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IMPROVING ENERGY EFFICIENCY WITHIN MANUFACTURING BY RECOVERING WASTE HEAT ENERGY

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ABSTRACT

In the UK, 25% of final energy consumption is attributed to the industrial sector (DECC, 2013) which also accounts for one third of the electricity consumption. However it is estimated that between 20 to 50 percent of industrial energy consumption is ultimately wasted as heat (Johnson et al., 2008). Unlike material waste that is clearly visible, waste heat 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, and the ability to recover it, there is an opportunity to reduce energy costs and associated environmental impacts. This research describes the design of a novel framework that aids manufacturers in making decisions regarding the most suitable solution to recover Waste Heat Energy (WHE) from their activities. The framework consists of four major sections: 1) survey of waste heat sources in a facility; 2) assessment of waste heat quantity and quality; 3) selection of appropriate technology; 4) decision making and recommendations. In order to support the implementation of the framework within the manufacturing industry, an associated software tool is discussed.

1. INTRODUCTION

In the 21st Century, fossil fuels remain a dominant component of the global energy grid. Therefore the depletion of these natural resources and increased environmental damage still plagues governments, industry and the public. Coupled with the growing energy demand with emerging economies, such as China and India, it is projected that worldwide energy consumption is to increase by more than 40 percent by 2035 (Chevron, 2014). Taking all new technology developments and policies into account, the world is still failing to put the global energy system onto a more sustainable path, currently with over 80% of the global primary energy demand is met by fossil based fuels (figure 1) (IEA, 2014). The problem is confronted by increased population, development of 'comfortable countries' and industrial development based on economic drivers which relegates energy to a minor consideration. New policy development, the introduction of economic incentives, wide spread publication of environmental concerns has been ineffective on large scale.

For the manufacturing industry, a reduction in activity is not an ideal solution as manufacturing activities are typically driven by production and sale business models (Spring, 2013) and would thus impact profitability, the primary objective of businesses. A large number of research programmes have sought to improve energy efficiency, but have not been hugely successful at achieving radical reductions on overall consumption due to difficulties in implementing new technologies and operational procedures in companies, especially where the renewal of equipment happens only over long timescales. In general, it is difficult to justify the time, expenditure and effort to implement energy efficiency improvements in light of the financial and energy gains achievable. The third option, recovery of waste energy, has not been studied extensively in research due to the perceived low return in energy saving in comparison to the required effort and expenditure to implement such solutions. Energy recovery as an energy efficiency approach is consequently under-developed and forms the focus of this research.

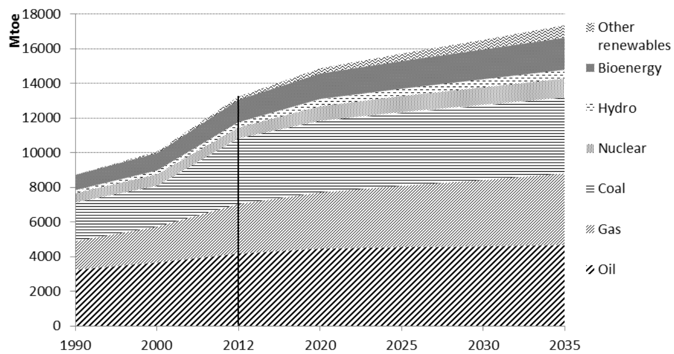

FIGURE 1 WORLD PRIMARY ENERGY DEMAND, SOURCE: IEA, 2014

The aim of this paper is to provide an overview of a novel framework which offers a systematic approach to evaluate the potential waste heat energy (WHE) available in a manufacturing plant and consequently determine the proportion of this WHE that is suitable for recovery. The originality of this research is that it is the first attempt to provide a systematic framework for understanding the WHE available within a manufacturing environment and that provides decision support in terms of identifying suitable energy recovery technologies for individual scenarios. The framework thus identifies suitable technologies and applications for the reutilisation of this WHE with the objective of improving overall energy efficiency. This paper begins with a review of literature to provide a background understanding of the current research in improving overall plant level energy efficiency and establishes the lack of structure in the understanding of WHE available within manufacturing businesses and suitable applications of this energy. The review is followed by a detailed description of the framework and uses a synthesised case study to demonstrate detailed functionality of it. The paper concludes with a discussion of the applicability of the framework for use in an industrial environment and a description of proposed future work.

2. LITERATURE REVIEW

Energy efficiency is a general term that does not define a particular set of actions or equipment and so can be misleading if used in isolation. To address this, and to provide some structure to research carried out in this field, a number of levels within a manufacturing enterprise have been identified and defined (Vijayaraghavan & Dornfeld, 2010). In manufacturing, energy using activities generally fall under five levels ranging from the detailed turret scale energy requirements to the broad enterprise scale activities (figure 2), and are useful for describing different energy requirements across the various manufacturing activities.

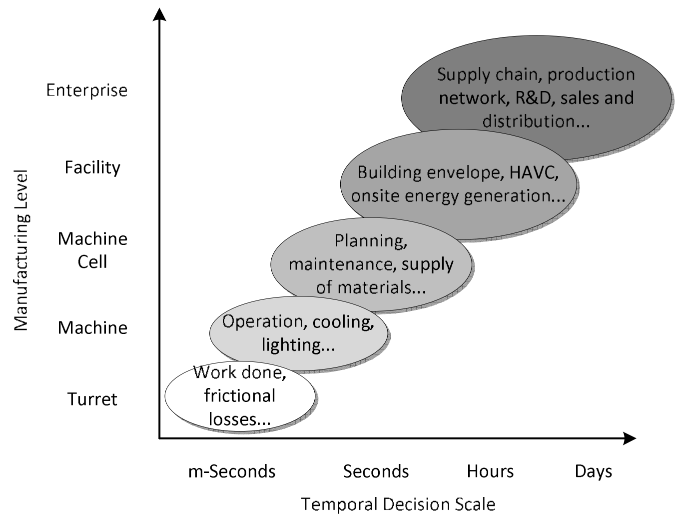

FIGURE 2 ENERGY CONSIDERATIONS AT THE VARIOUS MANUFACTURING LEVELS (ADAPTED FROM VIJAYARAGHAVAN & DORNFELD (2010)

Based on these five levels, there has been a significant amount of research carried out to improve energy efficiency of a wide range of manufacturing activities. At the enterprise level, Kara & Ibbotson (2011) identified that supplier location was a major factor that can increase overall energy requirements for the raw materials, thus by selecting local rather than international suppliers avoids use of energy intensive transport. At the facility level, investment of capital in energy-saving equipment such as insulation and waste-heat recovery could reduce overall energy demand with little or no effect on product quality (Despeisse, et al., 2012). At the machine cell level, most of the work involves process planning for improved energy performance. For example, Tan et al. (2006) combined manufacturing process planning and environmental impact assessments using check list analysis and suggested an optimal decision making algorithm for new components that involves energy consumption as part of the sustainable development evaluation. At the machine level of manufacturing, Dahmus and Gutowski (2004) reported that machine tools with increasing levels of automation have higher basic energy consumptions which result from the amount of additional integrated machine components. For example CNC machines carry a number of key components such as pumps, hydraulic systems, and numerical control systems which dominate the energy consumption of the process. Turret level of the manufacturing system represents the actual material transformation process and is typically studied based on theoretical analysis such as in the work of Sarwar et al. (2009) who carried out a detailed analysis on the specific energy consumption of bandsawing different work piece materials, Rajemi et al. (2010) have looked at the minimal energy required for turning and the optimal conditions for machining a product and finally Kuzman (1990) have carried out an energy evaluation of the cold forming process.

Clearly there is a substantial amount of work carried out across these different manufacturing levels to improve energy efficiency. However energy recovery should not be applied at one particular manufacturing level only. WHE is potentially recoverable from facility level activates, from individual processes and from actual products as they leave their respective processes. Here the manufacturing levels described by Vijayaraghavan and Dornfeld (2010) and used by so many to address energy consumption issues, become less useful. Instead it is useful to adopt another set of terminologies defined by Rahimifard et al. (2010) called the 3P perspective which describes energy modelling techniques which use either the Plant, Process or Product as the central perspective. As well as energy modelling, these three perspectives can be used to define potential sources of WHE and are useful for identifying possible waste heat flows within a manufacturing facility (figure 3). WHE available from plant level activities might include flue gases from boiler systems, heat generated by air compressors, or heat from lighting, all of which can be either concentrated or disperse. WHE available from process level activities includes sources such as heat from pumps, cooling fluids and exhaust gases, conduction and convection from hot castings (e.g. furnace). Finally WHE from products will typically be in the form of heat emanating from hot bodies (e.g. cooling cast or kilned parts).

With these categorisations it is then possible to identify potential sinks for where the waste heat can be reutilised. As shown in figure 3, WHE is typically suitable to be used at the same manufacturing level or cascade to a level above, with the exception of the product level, in which it is generally not feasible to reuse the energy outside of the context of a process.

Various published articles of energy recovery research in the categories of plant, process and product have been found which include development and application of new technologies. Khattak et al. (2014) undertook a case study into the use of waste heat from an engine machining line within an automotive factory to supplement the factory heating system whilst Bisio (1997) reported in their study of energy recovery potential of molten slag from a blast furnace, that a significant amount of energy can be recovered to produce either steam or heated air which can then be reutilised in the same blast furnace. In this way the recovered energy is supplied to match demand without having to be transported over long distances. Bell (2008) has presented work in the field of waste heat energy recovery with thermoelectric systems whose combination of thermal, electrical, and semiconducting properties allows them to be used either to convert waste heat into electricity or electrical power into cooling and heating.

Clearly there are a number of pieces of research which have developed technologies and applications for the recovery of waste heat within manufacturing and other environments, but these have been done as isolated pieces of work, without taking into account the manufacturing system within which the WHE is generated. In this respect, it is hypothesised that providing a structured framework within which one can measure, define and understand available WHE, and that can identify suitable applications for the use of recovered WHE in the context of available supporting technologies, could reveal additional financial and environmental benefit for manufacturers.

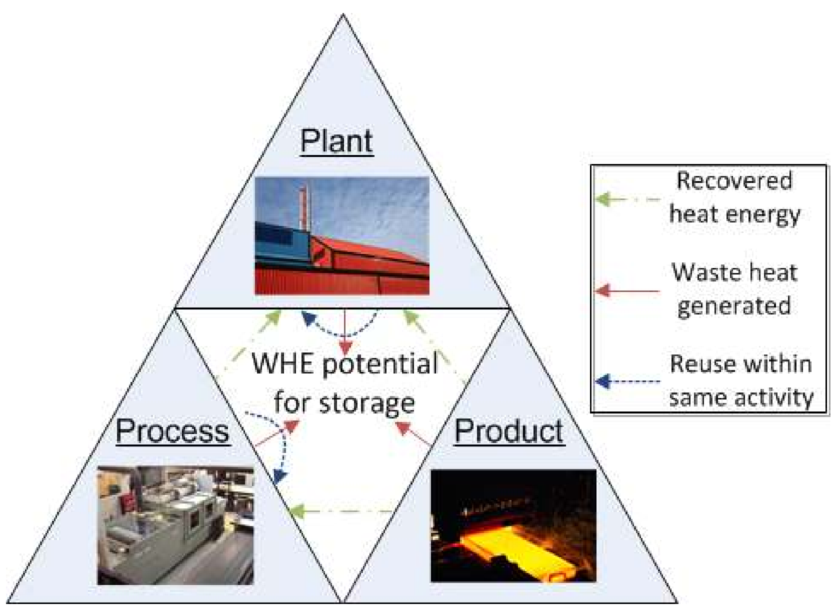

FIGURE 3 PLANT, PROCESS AND PRODUCT PERSPECTIVE FOR WHE RECOVERY

3. WASTE HEAT ENERGY RECOVERY FRAMEWORK

The literature survey of this research highlighted a lack of structure around the understanding of available WHE which limits the success of the application of heat recovery techniques. The framework presented in this paper has been developed to provide a systematic approach to evaluate and recover this heat energy and to identify optimised uses based on a range of suitable energy recovery technologies. The novelty of such framework is that it is an initial endeavour to enable manufacturers to methodically understand the amount of recoverable WHE within their manufacturing environment and to provide decision support to choose the most suitable energy recovery technologies for respective scenarios.

The structure of the framework is such that information gathered from a survey is processed and compared with a technology database to provide suitable options for WHE recovery. As shown in Figure 4, the framework consists of four main stages: collection of data; processing using predefined quantitative and qualitative defined terms; comparison of key parameters from a database of available technologies; and utilisation of a decision making algorithm to provide a number of options for waste heat recovery based on cost and environmental benefit analysis. The four waste heat recovery framework stages are:

Stage 1: Survey of waste heat sources in facility
Stage 2: Assessment of waste heat quantity and quality
Stage 3: Selection of appropriate technology
Stage 4: Decision making and recommendations

Although these stages define a generalised flow of information with which to follow to analyse the recovery potential of WHE from any industry, this research is concerned with overall energy efficiency within manufacturing facilities. The following sections hence describe in detail the four stages of the framework with respect to the information flow required to inform investment decisions within manufacturing business.

3.1 Stage 1: Survey of waste heat sources in facility

Undertaking a waste heat survey is the first stage in the WHE Recovery Framework. This stage provides a detailed description of how identification of waste heat sources within a manufacturing environment from the Plant, Process and Product perspectives is undertaken. In general, there are three approaches to which data collection for the survey of waste heat sources can be carried out by the energy or environmental manager of a particular facility. These approaches consist of empirical measurement, data acquisition from equipment manufacturers' specification or factory's existing database and theoretical calculation, and among which empirical measurement approach should always be prioritised. A facility-wide energy audit or useful data may already exist as part of an increased level of automation and monitoring by manufacturers. In the absence of a database or insufficient information, experimental measurement is recommended e.g. utilising a combination of thermocouple or infrared camera. In addition, data acquisition can be achieved by referencing a database from supplier data sheets or published research studies of the process equipment. Theoretical calculation also provides a useful tool when database or empirical measurement is not suitable, provided that the assumptions made be as close to the real scenario as possible. However, due to the demand in time and effort, and errors the approach may potentially introduce, this is the least preferable approach to generate data. These methods can not only be used to identify the hotspots of WHE sources but also to evaluate and visualise the amount of WHE in a manufacturing facility. Data acquired from this step can be both numerical and descriptive which is then fed into the next stage of the framework for conversion and categorisation into standardised descriptors that can be interpreted by a decision making algorithm.

3.2 Stage 2: Assessment of waste heat quantity and quality

The applicability of this stage is that the acquired data can be used for assessment and analysis by the following stages of the framework in a structured way to quantify and qualify the WHE sources in a facility. Investigation of the waste heat generated within a plant is able to reveal some potential opportunities from generic and sector-specific manufacturing processes. This research defines a number of quantitative and qualitative descriptors to be assigned to each of these opportunities with the aim of assessing their recoverability in the context of the plant, process and product perspectives and using best suitable recovery techniques. In order to quantitatively evaluate the heat source in a manufacturing environment, a number of key parameters must be defined to provide essential data for carrying out calculations using mathematical modelling techniques. The quantitative descriptors established in this framework include temperature (or temperature difference between waste heat source and sink), useful energy content (or exergy) content and temporal availability of the WHE sources. Unlike quantitative evaluation (use of numbers), qualitative evaluation is a more subjective approach which uses very different methods of processing information, the parameters defined in the framework are carrying medium of WHE sources, accessibility and potential risk of contamination. Using a combination of qualitative and quantitative descriptors of the available WHE enables targeted evaluation and ensures more effective matching of potential heat recovery solutions with the available sources.

3.3 Stage 3: Selection of appropriate technology

The objective of this framework is to understand the potential recoverability of WHE and this will unvaryingly involve the use of heat transfer mechanism (technology). The types of which will depend on the specific properties of waste heat source, such as the temperature or temperature difference between the source and sink, waste heat carrier form, contaminant of the exhaust stream, as well as the nature of the desired end-use for recovered heat.

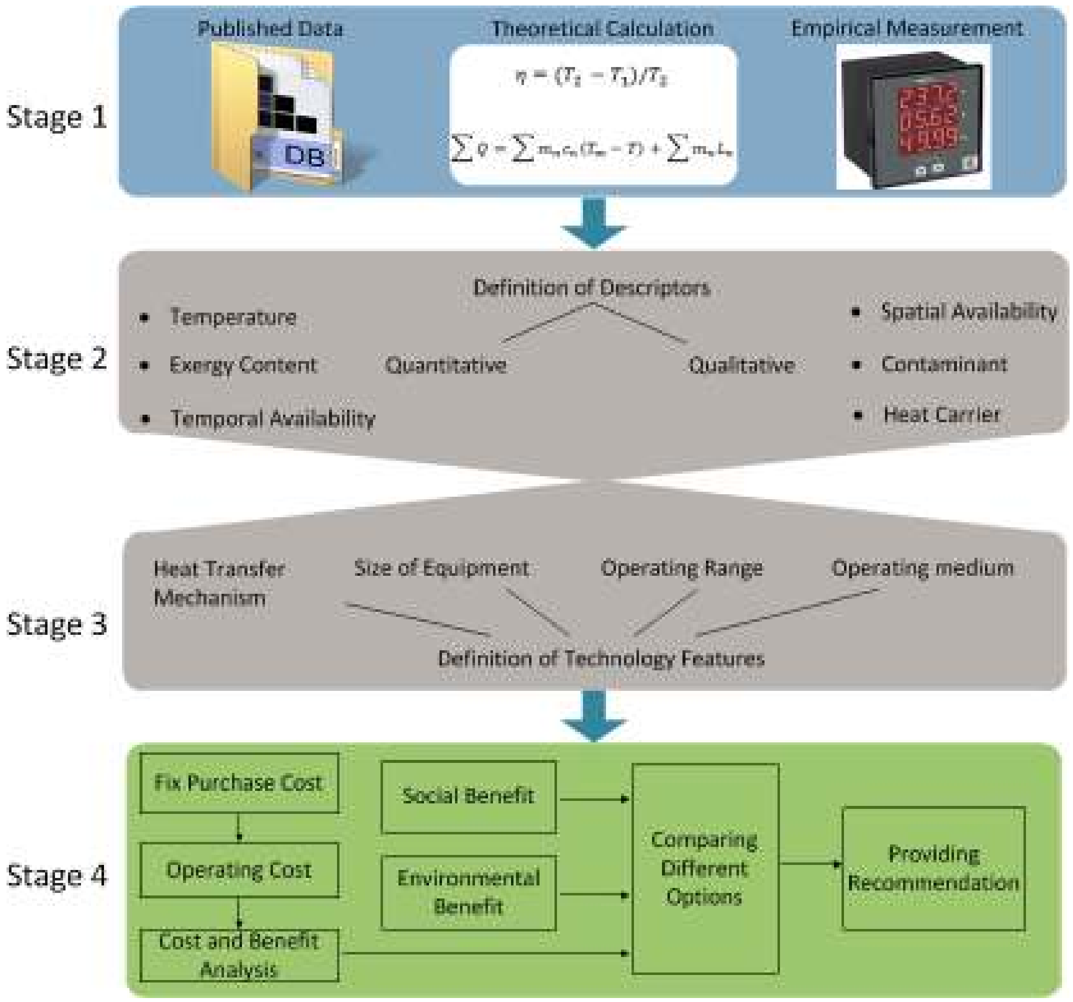

FIGURE 4 OVERVIEW OF THE WHE RECOVERY FRAMEWORK

It is essential to define the selection criteria for the available heat recovery technologies which consist of four fundamental properties. These selection criteria are heat transfer mechanism, medium of waste heat carrier, size of the equipment and operating temperature range. With the defined properties of WHE and heat recovery technology, matching and comparison can be carried out. The purpose is to use results from the waste heat quantity and quality assessment to filter down the range and number of technology options from the database created based on the existing heat recovery research and technology from a literature survey. This process yields a maximum of three feasible technology solutions which score similar in the comparison of criteria. The output results of this stage can be useful in the next stage of the framework, which carries out environmental, economic and social benefit analysis methods to further compare between the selected technology solutions to support decision making. Despite the variation in technology the objective is identical, which is the collection and reutilisation of recoverable WHE from any process that would otherwise be lost. The process might be inherent to a factory building, such as space heating, air conditioning and ventilation, or could be carried out as supportive manufacturing activity, such as the use of compressed air system, ovens or furnace etc. WHE recovery can be beneficial to reduce energy consumption of the process itself, or provide a useful energy source for other purposes, thus improving the overall energy efficiency within the factory.

3.4 Stage 4: Decision making and recommendations

It is to the interest of all manufacturers to evaluate the impact of their decisions and therefore a financial analysis is performed and measures are optimised for either environmental or economic potential. In the financial analysis both the annualised net financial benefit and overall payback period are calculated. For small scale WHE recovery technology with low capital cost, a rough estimate of the economic return should be sufficient to justify investment, while for larger WHE recovery systems with integrated components where there is a high capital cost, a full appraisal should be carried out. In addition, the implementation of environmental and social impact analysis such as the overall reduction in CO2 emission based on the fuel that is displaced to each of the feasible technology options and comparisons are undertaken to provide an optimised final solution for manufacturers.

4 CASE STUDY

A case study example of an installed air compressor is analysed using the waste heat energy recovery framework described in this paper. This case study is undertaken to demonstrate the applicability of the framework to a simulated installation of a plant level energy demand.

An air-cooled 300(635)l/s(cfm), 160kW capacity compressor is installed to provide compressed air 24 hours a day and 365 days a year for a manufacturing plant in order to support its activities. It has been suggested by the energy manager of the plant that the heat produced by the compressor could be harnessed and utilised for a useful purpose within the plant.

Stage 1: Survey of waste heat sources in facility

By consulting the air compressor manufacturer and carrying out an onsite WHE sources survey, the cooling air mass flow at 10°C is 4.5kg/s based on cooling air flow of 3.6m^3/s and air density of 1.25kg/m^3, measured inlet and outlet temperatures are 10°C and 38°C respectively. Therefore, theoretical heat available from compressor is 125kW. Since the compressor is constantly working throughout the year, the temporal availability is 1. It is known from the survey that the heat is generated in the surrounding air but is mainly concentrated around the compressor pump.

Stage 2: Assessment of waste heat quantity and quality

The data from the survey in stage 1 is reformatted into the quantitative and qualitative descriptors defined in the framework. (Table 1)

TABLE 1 INFORMATION ACQUISITION AND REFORMATION

Quantitative		Qualitative	
Descriptor	**Value**	**Descriptor**	**Assessment**
Temperature difference, °C	28	Spatial availability	From single outlet
Temporal Availability	1	Contaminant	None
Exergy content, GJ	3600	Heat Carrier	Air

Stage 3: Selection of appropriate technology

There are a number of potential technologies that can be utilised to harness the WHE in this case study constrained by the conditions given. Since the temperature difference between inlet and outlet of the waste heat carrier is only 28°C and the availability of WHE is constant, a number of approaches are suggested. Hot air can be recovered with a fully integrated control system to directly supply into a factory area or used to preheat air for combustion (figure 5a). Plate heat exchangers can be utilised to recover WHE from air or water-cooled machines, creating a closed circuit to avoid contamination and fouling of the compressor cooling system (figure 5b). The approach undertaken is likely to depend upon spatial availability and the particular requirements for space heating in individual building.

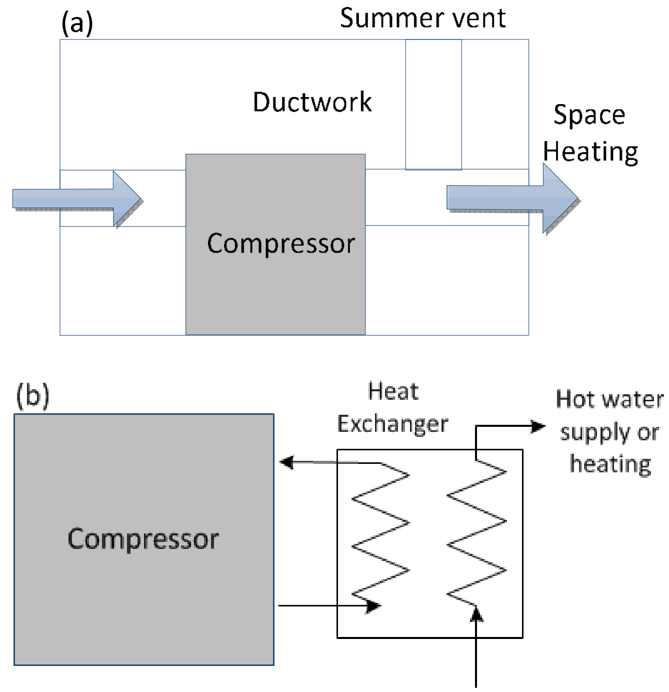

FIGURE 5: (A) SCHEMATIC OF A TYPICAL AIR-COOLED COMPRESSOR WITH DIRECT HEAT RECOVERY; (B) USING A HEAT EXCHANGER TO RECOVER WHE

The simple approach that redirects heat into the factory space and let space heating controls respond to this input can however cause overheating for more environmentally-sensitive manufacturing activities. In which case, integrated hot air recovery systems should be considered to avoid overheating and maximise savings.

Stage 4: Decision making and recommendations

It is also established that a large nearby workshop area requires space heating for half the year, currently heated by an onsite gas-fired boiler. Boiler efficiency is estimated at 75% and the current cost for gas is 0.6p/kW (DECC, 2014). The workshop area is heated for 10 hours per day for five days of the week, and 5 hours on Sunday before the Monday shift start. A quote from the compressor supplier to install the necessary ductwork for transport of hot air to nearby workshop is £2,500. The payback period for such an installation is calculated in table 2. In addition to the financial benefit, installing a suitable heat recovery system also provides wider environmental benefits. Saving energy can produce substantial reduction in

CO2 emissions at atmosphere and it is estimated that burning natural gas emits 0.21 kg CO2/kWh (Grant & Clarke, 2010).

TABLE 2 WORKED EXAMPLE OF AN AIR COMPRESSOR FOR HEAT RECOVERY

Entries	Working	Results
Average heat that can be utilised	-	125 kW
Hours per year where waste heat can be used	(50h +5h) x 24 weeks/yr	1,320 h/yr
Annual energy saved	125 kW x 1,320 h/yr	165,000 kWh/yr
Gross cost of fuel saved	£0.006/kWh / 75%	£0.008/ kWh
Annual fuel cost saving	165,000 kWh/yr x £0.008/ kWh	£1,320/yr
Capital cost	-	£2,500
Payback period	£2,500 / £1,320	1.9 yrs
CO_2 reduction	165,000 kWh/yr x 0.21 kg CO_2/KWh	35 tonnes CO_2 /yr

5 DISCUSSION AND CONCLUSIONS

The framework presented in this paper is developed to be useful and adaptable for all sectors, to enable the analysis of available WHE and to identify and assess potential energy recovery technologies. The novelty of such framework lies in an ability to provide a systematic approach to some of the energy recovery activities already being utilised within industry and it is therefore proposed that by applying this framework, the enhancement of overall energy efficiency improvement using energy recovery technologies can be achieved.

The framework has been developed with the manufacturing industry as the target implementer and hence the defined descriptors used are more aligned to the needs of manufacturers over other potential users (e.g. domestic users, service sectors). However in order for the framework to be fully suitable for use by industry members, there is a need for the development of accompanying software tools. Such a programme should include a user-friendly interface of data input module, a quality and quantity assessment module in conjunction with a technology database, a cost-benefit analysis to support decision making algorithm and finally a dashboard type output module which enables data visualisation and better decision and investment justification (figure 6).

In this paper it has been identified that there is an opportunity for creating a structure around which waste heat energy sources are analysed and considered in terms of implementing energy recovery technologies. A four stage framework has been proposed to provide this structure which can be implemented within any manufacturing site to highlight a number of the most beneficial recovery opportunities. The paper also provides a decision model for waste heat energy recovery based on a range of parameters such as temporal requirement, temperature, flow rate, pressure and input medium in addition to physical locality and accessibility. The described decision support software makes the link between available waste heat energy, potential use options and the most appropriate technologies to support energy recovery. Benefits to industry include streamlined implementation of optimised energy recovery technologies, minimising payback times and improving plant energy efficiency with minimal disruption to existing processes and operation procedures are illustrated using a case study of an industrial scale air compressor, which demonstrates the ease of use of the framework and the output which can be expected from its implementation, and the scope of the application of the framework has been discussed.

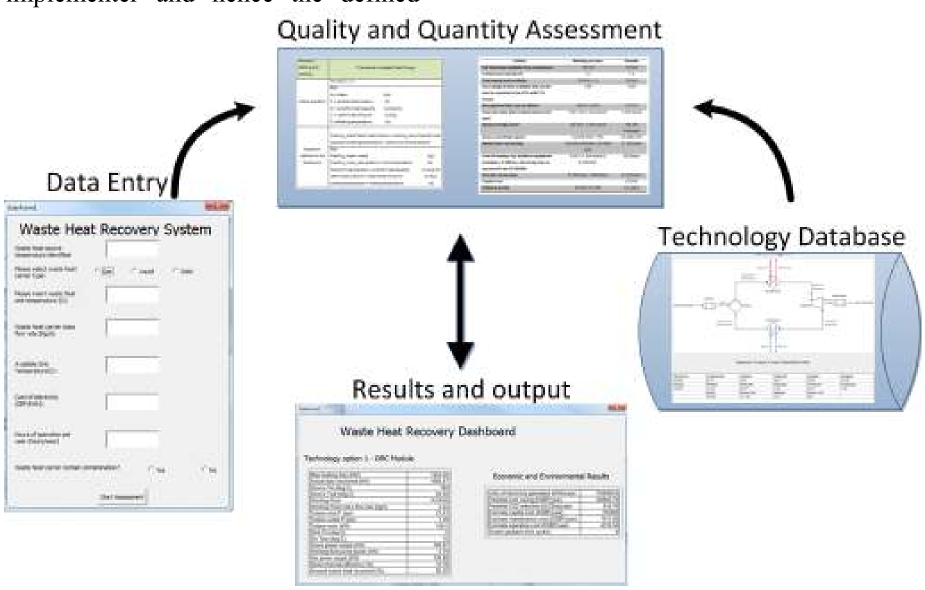

FIGURE 6 OVERVIEW OF THE SOFTWARE TOOL

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