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A framework for waste heat energy recovery within data centre

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Abstract

Data Centres are emerging as a large industrial sector, consuming three percent of the global electricity supply while contributing for two percent of total greenhouse gas emissions, with as much as half ultimately wasted as heat. Consequently, research has focused on technologies for harvesting this waste heat energy. A framework and its accompanying decision support tool is presented which identifies the compatibility of waste heat source(s) and sink(s), 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 data centre energy efficiency together with reduction in payback time for heat recovery has been demonstrated in the included case study.

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Keywords: Data centre; Energy efficiency; Waste heat recovery; Environment; Sustainable development.

1. Introduction

Energy security is important for governments, industry and the public, due to 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 level [1]. Of this energy consumption, the data centre sector is particularly important since it is emerging as one of the largest industrial sector, responsible for three percent of global energy

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use and two percent of total greenhouse gas emission. Moreover, the amount of energy used by data centres is doubling every four years [2]. There are currently 8 million private and commercial data centers globally and are projected to grow 44 times between 2009 and 2020. The industry is experiencing an exponential growth in data centre deployment, expanding the data centre capacity to 1.94 billion square feet today, from 1.6 billion in 2016.

Data centres must be adequately cooled as almost all of the energy supplied to the server is dissipated into heat, requiring the use of large scale cooling systems to keep the server rack temperature in a safe operational range. Despite increased energy demand by the data centre, equipment and space cooling is one of the largest components of energy consumption, accounts for about 40% of data centre energy use as depicted in Fig.1. Rising costs of energy along with server targets for the reduction of greenhouse gas emissions have led to an impetus towards efficiency improvements within data centre. 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 [3].

Consequently numerous research activities have sought to improve energy efficiency of data centre through methods and tools for minimisation of cooling energy and utilisation of free cooling [4–6]. Limited research has been reported on assessing the appropriateness of a specific technology for a particular data centre application, although a number of researches have identified suitability of technologies for waste heat energy recovery [7,8]. In particular, waste heat may be used for absorption cooling [7,9] or district heating [6,10]. In addition, waste heat may be converted into electricity through ORC [11] or indirectly into cold and power through Dearman engine [12].

The paper presents a framework specifically focused on waste heat recovery as an input to data centres where heat is required within the same facility.

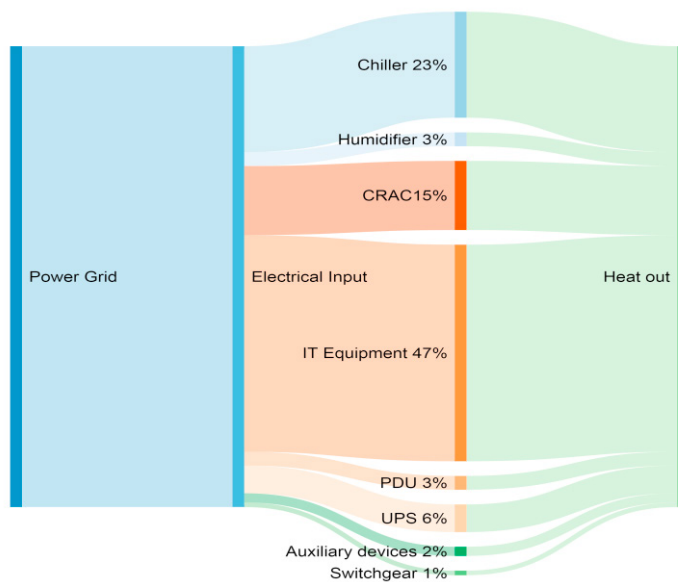


Fig. 1. Energy attributes within a typical data centre [12].

2. Framework for waste heat recovery within data centre

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

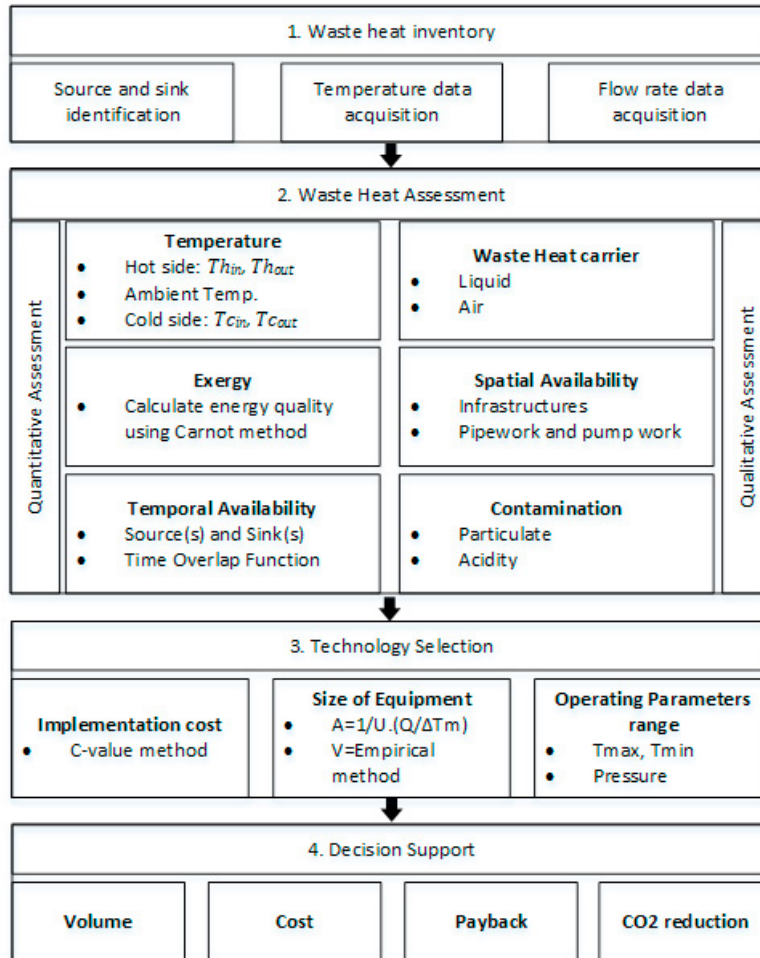


Fig.2. Overall framework scheme for waste heat recovery within data centres

2.1. Waste heat survey

The aim of the step is to identify waste heat sources and potential sinks within a data centre facility from both the data centre site and process perspectives, is carried out using either invasive techniques i.e. thermometers, thermistors, Resistor Temperature Detectors (RTDs), as well as non-invasive devices, such as infrared thermography. Flow rates of cooling liquid are measured using a range of flowmeters and flow sensors can be used according to the types of media involved. The output from this waste heat survey often identifies a limited number of opportunities to recover large quantities of waste heat within a facility using several specific parameters such as:

- Temperature range and number of heat sources and sinks
- Temporal availability in terms of time window (on hourly, daily or weekly basis) and time resolution (seconds, minutes or hours) of servers' load and energy in demand.
- T_{in} , T_{out} , T_{amb} (inlet and outlet hot medium and ambient temperature respectively) and the flow rate (m^3/s) for the source(s).
- T_{cin} , T_{cout} (inlet and outlet cold medium temperature respectively) and flow rate (m^3/s) for the sink(s).

The data generated by this inventory survey is used by the subsequent steps in the framework for the quantitative and qualitative 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 data centre environment, the following parameters are utilised:

i. Temperature

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 and waste heat, along with the heat transfer rate per unit of surface area, and the maximum theoretical efficiency of converting thermal energy from the heat source to another form of energy, i.e. electrical or chemical.

ii. Exergy

The exergy of a heat source is the 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 Equation 1.

$$\text{Exergy} = mc_p \Delta T (1 - T_{amb} / T) \quad (1)$$

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

The exergy analysis is undertaken to identify and quantify the amount of thermal energy and calculate the recoverable energy for each waste stream.

iii. 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 section. This procedure for evaluating the best source and sink matchup using exergy and temporal availability analysis initiate 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 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 sources and sinks, 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 source and sink combination. The value of this ratio is always between 0 and 1. A higher value of RI (i.e. values closer to 1) is indicative of larger percentage of source and sink synchronization, and therefore signifies a more suitable waste heat recoverability in terms of time. To narrow down the good match and improve system efficiency, 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 assessment of waste heat is carried out considering, the following parameters:

i. Carrying medium of waste heat sources and sinks

Waste heat medium can be in the form of liquid or gas. The physical property of the stream media can strongly influence the compatibility between the sources, sinks and the heat recovery method, its installation cost and other requirement.

ii. 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 consider the following factors:

- Accessibility to the server room for installation and maintenance of heat recovery units
- Positioning, i.e. underground or over ground pipework or pump unit, for health and safety reason
- Locality of the waste heat source and sinks to minimise the heat transportation costs and maximise the recovery

iii. Risk of contamination

Particulate and corrosion are the main causes of degraded performance or failure in heat recovery unit. Contamination can occur through fluid leakages in the equipment highlighting the need of a very careful selection of the construction materials, 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. Approach to selection of an appropriate technology

A pre-selection phase is carried out using heat transfer media, pressure, and temperature range to exclude non-compatible heat exchanger types listed in the ESDU database [14]. This is followed by a consideration of cost, volume and area based on the C-value method as described by Hewitt. 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. As for the decision support tool, the key target is the overall cost of the 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 starts with the computation of the heat load, defined as $Q = m c_p \Delta T$.

The next step involves the estimation of the mean temperature difference, ΔT_m , for which, the FT method [14] is used taking into account the FT 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 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 considered, 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 cost factor 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. Decision support tool for waste heat recovery

The last step of the framework provides final recommendations for data centre operators 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 reduction (tons/year) and presented in a dashboard style user interface for ease of use, as shown in Fig. 3 and explained in the next section.

A typical data centre operation is used as a case study to demonstrate the implementation of the decision support modelling for heat recovery. In this example, the objective is to recover waste heat energy generated from server operation to be fed into data centre's boiler system to supply preheated hot water for space heating.

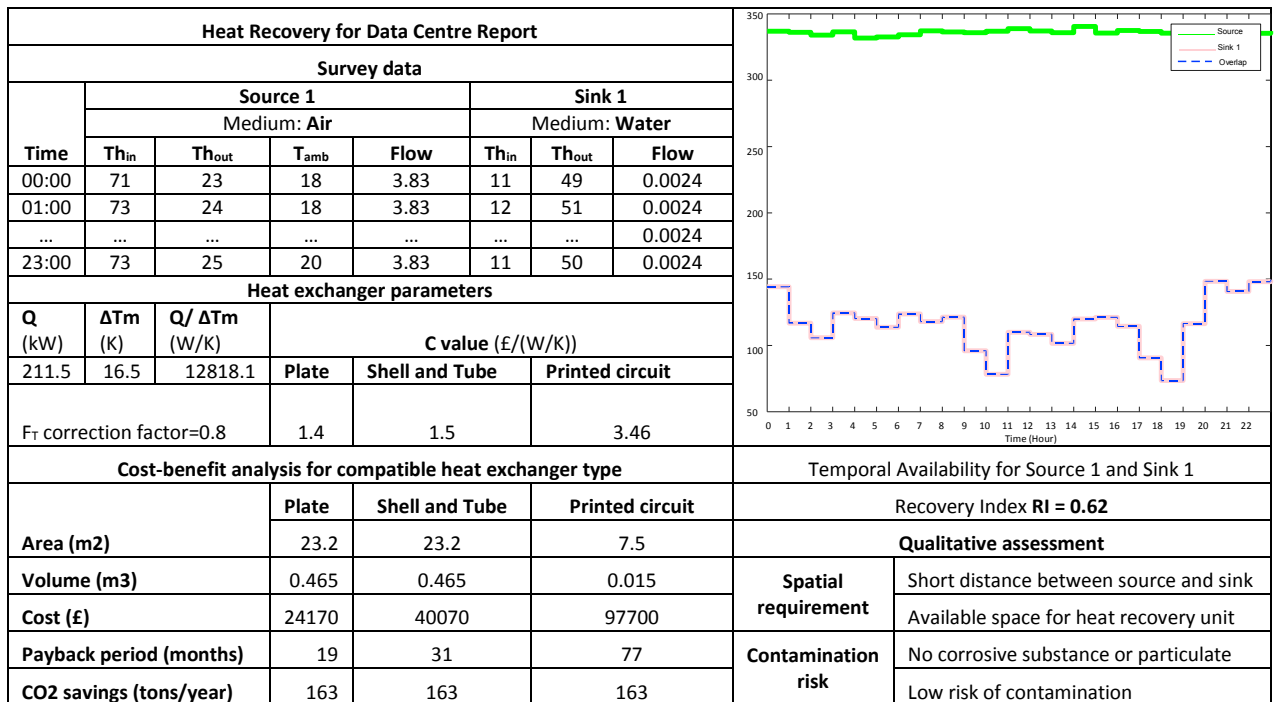


Fig.3. Modelling results generated by the decision support system in dashboard style

Step 1: The waste heat survey was conducted using a number of Temperature Data Loggers, inlet flow rate was measured using standard flow meter, and the outlet flow rate was calculated theoretically according to the hot water demand. The time window considered in this case study is 24 hours and resolution is set as one hour. Data can be seen in Fig.3.

Step 2: Exergy content of the waste heat stream is calculated accordingly based on the temperature data from the survey. As per exergy analysis results summarised in Fig. 3, temporal availability calculation was carried out leading to a Recovery Index of 0.62. The temporal availability chart reported in Fig. 3 displays power of waste heat source over 24 hours as a green line whereas waste heat sink is displaced in pink. The overlap function is represented by the blue dashed line.

Step 3: Using the selection criteria and the C-value method, three types of compatible heat exchangers for this case study were identified: plate, shell-and-tube and printed circuit respectively. Fig. 3 illustrates the model results and computed values for relevant parameters for the selected heat exchanger

Step 4: In order to compare the selected heat exchanger types, a cost-benefit analysis was carried out, including the computation of the heat transfer areas and volumes, the cost, payback period and the overall potential CO₂ reduction.

Finally, a summary of the qualitative descriptors involved in this case study is summarised in Fig. 3, indicating that there were no particular constraints in terms of spatial availability and contamination risks.

3. Conclusions

Waste energy recovery within a data centre is not limited to technological hardware improvements or changes in operation performance but can also be achieved by taking a more holistic view of the overall energy flow in the data centre. Specially, by coupling waste heat source with appropriate heat sinks, can lead to substantial energy and CO₂ savings, with optimised payback time and infrastructure requirement. To enable the successful implementation of this computational approach within the data centre section, it is essential to consider the exergy analysis of the waste heat stream and heat sinks alongside the temporal availability. In this work, a conceptual and computational methodology was developed to provide decision support to data centre operators to utilise an appropriate waste heat recovery technology. The main conclusions that can be drawn from this case study are:

- The decision support system uses algorithm to compare temporal availability of energy between waste heat sources and potential sinks within the facility.
- A range of recovery indexes can be obtained to determine the quality of match between multiple sources and sinks, thus most optimised value is picked
- Such analysis can be used in a computational technology selection for optimised energy recovery and minimised financial payback of implementation

It is envisaged that this methodical approach to implementing waste heat recovery within data centre will form part of a standard practice for next generation and retrofit facilities striving to reduce overall energy demand.

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