Project no.: 296003

Project full title: Efficient Energy Integrated Solutions for Manufacturing Industries

Project Acronym: EFENIS

Deliverable no.: 3.2

Title of the deliverable: Report on Technology Selection and Extension for Waste Heat Recovery

Contractual Date of Delivery to the CEC:	**Month 20**
Actual Date of Delivery to the CEC:	**Month 20**
Lead beneficiary:	**UNIMAN**
Author(s):	**Ning Jiang*, Robin Smith**
Participant(s):	**P1**
Work package contributing to the deliverable:	**WP1**
Nature:	**Report**
Version:	**3.3**
Total number of pages:	**29**
Start date of project:	**1st August 2012**
Duration:	**36 months**

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

* Current position: Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou, 310032, China

Abstract

A systematic low-grade waste heat utilisation method is proposed. This method deals with the low-grade waste heat recovery technology selection and system design, which is not settled by the existing total site integration technology. Waste heat potential identification, energy demand analysis, efficiency screening and economical optimisation constitute basic steps of the overall design method. A case study shows that the low-grade waste heat recovery system could be integrated into an existing total site efficiently and economically.

Keywords: Waste heat recovery; Technology selection; Total site; Energy integration

Contents

1. Introduction

Large amounts of energy are consumed for all kinds of applications. However, quite a part of energy consumption is rejected as waste heat. For example, two-thirds of input energy for electricity generation in the USA is lost as heat during conversion processes, while 43.9% of the energy for USA consumption is converted to electricity [1]; industrial waste heat comprises over 30% of the energy content of fuel in UK [2]. These facts have drawn attention to waste heat recovery along with to improve equipment energy efficiency for a few decades. Waste heat re-use has been regarded as an effective way to increase energy efficiency and reduce emissions. On the technique level, various waste heat recovery techniques have been developed, such as the organic Rankine cycle (ORC) using organic fluids to produce shaft work from low to medium temperature heat sources [3,4], thermally driven absorption refrigeration (AR) using heat to provide chilling [5,6,7], electrically driven mechanical heat pump (MHP) using vapour compression cycle to upgrade low-grade heat [6,7,8], thermally driven absorption heat transformer (AHT) using the inverse absorption refrigeration cycle to upgrade low-grade heat [9,10], district heating system (DHS) using industrial site waste heat for neighbouring commercial and residential energy demands [11,12], economizer recovering heat from exhaust gas for boiler feed water preheating [13], etc. There are a wide range of heat recovery technologies and design options for the recovery of low grade heat. Though these waste heat recovery methods can make waste heat re-use technically possible, how to choose among various waste heat recovery technologies and utilise waste heat efficiently on the system level still need to be addressed.

The industrial sector comprising agriculture, iron & steel, petrochemicals, non-metallic etc. is responsible for over 35% of the world energy consumption [14], generating over 30% of world greenhouse gases in the form of carbon dioxide (CO2) released from combustion of fossil fuels. Another 41% of world carbon dioxide emissions are attributed to generation of electricity from powerhouses [14]. Energy Intensive industries are responsible for over 70% of emissions from the industrial sector [14].

Total site integration technology has been developed for energy targeting, placements of utilities and design of heat and power networks for a site [15-22]. The process composite curves and site profiles can be used to identify the heat recovery potential within a single process and among processes, respectively. Although the process composite curves and total site profiles can tell how much heat deficit and surplus are and thus what hot utilities and cold utilities are required to compensate the heat deficit and surplus, the total site integration technology did not consider how to utilise residual low-temperature waste heat, which was assumed to be rejected into cold utilities.

Therefore this work aims to develop a systematic framework for low-grade waste heat use within a total site. The low-grade waste heat utilisation method is a supplementary to the current total site integration technology so that the waste heat can be integrated into the total site energy integration.

2. Identification of waste heat recovery potential on a total site

Pinch analysis has been widely used to identify heat recovery potential in a process or a total site. For a single process, targets for hot utility, cold utility and heat recovery potential among process streams as well as placements of utilities can be achieved using the composite curves and grand composite curve [23]. Also for a site with more than one process, total site analysis using site profiles has been developed for targeting heat recovery potential among different processes by means of pressurized steams (HP, MP, LP, etc.) as heat transfer mediums, cogeneration potential on a site and placements of steam levels [18]. The composite temperature-enthalpy curve provides a powerful tool showing the energy flow variation with temperature. The comparison between heat source profile and heat sink profile gives the maximum heat recovery potential under a specified minimum temperature approach and specified heat transfer mediums. For example, within a single process, direct heat transfer is feasible so that the hot stream composite curve and cold stream composite curve adjusted by the minimum temperature difference show the required external heating/cooling and corresponding heat recovery among process streams. The heat source removed by the external cooling is exactly the waste heat recovery potential in this process. Similarly, for a total site, steam system is the most commonly heat transfer medium used to recover heat among different processes within a site through steam generation and usage. The total site composite profiles comprising site source/sink profiles and steam system profiles show the required external heating/cooling and corresponding heat recovery among processes through the steam system. Again the site heat source removed by the external cooling is the waste heat recovery potential in this total site. However, the heat-and-power cogeneration within a total site will reduce the heat recovery through the steam system, since there is a trade-off between the heat recovery potential and power potential. Accordingly, the reduction of heat recovery through the steam system will increase the available waste heat from processes on a site. Besides, the inclusion of utility system will increase the available waste heat due to the addition of waste heat source existing in the utility system, for example, the flue gas of boiler, exhaust gas of gas turbine, utility steam condensing heat, etc.

Therefore, the waste heat available within a total site comes from both site processes and utility system. The waste heat recovery potential in processes can be identified using the site profiles. The waste heat available in the utility system is separately extracted from streams in the utility system. A composite temperature-enthalpy curve for waste heat potential on a total site can be built by adding together the site heat source profile and temperature-enthalpy diagrams of hot steams which carry the waste heat in the utility system. This temperature-enthalpy curve represents the waste heat available in different temperature ranges and thus identifies the waste heat recovery potential from a total site.

3. Scope of low-grade waste heat on a total site

Heat recovery through the steam system is prevailing on a total site, which offers the convenience for heat and power cogeneration. Considering that the power potential in pressurized steams generated by the site heat sources is already integrated in the site heat-and-power cogeneration design, the low-grade waste heat recovery on a total site in the current work refers to the waste heat available below the temperatures that the site steam system works. For example, if the site steam system comprises high pressure steam (HP) main, medium pressure steam (MP) main and LP main, then the waste heat sources below LP temperature from the site processes and utility system are identified as the low-grade waste heat on the total site. As seen in the total site profiles of Fig. 1, for the residual heat source below LP temperature on the site source profile, hot water or hot oil could be used as medium to transfer heat between site heat source and sink.

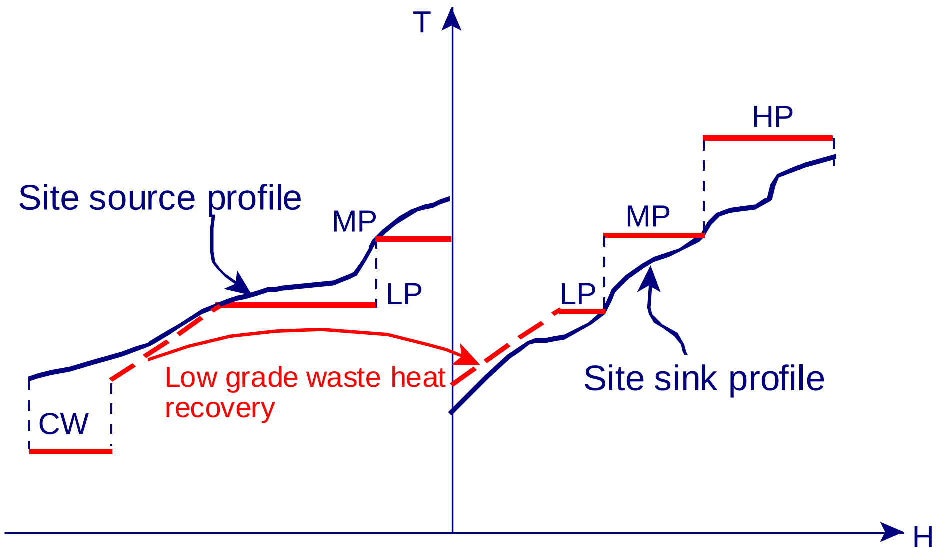

Fig. 1. Low-grade waste heat recovery using heat transfer medium runaround.

After the identification of low-grade waste heat available within a total site, the following proposed methodology will address how to select the appropriate technology to recovery the low-grade waste heat among a wide range of waste recovery technologies.

4. Problem statement

Given the low grade waste heat available within a total site, the waste heat recovery problem is described as to select the appropriate technologies and to design a waste heat recovery system which can utilise the waste heat to provide useful energy and meanwhile satisfy some design requirements. From the problem statement, it can be seen that the core of waste heat utilisation is to meet energy demand with waste heat by means of the waste recovery technology. Obviously, there are all kinds of energy demands, either on site or over the fence. Therefore, facing such a wide choice of waste heat recovery options and a variety of energy demands, a systematic stradegy is essential for the waste heat recovery utilisation and technology selection.

5. Methodology

5.1. Identification of available waste heat

Since the purpose of waste heat recovery is to satisfy energy demand with waste heat, the identification of waste heat potential should be the first step of waste heat utilisation. As given previously, the low-grade waste heat available within a total site can be identified in quality (temperature) and quantity by use of the composite temperature-enthalpy curve including waste heat flows from both site processes and utility system.

5.2. Energy demand analysis

Then as the second step, energy demand analysis follows. Energy demand could be classified into different types. Also, the energy demand could come from site processes, utility system, or off-site applications. The identification of energy demand can radically impact the design of waste heat recovery, because various waste heat recovery technologies supply different types of energy demand, for example, ORC for power output, MHP for heating at low or moderate temperatures, AR for refrigeration, DHS for space/water heating in the neighbourhood, etc. Since energy supply should match the demand, the energy demand inherently decides what kind of energy supply system would be adopted. For example, any refrigeration system would become useless in the application where there is no refrigeration demand. The energy demand is indeed case-specified. Among different types of energy demand, the heating demand in quality and quantity can be plotted in the temperature-enthalpy diagram, similar to the way to express the waste heat. A composite temperature-enthalpy curve for heat sink available for absorbing heat on a total site can be built by adding together the site heat sink profile and temperature-enthalpy diagrams of cold steams which require heating in the utility system and concerned over-the-fence applications. This temperature-enthalpy curve represents the heating demand in different temperature ranges. Based on similar consideration for the low-grade waste heat scope, the heating demand below the site steam system working temperatures is identified as heat sink available for the low-grade waste heat recovery on a total site.

5.3. Waste heat recovery technology screening and ranking

Knowing available waste heat sources and energy demand which could be met by waste heat, then a connection must be built between the energy supply (waste heat) and energy demand, which is fulfilled by heat recovery technologies. There are various technologies available for low-grade waste heat recovery, such as process heat recovery through heat distribution network (HDN), ORC, AR, MHP, AHT, economizer for boiler feed water (BFW) preheating, DHS, etc. Therefore, the third step of waste heat recovery is to make a selection from available heat recovery technologies so as to efficiently or economically link the available waste heat and energy demand. To make the waste heat recovery technology selection, a screening principle is proposed in Section 5.3.1.

5.3.1. Screening principle for waste heat recovery technology selection

A basic rule of energy utilisation is to use energy according to its quality. That is, high quality energy supply should be used to satisfy the high quality energy demand. The quality of energy is scaled by its exergy content. The logic in this rule is to reduce the energy degradation accompanying the energy utilisation/conversion process as little as possible. This rule also reflects that energy should be used according to demands, because the matching extent between energy supply and demand determines the energy degradation during the energy utilisation and conversion. Thus a basic waste heat utilisation/recovery principle to minimise energy degradation is set for waste heat recovery technology screening. This rule is adopted to screen the available waste heat recovery options. As an example, an industrial waste heat of 250°C can be recovered via the organic Rankine cycle (ORC) with 12% thermal efficiency, process heating (PH) at 200°C or oven-the-fence use for the district heating system (DHS) at 95°C. The energy degradations for these three waste heat recovery options can be quickly estimated, see Table 1. Among the available three options, the energy degradation of using the waste heat to satisfy the process heating at 200°C is the minimal, so process heating is ranked as the most appropriate waste heat recovery approach by the screening.

Table 1 Energy degradation for different waste heat recovery options.

Options	Input energy grade per unit heat input (-)	Output energy grade per unit energy input (-)	Degradation
ORC	$1-\frac{(15+273.15)}{(250+273.15)}=0.45$	0.12	0.33(73%)
PH at 200°C	$1-\frac{(15+273.15)}{(250+273.15)}=0.45$	$1-\frac{(15+273.15)}{(200+273.15)}=0.39$	0.06(13%)
DH at 95°C	$1-\frac{(15+273.15)}{(250+273.15)}=0.45$	$1-\frac{(15+273.15)}{(95+273.15)}=0.22$	0.23(51%)

*ambient temperature of 15°C is assumed.

In order to carry out the screening and selection, performance models of various waste heat recovery technologies are necessary for the estimation of energy degradation accompanying the waste heat recovery process. Only the commercially available and mature waste heat recovery approaches are considered here. Section 5.2 gives the performance models of different waster heat recovery systems.

5.3.2. Performance models of waste heat recovery systems

Waste heat recovery system (WHRS) utilises waste heat and converts it to a useful energy output, which builds a bridge between waste heat supply and energy demand. These systems use different working fluids adapted to the temperatures at which waste heat is available. The waste heat sources available in a total site may disperse at different locations in site processes and utility system. Besides, the waste heat sources may locate away from the WHRS. Therefore, a heat distribution network (HDN) using thermal medium such as soft water to collect heat from different heat sources and exchange heat with the WHRS is often required, see Fig. 2. The heat collection and distribution increase the required heat transfer temperature difference between the waste heat source and WHRS. The temperature difference required by the heat transfer process between the waste heat source and medium in the HDN has already been taken into account by the waste heat source profile.

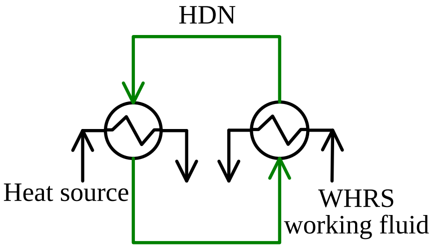

Fig. 2. Heat distribution network (HDN) transferring heat between heat source and WHRS.

Considering the scope of low-grade waste heat on a total site, the temperature of LP steam, T_{LP}, is taken as the highest temperature of waste heat composite temperature-enthalpy (T-ΔH) curve for a site.

Process heating (PH) below T_{LP}

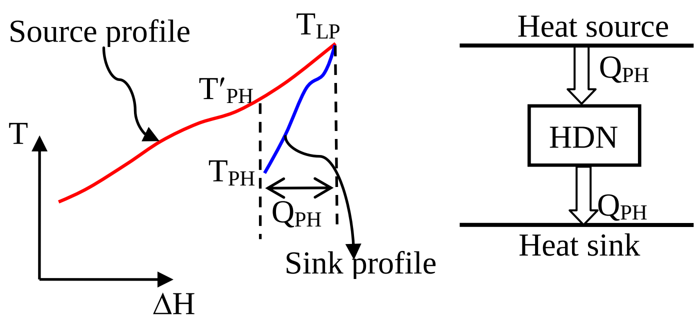

Fig. 3. Process heating (PH) by use of low-grade waste heat.

Assuming there is no heat transfer loss, heat absorbed by process heat sink is equal to heat rejected by waste heat source. Given the site waste heat potential in the form of the composite *T*-Δ*H* curve, then

$$Q_{PH} = \int dH_{\mathrm{sink}} \Big|_{feasible\ zones} \approx \int dH_{\mathrm{source}} \Big|_{feasible\ zones}$$

where Q_{PH} is the feasible heat transfer from the site waste heat source to the process heat sink, H_{sink} and H_{source} are the sink and source enthalpy, respectively.

Process heating feasibility analysis can be implemented by the use of the site waste heat source and sink profiles. To move the site waste heat source profile towards the site sink profile until they intersect at T_{LP}, at the region where the heat source profile lies above the heat sink profile, the corresponding heat source can be used to heat the process sink, and the corresponding enthalpy interval is identified as feasible zone; Otherwise, the process heating as the waste heat recovery approach is infeasible.

ORC system

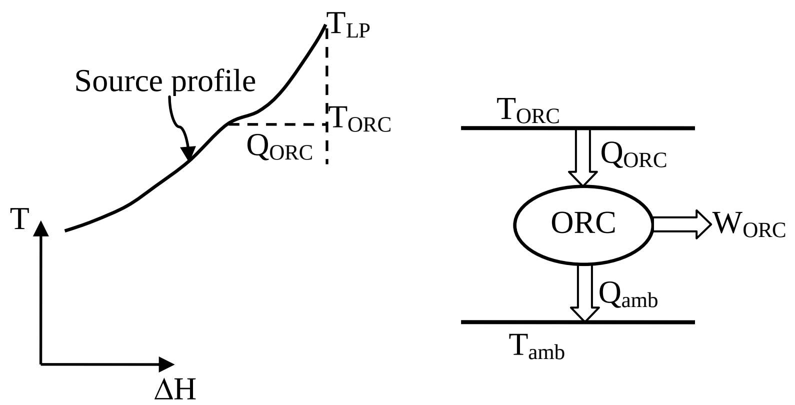

Fig. 4. Organic Rankine cycle (ORC) by use of low-grade waste heat.

The ORC work output can be calculateed as:

$$W_{ORC} = \eta_{ORC} \times Q_{ORC}$$

$$\eta_{ORC} = \eta_{ideal}\eta_s$$

$$\eta_s = a\eta_{ideal} + b$$

$$\eta_{ideal} = 1 - \frac{T_{amb}}{T_{ORC}}$$

$$Q_{ORC} = \int dH_{source}$$

where W_{ORC} = net work output of the ORC

η_{ORC} = efficiency of the ORC

η_s = isoentropic efficiency of the ORC

η_{ideal} = efficiency of the ideal ORC

Q_{ORC} = heat input from the heat source to the ORC

Q_{amb} = heat output from the ORC to the ambient

T_{ORC} = temperature of the heat source

T_{LP} = the low pressure steam generation/saturation temperature

T_{amb} = the ambient temperature

The constants '*a*' and '*b*' representing the slope and intercept for a plot of the isoentropic efficiency η_s against the ideal efficiency η_{ideal} are regressed from rigorous simulation of an organic Rankine cycle in HYSYS, see Table 2.

Table 2 Regression parameters for the organic Rankine cycle.

Working fluid	*a*	*b*
Toluene	-0.5456	0.7733
n-Pentane	-0.7804	0.749
n-Hexane	-0.7402	0.7506
Benzene	-0.5035	0.7632

Absorption refrigeration (AR) system

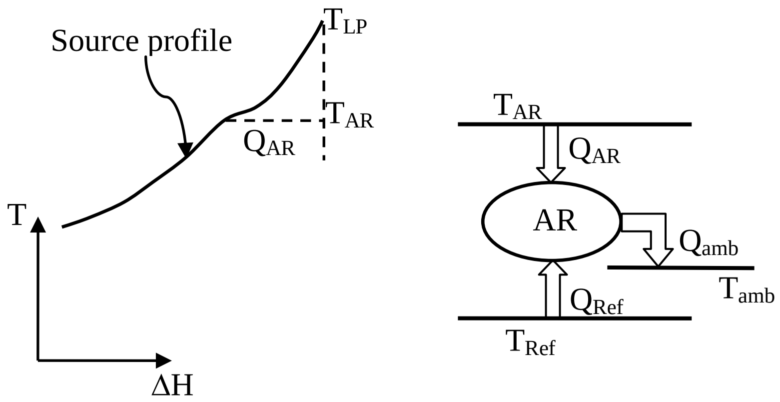

Fig. 5. Absorption refrigeration (AR) by use of low-grade waste heat.

The refrigeration load of AR can be calculated as:

$$Q_{Ref} = COP_{AR} \times Q_{AR,max}$$

$$COP_{AR} = COP_{ideal}\eta_s$$

$$COP_{AR} = c\eta_s + d$$

$$COP_{ideal} = \frac{T_{Ref}}{T_{con} - T_{Ref}} \frac{T_{AR} - T_{abs}}{T_{AR}} \frac{T_{con}}{T_{abs}}$$

$$Q_{AR} = \int dH_{source}$$

where

Q_{AR} = heat input from the heat source to the AR system

Q_{Ref} = cooling load of the AR system

Q_{amb} = heat released from the AR system to the environment, $Q_{amb} = Q_{AR}+Q_{Ref}$

COP_{AR} = coefficient of performance of the AR system

η_s = isoentropic efficiency (thermodynamic perfectness) of the AR system

COP_{ideal} = coefficient of performance of the ideal absorption refrigeration system

T_{AR} = generation temperature of the absorption refrigeration cycle

T_{Ref} = refrigeration temperature of the absorption refrigeration cycle

T_{abs} = absorption temperature of the absorption refrigeration cycle

T_{con} = condensing temperature of refrigerant

The constants '*c*' and '*d*' representing the slope and intercept for a plot of the absorption refrigeration performance coefficient COP_{AR} against the isoentropic efficiency η_s are regressed from rigorous simulation of an absorption refrigeration cycle in HYSYS, see Table 3. Typically, T_{AR}= 125°C for H_2O/LiBr; 130°C for NH_3/H_2O. $T_{amb} \approx T_{con} \approx T_{abs}$ can be assumed.

Table 3 Regression parameters for the absorption refrigeration cycle.

Fluid pair	*c*	*d*
NH_3/H_2O	-1.5415	0.9706
$H_2O/LiBr$	-0.5672	1.0049

Mechanical heat pump (MHP)

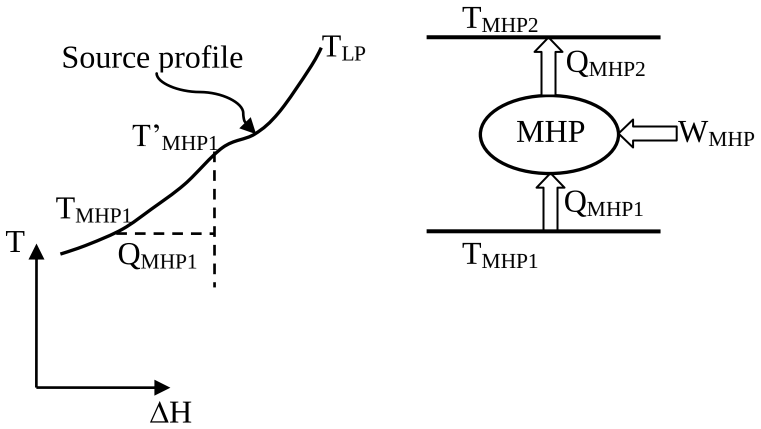

Fig. 6. Mechanical heat pump (MHP) by use of low-grade waste heat.

The heat output Q_{MHP2} of the MHP can be used for external heating or process heating. The performance of MHP can be modelled as:

$$Q_{MHP2} = \frac{COP_{MHP}}{COP_{MHP} - 1} Q_{MHP1}$$

$$COP_{MHP} = Q_{MHP2} / W_{MHP}$$

$$COP_{MHP} = COP_{ideal} \eta_s$$

$$\eta_s = eCOP_{ideal} + f$$

$$COP_{ideal} = \frac{T_{MHP2}}{T_{MHP2} - T_{MHP1}}$$

$$Q_{MHP2} = Q_{MHP1} + W_{MHP}$$

$$Q_{MHP1} = \int dH_{source}$$

where

W_{MHP} = work input of the MHP

COP_{MHP} = performance coefficient of the MHP

η_s = isoentropic efficiency of the MHP

COP_{ideal} = performance efficient of the ideal MHP

Q_{MHP1} = heat input from the heat source to the MHP

Q_{MHP2} = heat output of the MHP

T_{MHP1} = temperature of the heat source (evaporation temperature of the MHP)

T_{MHP2} = the condensation temperature of the MHP

The constants '*e*' and '*f*' representing the slope and intercept for a plot of the isoentropic efficiency η_s against the ideal performance coefficient COP_{ideal} are regressed from rigorous simulation of a vapour compression heat pump cycle in HYSYS, see Table 4. If the required heating temperature T_{MHP2} is known, Q_{MHP2}, Q_{MHP1} and W_{MHP} will decrease while COP_{MHP} increases with T_{MHP1}.

Table 4 Regression parameters for the mechanical heat pump.

Working fluid	*e*	*f*
NH3	-0.008	0.6174
n-Butane	-0.0197	0.5499
i-Butane	-0.0174	0.5437
Propane	-0.0073	0.4997
Chlorine	-0.0199	0.5849
Propylene	-0.0065	0.499

Absorption heat transformer (AHT)

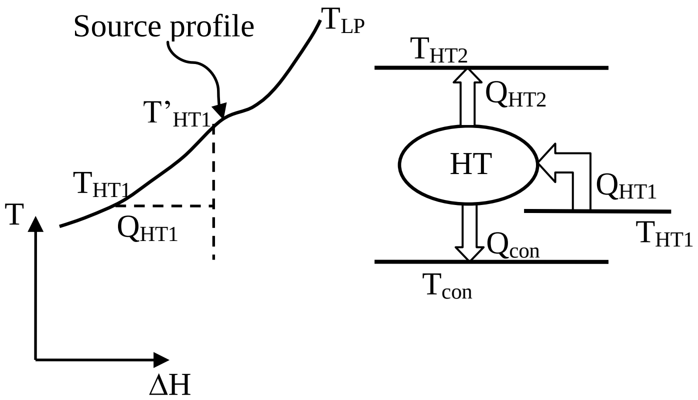

Fig. 7. Absorption heat transformer (AHT) by use of low-grade waste heat.

The performance of AHT can be modelled as:

$$Q_{HT2} = Q_{abs} = COP_{HT} \times Q_{HT1}$$

$$COP_{HT} = COP_{ideal}\eta_s$$

$$COP_{ideal} = \frac{T_{HT2}}{T_{HT1}}\frac{T_{HT1} - T_{amb}}{T_{HT2} - T_{amb}}$$

$$\eta_s = gCOP_{ideal} + h$$

$$Q_{HT1} = Q_{gen} + Q_{eva}$$

$$T_{HT2} = T_{abs}$$

$$Q_{HT1} = Q_{HT2} + Q_{amb}$$

$$T_{con} = T_{amb}$$

$$T_{HT1} \approx T_{eva} \approx T_{gen}$$

$$Q_{HT1} = \int dH_{source}$$

where

Q_{HT1} = heat input from the heat source to the AHT system, $Q_{HT1} = Q_{gen} + Q_{eva}$

Q_{gen} = generator load of the AHT system

Q_{eva} = evaporation heat of the AHT system

Q_{HT2}, Q_{abs} = heating load (absorbor load) of the AHT system

Q_{con}, Q_{amb} = heat released from the condenser of the AHT system to the environment

COP_{HT} = coefficient of performance of the AHT system

η_s = isoentropic efficiency (thermodynamic perfectness) of the AHT system

COP_{ideal} = coefficient of performance of the ideal AHT system

T_{HT1} = heat input temperature of the AHT cycle

T_{HT2} = useful heat output temperature of the AHT cycle

T_{abs} = absorption temperature of the AHT cycle

T_{con} = condensing temperature of the working fluid

The constants '*g*' and '*h*' representing the slope and intercept for a plot of the AHT performance coefficient COP_{HT} against the isoentropic efficiency η_s are regressed from rigorous simulation of an AHT cycle in HYSYS, see Table 5. Typically, $T_{HT2} \leq 150°C$, $T_{HT2} - T_{HT1} = 40\text{-}65°C$.

Table 5 Regression parameters for water-lithium absorption heat transformers.

Fluid pair	*g*	*h*
H_2O/LiBr	-0.9261	1.3576

Other external heating (EH)

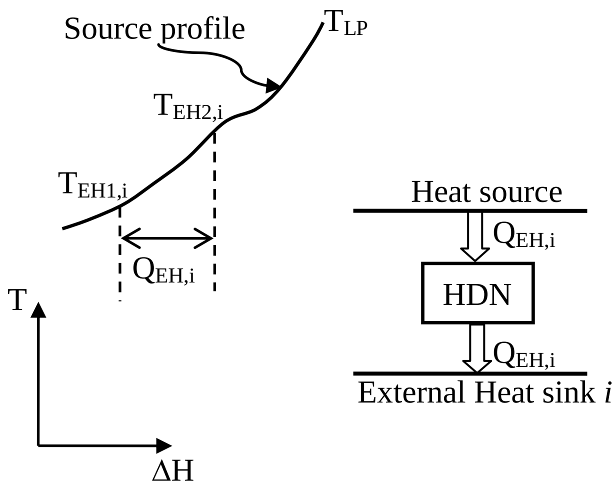

Fig. 8. External heating (EH) by use of low-grade waste heat.

Available external heat sinks include spacing heating (SH), water heating (WH), district heating system (DHS), boiler feed water preheating (BFW). For the external heating,

$$Q_{EH,i} = \int_{T_{EH1,i}}^{T_{EH2,i}} dH_{source}$$

where

$Q_{EH,i}$ = heat transferred from the process heat source to the external heat sink *i*

$T_{EH1,i}$ = lower bound temperature of heat transfer from the waste heat source to external sink *i*

$T_{EH2,i}$ = upper bound temperature of heat transfer from the waste heat source to external sink *i*

5.3.3. Screening based on technical limits

Various heat recovery methods have their respective technical limits, although the technology improvement/innovation about energy conversion and transfer will improve the efficiencies and widen the application ranges of heat recovery technologies. So the screening for waste heat recovery technology selection should be implemented based on the temperature ranges allowed by technical requirements. Table 6 list the current limits for different waste heat recovery technologies. For example, the common mechanical heat pump can effectively upgrade heat only up to 120°C, which is limited by the thermodynamic and environmental properties of working fluids and equipment constraints. The consideration or change of these limits does not affect the proposed methodology applicability, but guarantees the feasibility of waste heat recovery.

Table 6 Typical application ranges for various waste heat recovery techniques.

Techniques	Output	Feasible application
ORC	Shaft power	Waste heat ≥90°C
PH	Heat	Heat sink-dependent
AR	Refrigeration	Waste heat ≥75°C
AHT	upgraded heat	Output heat≤150°C
MHP	upgraded heat	Output heat≤120°C
WH	Heat	Waste heat ≥60°C
SH	Heat	Waste heat ≥40°C
DH	Heat	Waste heat ≥90°C

Based on the performance models and feasible temperature ranges of available waste heat recovery systems, energy degradation or exergy output per heat recovery for different waste heat recovery system can be obtained, see Table 7. The energy degradation assessment is used to screen and rank waste heat recovery options. If the waste heat is rejected to cooling water or cooling air, then the exergy output becomes zero. Heat transfer losses relating to the heat distribution are neglected for all the waste heat recovery options, which therefore won't affect the screening or ranking result.

Table 7 Exergy output of different heat recovery options.

Options	Temperature (°C)	Exergy output e_x or exergy loss Δe_x per heat recovery (-)
PH	T_{PH}	$e_x = 1 - T_{amb} / T_{PH}$
ORC	$T_{ORC,opt}$	$\Delta e_x = (1 - T_{amb} / T_{ORC}) - \eta_{ORC}$
		$e_x = \eta_{ORC}$
AR	$T_{AR,opt}$	$\Delta e_x = (1 - T_{amb} / T_{AR}) - COP_{AR} (T_{amb} / T_{Ref} - 1)$
		$e_x = COP_{AR} (T_{amb} / T_{Ref} - 1)$
AHT	$T_{HT1,opt}$	$\Delta e_x = (1 - T_{amb} / T_{HT1}) - COP_{HT} (1 - T_{amb} / T_{HT2})$

		$e_x = COP_{HT}(1-T_{amb}/T_{HT2})$
MHP	$T_{MHP1,opt}$	$\Delta e_x = (1-T_{amb}/T_{MHP1}) + [1-(1-T_{amb}/T_{MHP2})COP_{MHP}]/(COP_{MHP}-1)$
		$e_x = (1-T_{amb}/T_{MHP2})COP_{MHP}/(COP_{MHP}-1)$
BFW	T_{BFW}	$e_x = 1-T_{amb}/T_{BFW}$
DHS	T_{DHS}	$e_x = 1-T_{amb}/T_{DHS}$
WH	T_{WH}	$e_x = 1-T_{amb}/T_{WH}$
SH	T_{SH}	$e_x = 1-T_{amb}/T_{SH}$
CW	T_{CW}	$e_x = 0$

Further, based on the user preference and energy demand, the secondary or even the third energy transformation can also be taken into account. For example, the upgraded heat by the heat transformer could be used as input energy to the ORC or absorption refrigeration system; and the power output of the ORC used to drive the mechanical vapor compression cycle for cooling or heating. In the terms of exergy utilisation, the recovery option involving more than one energy transformation is hardly competitive over those single-transformation candidates, since the exergy losses are accumulated by each transformation. However, if there is no other options under consideration, the multi-transformation could still be reasonable in the view of reducing energy waste.

All the candidates available for waste heat recovery will be assessed according to their respective exergy losses in different temperature regions. By ranking the waste heat recovery options according to the rule of minimising the energy degradation, one heat recovery candidate best fitting each temperature region can be determined. The screening will be made sequentially from high temperature to lower temperature of the site heat source.

5.4. Dividing temperature intervals

Once the waste heat recovery options that have lowest exergy losses are picked out, the temperature scale of the site heat source below T_{LP} can be divided into a series of temperature regions which define the working temperature ranges of these waste heat recovery systems. These temperature intervals and corresponding enthalpy intervals of heat source will be used for the following optimisation step.

5.5. Waste heat recovery optimisation and design

With the divided temperature regions and heat recovery options specified for each temperature region, the optimal operation temperature at which the heat recovery between individual waste heat recovery system and waste heat source occurs is optimised by maximising the total profit. Accordingly, the optimal heat loads recovered from the waste heat source by various waste heat recovery systems are also allocated by the optimisation. So the optimal overall waste heat recovery design is obtained.

5.6. Methodology flowsheet

Fig. 9 illustrates the procedure of proposed low-grade waste heat utilisation method. The methodology consists of five steps:

Step 1: Identification of available waste heat within a site. To extract low-grade waste heat sources from total site profiles and site utility system; in other words, heat sources from the site processes and utility system which temperatures are lower than that of site steam system, for example, LP steam temperature, will be taken for the subsequent analysis.

Step 2: Energy demand analysis. The matching possibility of the site waste heat sources and energy demands will be analysed. For heating demand, the composite temperature-enthalpy diagram is a useful tool to represent the available heat sinks from the site processes, utility systems and other concerned applications.

Step 3: Waste heat recovery technology screening and ranking. The available waste heat recovery options will be screened and ranking by their respective energy degradations. The screening is made sequentially from higher temperatures to lower temperatures of the site source.

Step 4: Dividing temperature intervals. It is possible using different techniques for different temperature ranges. By making the energy demand analysis and ranking the waste heat recovery options according to the rule of minimising the energy degradation, one heat recovery candidate best suiting each temperature region can be determined and the temperature scale is therefore divided into several temperature intervals.

Step 5: Waste heat recovery optimisation and design. For each temperature interval, the heat recovery option possessing the lowest exergy loss has been chosen out. The optimisation for maximise the total profit will further decide the optimal operation temperatures of these heat recovery options. The heat loads recovered these heat recovery options can then be obtained with their respective optimal operating temperatures. The optimal overall design for waste heat recovery is determined.

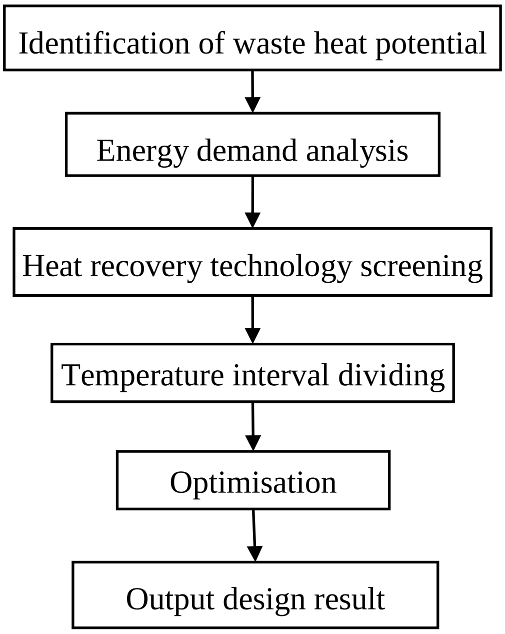

Fig. 9. Design flowsheet of waste heat recovery.

6. Case study

A case study is used to demonstrate the proposed methodology for low-grade industrial waste heat recovery. An existing oil refinery plant [24] comprises 7 units: the fluid catalytic cracking unit, crude and vacuum distillation units, visbreaker unit, platformer, naphtha hytrotreater, diesel hytrotreater and kerosene hydrotreater. Due to the lack of utility system details, the current case study only considers waste heat from processes, which won't affect the demonstration of the proposed methodology. The total site source and sink profiles extracted from individual processes are shown in Fig. 10. The minimum approach temperature of 10°C is assumed. Corresponding energy demand (heat sink) and surplus (waste heat source) data in different temperature ranges are summarized in Table 8 and Fig. 11. It can be found in the thermal energy profiles that this oil refinery site is characterised as a mismatch between energy demand and surplus/waste heat supply. The average temperature of thermal energy demand is 356.7°C while that of waste heat 99.1°C. The majority of process thermal energy demand (88%) occurs above 260°C, while the waste heat below 130°C occupies 77% of the overall available heat from processes. That is, the available high-temperature waste heat is limited, while there exists excess low-temperature waste heat. Actually this kind of mismatch in energy quality and quantity, especially in quality, is one of the main challenges the waste heat recovery system is facing. However, the ability of the available commercially mature waste heat recovery techniques to bridge such gaps is technically constrained, as mentioned in Section 5.3.3.

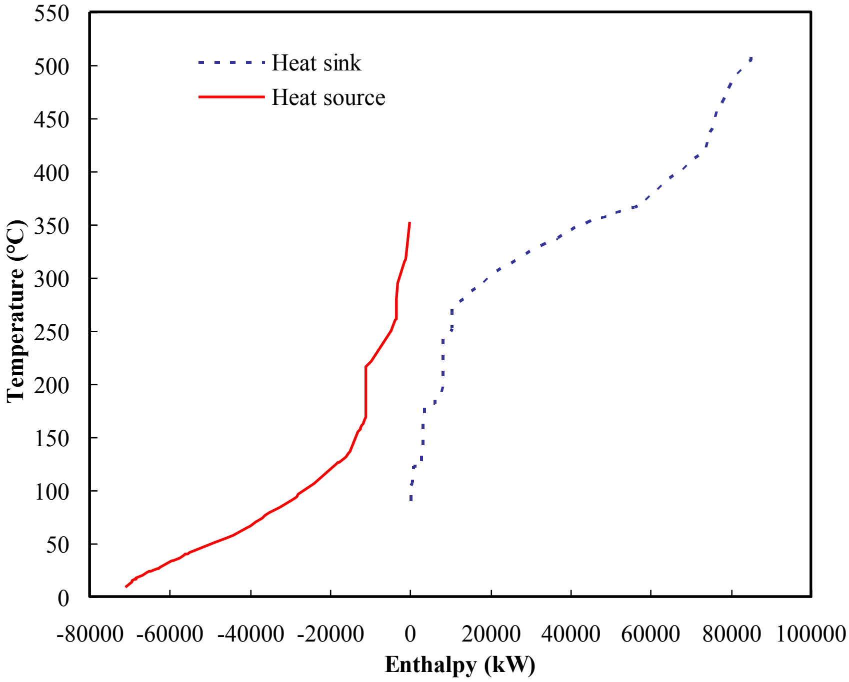

Fig. 10. Total site source and sink profiles.

Table 8 Heat sink and waste heat source data.

Temperature (°C)	Heat source (kW)	Fraction (%)	Heat sink (kW)	Fraction (%)
8-49	21625.03	30.41%	0	0.00%
50-99	23020.14	32.37%	328.0662	0.39%
100-129	10002.34	14.06%	2458.063	2.89%
130-179	5340.399	7.51%	2174.689	2.55%
180-259	7317.472	10.29%	5494.673	6.45%
260-329	3198.982	4.50%	22152.73	26.02%
≥330	615.48	0.87%	52538.13	61.70%
Total	71119.84	1	85146.35	1

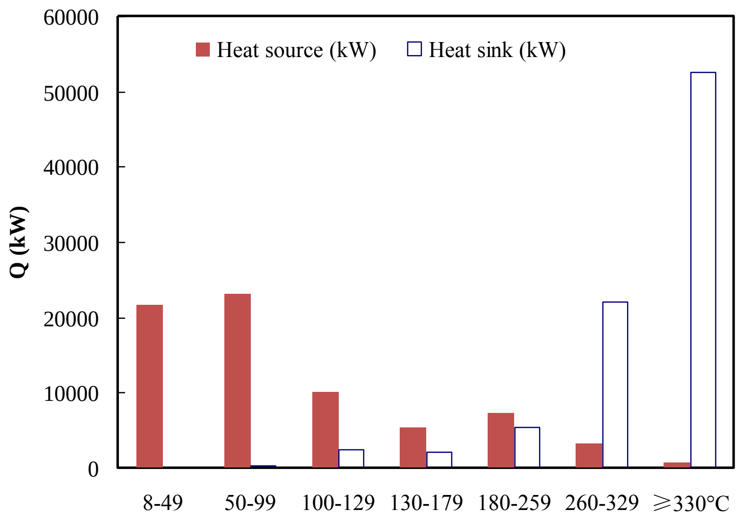

Fig. 11. Comparison of heat sink and heat source.

The waste heat below the site LP steam temperature, 130°C, is chosen for low-grade waste heat utilisation. Energy demand for this case study includes process heating, BFW preheating, shaft-power, refrigeration at 8°C and water heating at 60°C. The average ambient temperature for this site is 25°C. The heating requirement for site processes is represented as heat sink in Fig. 10 and Fig. 11. Obviously, the site low-grade waste heat can suffice the site low-grade process heating requirement. However, the following discussion will show that this straightforward heat recovery solution might be neither efficient nor economic from the whole site view.

For this case, process heating (PH) below 130°C, organic Rankine cycle (ORC) for power demand, absorption refrigeration (AR) for chilling demand, boiler feed water (BFW) preheating, water heating (WH), mechanical heat pump (MHP) for water heating, , and ORC combined with absorption heat transformer (AHT) for power demand are considered as candidates for heat recovery. Since there is no space heating or district heating demand, spacing heating and DHS are not considered as available heat sinks for site waste heat recovery. The heat supply temperature of MHP is taken as 70°C to allow the minimum temperature difference of 10°C for water heating at 60°C. The AHT is used to upgrade heat to 140°C. BFW preheating is from 25°C to 130°C, so that the flue gas from the utility system or fired heater could be specially used for BFW preheating in the temperature region above the sulphur corrosion temperature. The screening result of these heat recovery options is given in Fig. 12.

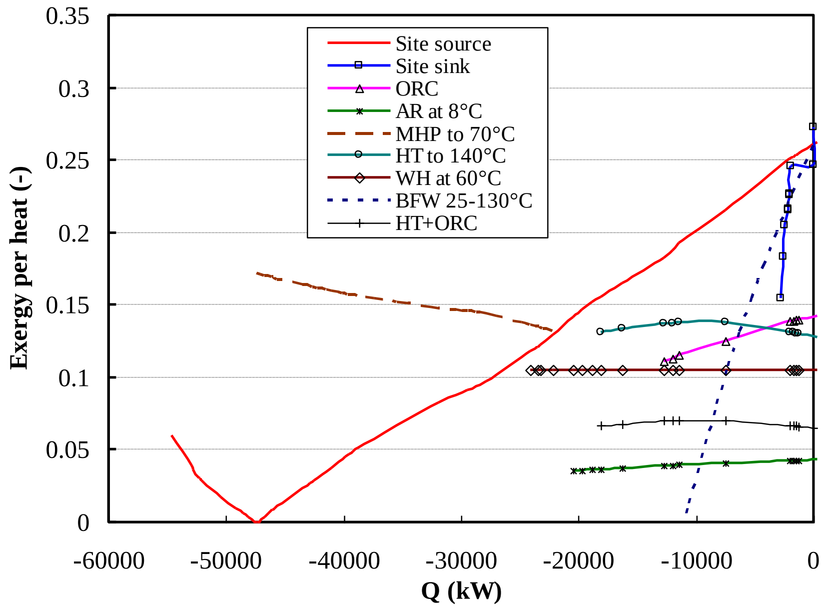

Fig. 12. Screening result of heat recovery options.

The heat recovery options can be ranked based on their respective exergy output per unit heat recovery. Accordingly, the temperature scale of waste heat source is divided into several intervals, and each interval has its preferred heat recovery technology selection. For this case, process heating is chosen as the most efficient recovery candidate for waste heat temperature region 124.8-130°C; BFW for 113.9-124.8 °C region; PH for 111.5-113.9°C region; ORC for 90-111.5°C region; AR for 75-90°C region; WH for 70-75°C region; and MHP for 25-70°C region. For the heat source below ambient temperature, chilling is provided by the AR system. As for the ORC combined with AHT or AHT option, the complexity, large economic penalty and weak efficiency advantage make them impossible competitive during the following optimisation and thus out of selection here.

Constrained by these temperature intervals obtained by minimising the exergy loss, an optimisation is carried out to maximise the total profit. The optimal operating temperature and heat recovery load of each candidate are obtained. Cost data in Table 9 is assumed for the optimisation. The lifetime is taken as 10 years. The design result is given in Fig. 13. The waste heat is recovered by site sinks from processes, BFW preheating (from 64.5°C to 112.3°C), generator of absorption refrigeration system, water heating and BFW preheating (from 25°C to 64.5°C) sequentially in temperature descending order. Compared with the existing site, part of waste heat which was rejected into cooling water now is utilised for process heating, BFW preheating, driving absorption refrigeration cycle and water heating, In total, waste heat of 26101.25kW (from 130°C to 60.8°C) is utilised, and corresponding cooling water usage for absorbing that waste heat in the existing site is saved as well. Since the AR system requires 19579.80kW cooling water for its absorber and condenser, the cooling water saving becomes 6521.45kW. The residual waste heat above ambient temperature is still rejected to cooling water. Site heat source below ambient temperature is now cooled by the AR system, which can provide 7254.58kW refrigeration at 8°C and completely satisfy the site chilling demand. Thus no refrigeration utility is required any more. The total net profit is 1,811,211 $/yr. Compared with the existing site, the low-grade waste heat recovery system can save LP utility 2786.13kW, cooling water 6521.45kW and refrigeration utility 7254.58kW, meanwhile provide 60°C hot water 1818.85 kW and preheat BFW from 25°C to 112.3°C (9171.05kW). The ORC and MHP techniques are eliminated by the economic optimisation, obviously due to their higher capital costs. The optimisation prioritises the heat recovery by site heat sink because of its economics, so that the BFW preheating is chosen to operate after the site heat sink is fully met.

Table 9 Cost data for case study [25-28].

Operating cost	
Hot utility (LP)	160 ($/kW-yr)
Cold utility (cooling water)	9.24 ($/kW-yr)
Refrigeration	264 ($/kW-yr)
Electricity or power	924 ($/kW-yr)
BFW preheating	142.3 ($/kW-yr)
Hot water (60°C)	134.4 ($/kW-yr)
Capital cost	
Distribution network cost	804 ($/kWe)
Organic Rankine cycle	3300 ($/kWe)
Absorption refrigeration	800 ($/kW)
Mechanical heat pump	400 ($/kW)
Absorption heat transformer	800 $/kW

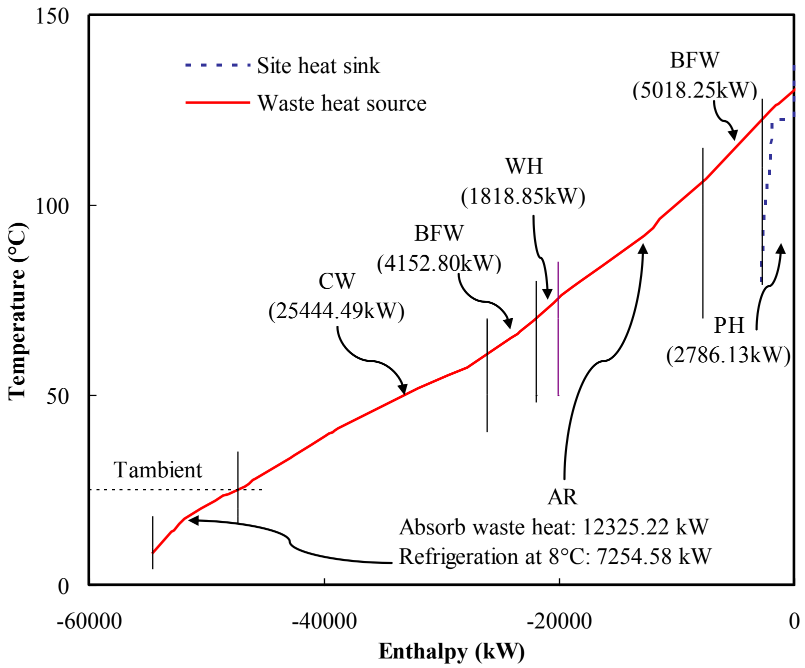

Fig. 13. Waste heat recovery design.

Both the efficiency and cost have great impact on the waste heat recovery technology selection and design. High capital costs and low efficiency related to existing heat recovery technologies, particular those using thermodynamic cycles and heat/cold distribution networks, make waste heat recovery economically unattractive. Normally, waste heat recovery will take a long payback period. For example, for this case, if a 3-year payback period is expected, then waste heat recovery through the distribution network is impossible profitable and would not be recommended by the economic optimisation; if 5 years allowed, site process heating by low-grade waste heat through the heat distribution network would be preferred; if 8 years allowed, BFW preheating and water heating would be selected as heat recovery options besides site process heating, which is because indirect heat transfer is cheaper and more efficient than thermodynamic cycles.

7. Conclusions

A systematic methodology for low-grade waste heat recovery within a total site is proposed, which is not managed by the existing total site integration technology. Waste heat potential identification, energy demand, efficiency and economics are essential factors, which have large impact on the waste heat recovery design. These four aspects are considered sequentially and form basic steps of the design procedure. Accordingly, this method can make the low-grade waste heat recovery technology selection and optimal design based on the site energy supply/demand situation and techno-economic performance of various waste heat recovery techniques. The low-grade waste heat recovery system could be integrated into an existing total site efficiently and economically, which increases the opportunity to reduce energy consumption and related emission.

References

[1] Rattner AS, Garimella S. Energy harvesting, reuse and upgrade to reduce primary energy usage in the USA. Energy 2011; 36(10): 6172-83.

[2] Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. Applied Energy 2012; 89(1): 3-20.

[3] Desai NB, Bandyopadhyay S. Process integration of organic Rankine cycle. Energy 2009; 34(10): 1674-86.

[4] Tchanche BF, Lambrinos G, Frangoudakis A, Papadakis G. Low-grade heat conversion into power using organic Rankine cycles - A review of various applications. Renewable and Sustainable Energy Reviews 2011; 15(8): 3963-79.

[5] Ghaebi H, Karimkashi S, Saidi MH. Integration of an absorption chiller in a total CHP site for utilizing its cooling production potential based on R-curve concept. International Journal of Refrigeration 2012; 35(5): 1384-92.

[6] Kew PA. Heat pumps for industrial waste heat recovery - A summary of required technical and economic criteria. Journal of Heat Recovery Systems 1982; 2(3): 283-96.

[7] Deng J, Wang RZ, Han GY. A review of thermally activated cooling technologies for combined cooling, heating and power systems. Progress in Energy and Combustion Science 2011; 37(2): 172-203.

[8] Becker H, Vuillermoz A, Marechal F. Heat pump integration in a cheese factory. Applied Thermal Engineering 2012; 43: 118-27.

[9] Horuz I, Kurt B. Absorption heat transformers and an industrial application. Renewable Energy 2010; 35(10): 2175-81.

[10] Aly G, Abrahamsson K, Jernqvist A. Application of absorption heat transformers for energy conservation in the oleochemical industry. International Journal of Energy Research 1993; 17(7): 571-82.

[11] Holmgren K. Role of a district-heating network as a user of waste-heat supply from various sources - the case of Goteborg. Applied Energy 2006; 83(12): 1351-67.

[12] Kapil A, Bulatov I, Smith R, Kim JK. Process integration of low grade heat in process industry with district heating networks. Energy 2012; 44(1): 11-9.

[13] Wang C, He B, Sun S, Wu Y, Yan N, Yan L, et al. Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600MW power plant. Energy 2012; 48(1): 196-202.

[14] International Energy Agency. Key world energy statistics; 2012.

[15] Townsend DW, Linnhoff B. Heat and power networks in process design. AIChE 1983; 29(5 Pt 1): 742-8.

[16] Papoulias SA, Grossmann IE. A structural optimization approach in process synthesis – I. Utility systems. Computers and Chemical Engineering 1983; 7(6): 695-706.

[17] Dhole VR, Linnhoff B. Total site targets for fuel, co-generation, emissions, and cooling. Computers and Chemical Engineering 1993; 17 (Suppl 1): S101-9.

[18] Klemes J, Dhole VR, Raissi K, Perry SJ, Puigjaner L. Targeting and design methodology for reduction of fuel, power and CO2 on total sites. Applied Thermal Engineering 1997; 17(8-10): 993-1003.

[19] Kimura H, Zhu XX. R-curve concept and its application for industrial energy management. Industrial and Engineering Chemistry Research 2000; 39(7): 2315-35.

[20] Bandyopadhyay S, Varghese J, Bansal V. Targeting for cogeneration potential through total site integration. Applied Thermal Engineering 2010; 30(1): 6-14.

[21] Karimkashi S, Amidpour M. Total site energy improvement using R-curve concept. Energy 2012; 40(1): 329-40.

[22] Ghannadzadeh A, Perry S, Smith R. Cogeneration targeting for site utility systems. Applied Thermal Engineering 2012; 43: 60-6.

[23] Linnhoff B, Hindmarsh E. The pinch design method for heat exchanger networks. Chemical Engineering Science 1983; 38(5): 745-63.

[24] Fraser DM, Gillespie NE. The application of pinch technology to retrofit energy integration of an entire oil refinery. Chemical Engineering Research and Design 1992; 70(A4): 395-406.

[25] Law R, Harvey A, Reay D. Techno-economic comparison of a high-temperature heat pump and organic Rankine cycle machine for low-grade waste heat recovery in UK industry, International Journal of Low-Carbon Technologies 2013; 8(Suppl 1): S47-54.

[26] U.S. Department of Energy. Waste heat recovery: technology and opportunities in U.S. industry,http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf; 2008.

[27] International Energy Agency. Combined heat and power, http://www.iea.org/publications/freepublications/publication/chp_report.pdf; 2008

[28] Smith R. Chemical process design and integration. John Wiley: West Sussex; 2005.