

A decision support system for waste heat recovery in manufacturing

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ABSTRACT

One third of energy consumption is attributable to the industrial sector, with as much as half ultimately wasted as heat. Consequently, research has focused on technologies for harvesting this waste heat energy, however, the adoption of such technologies can be costly with long payback time. A decision support tool is presented which computes the compatibility of waste heat source(s) and sink(s), namely the exergy balance and temporal availability, along with economic and environmental benefits of available heat exchanger technologies to propose a streamlined and optimised heat recovery strategy. Substantial improvement in plant energy efficiency together with reduction in the payback time for heat recovery has been demonstrated in the included case study.

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1. Introduction

Energy security is of significant concern for governments, industry and the public because of the increasing level of consumption, depletion of resources and its known contribution to climate change. Global energy demand is expected to increase by 50% in 2040 compared to today's levels [1]. Of this energy consumption, the manufacturing sector is particularly important since it is directly and indirectly responsible for one-third of global energy use [2]. Industrial heating or heat related treatment is one of the largest components of energy demand, and in the UK, accounts for about 72% of industrial energy use as depicted in Fig. 1 [3]. Of this demand two-thirds can be attributed to low and high temperature processes [4].

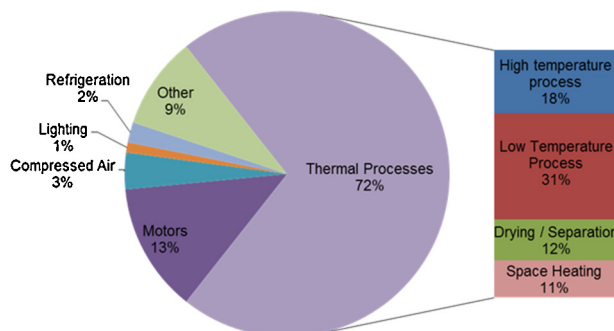


Fig. 1. Energy consumption in UK manufacturing industry [4].

Rising costs of energy along with severe targets for the reduction of greenhouse gas emissions have led to an impetus towards efficiency improvements in industry. In the short to medium term,

the reduction in primary energy demand is reported to be more cost-effective than implementation of renewable energy technologies [5].

Consequently numerous research activities have sought to improve energy efficiency through methods and tools for energy minimisation management [6,7]. Limited research has been reported on assessing the appropriateness of a specific technology for a particular industrial application, although a number of researchers have identified suitability of technologies for waste energy recovery [8] and methods for assessing their environmental benefits and payback time [5,9,10]. In particular, waste heat may be used for heat pumps [11], or absorption refrigerators [12]. Moreover, waste heat may be converted into electricity [10].

This paper presents a framework and an associated decision support tool specifically focused on waste heat recovery as an input to processes where heat is required within the same facility.

2. Decision support tool for waste heat energy recovery

The WHER framework consists of four steps that aim to define a process for the identification and matching of waste heat sources and potential sinks within a manufacturing facility as shown in Fig. 2 and described below.

2.1. Step 1: waste heat survey

Waste heat survey, aimed at the identification of sources and sinks of waste heat within a manufacturing environment from both the plant and process perspectives, is carried out using either invasive techniques, i.e. thermometers, Resistor Temperature Detectors (RTDs) and thermistors, as well as non-invasive devices (infrared thermography). Flow rates are measured using a range of flowmeters and flow sensors can be used according to the types of media involved (see Fig. 3). The output from this survey often highlights a limited number of opportunities to recover large

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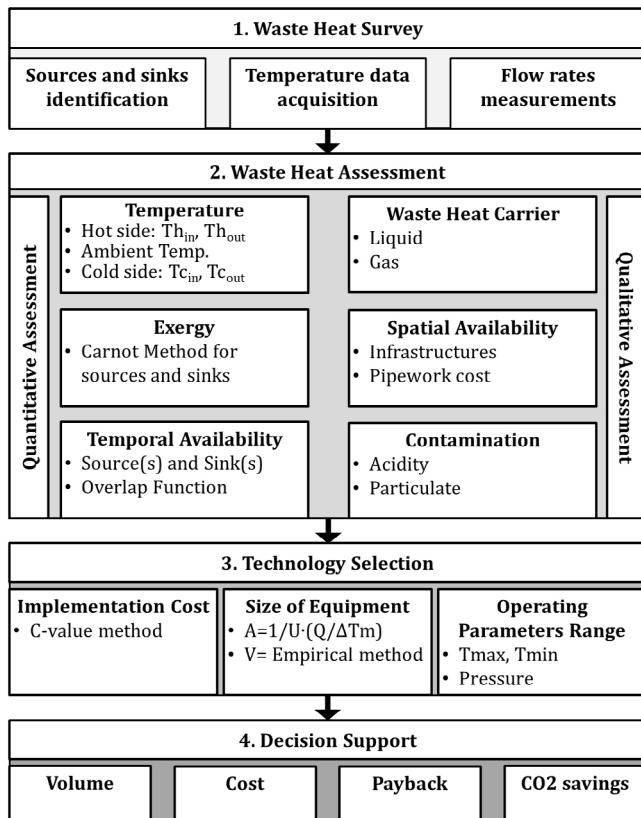


Fig. 2. Overall framework scheme.

quantities of waste heat within a facility using a number of specific parameters such as:

- Range and number of heat sources and sinks.
- Temporal information in terms of time window (hour, day or week) and time resolution (seconds, minutes, hours).
- $T_{h_{in}}, T_{h_{out}}, T_{amb}$ (inlet and outlet hot medium and ambient temperature, respectively) and the flow rate (m^3/s) for the source(s).
- $T_{c_{in}}, T_{c_{out}}$ (inlet and outlet cold medium temperature, respectively) and flow rate (m^3/s) for the sink(s).

The data generated by this survey is used by the subsequent steps in WHER for the quantitatively and qualitatively assessment of waste heat and selection of appropriate technologies to recover this energy.

2.2. Step 2: quantitative and qualitative assessment of waste heat

In order to quantitatively evaluate waste heat in a manufacturing environment, the following parameters are utilised.

2.2.1. Temperature

Clearly, the heat transfer and recovery can be enabled only if the waste heat source temperature is higher than the heat sink temperature. Hence, the magnitude of the temperature difference between the heat source and sink is an important determinant of the quality of waste heat, along with the heat transfer rate per surface area unit, and the maximum theoretical efficiency of converting thermal energy from the heat source to another form of energy, i.e. mechanical or electrical.

2.2.2. Exergy

The exergy is that part of energy that is convertible into all other forms of energy. The common energy analysis methods ignore the degradation of energy quality, and therefore exergy analysis is required to distinguish between recoverable and non-recoverable energy. The exergy can be calculated as outlined in publication by Taheri et al. [13] and formulated in the Eq. (1).

$$\text{Exergy} = m \cdot c_p \cdot \Delta T \left(1 - \frac{T_{amb}}{T} \right) \quad (1)$$

where m is the mass flow rate (kg/s), c_p is the stream specific heat capacity ($kJ/kg K$), ΔT is the temperature difference between the hot and the cold streams, T_{amb} is the ambient temperature and finally T is the measured temperature.

The exergy analysis is utilised to identify and quantify the heat energy loss and calculate the recoverable energies for each process [14].

2.2.3. Temporal availability for sources and sinks selection

One of the key factors in maximising the potential of energy recovery is the consideration for temporal availability for sources and sinks. A methodical approach is used to undertake source and sink selection. This procedure for evaluating the best source and sink matchup using exergy and temporal availability analysis starts with listing of all the possible combinations of sources and sinks. For each combination, the exergy availability from the source(s) and exergy demand from the sink(s) are computed using the Carnot Method [13] and plotted according to the time window and resolution defined by users.

The next step is the computation of the overlap function $O(t)$ between sinks and sources, which is defined as:

$$\begin{aligned} O(t) &= \text{Exergy}_{\text{sink}}(t) & \text{if } \text{Exergy}_{\text{sink}}(t) < \text{Exergy}_{\text{source}}(t) \\ O(t) &= \text{Exergy}_{\text{source}}(t) & \text{if } \text{Exergy}_{\text{sink}}(t) \geq \text{Exergy}_{\text{source}}(t) \end{aligned} \quad (2)$$

This operation is repeated for all of the possible combinations of sources and sinks.

Finally, the Recovery Index (RI), defined as the ratio of areas under the Overlap function and the Source exergy curves, is used for ranking the temporal availability. In this research, the values of $RI > 0.5$ are only considered for heat recovery. Given amount of heat flow, ambient temperature, and temperature difference between hot and cold streams, the material properties library in MATLAB[®] is accessed to supply physical properties (i.e. density, specific heat capacity) for selected stream media type. Similarly, qualitative

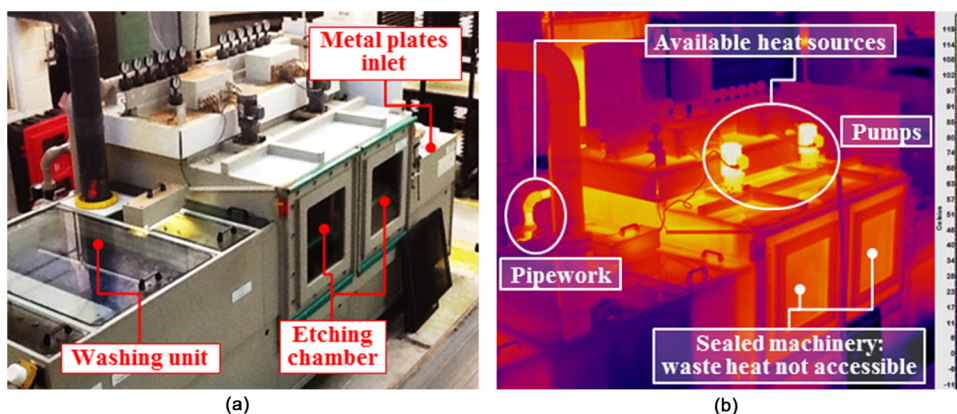


Fig. 3. Identification of waste heat hotspots in a chemical etching production line (a) using an infrared camera (b).

assessment of waste heat is carried out taking into account, the following parameters.

2.2.3.1. Carrying medium of waste heat sources and sinks. Waste heat medium can be in the form of liquid, gas or solid. The physical nature of the stream media can strongly influence the compatibility between the sources, sinks and the heat recovery equipment, its installation cost and other requirements.

2.2.3.2. Spatial availability. The need of a spatial availability assessment is important to evaluate possible constraints in the area where the heat recovery equipment needs to be installed. This assessment must take into account the following factors:

- Accessibility to the units for installation and maintenance.
- Positioning, i.e. underground or over ground pipework, for health and safety reasons.
- Locality of the waste heat sources and sinks to minimise the heat transportation costs and maximise the recovery.

2.2.3.3. Risk of contamination. Fouling and corrosion are the main causes of degraded performance or failure in heat recovery units [15]. Contamination can occur through fluid leakages in the equipment highlighting the need of a very careful selection of the construction materials, in order to ensure their compatibility with the working fluids and to avoid other mechanical and chemical failure.

These qualitative and quantitative descriptors of the available waste heat energy are used to compare potential heat recovery solutions with the available sources.

2.3. Step 3: selection of appropriate technology

A pre-selection phase is carried out using media, pressure, and temperature range to exclude non-compatible heat exchanger types listed in the ESDU database [16]. This is followed by a consideration of cost, volume and area based on the C method as described by Hewitt [17]. This enables a direct comparison between heat exchangers in terms of the heat duty carried out (Q) and the available temperature driving force (ΔT_m), which are related to the process specification. The quotient $Q/\Delta T_m$ is characteristic of the heat exchanger duty being carried out. From the point of view of the software tool, the key target is the overall cost of the particular duty, specified in terms of $Q/\Delta T_m$. The cost

factor C is defined as the cost in pounds sterling per unit $Q/\Delta T_m$, and as the units £/(W/K).

The procedure for evaluation of the alternative feasible types of heat exchanger using C value method [17] starts with the computation of the heat load, defined as $Q = m \cdot c_p \cdot \Delta T$.

The next step involves the estimation of the mean temperature difference, ΔT_m , for which, the F_T method [18] is used taking into account the F_T correction factor designed for worst case scenario.

For each proposed configuration the quotient $Q/\Delta T_m$ is then calculated and used to access the ESDU data tables [16] provided for each heat exchanger type in order to obtain the value of cost factor C , through a logarithmic interpolation between the levels of $Q/\Delta T_m$ given in the tables. Other technical constraints are taken into account, such as operating temperatures and pressure in order to exclude the non-compatible solutions.

The cost of each heat recovery configuration can be calculated by multiplying $Q/\Delta T_m$, by C . In this way it is possible to make a comparison of the selected configurations.

The results from this step are carried forward into the next stage of the framework, which utilises environmental and other economic analysis methods to compare between the selected options to provide the final recommendation.

The output of this tool provides a starting point for a detailed heat exchanger design at which point additional energy loss consideration of the chosen technology are required.

2.4. Step 4: decision support tool for waste heat recovery

The last step of the framework provides final recommendations for manufacturers to identify an appropriate technology to recover waste heat energy. A computational model is developed to utilise the data generated in the previous steps together with a cost and benefit analysis to assess the list of feasible technologies. The most suitable technologies are ranked according to the cost (£), the payback period (years) and CO₂ savings (tonnes/year) and presented in a dashboard style user interface for ease of use, as shown in Fig. 4 and explained in the next section.

PCB manufacturing process is used as an example to demonstrate the implementation of the decision support modelling for heat recovery. In this case study, the objective is to recover waste heat energy from 5 compressors to be fed into their plant boiler system in order to supply hot water and plant heating. All the compressed air units are positioned in the same location which is

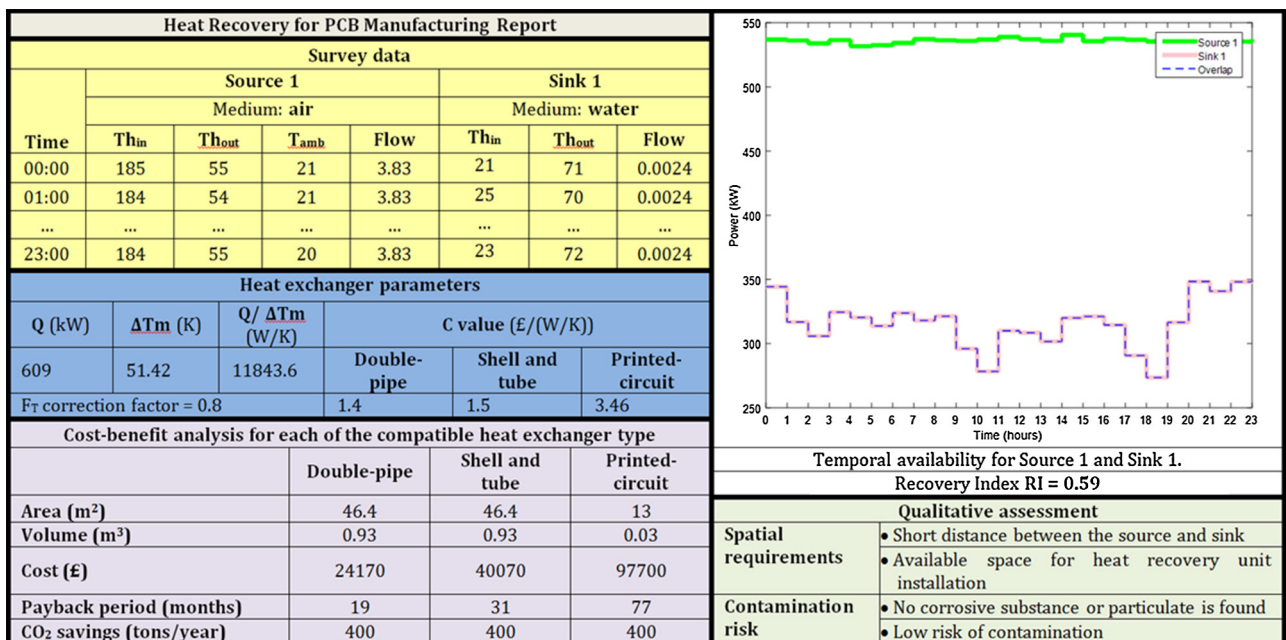


Fig. 4. Dashboard of results generated by the decision support tool.

close to the boiler room; therefore it is possible to cluster the individual compressors as one single source of waste heat.

Step 1 The waste heat survey was conducted using two Temperature Data Loggers, inlet flow rate was measured using standard flow metre, and the outlet flow rate was calculated theoretically according to the hot water demand. The time window considered is one day and the time resolution is 1 h. These data appear in Fig. 4 (yellow section).

Step 2 The exergy amount is calculated based on the inlet and outlet temperature of the waste heat source and sink provided by the survey. As per exergy analysis results summarised in Fig. 4, temporal availability calculation was carried out leading to a $RI = 0.59$. The temporal availability chart reported in Fig. 4 displays power of waste heat source over 24 h as a green line whereas waste heat sink is displayed in pink. The overlap function is represented by the blue dashed line.

Step 3 Using the selection criteria and the C method, three types of compatible heat exchangers for this case study were identified: double-pipe, shell-and-tube, printed circuit, respectively. Fig. 4 shows (blue section) the computed values for relevant parameters for the selected heat exchanger.

Step 4 To enable a comparison of the three selected heat exchanger types, a cost–benefit analysis was carried out, including the computation of the heat exchangers areas and volumes, the cost, the payback period and the potential CO₂ savings, as shown in Fig. 4 (purple section).

Finally, a summary of the qualitative descriptors involved in this case study is summarised in Fig. 4 (in the green section), indicating that there were no particular constraints in terms of spatial availability and contamination risks.

A further way to display all the solutions generated by the decision support tool is reported in Fig. 5 in which the five axes represent the cost–benefit analysis parameters and a visual simultaneous comparison is allowed.

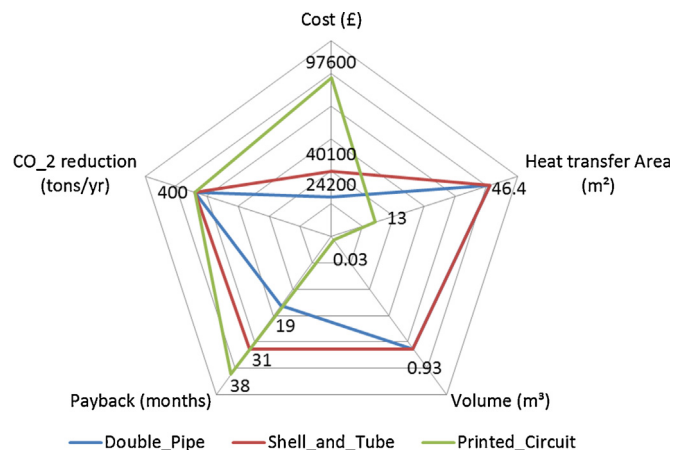


Fig. 5. Visual comparison of the solutions generated by the decision support tool.

3. Conclusions

Energy minimisation within a facility is not limited to technological process improvements or changes in operation performance, but can also be achieved by taking a more holistic view of energy flows. In particular, by coupling sources of waste heat energy with suitable sinks, can lead to substantial energy savings, with short payback period for any new infrastructure required. For successful implementation of this approach within

the manufacturing environment it is essential to consider the exergy balance of the potential sources and sinks alongside the temporal availability of energy. In this work a conceptual and computational methodology for decision support on waste heat recovery was developed and applied to an industrial case study. The main conclusions that can be drawn from this case study are:

- The decision support system is able to compare temporal availability of exergy between sources and sinks of waste heat energy.
- A range of recovery indexes can be obtained to determine the quality of the match between multiple sources and sinks.
- Such an analysis can be used in a computational technology selection for optimised energy recovery and minimised financial payback of implementation.
- The user interface is straight-forward enough to be utilised by competent facility or energy management teams.

Beyond the scope of the current research, there are three scenarios where this decision support tool could be utilised to improve overall plant energy efficiency:

- Recovery of waste heat energy within an existing manufacturing plant.
- Implementing waste heat recovery within a reconfigurable manufacturing system.
- Process design stage of a manufacturing system with waste heat recovery consideration.

It is envisaged that this methodical approach to implementing waste heat energy recovery within manufacturing will form part of a standard practice for new and old facilities striving to reduce overall energy demand.

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