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A Hierarchical Approach for Evaluation of Waste Heat Utilization Opportunities

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This paper presents a ranking criterion for evaluating opportunities that utilize recovered energy from the available waste heat in a process site. The ranking criterion takes into account the energy performance of waste heat recovery technologies associated with each opportunity, their potential to reduce greenhouse gas emissions (namely CO_2) and the economics (costs and benefits). Mathematical modelling of the opportunities using the ranking criterion is also developed to allow for systematic evaluation of opportunities, for example within an optimization framework.
The methodology is applied to a case study of a petroleum refinery. Hierarchy and performance of waste heat utilization opportunities depends on the temperature of the heat available, amongst other factors. Sensitivity of the ranking to energy prices is studied, to explore the outlook for low-grade heat utilization in the future. The methodology can be applied to the process industries and other facilities producing low-grade heat.

1. Introduction

Recovery of waste heat in the process industries has been identified as an effective way of improving the energy efficiency of process sites, reducing operating costs and reducing CO_2 emissions (Walsh and Thornley, 2012). To these ends, different opportunities have been identified (Law et al., 2013) for using the recovered energy from available waste heat in a process site. Examples of such opportunities include: power for site use using an Organic Rankine cycle; boiler feed water preheating using an economiser; space heating using heat exchangers to generate hot water; and space cooling using absorption chillers. The technologies required to implement these opportunities are mature and commercially available. However, with constraints on capital investment and space in an existing process site, it is important to rank these opportunities to identify the most promising technology, to support decision-making related to conserving resources and to reducing CO_2 emissions and operating costs. The aim of this paper is to develop a systematic way of ranking and evaluating waste heat utilization opportunities.

2. Previous work

Recovery and re-use of waste heat in the process industries has received interest in recent years. In the work of Kapil et al., (2012), opportunities for using recovered energy from the available waste heat in a process site (a petroleum refinery) such as boiler feed water preheating, electricity for site use and chilling for site processes are explored. The impact on the site operating costs is used to determine the most promising opportunity. Benefits from emissions reduction and total cost, including capital, operating and maintenance costs of the heat recovery technologies are not considered, also the available waste heat sources are represented in a simplistic manner i.e. at a single temperature. A similar analysis is performed for available waste heat in the UK food and drink industry (Law et al., 2013) where saving in operating costs and reductions in CO_2 emissions are used to evaluate opportunities to utilize waste heat. A major barrier to waste heat utilization is capital investments in technologies (Walsh and Thornley, 2012) but was not considered in their work. The useful energy recovered and CO_2 emissions reduced is used in Viklund

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and Johansson (2014) to evaluate opportunities for utilizing industrial waste heat again the economics (costs and benefits) of waste heat recovery is neglected and the waste heat sources are assumed to be at a single temperature. Hammond and Norman (2014) use only the CO_2 emissions reduction potential to evaluate waste heat utilization opportunities, also neglecting the economics (costs and benefits) again the heat sources are represented in a rather simple manner i.e. in particular, it is assumed that all waste heat is available at one temperature.

There is potential in industrial waste heat to increase the energy efficiency of a process site, reduce operating costs and CO_2 emissions, hence evaluation of opportunities for waste heat utilization should take into account these issues as well as capital investment in waste heat recovery technologies. A more comprehensive and systematic way for representing the available waste heat in a site considering the temperatures and duties of the heat sources (Oluleye et al., 2014) is used in this work. Furthermore, estimation of the useful energy recovered (heating, cooling or electricity) is done using the simple models developed in Oluleye et al., (2014).

3. Industrial Waste Heat Utilization Opportunities

The opportunities to utilize the recovered energy from waste heat on a site are diverse; each opportunity is associated with one or more waste heat recovery technologies. In this work, opportunities for a site will be classified in terms of the end-user (on-site or off-site e.g. for community heating and electricity to the grid).

3.1 On-site waste heat utilization opportunities

Recovered energy in form of electricity can be used within the site; and associated benefits include the reduction in fuel consumed in a cogeneration system or cost of imported electricity. Site chilling demands can be supplied using waste heat to drive an absorption chiller. The chilling demand could be for a process or the inlet air to a gas turbine compressor: chilling the inlet air increases the density and mass flowrate of the air into the compressor for a fixed volumetric flowrate thus increasing the power output (Popli et al., 2013). Other opportunities associated with using the heat directly include boiler feed water preheating, resulting in a reduction in fuel consumption on-site; space cooling reducing electrical consumption in a conventional vapour compression chiller, and space heating using hot water circulation, reducing the fuel consumption in a boiler that would otherwise be used. In summary, opportunities identified for on-site use of recovered energy considered in this work are (1) electricity generation for on-site use; (2) gas turbine compressor inlet air chilling; (3) boiler feed water preheating; (4) space cooling and (5) space heating.

3.2 Off-site waste heat utilization opportunities

There are two forms of energy for export from a site: heat and electricity. It may be permitted for electricity produced from waste heat to be exported to the grid, thereby displacing fossil fuel consumption in power stations. Revenue may also be generated by the site from selling electricity. Another form of energy for export is heat, even though most industrial sites are situated outside residential areas, there could still be agricultural activities and people living within 15 to 20 km of a process site (the distance identified as the maximum feasible distance for heat transfer in Chae et al., 2010). Heat exported to existing buildings around the site displaces fossil fuels that would otherwise be burned to provide heating in homes, and the cost of installing and operating a boiler in new buildings around the site is off set when heat is exported. Revenue can be generated from the sale of heat to both existing and new buildings around the industrial site. The revenue generated from the sale of heat (or electricity) is determined in a way that results in a win-win situation, i.e. profit for the site and savings for off-site heat users (or the grid). In summary, opportunities for waste heat utilization off-site are: (1) electricity export to the grid; (2) heat for new buildings via direct hot water generation; and (3) heat for existing buildings (via direct hot water generation).

4. Ranking Criterion for Industrial Waste Heat Utilization Opportunities

The opportunities for waste heat utilization can be ranked with respect to the useful energy recovered or the potential to reduce CO_2 emissions or the economic benefits (income less costs). Using any of these criteria alone cannot capture tradeoffs between efficiency, useful energy (heat, power or cooling) produced from waste heat, emissions and economics (costs and benefits). Therefore it is important to develop a ranking criterion to capture all three. In this work, the proposed ranking criterion (RC) measures the economic potential associated with reduced CO_2 emissions resulting from waste heat recovery. The basis is emissions reduction because fossil fuel combustion is responsible for over 70 % of atmospheric greenhouse gas emissions especially CO_2 (International Energy Agency, 2012). The economic potential (EP) is used to evaluate and compare design options and is suitable for use as an objective function to optimize process designs (Smith, 2005). In this work, estimation of the economic potential depends on the

location of the end-user (on or off-site). For on-site utilization opportunities, the EP is the difference between the annual financial benefits from operational savings associated with recovered energy and the total annualized cost (TAC) (sum of the annualized capital cost, operating cost and maintenance cost) of operating waste heat recovery technologies (j) required to implement the opportunity, shown as the numerator in Eq(1). While for off-site utilization opportunities the EP is the profit associated with the sale of energy (heat or power).
The RC for on-site opportunities utilizing recovered energy from available waste heat is shown in Eq(1) and off-site opportunities in Eq(2).

$$RC_{\text{on-site opportunities}}\ (£/kg) = \frac{\text{Financial Benefits}\ (£/y) - TAC_j(£/y)}{\text{reduced } CO_2 \text{ emissions}\ (kg/y)} \tag{1}$$

$$RC_{\text{off-site opportunities}}\ (£/kg) = \frac{\text{Profit}(£/y)}{\text{reduced } CO_2 \text{ emissions}\ (kg/y)} \tag{2}$$

The profits can be calculated from Eq(3) for electricity sales, and Eq(4) and (5) for heat to new and existing buildings, respectively. To allow for a win-win situation, i.e. equal profit for the site and savings for off-site heat users, the constant *A* in Eq(3), (4) and (5) is 0.5.
In Eq(3), the site profit from electricity exported to the grid is half the difference between the cost of domestic electricity and the total annualized cost of the organic Rankine cycle required to produce electricity from waste heat. The electricity generated from waste heat can be calculated using the model developed in Oluleye et al., (2014). Furthermore in Eq(4), the profit from heat exported to new heat users off-site is half the difference between the total annualized cost of installing a boiler in a new building and the total annualized cost of heat exchangers required to generate hot water from waste heat on-site. In addition the profit from heat exported to existing building is half the difference between the operating (fuel) cost of a boiler in an existing building and the total annualized cost of heat exchangers required to generate hot water from waste heat on-site shown in Eq(5) below.
The equation proposed in Eq(3), (4) and (5) to estimate the site profit from energy (electricity or heat) exported ensures that if it is economic to export energy i.e. the total cost otherwise paid by the energy users off-site greater than the total annualized cost of generating useful energy for export, then the selling price of energy (electricity or heat) will be less than what is paid by the energy users off-site making electricity or heat generated from available waste heat in a process site competitive.

$$Profit_{\text{electricity exported}}\ (£/y) = A.\left(TEC_{\text{domestic electricity}}(£/y) - TAC_j(£/y)\right) \tag{3}$$

$$Profit_{\text{Heat exported to new buildings}}\ (£/y) = A.\left(TAC_{\text{boiler}}\ (£/y) - TAC_j(£/y)\right) \tag{4}$$

$$Profit_{\text{Heat exported to existing buildings}}\ (£/y) = A.\left(TFC_{\text{boiler}}\ (£/y) - TAC_j(£/y)\right) \tag{5}$$

Where TEC is the total electricity cost incurred by a domestic user, TAC is the total annualized cost for installing a boiler (sum of capital, fuel and maintenance cost) in a new building and TFC the total fuel cost for operating a boiler in an existing building. Table 1 is a summary of how financial benefits and CO_2 emissions reduction associated with the waste heat utilization opportunities on-site can be evaluated.

Table 1: Financial benefits and CO_2 emissions reduction potential for on-site use of recovered energy

Opportunity	Financial Benefits	Impact on CO_2 emissions
1. Electricity for site use, gas turbine compressor inlet air chilling and boiler feed water preheating	Savings from reduction in site electricity imports or fuel saved from site cogeneration system	CO_2 displaced from fossil fuel combustion in the grid or directly from fuel saved in the site cogeneration system
2. Space cooling	Savings from electricity required to operate a conventional vapour compression chiller	CO_2 emissions displaced from electricity required to operate a vapour compression chiller
3. Space heating	Savings in fuel consumption from a boiler that would otherwise be used	CO_2 Emissions displaced from a boiler that would otherwise be used

The potential to reduce emissions from opportunities that involve export of heat and power is evaluated from the emissions displaced from fossil fuel combustion.

The methodology presented in this paper is focused on using the ranking criterion to identify the most promising waste heat utilization opportunity in order to support decision-making related to conserving resources and to reducing CO_2 emissions and operating cost.

5. Case Study

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).

In Oluleye et al., (2014) a systematic way of representing the available waste heat is proposed. The waste heat source profile showing the temperatures and net duties of available waste heat that was rejected to cooling water in the refinery is generated. Also preliminary heat recovery temperatures representing the kinks on the profile are suggested for any analysis of the heat sources. Figure 1 show the waste heat source profile for heat otherwise rejected to cooling water and the vertical lines represent the preliminary heat recovery temperatures and associated duties. The refinery site currently imports electricity; has a cogeneration system consisting of a natural gas boiler, gas turbine and steam turbines, and a refrigeration system (vapour compression system) producing chilling at 7 ^oC. The closest off-site heat users (requiring hot water at 80 ^oC) are 14 km away from the site and sale of electricity to the grid is permitted.

The ranking criterion develop in Eq(1) and (2) is used to introduce hierarchy for the waste heat utilization opportunities identified for on-site use of recovered energy in Section 3.1 and off-site opportunities in section 3.2. Assumptions of 2013 UK energy prices, emissions factors and equipment capital costs are presented in Table 2. The maintenance cost of the technologies is assumed to be 2 % of the equipment capital cost (Arvay et al., 2011). To generate electricity, an Organic Rankine cycle using benzene and cyclopentane as working fluid is available; chilling using a lithium bromide/water absorption chiller, and hot water generation using a shell and tube heat exchanger. The site boiler feed water is at 94 ^oC, it is desirable to heat it to 130 ^oC, and the gas turbine compressor inlet air is currently at ambient condition and is to be chilled to 8 ^oC.

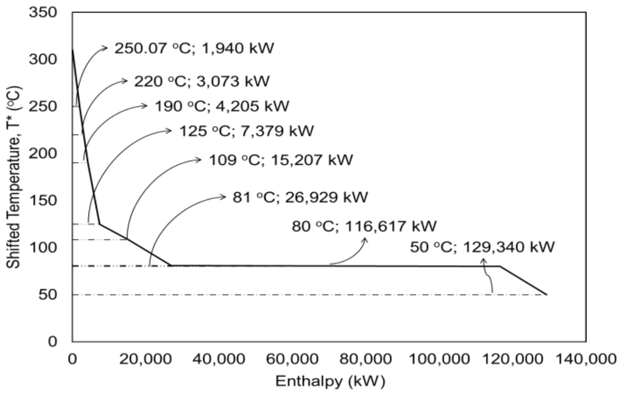

Figure 1: Waste heat source profile (Oluleye et al. 2014)

Table 2: Design assumptions on prices and emissions

Energy Prices (DECC, IAG 2012)	Emission factors (DECC, IAG 2012)	Capital costs
Industrial electricity price: 13.4 p/kWh Industrial natural gas price: 3.2 p/kWh Domestic electricity price: 16.7 p/kWh Domestic natural gas price: 5.0 p/kWh	Grid emission factor: 0.485 kg/kWh Natural gas emission factor: 0.193 kg/kWh	Organic Rankine cycle (Arvay et al., 2011): 2141 £/kW$_{electricity}$ Absorption chiller (Popli et. al., 2013): 228 £/kW$_{chilling}$ Economizer (Wang et al., 2012): 227.5 £/m^2 Distribution network (Kapil et al., 2012): 949 £/m Discount rate: 15 % Operating hours: 8,600 y

Ranking of waste heat utilization opportunities for the site is done for every preliminary heat recovery temperature shown in Figure 1 represented as vertical lines in Figures 2, 3, 4, and 5. Hierarchy of opportunities using the ranking criterion in Eq(1) and Eq(2), and energy prices in Table 2 is shown in Figure 2 as the base case. A major assumption is that the cost of infrastructure for the heating network is not borne by the industrial site, however if the industrial site commits to construct a heating network of length 14 km, the capital cost is presented in Table 2, where costs include pipe installation, heat losses and pumping. In this case the ranking is shown in Figure 3.
Sensitivity of the ranking to electricity price increase (industrial and domestic) is shown in Figure 4 and sensitivity to domestic and industrial natural gas price increase is shown in Figure 5.
The ranking of opportunities for the base case indicated in Figure 2 depends on the preliminary heat recovery temperature. At 50 ^{o}C, the most promising opportunity is electricity generation for use in the process site. Electricity generation for site use and for export both have the same potential to reduce emissions however the economic value of electricity for site use is higher than for export. The profits from export are calculated to ensure a win-win situation for the site and the grid as shown in Eq(3). The economic value of both opportunities increase when domestic and industrial electricity prices increases as shown in Figure 4. Also, hierarchy of opportunities at 80 and 81 ^{o}C is the same; the most promising is hot water to new buildings. The recovered energy (heat) for hot water distribution is higher than cooling and power recovered from available waste heat at this temperature, hence the economic value and potential to reduce emissions will be higher. Even though the useful heat recovered for hot water to new and existing buildings are the same, the profit from heat exported to new buildings is with respect to the total annualized cost of installing a boiler Eq(4) while for existing buildings, the operating cost for an already installed boiler is used Eq(5). Ranking of opportunities at 80 and 81 ^{o}C changes when investment in the heating work is borne by the site as shown in Figure 3, opportunities associated with heat export become uneconomic.

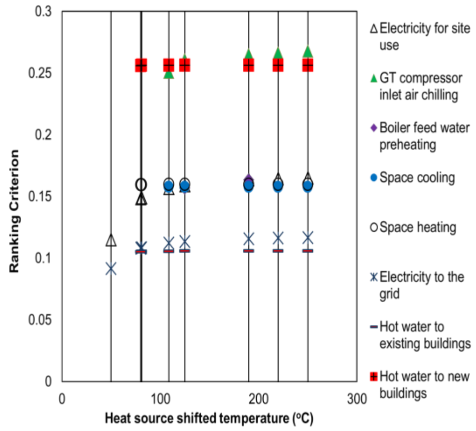

Figure 2: Hierarchy of opportunities (Base case)

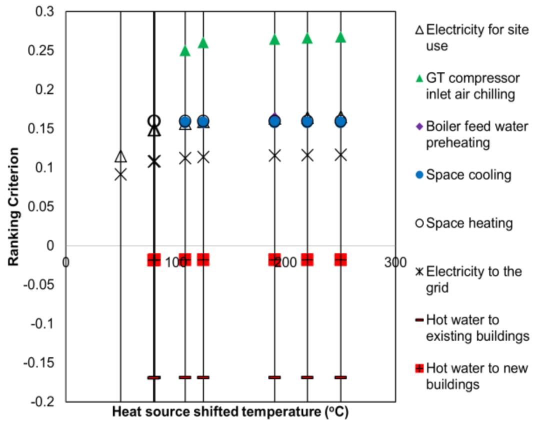

Figure 3: Hierarchy of opportunities (Heating network cost included)

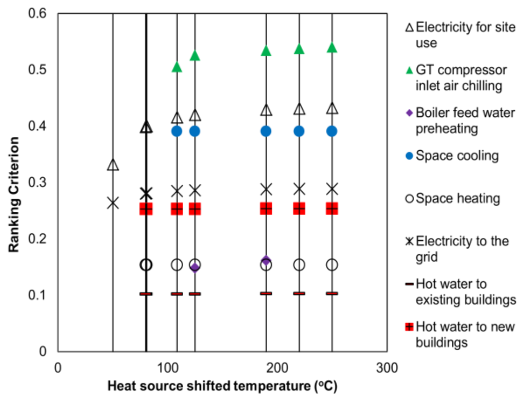

Figure 4: Hierarchy of opportunities (high industrial and domestic electricity price)

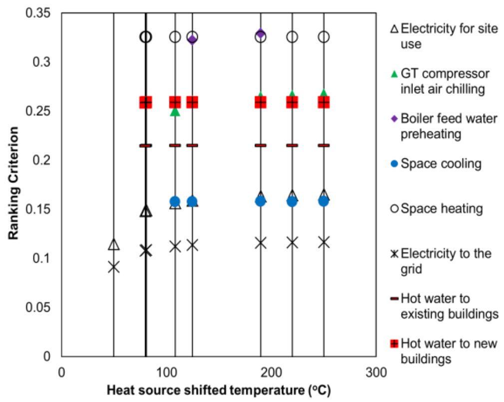

Figure 5: Hierarchy of opportunities (high industrial and domestic natural gas price)

Chilling of the inlet air to a gas turbine compressor becomes most promising above 125 ^{o}C and the economic value of this opportunity increases with temperature since the operating cost of the absorption chiller reduces as less heat is rejected to cooling water at higher temperatures. However when the price of natural gas increases as shown in Figure 5, boiler feed water preheating and space heating becomes more promising than chilling the inlet air into a gas turbine compressor. In Figure 2, the ranking criterion for opportunities such as electricity generation for site use and export increases with temperature because the efficiency – ratio useful power produced to heat consumed of organic Rankine cycles increases with temperature.

6. Conclusions

A ranking criterion accounting for the economic value of useful energy recovered from waste heat and impact on CO_2 emissions is introduced in this work to evaluate opportunities for waste heat utilization in a process site. The RC can be used to screen and select waste heat utilization opportunities for a process site depending on the waste heat source temperature. In this work, it is applied to evaluate opportunities to reuse waste heat available in a site. In the case study, results show that ranking of opportunities depends on the heat recovery temperature. For opportunities such as electricity generation for site use and export the value (economic and potential to reduce emissions) increases with the heat source temperature, therefore waste heat at high temperature should be exploited before low temperature waste heat as there are more opportunities to exploit the heat and the value is higher. Sensitivity of the criterion to energy prices is conducted and results show that as energy prices increase, waste heat recovery becomes more attractive both economically and environmentally.

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