with an energy balance of energy sources and uses (loads);
- Identify waste-heat recovery and reuse opportunities;
- Utilize pinch analysis, if applicable;
- Consider new technology options, such as energy-efficient motors, adjustable speed drives, advanced controls, heat exchangers, heat pumps, electric boilers, energy-efficient lighting, combined heat and power, cogeneration, energy storage and distributed generation;
- Identify and implement cost-effective projects that minimize energy intensity.

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