Evaluating the Potential of a Process Site for Waste Heat Recovery

Gbemi Oluleye*, Megan Jobson, Robin Smith, Simon J. Perry

Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL, UK
gbemi.oluleye@manchester.ac.uk

In this work, waste heat is defined and a methodology is developed to identify the potential for waste heat recovery in a process site, considering the temperature and quantity of waste heat sources from the site processes and the site utility system (including fired heaters and, the cogeneration, cooling and refrigeration systems). To support the methodology, the concept of the energy efficiency of a site is introduced – the fraction of the energy inputs that is converted into useful energy (heat or power or cooling). Mathematical models of waste heat recovery technologies using heat as primary energy source, such as organic Rankine cycles (using both pure and mixed organics as working fluids), absorption chillers and absorption heat pumps are provided and applied to assess the potential for recovery of waste heat.
The methodology is illustrated using a case study of a petroleum refinery. The energy efficiency of the site increases by 12 % as a result of the energy recovered from waste heat.

1. Introduction

In spite of depleting reserves of fossil fuels and increasing prices, energy is still being wasted. In the process industries, at least 40 % (Ammar et al., 2012) of the energy content of fuel is wasted. Using energy more efficiently can reduce demand for fuel, thereby conserving resources, reducing operating costs and reducing CO_2 emissions.

The concept of pinch analysis was introduced in the process industries to maximize energy recovery in a process plant (Linnhoff and Hindmarsh, 1983). However, it is unclear what happens to the residual heat when a process site has maximized its process-to-process heat recovery. Conventionally this heat is rejected to cooling water or to air.

Various definitions have been attributed to industrial waste heat. Viklund and Johansson (2014) define waste heat as heat generated as a by-product of industrial processes. In this definition, the possibility for heat recovery is omitted. Ammar et al. (2012) define waste heat as heat for which recovery is not viable economically, while Bendig (2013) defines waste heat as the sum of the exergy available in a process after heat recovery and utility integration. Both Ammar et al. (2012) and Bendig (2013) recognise the possibility of heat recovery within a process but neither accounts for heat rejected from a site utility system designed to satisfy the process energy demand.

In this paper, industrial waste heat is defined as heat rejected from the processes in a site and the site utility system designed to satisfy the energy demand namely heating, power, cooling and refrigeration. With respect to the site processes, waste heat is the residual heat after heat recovery within a process or heat recovery between processes on a site using Total Site Integration (Dhole and Linnhoff, 1993). With respect to a utility system, waste heat is heat rejected to cooling water and air from a utility system designed to satisfy the energy demand of a site.

Diverse mature and commercialised technologies exist to recover energy in the form of work, cooling and heat from waste heat. Examples include the organic Rankine cycle, Kalina cycle, absorption heat pumps, mechanical heat pumps, absorption chillers and economizers for boiler feed water preheating. The operational limits of these technologies and physical limitations of a site dictate what waste heat it is feasible to recover.

The potential for work generation is analysed in Bendig (2013) using exergy analysis to evaluate the maximum extractable work from waste heat rejected from a process. The potential for work generation is a theoretical maximum that disregards the efficiency of the technologies as well as other useful forms of energy, such as cooling, that can be derived from waste heat. Also, waste heat available from the site utility system was not considered. In the work of Kapil et al. (2012) and Kim et al. (2012), the potential to generate work, chilling and heat is evaluated using the heat available after heat recovery between processes on a site. In their work, the waste heat sources are collected at a single temperature, and heat rejected from the site utility system is not included, thus interactions between the processes and the utility system are neglected. A complete analysis for waste heat recovery should consider various sources of waste heat at various temperatures from site processes and the site utility system.

The aim of this paper is to develop a systematic way to represent the waste heat available in a site and to evaluate the potential to generate work, chilling and heat from the available waste heat.

2. Mathematical Modelling of Waste Heat Recovery Technologies

Waste heat recovery technologies can be modelled rigorously using process simulation software such as HYSYS (Kapil et al., 2012). However simple models are needed as they are more useful for optimization. Such models show the relationship between key variables. In this work, established mathematical models and new models are proposed for a basic organic Rankine cycle, absorption chiller and absorption heat pump.

2.1 Organic Rankine cycle (ORC)

An ORC produces shaft work from low to medium temperature heat sources (50 to 220 ^{o}C, Ammar et al., 2012) using pure and mixed organic fluids (Viklund and Johansson 2014). A schematic of a basic cycle is shown in Figure 1, where expansion of a vaporized working fluid using waste heat produces power. Efficiency (η) of an ORC is defined as the fraction of power (W) produced from heat as shown in Eq(1). The ideal performance is expressed using the Carnot efficiency (Bendig, 2013) in Eq(2), relating this to the real efficiency in Eq(3) and a factor accounting for inefficiencies in the system components (the condenser, evaporator, pump and turbine). This factor can be correlated with the ideal efficiency for a pure working fluid Eq(4) or an organic mixture Eq(5) by regression against the results of rigorous simulations. Figure 2 shows the validation of the model Eq(4) using benzene as working fluid in an ORC.

$$\eta_{real} = \frac{W_{turbine} - W_{pump}}{Q_{waste\ heat}} \tag{1}$$

$$\eta_{ideal} = 1 - \frac{T_{condenser}}{T_{evaporator}} \tag{2}$$

$$\eta_{real} = Factor_{ORC} \cdot \eta_{ideal} \tag{3}$$

$$Factor_{ORC} = \alpha \cdot \eta_{ideal} + \beta \tag{4}$$

$$Factor_{ORC} = \alpha \cdot \eta_{ideal}^2 + \beta \cdot \eta_{ideal} + \gamma \tag{5}$$

2.2 Absorption Chillers (AbC)

Absorption chillers are thermally driven devices producing chilling. The system has two working fluids: an absorbent and a refrigerant. Common pairs are lithium bromide/water and water/ammonia. A single-effect absorption chiller as shown in Figure 3 has four main components the generator, absorber, condenser and evaporator (Kew, 1982). The ideal coefficient of performance (COP) is the product of the ideal efficiency of a turbine operating between the generator and absorber temperatures and a vapour compression heat
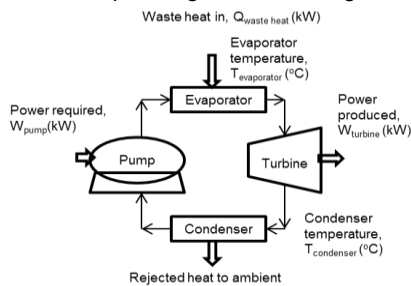

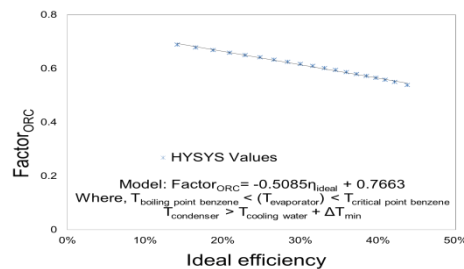*Figure 1: Organic Rankine Cycle schematic*
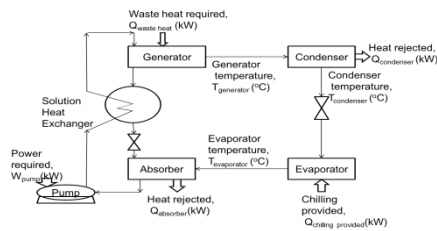

Figure 2: Validation of ORC model

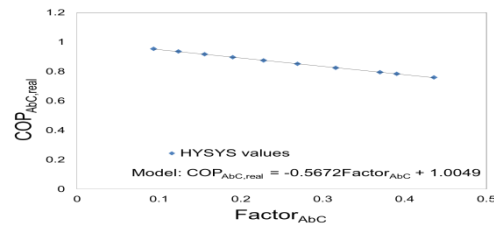Figure 3: Absorption chiller schematic

Figure 4: Validation of absorption chiller model

pump operating between the sink (evaporator) and source (condensing) temperatures (Heppenstall, 1983) as shown in Eq(6). The actual COP is the fraction of the energy input converted to chilling Eq(7); this can be expressed in terms of the ideal COP and a factor that accounts for inefficiencies in the system components Eq(8). To determine the factor and the real COP, Eq(8) and (9) can be solved simultaneously, where the parameters in Eq(9) can be determined from rigorous simulation or manufacturer data. Validation of the model using lithium bromide/water as the fluid pair is shown in Figure 4 above. The generator temperature is determined from the system saturation pressure set to prevent the working fluid from crystallizing (Chua et al., 2000).

$$COP_{AbC,ideal} = \left(1 - \frac{T_{condenser}}{T_{generator}}\right)\left(\frac{T_{evaporator}}{T_{condenser} - T_{evaporator}}\right) \tag{6}$$

$$COP_{AbC,real} = \frac{Q_{evaporator}}{Q_{waste\ heat} + W_{pump}} \tag{7}$$

$$COP_{AbC,real} = factor_{AbC} \cdot COP_{ideal} \tag{8}$$

$$COP_{AbC,real} = a \cdot (factor_{AbC}) + b \tag{9}$$

2.3 Absorption Heat Pumps (AHP)

Heat pumps can be driven by electrical power or thermally driven, as in absorption heat pumps. As shown in Figure 5, absorption heat pumps are identical to absorption chillers; however, the objective of a heat pump is to recover heat from the absorber and condenser (Heppenstall, 1983). The ideal coefficient of performance is estimated using by Eq(10) (Heppenstall, 1983) and the real COP is expressed in form of energy flows in the condenser, absorber, generator and pump as shown in Eq(11). To evaluate the real COP in terms of the system temperatures, Eq(12) and (13) are solved simultaneously. The factor in Eq(13) accounts for inefficiencies in the system components and the parameters c and d can be regressed from rigorous simulations or from manufacturer data. Validation of the model is shown in Figure 6 using a Lithium Bromide/water mixture. The generator temperature is determined from the system saturation pressure set to prevent the working fluid from crystallizing (Chua et al., 2000).

$$COP_{AHP,ideal} = 1 + \left(1 - \frac{T_{condenser}}{T_{generator}}\right)\left(\frac{T_{evaporator}}{T_{condenser} - T_{evaporator}}\right) \tag{10}$$

$$COP_{AHP,real} = \frac{Q_{Absorber} + Q_{condenser}}{Q_{waste\ heat} + W_{pump}} \tag{11}$$

$$COP_{AHP,real} = factor_{AHP} \cdot COP_{ideal} \tag{12}$$

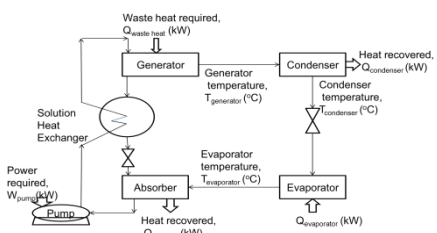$$COP_{AHP,real} = d \cdot (factor_{AHP}) + C \tag{13}$$
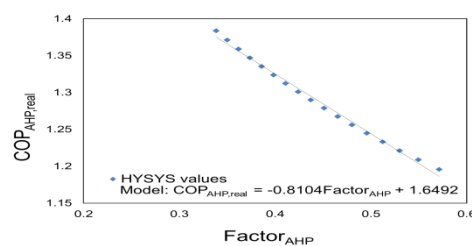

Figure 5: Absorption heat pump schematic

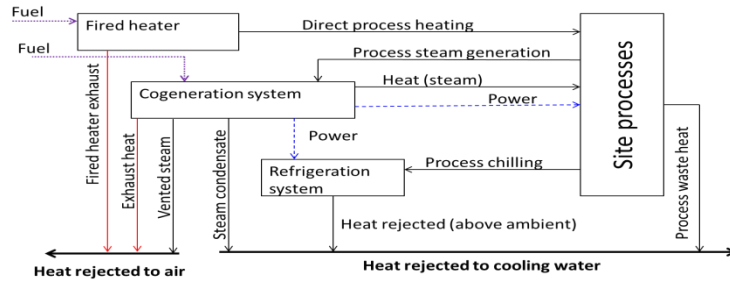Figure 6: Validation of absorption heat pump model

Figure 7: Energy flows in a process site

3. Site Energy Efficiency

The cogeneration efficiency i.e. the fraction of the energy in fuel consumed producing useful heat and power, has been used to evaluate the performance of a cogeneration system (Smith, 2005). In considering waste heat recovery in a process site, this indicator is inadequate as it does not consider energy flows in other systems, such as refrigeration cycles and fired heaters. In this work, the concept of the energy efficiency of a site is defined as the fraction of the total energy inputs (from fuel combustion, process steam generation, power imports, etc.) converted into useful energy consumed i.e. heat, power and cooling (where the cooling cannot be avoided due to physical limitations) required by the site processes Eq(14). The site energy efficiency captures interactions between the utility systems on a site, as shown in Figure 7.

$$\text{Site Energy Efficiency} = \frac{\text{Total Useful Energy Consumed}}{\text{Total Energy Input}} \tag{14}$$

4. Waste Heat Source Profile

The energy profile for a process has been represented using composite curves (Linnhoff and Hindmarsh 1983); in Linnhoff and Dhole (1993) the total site profile was introduced to represent energy profiles for several processes on a site. The composite curves and the site profiles show the potential for heat recovery within a process and between processes on a site respectively (Smith, 2005). These concepts can be extended to represent the waste heat sources in a process site.

To create a waste heat source profile, first data related to the waste heat rejected from the site processes and the site utility systems are extracted. The duties of the sources, as well as the supply and target temperatures are extracted. The target temperature is determined to account for operational limits of these technologies and physical limitations of a site such as the stack temperature for fired heaters to avoid corrosion. The waste heat source profile is generated by plotting the heat source temperature (shifted by an appropriate minimum temperature difference, ΔT_{min}, to allow for heat transfer) against the net duties of the waste heat sources. For design purposes, two waste heat source profiles can be generated: a profile for waste heat rejected to cooling water and waste heat rejected to air. The waste heat source profile allows evaluation of the potential for waste heat recovery in a site.

To evaluate the potential of a process site for waste heat recovery, appropriate waste heat recovery technologies can be identified considering the temperature range at which the technology can exploit the waste heat and assigned against the profile using the heat recovery temperature.

The heat recovery temperature is determined in two stages, first preliminary recovery temperatures are determined corresponding to the kinks on the profile as they represent the beginning or end of a stream. The final heat recovery temperature is then determined by selecting the preliminary heat recovery temperature where the useful energy recovered is highest for a particular form of energy (heating, cooling or work).

The methodology presented in this paper is focused on (1) generating the waste heat source profiles for a site, (2) using the kinks on the profiles as the preliminary heat recovery temperature, (3) assigning recovery technologies against the profile (at the kinks), (3) using the simplified models to estimate the quantity of useful energy in the form of work, chilling and higher temperature heating for every preliminary heat recovery temperature, (4) determining the final heat recovery temperatures by selecting the preliminary temperatures corresponding with the highest useful energy recovered and (5) evaluating the waste heat recovery impact on a site by estimating the site energy efficiency before and after generating useful energy from the available waste heat.

5. Case Study for a refinery

The case study presented is for a petroleum refinery with seven processing units; crude distillation unit, three hydrotreaters (for naphtha, kerosene and diesel), a vacuum distillation unit, a platformer, a visbreaker and a fluidised catalytic cracking unit (Fraser and Gillespie, 1992). Data extracted for waste heat rejected from the site processes after energy recovery and from the utility system are shown in Table 1. The waste heat source profiles for heat rejected to cooling water and air are shown in Figures 10 and 11, respectively. Utility systems for this site comprise of a cogeneration, refrigeration and cooling system, and a fired heater that is used for direct process heating. The site energy efficiency before waste heat recovery is 44 %. It is desirable to produce work, chilling at 7 ^{o}C and to provide heating at 80 ^{o}C from the waste heat sources on this site. Available working fluids include benzene and cyclohexane for the ORC, and lithium bromide/ water for the absorption chiller and heat pump. The preliminary heat recovery temperatures and duties are shown in Figures 10 and 11. The energy recovered in the form of work, chilling and heating for heat that would otherwise be rejected to cooling water and air is shown in Figures 12 and 13 respectively.

In Table 1, the target temperature for waste heat rejected to cooling water from the site processes is at 60 ^{o}C (above the boiling point of the working fluid; cyclopentane). Also the target temperature for waste heat from the utility system is evaluated using an energy balance for the system. For heat rejected to air, the stack temperature is set at 150 ^{o}C above the acid dew point.

Table 1: Waste heat rejected to cooling water and air

| Stream	Source		Supply Temperature (^{o}C)	Target Temperature (^{o}C)	Heat Duty (kW)
1		Site processes	135	60	31,810
2		Condensing main	90	90	89,264
3	Waste heat	Steam main condensate 1	320	119	6,520
4	rejected to	Steam main condensate 2	260.07	119	750
5	cooling water	Steam main condensate 3	230	119	6
6		Steam main condensate 4	200	119	904
7		Steam main condensate 5	135	119	91
8	Waste heat	Natural gas boiler exhaust	291	150	5,540
9	rejected to	Coal boiler exhaust	291	150	5,552
10	air	Fired heater exhaust	350	150	8,510
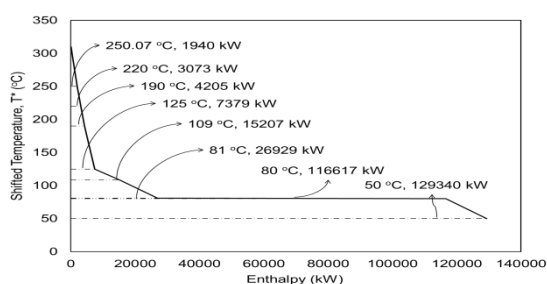
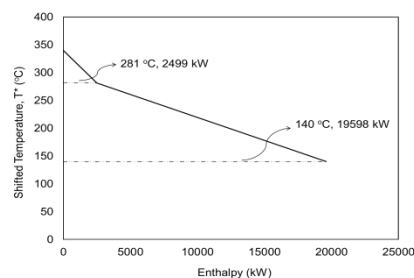*Figure 10: Profile for heat rejected to cooling water*

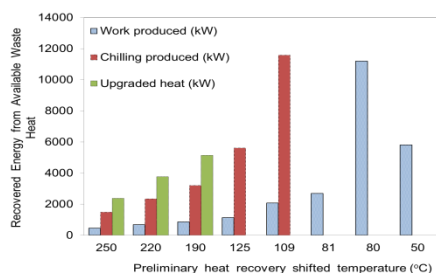*Figure 11: Profile for heat rejected to air*

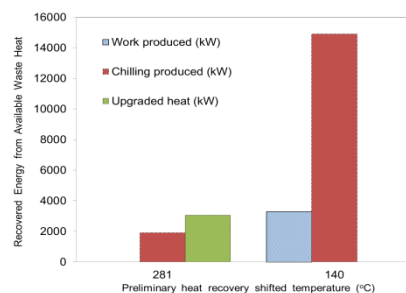*Figure 12: Useful energy recovered from heat otherwise rejected to cooling water*

Figure 13: Useful energy recovered from heat otherwise rejected to air

Table 2: Useful energy recovered and final heat recovery (shifted) temperature

Final Heat recovery shifted temperature (^{o}C)	Recovered energy	Waste heat recovery technology
Waste heat rejected to cooling water		
109 ^{o}C	11,600 kW chilled water	LiBr/H$_2$0 absorption chiller
80 ^{o}C	9,730 kW electricity	ORC using benzene
50 ^{o}C	571 kW electricity	ORC using cyclopentane
Waste heat rejected to air		
140 ^{o}C	14, 907 kW chilled water	LiBr/H$_2$0 absorption chiller

Based on the useful energy (power, cooling and heating) recovered from the available waste heat as shown in Figure 12, producing chilling at 7 ^{o}C using waste heat at 109 ^{o}C to drive an absorption chiller, work using the residual heat at 80 ^{o}C and 50 ^{o}C maximizes useful energy from heat that would otherwise be rejected to cooling water, while producing chilling at 7 ^{o}C using waste heat at 140 ^{o}C maximizes useful energy from heat otherwise rejected to air (Figure 13). The final heat recovery temperatures correspond to the heat source temperatures that maximize the useful energy recovered from waste heat. They are selected as 109 ^{o}C, 80 ^{o}C and 50 ^{o}C for heat that was rejected to cooling water and 140 ^{o}C for heat that was rejected to air shown in Table 2. The total useful energy recovered is 37 MW, increasing the site energy efficiency by 12 %.

6. Conclusions

A methodology is presented to explore the potential to generate electricity, chilling and heating from available waste heat in a process site. This work accounts for waste heat from site processes and also from the site utility system by formulating a waste heat source profile that captures the temperature and duties of the heat sources. New simple mathematical models of waste heat recovery technologies are presented and applied to identify and compare feasible technical opportunities to convert the waste heat to useful energy.

References

Ammar Y., Joyce S., Norman R., Wang Y., Roskilly A.P., 2012, Low grade thermal energy sources and uses from the process industry in the UK, Applied Energy, 89, 3-20.

Bendig M., Marechal F., Favrat D., 2013, Defining "Waste heat" for industrial processes, Applied Thermal Engineering, 61(1), 134-142.

Chua H.T., Toh H.K., Malek A., Ng K.C., Srinivasan K., 2000, Improved thermodynamic property fields of LiBr-H$_2$0 solutions, International Journal of Refrigeration, 23(6), 412-429.

Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers and Chemical Engineering, 17, 101–109.

Fraser D.M., Gillespie N.E., 1992, The application of pinch technology to retrofit energy integration of an entire oil refinery, Trans IChemE, Part A, 70, 395-406.

Heppenstall T., 1983, Absorption cycle heat pumps, Heat Recovery Systems, 3, 115-128.

Kapil A., Bulatov I., Smith R., Kim J.-K., 2012, Site-wide low -grade heat recovery with a new cogeneration targeting method, Chemical Engineering Research and Design, 90, 677-689.

Kew P.A., 1982, Heat pumps for industrial waste heat recovery - A summary of required technical and economic criteria, Heat Recovery System, 2(3), 283-296.

Kwak D.-H., Oh S.-Y., Kim J.-K., 2012, Process integration study for the use of industrial low grade heat, Chemical Engineering Transactions, 29, 1591-1596.

Linnhoff B., Hindmarsh E., 1983, The pinch design method for heat exchanger networks, Chemical Engineering Science, 38(5), 745-763.

Smith R., 2005, Chemical Process Design and Integration, Wiley, UK

Viklund S. B., Johansson M.T., 2014, Technologies for utilization of industrial excess heat: potentials for energy recovery and CO$_2$ emission reduction, Energy Conversion and Management, 77, 369-379.