



How do small changes enable the shift to net-zero? a techno-environmental-economic analysis

Yousef Haddad¹ · Emanuele Pagone¹ · Rodrigo Valdez Parra¹ · Nicholas Pearson² · Konstantinos Salonitis¹

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Abstract

With many of the world's governments committing to achieve net-zero greenhouse gas (GHG) emissions by mid-century, with well-defined milestones along the road, it is important to investigate how each sector can contribute towards achieving this global goal. The manufacturing sector, with its energy-intensive processes, large amounts of wastes, and hazardous and harmful emissions, is one of the main contributors to global GHG emissions, as well as other sustainability aspects, and, thus, it has great potential to contribute substantially to achieve net-zero objectives. This paper presents a techno-environmental-economic analysis of technologies that can play a key, enabling and leading role in the quest towards net-zero. Such technologies typically bring modest improvement in the environmental performance; however, the aim of this paper is to demonstrate how such small changes, when implemented in an industrial setting, can contribute significantly to the collective improvement in the environmental performance. In order to put the potential improvements into perspective, a real case study from the UK aerospace manufacturing sector is conducted. In the case study, metrics measuring potential improvements from the installation of a low-to-medium waste heat recovery system, and the upgrade of electric motors in the shopfloor to more energy efficient ones, are calculated through environmental and economic models. The models are then subject to a series of sensitivity analyses experiments to help understand the impact of different sources of uncertainty on the perceived GHG emissions, and economic and energy savings. The techno-environmental-economic analysis results revealed that these small changes, when implemented in an industrial setting, can indeed bring valuable improvements in the environmental performance of a manufacturing institute. Further, the sensitivity analysis experiments demonstrated how the environmental and economic performances are not adversely affected by different levels of fluctuations in key, likely to fluctuate, input parameters.

Keywords Sustainable manufacturing · Net-zero · Techno-environmental-economic analysis · Waste heat recovery

1 Introduction

Although the realisation of net-zero necessitates massive efforts, large-scale collaborations and investments, and foundational infrastructural changes, small changes can still contribute to net-zero realisation. Small, incremental, changes in this context refer to changes (i.e. technologies/practices) that bring, in absolute numbers, relatively modest improvements in the environmental performance with respect to the chosen environmental metric(s). In other words, the road

to net-zero is rather filled with small changes that, when considered collectively and in combination with their more pronounced counterparts, constitute the realisation of net-zero. This paper follows up on the work presented in [1] where the authors present a roadmap timeline methodology for the selection of sustainability-improving technologies. In this paper, the role of technologies/practices that typically yield relatively modest improvements in the environmental performance is emphasised and investigated. In doing so, a techno-environmental-economic assessment framework is developed to examine the potential yield, and viability, of such technologies/practices within industrial settings.

The selection of the sustainability improving technologies in [1] is based on different filtering criteria. First, the technology readiness level (TRL) score of a technology is determined, which leads to the inclusion of technologies deemed mature (i.e. meets the standards of the highest TRL

✉ Konstantinos Salonitis
k.salonitis@cranfield.ac.uk

¹ Sustainable Manufacturing Systems Centre, Cranfield University, Bedford MK43 0AL, UK

² GKN Aerospace, Bristol BS34 9AU, UK

score) enough for implementation in an industrial setting. Then the relationship between the perceived impact of the sustainability-improving technology against the ease of implementation or integration into a production system is analysed. TRL is a well-established model that categorises technologies into levels (from 1 to 9) based on their maturity level. This paper utilises the methodology developed in [1] for the selection of the sustainability-improving technologies, and stresses, and numerically demonstrates the role that technologies that typically yield modest environmental savings can play in the quest towards achieving net-zero. In particular, at early stages of integrating sustainability-improving technologies, only technologies that are proven to meet the standards for TRL 9 score are considered since the focus at this stage is to achieve immediate, or short-term, improvements in environmental performance. In order to do so, a techno-environmental-economic analysis (TEEA) of low- to medium-grade heat recovery system, and the upgrade to efficient electric motors in the shopfloor, is conducted. These two technologies are chosen as exemplars to demonstrate potential environmental performance improvements that could be attained from minor modifications targeting two rather ominous functions/waste types in most manufacturing facilities. To explain more, waste heat is a by-product of numerous manufacturing operations, particularly those that involve ovens, and heat is estimated to account for more than 50% of the world's wasted energy [2]. On the other hand, electric motors are integral parts of almost all machine tools, conveyor belts, and any other equipment that performs some motion or rotary movements. In addition, utilising the methodology presented in [1], both ORC and the upgrade to efficient (IE4 as will be explained later) electric motors demonstrated to have relatively modest environmental savings. Therefore, in this paper, a formal investigation of these two technologies on a real case study will be carried out to demonstrate the environmental savings that can be realised from 'low-impact' technologies.

Several papers have addressed the issue of sustainability in the manufacturing industry; in [3], the authors developed a context-independent framework for the identification of GHG emitting processes, and the mitigation of these emissions in industrial settings. The framework was applied on a case study in the secondary steelmaking industry, as an exemplar production environment to demonstrate the applicability of the framework. In [4], the authors reiterated on the concept of integrating sustainability as a system design attribute, an addition to the classical ones (i.e. cost, time, quality, and flexibility). Concerning the sustainability-improving technologies investigated in this paper, much work has been done with regard to waste heat recovery (WHR) and efficient electric motors. With regard to WHR, several technologies exist in order to utilise the discarded heat to generate power such

as recuperators, economisers, heat pumps, and thermodynamic cycles. For an extensive list and thorough discussion of different industrial WHR technologies, the interested reader can refer to [5]. This research, with regard to WHR, will focus on the impact of employing thermodynamic cycles, in particular organic Rankine cycles (ORCs), on the environmental performance of manufacturing activities. ORC in particular has been chosen as a candidate technology for the following reasons: their ability to capture low- to medium-grade waste heat, their relative affordability [6], ease of installation, and minimal maintenance requirements [7]. Waste heat can be classified into three categories, based on temperature: low-grade (< 230 °C), medium-grade (230–650 °C) and high-grade (> 650 °C) [8]. Generally, low- and medium-grade heat are considered the most difficult, compared to high grade, to generate power from [5]. It should be noted, however, that there is an active community of researchers investigating WHR by the not-yet-mature but promising cycles based on supercritical CO₂. Furthermore, there is a significant body of the scientific literature investigating complex cycle arrangements that, nevertheless, do not directly apply to the recovery of industrial heat streams.

Several experimental tests in industrial settings have evaluated the performance of ORC systems for power generation from low- to medium-grade waste heat. In [2], the authors carried out a thorough review of waste heat recovery by ORC showing it in the context of other competing cycles and highlighted the effect of operating conditions on the efficiency. In [9], the authors developed regression models of the subcritical ORC, transcritical ORC, and partial evaporation ORC considering low, medium, and high heat source temperatures. In [10], the authors employed a recovery ORC system for the waste heat of a ceramic plant furnace. The exhaust heat warmed the working fluid in the range of 150 °C to 170 °C, resulting in a net efficiency of 10.94% and a payback time of 4.63 years. Experiments reported in [11] suggest a maximum net output power of 17%, with the usage of a model predictive control, an advanced control mechanism, to control the evaporator temperature. Other low- to medium-grade waste heat recovery systems utilising ORC were reported in [12, 13] where net electrical efficiencies of 7.9% and 8.75% were attained, respectively.

As for the importance of electric motors, it was estimated by the International Energy Agency that 43–46% of all electricity consumption worldwide is consumed by electric motors and the systems they drive [14]. Contributing to such a substantial share of electricity consumption, which is still, in considerable part, generated from fossil fuels, renders even infinitesimal improvements in motor power efficiency counts on the road towards net-zero.

Motors are classified according to their efficiency level expressed in the International Energy efficiency classes (IE).

IE1 is the lowest class and IE5 is currently the highest. The improvements in efficiency when upgrading from one IE level to another, more efficient one, seem, when expressed in absolute numbers, rather small. However, given that motors' efficiency, even for the lowest IE grade (i.e. IE1), is still relatively reasonable at more than 70%, improvements in motor efficiencies will then be limited. Therefore, the efficiency improvement that is gained from upgrading IE3 to IE4 class motors can be as high as 4% on the lower end of powers (below 10 kW), while the improvement on all classes is about 1–3% when the motors power exceeds 10 kW [15]. In [16], the authors found that an 11 kW IE4 motor will reach a payback time of 2 years if it is operational 4000 h per year. The concept of payback time, along with other performance metrics calculated in this paper, will be explained in the next sections.

This paper aims to develop a methodical approach for the environmental, technical, and economic assessment of sustainability-improving technologies in manufacturing. The work presented in this paper also aims to demonstrate and prove that even modest improvements can still contribute towards the improvement in the environmental performance. The rest of the paper is organised as follows: the next section presents the overarching approach developed in this paper. Section 3 presents the environmental, technical, and economic assessment that will form the backbone of the methodical approach, along with the most commonly used metrics in environmental, technical, and economic assessment of manufacturing systems. Section 4 will present a case study from the UK aerospace sector. Section 5 presents the numerical results obtained from the models followed by sensitivity analysis experiments, and finally Sect. 6 will present the concluding remarks and future research directions.

2 The overarching methodical assessment approach

In this section, the methodical approach for the assessment of sustainability-improving technologies is developed as shown in Fig. 1. It can be noticed from Fig. 1 that the main criterion that triggers, and then drives, the selection of the proposed technologies is the environmental profile of a manufacturing enterprise. Although the subsequent analysis, and eventually the decision on what sustainability-improving technologies to adopt, also considers the perceived economic performance, the inclusion and elimination criteria before the TEEA solely consider environmental aspects. The first step of the process is to conduct an audit of the energy consumption and waste. Although these two terms are closely related (energy can be a type of waste), a distinction has been made to differentiate physical waste (e.g. solid wastes, chemical wastes) from energy waste, which can

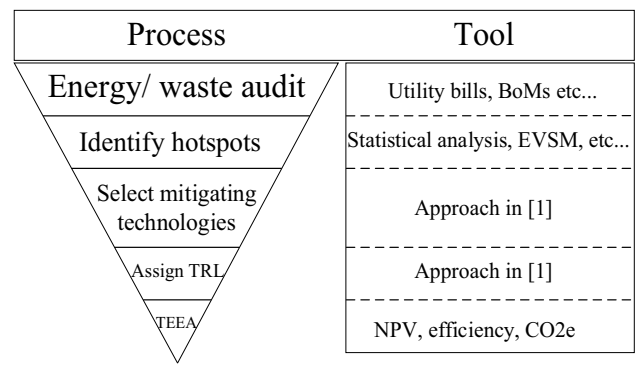


Fig. 1 High-level generic depiction of the methodical approach

take different forms (e.g. waste heat). This step can be done using a variety of resources such as analysing utility bills to calculate energy and water consumption or analysing the manufacturing bills of materials (BoM) to calculate material waste, amongst others.

In the next step, after developing a sufficient understanding about the waste types and quantities, a more formal analysis can take place. This analysis can be conducted using well-established modelling tools such as statistical modelling, energy value stream mapping, and simulation modelling, amongst others. This step might seem identical in purpose to the preceding one; however, this step, as is the case with all subsequent steps, narrows down (by inclusion or elimination) the number of processes that are considered for improvement based on more specific quantitative formal analysis. The next two steps, which are discussed at greater length in [1], select technologies that can be used to mitigate the environmental impact resulting from the processes identified in the preceding step, and then assigns a TRL score as per [1]. More details about the first four processes depicted in Fig. 1, with case study application demonstrating how to carry out these tasks, can be found in [1].

For the TEEA, any number of analysis tools can be used to determine the environmental and economic performance of the potential sustainability-improving technologies, as well as the technical aspects of these technologies. Traditionally, the term techno-economic analysis is often used; however, in this study, the viability of a proposed technology is assessed not solely on economic metrics, but also on environmental ones. Indeed, it has been argued that sustainability of a manufacturing system should be included as a design attribute, in addition to the classical ones (i.e. cost, quality, flexibility, and time) [4]. The methodical approach presented in Fig. 1 is kept at a high level, and no specific sustainability-improving technologies/practices or specific KPIs are highlighted in this approach to preserve the generalisability and transferability aspects of the approach. The performance metrics that measure the environmental and

economic performance of sustainability-improving technologies can differ, depending on context of application. The performance metrics calculated in this paper will be discussed in the next section.

In the next section, the environmental, technical and economic assessment, the selected exemplar sustainability-improving technologies, and the KPIs used in the assessment will be presented and explained.

3 Environmental, technical, and economic assessment

In this section, the performance metrics pertaining to the environmental, technical, and economic performance for each of the proposed technologies will be presented, and the models that determine the values of these metrics will be presented and discussed.

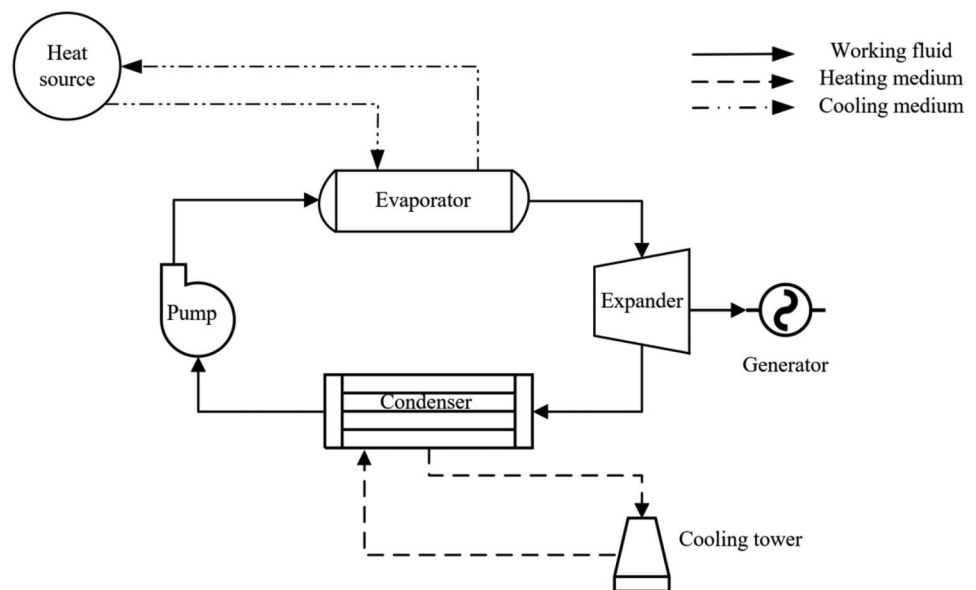
The selection of the proposed sustainability-improving technologies is based on the methodology presented in Fig. 1, which complements the approach presented in [1]. The data and subsequent analysis provided in [1] revealed the amount of energy consumption per three energy intensive processes (painting, anodizing, and vacuum furnace). Therefore, there was considerable energy waste resulting from these processes, in the form of waste heat. As for the electric motors, they are ubiquitous on all shop-floors; therefore, the examination of replacing some of them with more efficient ones would reveal the extent (and whether it is worth to, or not) of improvement in the environmental performance attributable to them. As a result, and as per the discussion provided in the previous section, the technologies that are going to be investigated

are ORC WHR systems and the upgrade to more efficient IE motors.

As mentioned earlier, the two exemplar sustainability-improving technologies were identified based on the analysis presented in [1], where, when analysing the waste streams and energy consumption of a UK-based aerospace manufacturer, most waste was found to be coolant waste and most energy consumption was created by the aforementioned processes (i.e. painting, anodising and vacuum furnace). In order to realise the biggest improvement in environmental sustainability, it is obvious that coolant waste minimization should be tackled first. However, and as per the analysis conducted in [1], switching coolant, although rewarding, is a difficult task. Briefly, switching to advanced cooling and lubrication techniques is not always a universal solution, particularly when machining certain metallic alloys (e.g. titanium alloys) where their thermal properties require flood cooling to machine. In addition, increased tool wear is also a significant problem when departing from flood cooling [17]. Therefore, environmental impact caused by cooling is, in industrial settings, a considerable task to achieve. As a result, in this paper, the two relatively easy to implement with relatively limited environmental impacts have been chosen to further examine their impact on the sustainability performance of manufacturing systems.

The two sustainability-improving technologies serve different functions on the shopfloor. As for the electric motors, their main function is to convert electric energy into mechanical one. As for the ORC, it converts waste heat into mechanical work, which can then be used to generate electricity. The function of ORC, which is demonstrated at a high level in Fig. 2, can be explained as follows [18]: high-pressure vapour enters the expander from the evaporator; as

Fig. 2 Basic flow diagram of a simple ORC. Adapted from [18]



the vapour expands and its pressure decreases, its thermal energy is converted to mechanical energy through a shaft. The low-pressure vapour then enters a condenser where it is then transformed to a liquid state through cooling. The resulting liquid then enters a pump where it is pressurised, and then vaporised in the evaporator with the waste heat source. This process is cyclic and continues to occur as long as the heat source exists.

In the next section, key performance indicators (KPIs) are categorised into environmental and economic KPIs and are discussed at a high level, in a context-independent manner, so that they can be applied to any sustainability-improving technologies in any industrial setting.

3.1 Key performance indicators

This section will present the environmental and economic performance indicators that provide quantitative measures of the achieved performance improvements. The next paragraphs will provide a discussion of, and the rationale behind, the selection of these performance indicators.

3.1.1 Environmental performance metrics

The environmental performance of a manufacturing enterprise can be measured by varying metrics, most notably the amount of CO₂ or CO₂ equivalent emitted by a manufacturing enterprise. There are, however, many more metrics that can be used to measure the environmental performance of a manufacturing enterprise, depending on the specific aspect of the environmental performance that is being investigated. For example, an increasingly important metric is water usage (commonly referred to as water footprint). Environmental metrics can also be located anywhere along the so-called environmental damage pathway. To understand the concept of damage pathway better, an illustrating example might be necessary. For example, the often-used CO₂e metric refers to the amount of CO₂e emitted, but does not indicate what is the impact of emitting such amount. Further down the damage pathway, the impact of this certain mass of CO₂e on global warming is then quantified. On the extreme end of the damage pathway, the impact of the global warming, caused by the specific amount of CO₂e, is further quantified to calculate the impact on natural resources, human health, and the ecosystem.

This study will focus on the environmental sustainability in the early parts of the damage way (i.e. what causes environmental damage, not the eventual impact of such damage). The improvement in the environmental performance here is measured by the amount of CO₂e avoided from the adoption of the proposed technologies. The amount of CO₂e emissions avoided is calculated as demonstrated in Eq. (1):

$$CO_2e \text{ avoided} = \Delta E \times F \quad (1)$$

where ΔE is the total energy saved by implementing the proposed technology and F is the carbon emission factor (CEF) that, when multiplied by, produces the total CO₂e emissions that result from energy consumption (E). The carbon emission factor F depends on the source(s) of primary energy used to power the production processes. Such figures are usually published by governments, e.g. Department for Business Energy and Industrial Strategy in the UK [19].

3.1.2 Economic metrics

To measure the economic performance, and hence determine the economic viability, achieved by the implementation of the proposed technologies, the following performance indicators have been chosen, which are in line with those adopted in [20]. Briefly, the economic metrics are net present value (NPV), which is a widely used approach in analysing the profitability of future investments (in this case the economic viability of the sustainability-improving technologies), by calculating the *present* value of future investments or any stream of cashflows generated from a potential investment. The mathematical formula that was used to calculate NPV is:

$$NPV = \sum_{t=1}^n \frac{S_t}{(1+i)^t} \quad (2)$$

where S_t is the monetary savings during time period t , i is the weighted average cost of capital (%), and n is the number of time periods. The second economic performance indicator is the weighted average cost of capital (WACC), also known as discount rate, interest rate, and cost of capital. WACC is the rate of return used to discount future cash flows. WACC is used to discount all future cash flows into a current currency value.

The third economic performance indicator is the payback (PB) period, which provides the point in time when an investment, in this case the proposed technologies, will reach a break-even point. In other words, it is the point in time when the returns, in the context of this paper economic savings, become equal with investment cost. The formula used in this paper to calculate the payback period is as follows where:

$$PB = \frac{C}{CF} \quad (3)$$

C is the cost of application (i.e. proposed technology a, CF is annual cash flow (savings) attained from the proposed technology).

The final economic performance metric used to measure the economic performance of the proposed

technologies is the internal rate of return (IRR). IRR could be defined as the discount rate at which the NPV value of a project is exactly 0. Therefore, the formula that is used to calculate IRR stems from the NPV formula where the NPV value is set as 0 and the discount rate equals the IRR:

$$\sum_{t=0}^n \frac{S_t}{(1+i+IRR)^t} = 0 \quad (4)$$

The project will bring no financial benefit if the IRR equals the company's discount rate; therefore, a higher IRR rate is always desirable. The rest of the economic and environmental metrics are largely application-specific; therefore, the models that find these metrics will be presented in the next section.

4 Industrial case study

To demonstrate the usefulness, and economic viability, of implementing what is typically thought to be 'small' steps, an industrial case study from the UK's aerospace manufacturing sector is presented and discussed in this section. The case study company is a UK-based Super Tier 1 aerospace part supplier and system integrator that supplies aircraft and engine manufacturers all over the world. The case study is conducted on one of its manufacturing facilities, located in the UK, housing 1300 employees and generates a turnover of £300 million annually. The company is on track to achieve its net-zero goal in, or before, 2030 and is investigating different technologies that it could implement to improve its environmental performance. The company has conducted an analysis of its energy and resources consumption patterns, which, highlights of, can be found in [1]. The company is aiming to complement practices that yield significant improvements in environmental performance such as switching from flood cooling to minimum quantity lubrication, and switching to 100% clean energy, with smaller ones to ensure that, as the saying goes, no stone is left unturned in the journey to net-zero.

In line with [1], and the technologies along with their impact on the environment, this paper targets technologies that are placed, in the previous paper's context, on the lower end of the improvements in the environmental performance. Therefore, the technologies that are considered in this paper are the installation of an ORC system to capture and recover some of the waste heat generated from the exhaust airflow of a vacuum furnace used for heat treatment and high-efficient electric motors (in specific IE4 and IE5).

4.1 Organic Rankine cycle

The basic ORC system depiction and its associated models that calculate work, efficiency, and electricity production that have been utilised in this paper can be found in [8]. Regarding the economic models, specific to the ORC application, i.e. apart from the ones represented earlier which are applicable to any technology, the investment cost and annual economic savings are calculated. These performance metrics are calculated as follows:

$$C = W_{net} \times SIC \quad (5)$$

where SIC is the specific investment cost, which corresponds to the approximate price of an ORC system relative to its power output. The annual economic savings can be calculated as follows:

$$S_e = (\Delta E \times ET) + (CO_{2e} \times ETS) \quad (6)$$

where ET is the electricity tariff (£/kWh), CO_{2e} is the amount of avoided CO_{2e} gases, ETS is the emission trading scheme (in the UK, at the time of writing this paper, it amounts to £50 per ton of CO_{2e}), and ΔE , total energy saved, can be calculated by using the following equation:

$$\Delta E = W_{net} \times OpT \quad (7)$$

where W_{net} is the net work of the ORC and OpT is the operational time (i.e. uptime).

4.2 IE4 electric motors

As mentioned earlier, electric motors are ubiquitous, not only in shopfloors, where they are integral parts of most processes, but in almost all other industrial settings. Electric motors' efficiency is expressed as the ratio between the mechanical output power of the motor to its required electrical input power, as follows:

$$\eta_{Motor} = \frac{W_{Motor}}{W_{electricity}} \quad (8)$$

The electricity consumption per time period, typically 1 year, by a motor can be calculated as follows:

$$E_{motor} = OpT \times W_{electricity} \quad (9)$$

The investment cost for the IE motors is calculated in a different way than that of the ORC. This is because, in the case of the ORC system, the specific investment cost was used, relative to the power output of the cycle, while in the case of the electric motors, the cost of acquisition

Table 1 ORC system parameters

Parameter	Value
Mass flow (kg/s)	0.1
Turbine efficiency [%]	95%
Pump efficiency [%]	90%
T1 (boiler) [°C]	285
T3 (condenser) [°C]	50
SIC [£/kW]	2000
C _{ORC} [£]	40,000
Operational time [h/year]	2700
ORC efficiency [%]	27.35%

and installation suffice to give a clear image of the cost of the motors’ upgrade. There is however one more cost segment related to the upgrade of the electric motors, which is related to the inevitable removal of already-existing motors. These already existing motors, although less efficient, still hold some value, and therefore this remaining value in the already-existing electric motors should be accounted for. The formula to calculate the cost of upgrading the electric motors in the shopfloor is as follows:

$$C = P - RV \tag{10}$$

where *P* is the price and *RV* is the remaining value. Finally, the annual economic savings achieved from the upgrade of the electric motors is the same as the one in Eq. (6).

4.3 Sensitivity analysis

In order to understand the perceived environmental performance, and the economic viability, of the proposed technologies, in the presence of inherent uncertainty, sensitivity analysis experiments were conducted on key parameters. Sensitivity analysis allows for the identification of the most important (i.e. sensitive) parameters, that a small change in their values could have an unproportionally big impact on the performance of the system. Sensitivity analysis, therefore, is an invaluable approach in decision-making that informs decision-makers of what parameters they should more carefully assign values to, prior to committing to a new project [21]. When conducting the sensitivity analyses, each parameter will be increased/decreased by 10% increments/decrements.

Table 2 ORC system environmental and economic results

Metric	ΔE [mWh]	W_{net} [£]	S_e [£]	PB [year]	CO ₂ e savings [ton]	NPV [£]	IRR [%]
Value	52.02	19.27	7,458	5.36	12.14	16,715	16.84%

Table 3 CO₂e avoided

Change in uptime	CO ₂ e avoided (ton)
–20%	9.71
–10%	10.93
0%	12.14
10%	13.35
20%	14.57

5 Numerical results and discussion

In this section, results obtained from the TEEA are presented. First, the results achieved through the implementation of the ORC to salvage waste heat, then those attained from the replacement of motors in the shopfloor are presented and discussed.

5.1 Waste heat recovery

The selected vacuum furnace, in the production facility site where the case study is conducted, operates in temperatures within a range of 500–1000 °C, depending on the heat treatment activity and material that is under the operation. The exhaust temperature is assumed to be between 200 and 300 °C. The selection of the working fluid for the ORC was based on [22], where the authors demonstrated that toluene is particularly suitable with a heat exchange of 200–300 °C, which is the exhaust temperature. The technical parameters for the ORC system are presented in Table 1.

CO₂e emissions avoided by each kilowatt per hour generated by the ORC system equals 0.23314 kg (i.e. carbon emission factor from the UK’s electricity grid to CO₂e) as stated by the UK government’s Department for Business Energy and Industrial Strategy, 2020 [19]. As for the savings made from generating electricity from waste heat (i.e. the avoidance of purchasing electricity supply), the figure was provided by the case study company, which cannot be provided due to confidentiality reasons. The price per kilowatt salvaged by an ORC system is set, based on [20, 23], at £2000. The final price for the ORC system is calculated as follows, where *SIC* stands for the specific investment cost:

$$P_{ORC} = W_{net} \times SIC \tag{11}$$

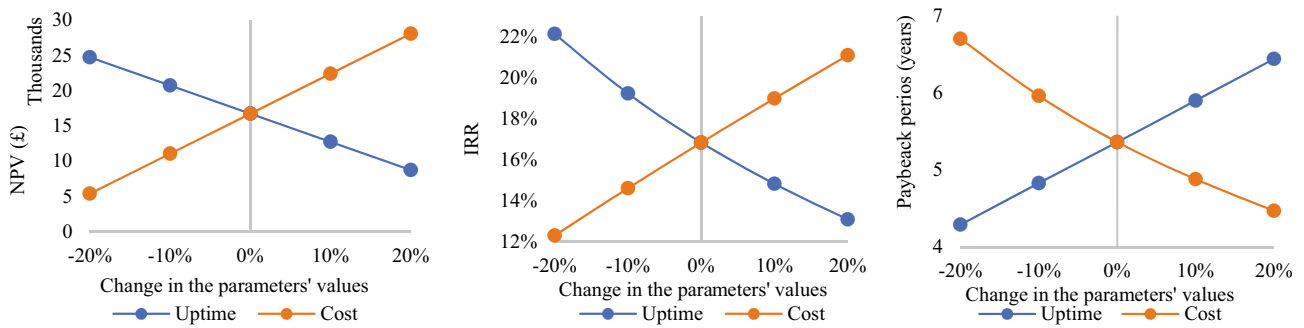


Fig. 3 The impact of cost and uptime of the ORC system on NPV, IRR, and payback period

The ORC model was solved, with the input parameters presented in Table 1, using CoolProp, a C++ thermophysical library for fluids [24]. The technical, environmental, and economic performance metrics are reported in Table 2.

In order to further investigate the collective impact that the change in different parameters has on the selected performance indicators, sensitivity analysis experiments are conducted. First, sensitivity analysis is conducted on environmental performance, represented by the amount of CO₂e avoided emissions. Table 3 depicts the amount of CO₂e emissions avoided.

It can be observed from Table 3 that, intuitively, as the uptime of the vacuum furnace increases, more CO₂e emissions can be avoided. This result, however, should be interpreted carefully as the increase in the uptime of the vacuum furnace will naturally entail a far more increase in CO₂e emissions than those saved by converting some of the waste heat to electricity. Regardless, this means that in the case of a spike in production rate, where the vacuum furnace will operate for longer times, more power can be generated from waste heat.

For the economic side of the analysis, Fig. 3 and Table 4 depict the collective impact of changes in uptime and SIC on the NPV, IRR, and PB, respectively.

The figures reported in the Table 4 reveal that the SIC and uptime both have a significant impact on the economic performance metrics. The only negative result from the sensitivity analysis of different NPV scenarios resulted, as could be seen in Table 4, when the uptime decreased significantly simultaneously when the cost increased by the same magnitude. This finding could indicate that an ORC system is not particularly suitable if the heat source, such as a furnace, is not used often, or if the cost of the ORC system surpasses a certain threshold, which in this case is relatively low. However, ORC systems are characterised, as mentioned earlier, by relatively low cost, as well as minimal maintenance requirements, which renders their installation, even if not often utilised, not an economic burden. Finally, although ORC provides a valuable opportunity to generate power from waste heat, other uses for waste heat can be considered as well if an ORC cannot be utilised (e.g. with high-grade waste heat), such as remote heating.

Table 4 Sensitivity analysis for NPV (£), IRR (%), and PB (years)

% SIC		-20%	-10%	0%	10%	20%
-20%	NPV	13,372	9372	5372	1372	-2628
	IRR	16.84	14.36	12.30	10.55	9.03
	PB	5.36	6.03	6.70	7.37	8.05
-10%	NPV	19,044	15,044	11,044	7044	3044
	IRR	19.53%	16.84	14.61	12.72	11.10
	PB	4.77	5.36	5.96	6.56	7.15
0%	NPV	24,715	20,715	16,715	12,715	8715
	IRR	22.15	19.24	16.84	14.82	13.08
	PB	4.29	4.83	5.36	5.90	6.44
10%	NPV	30,387	26,387	22,387	18,387	14,387
	IRR	24.70	21.57	19.00	16.84	14.99
	PB	3.90	4.39	4.88	5.36	5.85
20%	NPV	36,058	32,058	28,058	24,058	20,058
	IRR	27.21	23.85	21.11	18.81	16.84
	PB	3.58	4.02	4.47	4.92	5.36

Table 5 Electric motors

Power rating (kW)	IE 3 efficiency (%)	IE 4 efficiency (%)	Number in shopfloor	IE4 cost (£)
7.5	90.1	91.7	5	600
11	91.4	93.3	5	1000
15	92.5	93.9	4	1100
55	94.6	95.7	1	3900

The next section will present and discuss the analysis of the upgrade of electric motors in the shopfloor.

5.2 Electric motors

Electric motors are ubiquitous, as would be expected, in the shopfloor of the manufacturing facility. In the chosen production site alone, there is an excess of 100 electric motors. However, not all of these motors require replacement as some of them still have lengthy expected useful remaining life, operate for a short amount of time, or perform tasks that require low power outputs, rendering their replacement economically difficult to justify, resulting in minimal environmental impact. After careful investigation of the entire list of electric motors in the shopfloor, which took into account their power ratings, uptime, and commission date (so that the remaining useful life can be estimated), a total of 15 electric motors that match the criteria for upgrade were chosen. The number of motors to be replaced, their power ratings, efficiency, and cost of upgrading to IE 4 efficiency grade are listed in Table 5. The cost of upgrading to IE4 motors was taken from electric motor dealers in the UK (e.g. Tecmotors, Radwell, ERIKS, amongst others), and the efficiencies were obtained from a technical report issued by Siemens [25].

It is clear from Table 5 that the efficiency gains resulting from upgrading from IE3 to IE4 motors are relatively modest. However, combined with the relatively small investment cost (as presented in Table 5), the investment in upgrading the electric motors can be viable, from an environmental and economic perspectives. The uptime of the selected electric motors was set at 7300 h annually, which reflects the actual uptime of these motors in the shopfloor. The environmental and economic metrics results are reported in Table 6.

Similar to the ORC, a series of sensitivity analysis experiments are conducted for both the environmental and economic

Table 6 IE4 electric motors upgrade environmental and economic results

Metric	Cost [£]	S_e [£]	PB [year]	CO ₂ savings [ton]	NPV[£]	IRR[%]
Value	16,300	3754	4.34	6.11	12,254	21.84%

Table 7 CO₂e avoided

Change in uptime	CO ₂ e avoided (ton)
-20%	4.89
-10%	5.50
0%	6.11
10%	6.72
20%	7.33

performance metrics. For the environmental metrics, and keeping in line with the ORC sensitivity analysis, CO₂e emissions avoided were chosen as the environmental performance indicator for the sensitivity analysis. The parameters varied in the sensitivity analyses are, similar to the ORC scenarios, the uptime and cost. Table 7 depicts the impact of changing the value of the operational time on CO₂e emissions (other parameters were unchanged as they have no impact on CO₂e emissions).

It can be noticed from Table 7 that the relationship between the changes in the value of the uptime is linear with that of the resulting CO₂e emissions avoided. This indicates that CO₂e emissions avoided will always increase/decrease at a fixed rate in response to increase/decrease in uptime. As for the economic parameters, Table 8 depicts the impact of collectively changing the cost of upgrading to IE4 motors and uptime on NPV, IRR, and PB.

It could be observed from examining Table 8 and Fig. 4 that 80% (20 out of 25) of the scenarios investigated result in a perceived NPV that is equal to, or greater than, 50% of the investment cost, which is considered a very good NPV, from an economic perspective. As for the IRR, 60% of the scenarios investigated yielded an IRR that is equal to, or greater than, 20%, which also constitutes a low-risk investment from an

Table 8 Sensitivity analysis for NPV (£), IRR (%), and PB (years)

% Cost		-20%	-10%	0%	10%	20%
% Uptime						
-20%	NPV	9803	8173	6543	4913	3283
	IRR	21.84	18.96	16.58	14.57	12.85
	PB	4.34	4.88	5.43	5.97	6.51
-10%	NPV	12,658	11,028	9398	7768	6138
	IRR	25.00	21.84	19.25	17.07	15.21
	PB	3.86	4.34	4.82	5.31	5.79
0%	NPV	15,514	13,884	12,254	10,624	8994
	IRR	28.09	24.65	21.84	19.49	17.48
	PB	3.47	3.91	4.34	4.78	5.21
10%	NPV	18,369	16,739	15,109	13,479	11,849
	IRR	32.12	27.40	24.37	21.84	19.69
	PB	3.16	3.55	3.95	4.34	4.74
20%	NPV	21,224	19,594	17,964	16,334	14,704
	IRR	34.12	30.12	26.86	24.14	21.84
	PB	2.89	3.26	3.62	3.98	4.34

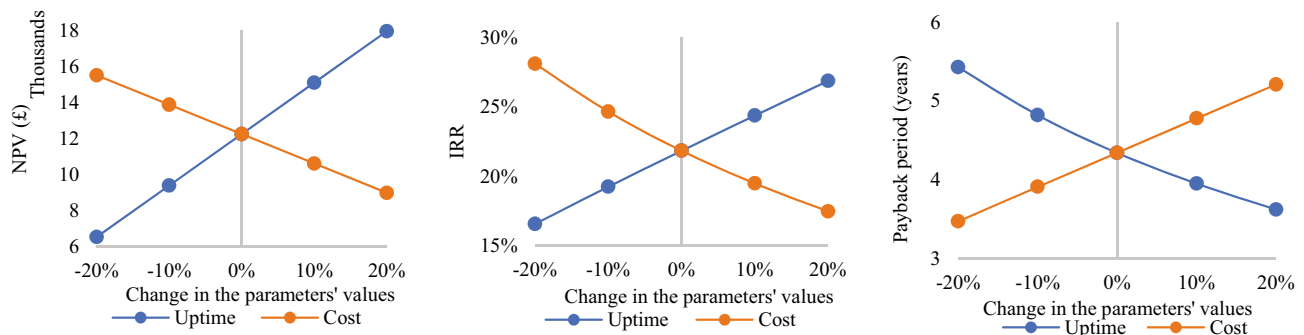


Fig. 4 The impact of cost and uptime of the ORC system on NPV, IRR, and payback period

economic perspective. Finally, in the payback period, 76% of the investigated scenarios had a PB period of 5 years or less. This is generally a desirable finding; however, all of the scenarios in Table 8 yielded a higher PB period than that calculated by the authors in [16], who concluded a PB period of 2 years. This could be attributed to the power rating of the motors studied in [16] where the authors only examined 11 kW motors, while in this paper power varied from 7.5 to 50 kW.

6 Conclusion

In this paper, the importance of technologies that generally, in absolute terms, yield low environmental impact is stressed. The significance of the contribution of this paper lies not only in the context-independent TEEA-based methodical approach, but also in the case study findings which stress, and promote, the importance of implementing sustainability-enabling technologies/practices, even if the perceived savings are considered modest. In order to demonstrate the importance of such technologies, two exemplar technologies were chosen to demonstrate the magnitude of their impact on the environmental performance. At the same time, the economic viability of these technologies was also taken into consideration by the calculation of relevant economic performance indicators. In order to numerically demonstrate the improvement that can be achieved from implementing such technologies, a case study from the UK aerospace sector was conducted. Although the validation, and demonstration of the usefulness, of the approach was achieved through a case study in the aerospace manufacturing sector, the TEEA methodical approach presented in this paper can be applied to any other industrial setting, with a completely different set of KPIs and sustainability-enabling practices/technologies. The generalisability and transferability of the approach to different industrial settings are stressed in Sect. 2 where the overarching methodical approach is presented as a context-independent approach. To further stress the generalisability and transferability aspects, the exemplar technologies selected for the case are present in almost any

manufacturing system, as well as the KPIs, which are relevant to almost any establishment.

The main takeout from this paper is that technologies/practices that are considered to bring modest improvement to the environmental performance are still vital, collectively, in order to realise a company's set net-zero goals. Sensitivity analysis also demonstrated that the two exemplar technologies are generally still economically viable, regardless of fluctuations in their cost and uptime. However, and this is particularly the case with the ORC system, the increase in the environmental savings (measured by avoided CO₂e) was found to be, through sensitivity analysis, correlated to the overall CO₂e emissions by a manufacturer. This means that the increase in avoided CO₂e emissions does not necessarily imply that the overall CO₂e emissions will decrease; on the contrary, overall emissions will still increase, but by smaller rates. This relationship can, however, change, or even be reversed, once electricity generation becomes entirely from clean, renewable resources.

Finally, this research can be extended in a number of directions. First, physical experimentation (e.g. exhaust temperature readings for the ORC system) can be conducted in order to generate more accurate results, and to reduce the uncertainty associated with the models' parameters. Also, a deeper investigation that takes into account different end-of-life scenarios into the upgrade of the electric motors (or any other technology) can shed some light into the bigger impact of adopting new technologies. Finally, the generalisability of this study can be further validated by extending the case study to include different geographical location, other than the UK, or by adding other environmentally-friendly technologies.

Code availability The code used in this paper can be obtained by contacting the corresponding author.

Data transparency All necessary data are included in the manuscript.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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