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Industrial waste heat recovery: A systematic approach

Elliot Woolley[a], Yang Luo[b], Alessandro Simeone[c,*]

[a] Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK
[b] Research Centre for Carbon Solutions (RCCS), Institute of Mechanical, Process and Energy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, UK
[c] Intelligent Manufacturing Key Laboratory of Ministry of Education, Shantou University, Shantou 515063, China

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ABSTRACT

Globally one third of energy consumption is attributable to the industrial sector, with up to fifty percent ultimately wasted as heat. Unlike material waste that is clearly visible, waste heat (WHE) can be difficult to identify and evaluate both in terms of quantity and quality. Hence by being able to understand the availability of waste heat energy, and the ability to recover, there is an opportunity to reduce industrial energy costs and associated environmental impacts. A waste heat energy recovery framework is developed to provide manufacturers with a four step methodology in assessing production activities in facilities, analysing the compatibility of waste heat source(s) and sink(s) in terms of exergy balance and temporal availability, selecting appropriate heat recovery technologies and decision support based on economic benefits. The economic opportunity for industrial energy recovery is demonstrated in an industrial case study. The applicability of the framework for wider industrial application is discussed.

Introduction

The need for improved energy efficiency in manufacturing is unquestionable. Responsible for one third of global energy demand [1] and set against the backdrop of increasing consumption and depleting energy-rich fossil-based fuels, it is likely that the future will bring increased energy prices and both short and long-term energy insecurities. This is not an ideal situation for manufacturing and a response to this threat is urgently required.

For manufacturers to reduce reliance on fossil-based fuels and at the same time reduce environmental impact of their activities there are two basic options: the use of renewable energy systems or the reduction of energy consumption. The incorporation of renewable energy technologies is an increasingly attractive option as prices fall but are not suitable for all locations and investment costs can still be prohibitive. The alternative, reducing energy demand, can be divided into three further options: a reduction in total activity (e.g. [2]); better energy management(e.g. [3]); and recovery and use of waste energy (e.g. [4]). A reduction in total activity can occur without detrimental impact on the profitability of a company [5] but requires a significant change to the business model and is not suitable for all company types [6]. Energy management has been explored at a number of manufacturing levels [7] and has been shown to be suitable for long, medium and short-term energy consumption improvements. Energy recovery and use is founded on the principle that energy is never actually consumed, it is only converted from one form to another, and so there is a potential to capture this and utilise it as an energy supply. This is best conceptualised when considering the lifecycle of energy within a plant (Fig. 1), where energy (typically waste heat) can be recovered closed loop (reused back into the same process) or extended loop (recover into the energy supply of the facility). Recovered energy, in effect, replaces the need for a proportion of final energy demand by a facility.

The amount of useable energy is defined by its exergy, the component of energy that can be used to carry out work within a system. Additionally, most ‘waste’ energy available within a system is in the form of heat (Fig. 2) which is typically of lower exergy than stored chemical or electrical energy for example. Whereas energy within a system remains constant, the amount of exergy always decreases and so energy recovery must be undertaken in a well-informed manner to minimise exergy loss and maximise benefits. The objective of this work is therefore to create a framework for the identification and classification of waste heat energy within a facility and to provide a decision support tool to enable plant managers to make informed decision on the type of technology required to capture and harness waste heat energy.

This paper begins with a brief review of current industrial energy management and recovery used within industrial production facilities, before defining a framework for evaluating opportunities for reuse and recovery of energy within industrial environments. Both quantitative

* Corresponding author.
E-mail address: simeone@stu.edu.cn (A. Simeone).

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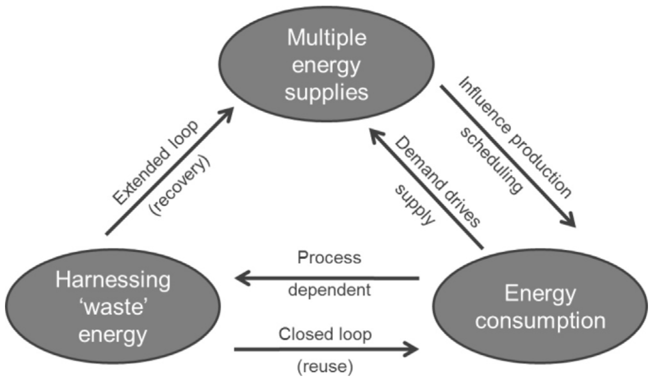

Fig. 1. Life cycle of energy in a manufacturing facility.

and qualitative descriptors are defined and a process established for the comparison of available sources and sinks. Primarily targeted for discrete production, the approach is also applicable to continuous processing. A decision support process is described and demonstrated via an industrial case study. The suitability of the framework is discussed in the context of industrial applications.

Literature review

Energy efficiency is often overshadowed by economic efficiency, particularly when it comes to decision making within industrial environments. It is true that not all energy efficiency improvements are beneficial economically (i.e. they may require significant investment) [9] but there are a wide range of energy efficiency improvements that can be made across a manufacturing facility, of which some should certainly lead to cost savings within acceptable time periods. Within manufacturing energy using activities can be categorised under six levels, five of which (turret, machine, machine cell, facility and enterprise) have been described by Vijayaraghavan and Dornfeld [10] while a sixth level, business strategy, has been proposed [7] to incorporate ramifications from longer term decision making. A vast amount of literature exists describing various approaches for reducing energy consumption across these manufacturing levels (see [11;12] for example). The levels are useful for focusing and categorising energy management efforts, and can be adopted for describing the possibility of energy recovery. On whichever level energy is used there is the potential for energy recovery, be it from the heat generated from the friction of material removal from a work piece at the turret level, or the heat generated by the compressor pumps for pneumatic lines powering a facility. However, in terms of energy recovery, the number of these manufacturing levels is too great (e.g. there is little difference between waste energy generated at the process level and at the cell level) and in practical terms waste energy at the enterprise level would be too dispersed to harness (although some technologies exist (e.g.[13]) and the business strategy level becomes irrelevant. In addition, there is the potential to recover heat directly from a product which has been recently processed (e.g. a freshly cast engine block). Therefore, instead of the manufacturing levels described by [9], which are highly useful for analysing energy inputs into a system, it is useful to adopt a set of terminologies defined by Rahimifard et al. [14] called the *3P perspective* referring to Plant, Process and Product. Developed for energy modelling, these three perspectives can also be used to define potential output sources of WHE and are useful for identifying possible waste heat flows within a manufacturing facility (between the different perspectives). In general, the highest temperatures, but smallest amounts of waste heat are available directly from the product, with the lowest temperatures, but greatest amount of heat being available at the plant level. This implies that suitable sinks for waste heat recovery (WHER) are unlikely to be found at a lower level, but could be identified at the same or higher levels (Fig. 3). The three opportunities for energy recovery then are for it to be reused for the same purpose recovered for another use within the factory or reutilised for energy storage or power generation (i.e. electricity).

Given this backdrop of energy recovery technologies and the 3P perspective for WHER, it has been identified that there is need to create an economic model that successfully 'bridges' available WHE sources with suitable, potential WHE sinks [15]. In support of this, it has been shown that it is more economical to recover heat for transfer to a sink rather than to invest in heat pumps or convert the heat into other forms such as electricity [16]. It is also preferable to reuse the heat in the same process, or a sink in the immediate facility, to avoid the cost of pipework, ducts and auxiliary equipment which themselves, also lead to thermal losses. Further, heat exchangers have been proposed as one of the best systems for recovering WHE energy [17,18], and for these, there needs to be an emphasis on matching heat sources with heat sinks. Such research supports the idea of reusing WHE energy within the same level (shown in Fig. 3) and where this is not possible, cascading it to the next level.

Energy recovery has been investigated for a range of different industrial sectors including aluminium casting [19], steel production [20], low grade heat from the food manufacturing [21] and district heating [22] with many other sectors, such as cement, glass, chemicals and ceramics having been highlighted as ideal for low grade energy recovery [23].

Clearly, this is an active area of investigation and the number of installation of WHER technologies continues to increase [24]. However,

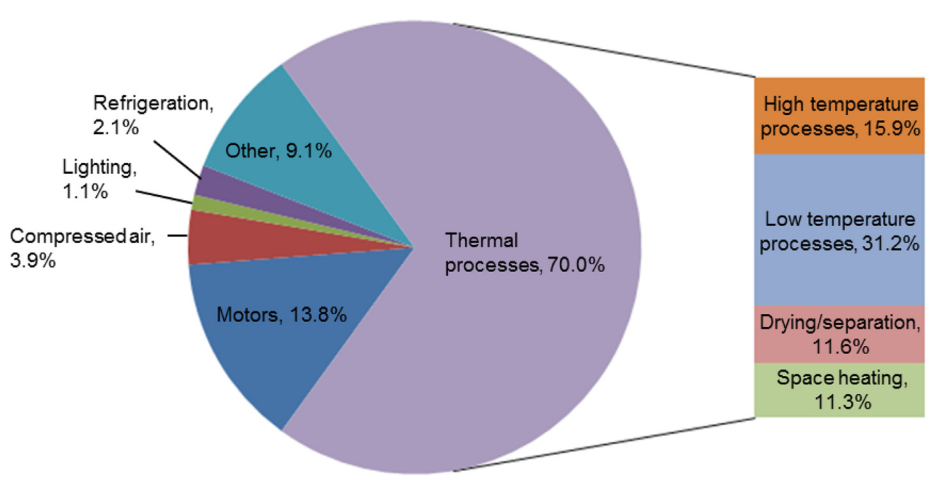

Fig. 2. 2016 Energy consumption in UK manufacturing industry by type (Data from Department of Business, Energy and Industrial Strategy, [8]).