Energy efficiency potentials: Contrasting thermodynamic, technical and economic limits for organic Rankine cycles within UK industry

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Abstract

The laws of thermodynamics set a theoretical limit on the energy savings that can be realised in a given application. This thermodynamic potential cannot be reached in practice, and a technical potential for energy savings is defined by the performance of available technology. Only applications of the technology that are considered economic will usually be considered for installation. This economic potential will itself not be fully realised, with the actual savings that are achieved limited by further barriers. A database on surplus heat availability within UK industry was used to estimate the thermodynamic, technical, and economic potentials when converting this surplus heat to electricity using organic Rankine cycles (ORCs). Technical and economic information was based on that reported from existing installations and manufacturers. Installations economic over the target payback period totalled approximately 3.5 PJ/yr of electricity generation, primarily in the steel, chemicals and cement subsectors. However this result is sensitive to the input parameters, particularly the future price of electricity and required payback period, which are uncertain. Therefore a range of possible scenarios were investigated. The results form a basis for discussion on how to close this "gap" between the identified potentials and the savings realised in practice.

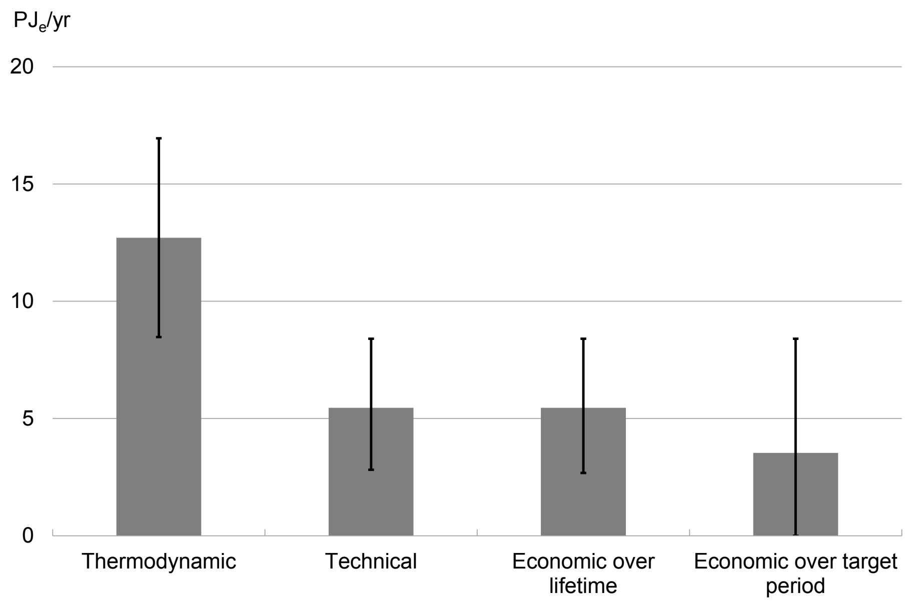
Keywords: Surplus heat; Energy efficiency gap; Organic Rankine cycle; Industry; Barriers; Manufacturing.

Highlights:

- Energy savings have a thermodynamic, technical and economic limit.
- The potential for organic Rankine cycles in UK industry was assessed.
- 3.5 PJ/yr of electricity was generated by economically attractive opportunities.
- The steel, chemical and cement subsectors comprised the majority of potential.
- Drivers and barriers to realising the potentials were discussed.

The short version of the paper was presented at The International Conference on Applied Energy (ICAE 2014). This paper is the full paper with significant revision of the previously presented short version at the Conference.

Graphical abstract



1. Introduction

The potential energy savings (or energy generated) from installing new industrial equipment are subject to thermodynamic, technical and economic limits [1, 2]. The laws of thermodynamics define the absolute theoretical limit of savings. However, in practice this thermodynamic potential cannot be reached. The performance of technology imposes a practical limit on the available energy savings, and defines the technical potential for energy savings. This is normally based on current technology, although some studies may consider the expected performance of a technology not commercially available. Whether the installation of equipment is considered a sound economic decision will often be the most important criterion for a company. Therefore there is also an economic potential for the energy savings available. The technical potential for energy savings will always be below the thermodynamic potential. The economic potential will often sit below the technical potential. In practice not all economic energy saving opportunities will be realised, due to a diverse number of barriers and the market trend potential describes what might be achieved in practice.

Surplus heat arises from many processes within industry [3]. If this heat can be captured and used rather than being rejected to the environment, then energy savings can be made. The technically recoverable surplus heat available from UK industrial sites covered by the EU Emissions Trading System (EU ETS) has been estimated at 36-71 PJ/yr [3]. The potential for utilising this heat through use on-site, using heat exchangers; upgrading the heat to a higher temperature, using heat pumps; conversion of the heat energy to fulfill a chilling demand, using absorption chillers; conversion of the heat energy to electrical energy, using Rankine cycles; and transport of the heat to fulfill an off-site heat demand has been assessed in previous work [4]. The greatest potential was offered through use on-site, using heat exchangers (especially at low temperatures) and by conversion to electricity, primarily using organic Rankine cycle (ORC) technology [4]. Element Energy [5] recently conducted an assessment of the technical, economic and commercial opportunities for surplus heat recovery at the seventy-three largest industrial sites in the UK. Heat sources totaling 173 PJ/yr were identified, of which 40 PJ/yr were technically recoverable utilising a range of technologies for heat recovery (heat exchangers), heat conversion (heat pumps and heat to electricity technologies), and heat transport. The economic potential for recovery was 25-29 PJ/yr; 18 PJ of which was regarded as being commercially attractive [5].

Converting surplus heat to electricity can be an appealing option [4, 5]. Electricity is used in a wide range of energy using processes, and can be transported significant distances. However, the surplus heat available from industrial processes is often at a temperature or magnitude that is too small for the use of traditional, water-based, electricity generation technology [6]. ORCs are the most well-established technology for converting industrial surplus heat to electricity at lower temperatures [6, 7]. Alternative power generation cycles include the Stirling engine, the inverted Brayton cycle [7] and the Kalina cycle [6]. But these are not as well proven as ORCs in waste heat to power applications, and are generally less economic [8]. It is also technically feasible to convert heat directly to electricity, although this is not currently a viable solution for industrial waste heat [6].

There are a number of different variants on the ORC. These include the addition of a recuperator, regenerative cycles, organic flash cycles, trilateral cycles, transcritical cycles, and two-phase expanders [9, 10]. There are also a number of working fluids available for ORCs. The optimal fluid in terms of technical efficiency or economic considerations will vary depending on the specific technology variant, temperature of heat source and other operating conditions [9-14]. A number of studies provide detailed thermodynamic analysis of different types and applications of ORCs (see for example, [9, 14-17]).

The market for ORCs is in a rapidly growing phase of evolution with increases in the number of companies offering the technology [13]. There will likely be further developments in smaller scale plants (those at a kW, rather than MW scale of output) [13]. The technology is thought to be at a "very promising" stage of maturity for waste heat applications [10]. ORCs have been adopted or proposed for surplus heat utilisation in a range of industrial subsectors including steel [16, 18, 19], cement [13, 19], glass [19], food processing [17], metals processing [13, 20], chemicals [20], and ceramics [21, 22]. A recent study [19] estimated the technical potential for ORC installation within twenty-seven EU countries for a number of industrial subsectors (cement, steel, and glass) selected on the basis of their overall energy demand. The estimates were made based on the physical throughout of the plants.

The aim of the current article is to assess the energy savings[1] available through the use of ORCs in generating electricity from the surplus heat available at industrial sites in the UK that are involved in the EU ETS. The energy savings under thermodynamic, technical and economic constraints are assessed. The drivers and barriers that interact to determine whether these savings can be realised, along with the mechanisms through which the gap between the thermodynamic, technical and economic potentials can be closed, are discussed. This builds on previous work identifying sources of surplus heat in UK industry [3], and an assessment of the technical potential for the use of this surplus heat in a wide range of technologies [4]. By focusing on the application of a single technology, a more detailed analysis, including an economic assessment, was possible. By analysing all sites in the UK subject to the EU ETS, this study covers more sites than any extant analysis of ORC systems in UK industry.

2. Methodology

A dataset detailing the surplus heat available at industrial sites in the UK was available from previous work [3, 4]. This covered those sites involved in the EU Emissions Trading System (EU ETS). There were a total of 425 such sites included in the analysis. The data used referred to the time period from

[1] When assessing ORC systems it could be argued that "energy generated" is a more accurate term than "energy saving". However, the generation of electricity by an ORC will result in energy savings in comparison to obtaining the electricity from conventional generation technology. Energy saving is the preferred term here as it allows for a broader discussion that encapsulates efficiency improvement technologies that lead to more direct energy savings.

2000-2004 with the surplus heat available being based on the mean for these years. This assessment covered sites responsible for approximately 60% of industrial energy demand [3].

For each site in the study information was available on the temperature of surplus heat, the load factor of the site, and the magnitude of the surplus heat source [3, 4]. The magnitude of the heat source was given as a range to represent the uncertainty in the heat available [3, 4]. A number of input parameters were used in the calculation of the results, as discussed below. Due to the uncertainty associated with many of these parameters, especially when conducting a broad assessment of many industrial sites, a mean, minimum and maximum value was estimated for a number of parameters. The mean case, best case and worst case scenarios were therefore quantified using a combination of input parameters and the range in the magnitude of each surplus heat source.

The thermodynamic potential for converting the available heat to electricity was calculated using the Carnot efficiency [23], assuming an environment temperature of 25°C[2]. This represents the maximum theoretical efficiency with which the heat available could be converted to electricity. As the temperature of the available heat increases, the Carnot efficiency also increases; as shown in Fig 1. In calculating the thermodynamic potential the only constraint imposed was that surplus heat sources above 400°C were discounted, as these sources would likely be used in conjunction with a water-based Rankine cycle in order to generate electricity. It should be noted that the current study is not a detailed thermodynamic analysis of the ORC itself [as that has been undertaken in a number of previous studies; as referenced in the 'Introduction' (Section 1 above)] but a simplified assessment of the thermodynamic limits of converting heat to electricity through any cycle.

The temperature of surplus heat that could technically be utilised by ORC equipment was taken as 80-400°C, and the minimum power output was set as 50kW$_e$, based on information from a number of manufacturers[3]. There are examples of ORC systems being used with higher temperature sources [6], although it was felt that a 400°C upper limit was correct for the broad analysis conducted here. A number of different operating fluids and technology variants could be used in the ORC over this temperature and power range. The efficiency achieved by operational equipment was based on that reported by manufacturers and in case studies [13, 15, 17, 24-26]. A logarithmic trend line was fit to the efficiency data, maximum and minimum efficiencies were calculated in a similar manner; see Fig 1. Efficiencies were found to vary with the temperature of the heat source. The estimated efficiency was used to calculate the technical potential for energy savings. It may be the case that larger ORC units, outputting more power could exhibit greater efficiency than smaller units at the same temperature. This effect was not accounted for, but the spread of efficiencies used in the analysis should capture this uncertainty.

[2] This environment temperature is fairly high, if the ORC rejected heat to the outside environment it would be lower for the majority of the operating time in the UK. With a lower environment temperature the Carnot efficiency would be higher. The thermodynamic efficiency shown in Fig 1 is therefore conservative.

[3] Manufacturer information used in this study covered: Turboden, Cryostar, ElectraTherm, Freepower, GMK, Triogen, Pratt & Whitney, Barber-Nichols, TransPacific Energy, and Infinity Turbine. However, not all manufacturers provided information on every parameter.

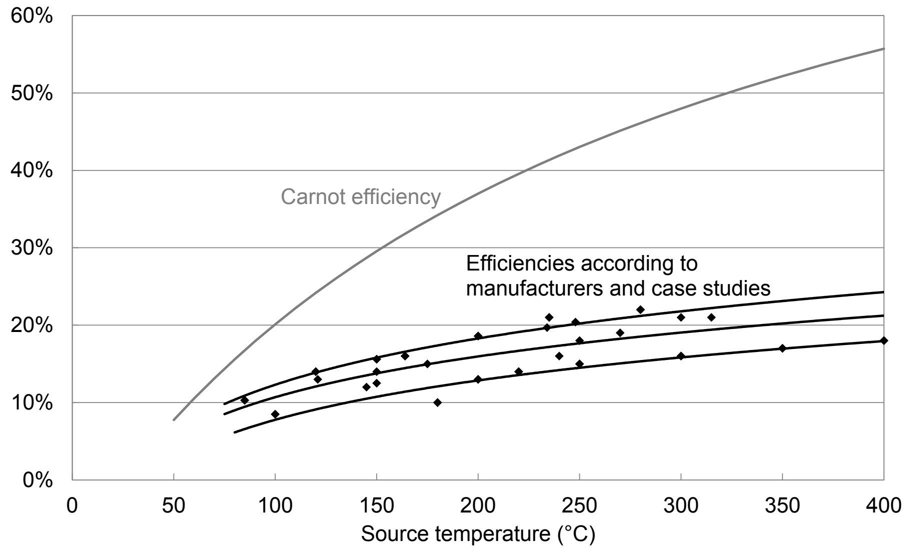


Fig 1: Efficiency of ORC systems as source temperature varies. The theoretical maximum (Carnot) efficiency and the actual efficiency reported by manufacturers and in case studies are shown. The spread of efficiencies was used to construct a mean, maximum and minimum logarithmic best fit line.

The definition of the economic potential for energy savings is dependent on the method of economic assessment used; this will often vary between companies. Here the financial payback period (PBP) was used, although it is recognised that other measures, such as the discounted cash flow (DCF) rate of return (or yield), or benefit/ cost ratio may be used [27]. The financial PBP is that timescale over which the net present value (NPV) of the project reaches zero. After this payback period the project generates a profit. The calculation of NPV requires information on investment (or capital) cost, operating costs, revenue generated, and the discount rate. Two decision criteria were used here is determining economic potential. Firstly, if the payback time was less than the expected lifetime of the equipment, secondly if the payback time was less than a period that indicated an attractive investment. The payback period for energy efficiency projects is typically one to three years [28, 29]. Here a period of three years was assumed for the mean case, with a range of one to five years used to account for the uncertainty in this value.

The specific investment (or capital) cost of the equipment (£2012/kW$_e$) was found to vary with the power output (see Table 1 for approximate monetary conversions for 2012). A logarithmic trend line was fit to the investment cost data (based on manufacturer information, and case studies [30-32]), using relevant conversion factors where needed [33, 34]; see Fig 2. Similar relationships were observed in other work [13]. Maximum and minimum costs were calculated in the same manner. It was assumed that specific investment costs for power outputs of 6.5 MW and above were constant, as this is the size limit of commercially available equipment. Systems above this size were included in the analysis, but the specific investment costs were not assumed to continue to fall. Other costs, including operation and maintenance (O&M) costs, and insurance were estimated as 5.25% (1.5-9%) of the investment costs per annum [13]. The commercial discount rate used in calculations was assumed to be 10% (5-15%), which is typical [5]. The lifetime of ORC equipment was estimated as 20 years (15-25 years) [35].

Table 1: Approximate monetary conversion rates (2012) [34]. NB: 1 Pound Sterling (£) = 100 pence (p)

British Pound Sterling (£ or GBP)	**1.00**
Euro (€)	1.23
US Dollar ($ or USD)	1.58

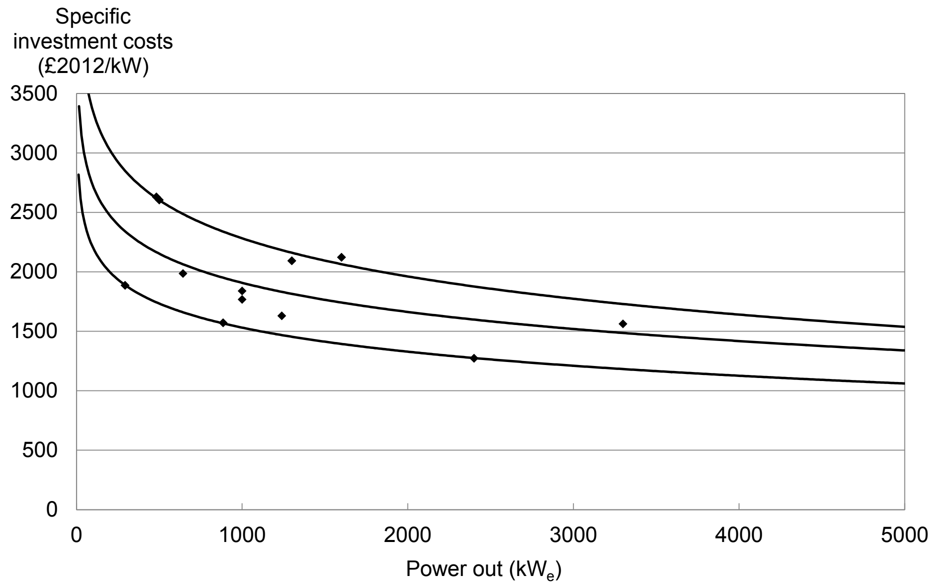


Fig 2: Variation of specific investment costs of ORC systems with power output. Data taken from manufacturers and case studies. The spread of costs was used to construct a mean, maximum and minimum logarithmic best fit line.

The electricity output from ORC equipment was assumed to generate revenue my offsetting the purchase of grid electricity. The future electricity price was taken from UK Government projections [36], which estimated the future retail price for industry, including taxes, out to 2030. Central, low price, and high price scenarios were used to represent the mean, best, and worst cases respectively. The year of installation was taken as 2013. The effect of "carbon prices" imposed on electricity generators through the EU ETS and other schemes was included in these projections. Prices varied from a minimum of 3.9 p/kWh to a maximum of 14.1 p/kWh under these projections. Surplus heat was not priced, it was assumed to be available at no cost. Heat would otherwise be exhausted to the environment and the costs of recovery were included within the estimate of equipment investment costs.

3. Results

Fig 3 shows the calculated thermodynamic, technical, and economic potentials for annual electricity generated by ORC systems at the UK industrial sites included in this study. Two cases of economic potential are shown: whether the equipment will payback over its expected lifetime, and whether it would payback within the target period. The error bars represent the combination of parameters that gave best and worst case scenarios. All sites assessed were economic over the expected lifetime of the equipment, although this was not necessarily the case if equipment was required to pay back within the target period. This finding is sensitive to the input parameters; under the best case all projects pay back in the target period, whilst in the worst case scenario there were no projects that paid back in the required timeframe.

The electricity generated, as shown in Fig 3, can also be represented as primary energy savings (accounting for the losses in traditional electricity generation and distribution) and as the emissions avoided by not utilising grid electricity. Assuming an efficiency of electricity generation and distribution of 40%, primary energy savings will be two and a half times the electricity generated as shown in Fig 3. The emissions factor of UK generated electricity (including transmission and distribution losses) in 2013 was 134 $ktCO_{2e}$/PJ [37]. For the mean case, this implies that projects economic over their lifetime would avoid 733 $ktCO_{2e}$/yr, whereas projects that are economic over the target period would avoid 474 $ktCO_{2e}$/yr. It could be argued that the savings from the use of ORC systems should use a higher emissions factor as their installation would be likely to reduce the use of fossil fuel generation, rather than nuclear or renewables. Conversely, if using the mean emissions factor for the grid, the emissions savings over the lifetime of the project may reduce should the UK see greater use of renewable electricity generation in future years.

The total grid electricity demand of sites in the study was estimated at 105 PJ/yr. At those sites with an ORC opportunity that is economic over the target period (in the mean case) the ORC met an average of 13% of the grid electricity demand. Most sites are likely to use the electricity generated on-site rather than selling it to the national grid, as this avoids possible costs of an additional connection to the grid.

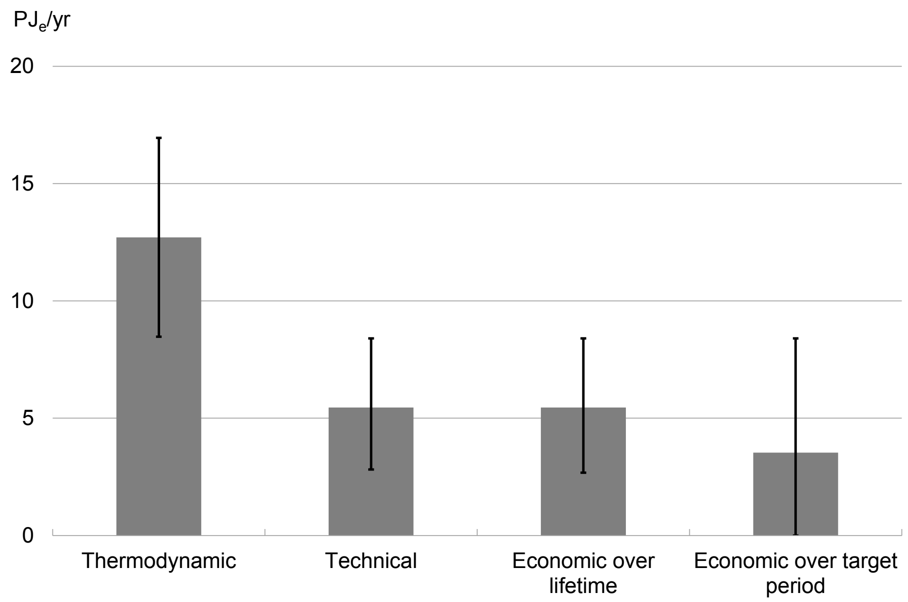


Fig 3: Electricity output per annum from ORC systems, shown under thermodynamic, technical and economic constraints.

The domination of a small number of sites on cumulative output from sites that are economic over the equipment's lifetime in the mean case is reflected in Fig 4. The ten sites with the largest output represents approximately 50% of the total potential. There are 22 sites that are economic over the target period in the mean case (in total there were 425 sites in the analysis dataset, 376 of them with surplus heat sources in the temperature range of interest).

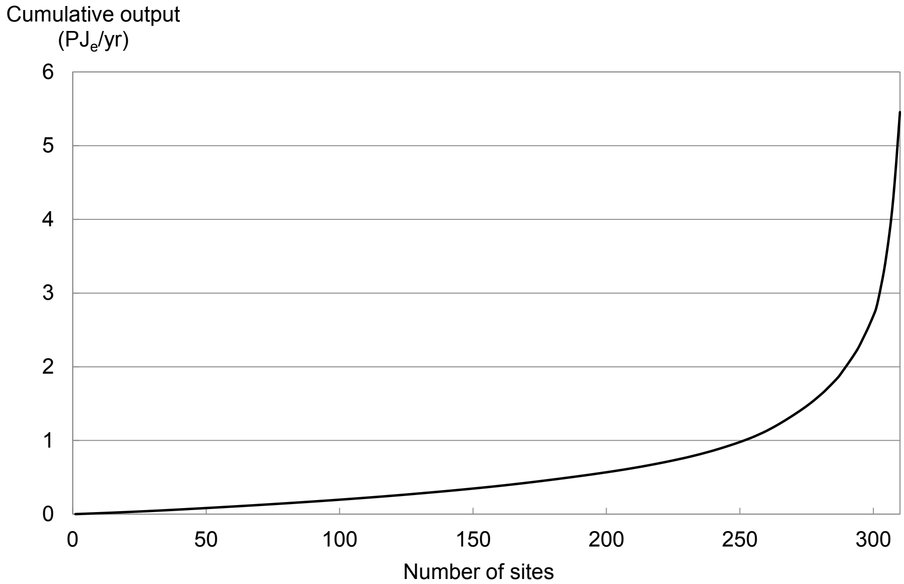


Fig 4: Cumulative output from ORC systems as the number of sites increases, the mean case is shown and sites that are economic over the equipment's lifetime are included. Sites are ordered from smallest to largest output.

Fig 5 shows how the payback period varies with power output from the ORC systems under the best, worst and mean cases (load factors of 95%, 75% and 85% respectively were used here, which are representative of those found throughout the sites in this study). Even under the best case the payback period does not drop below one year, indicating the importance of the payback period (or other investment decision criteria) imposed by the company. Further, if the PBP for the mean case was taken as 2 years, then no projects would be economic over the target period. There is a substantial spread in the results from the range of parameters used in the study, with the worst case scenario having substantially longer payback times. In order to determine what the key parameters were in determining the payback time each of the input parameters associated with the worst case were individually changed to the value for the mean case (keeping all other parameters set for the worst case), and the effect was observed. Varying the discount rate, electricity price, operating costs and load factor all had a significant effect, with a change of electricity price to the mean case having the greatest influence on payback times.

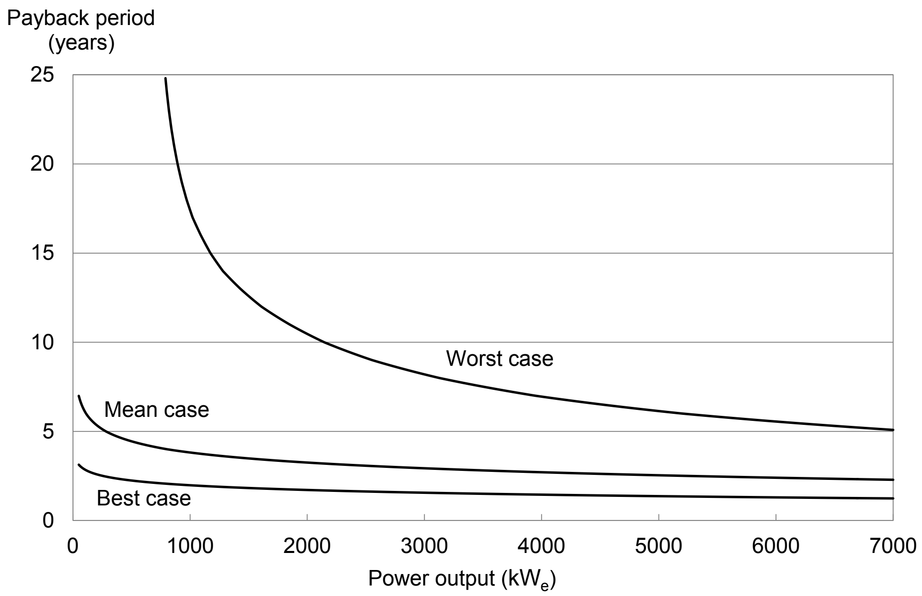


Fig 5: Variation of the payback period of ORC systems with the power output, under the three analysed scenarios.

Fig 6 shows the sectoral split of electricity output from ORC systems under each of the constraints. The sectoral split is similar for all cases except for being economic over the target period. In this last situation the contribution from some sectors, such as 'Food and drink' and 'Pulp and paper' disappears. The heat available from these sectors does not have the required characteristics (a particular combination of temperature, magnitude and load factor) to be economic over the target period. Of those sites that were economic over the target period, 53% of output was from the steel sector, 23% from Chemicals, and 18% from Cement.

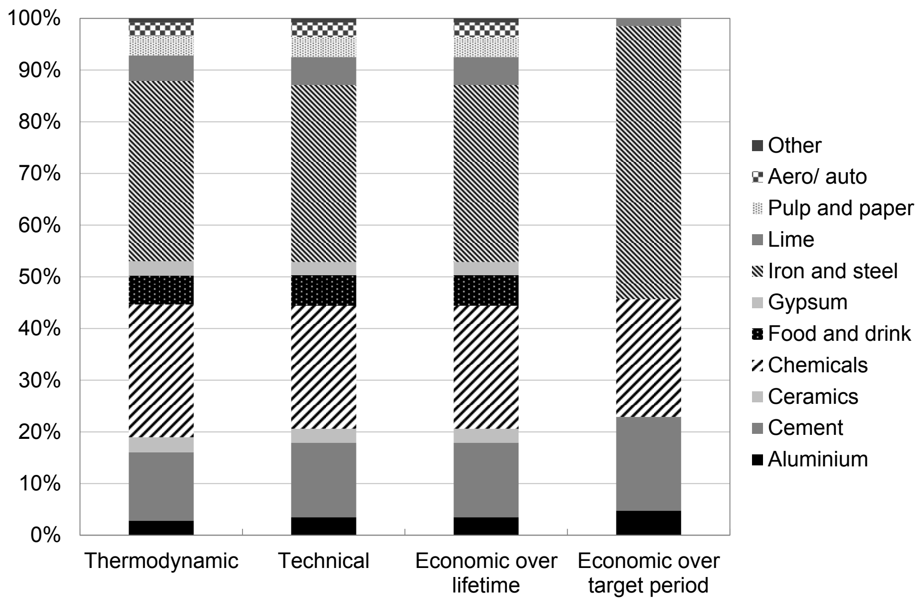


Fig 6: Sectoral split of electricity output from ORC systems under different constraints (results for the mean case are shown).

4. Discussion

The “gaps” between the potential energy savings under different constraints (see Fig 3) can be narrowed with the right interventions. Future developments in technology can close the gap between the thermodynamic and technical potentials by improving the efficiency of equipment. Such improvements would likely have the knock on effect of increasing the economic potential. The gap between the economic potential (under the target payback period) and the technical potential can be narrowed by decreasing costs, increasing revenues, or a change in target PBP. In the current study varying the discount rate, electricity price, operating costs and load factor all had a significant impact on economic potential, with a change of electricity having the greatest influence. The target payback period was also found to be a key parameter in determining economic potential. If ORC equipment becomes widely adopted there may be falls in the investment and operating costs, as equipment gets produced in greater numbers and there are more installers. Higher electricity prices could be driven by higher carbon prices, or similar policies. Schemes such as a feed-in tariff (FiT) could also increase revenues, although the UK FiT is not currently applicable to ORC schemes [38]. The market trend potential is often used to refer to what is actually achieved in practice, as not all schemes that are economic over the target period will ultimately be installed. The difference between the economic and market trend potential is often known as the “energy efficiency gap” [39], or “energy efficiency paradox” [40][4].

Barriers to realising the full economic potential of energy efficiency projects (causes of the “energy efficiency gap”) include: a lack of information relating to the savings potential, a focus by management mainly on production issues, a lack of capital, lack of staff time or skills, hidden costs, perceived risks and uncertainty, a limited window of opportunity to install equipment, and split incentives between the instigator of the project and the profiteer [27]. The importance of the different barriers is often dependent on the characteristics of the project under assessment and the company involved. For example, access to capital is most likely to be an important issue to small and medium size enterprises, and lack of information is found to be more prevalent in non-energy-intensive sectors of industry [21]. In the current analysis hidden costs were thought to be a particularly important factor in determining the difference between what is here identified as the economic potential and what could be realised in practice. Hidden costs were identified as a key barrier by a recent assessment of opportunities for recovering and using surplus heat [5]. When installing ORC equipment, examples of hidden costs include the possible disruption to production activities during installation. Although the heat recovery potentials included here have been identified as being technically recoverable [3] there may be some sites at which installation is more costly, for example, due to the heat source being corrosive. The range used in calculating costs (see Fig 2) and other input parameters should account for some variation between individual sites. An additional barrier is that at some sites there may not be the physical space to install ORC equipment, which could stop the installation of an otherwise attractive opportunity. It should also be noted that in using a heat source to drive an ORC other opportunities to use the surplus heat cannot be pursued. If

[4] ORCs can be classified as energy efficiency measures when considering energy inputs to an industrial site per unit of output. Grid electricity input will decrease as a result of the installation of an ORC.

the opportunity exists to recover the heat for use at a lower temperature elsewhere on site, then this may be preferable [4, 5].

The drivers to installing ORC equipment can go beyond the potential cost savings analysed here. Additional drivers include a desire to insulate a site from electricity price fluctuation and future legislation. Long-term strategy was found to be a key driver for energy efficiency projects in a recent survey of UK industry [41]. There may be hidden benefits to the installation of equipment, not accounted for in the economic analysis here. Where heat-to-power technology is used to supply on-site electrical demands it can result in smaller capacity requirements for electrical equipment used in the interconnection and distribution of grid electricity [42]. The savings on this equipment can completely offset the capital costs of the heat recovery system in new builds [42]. Indirect benefits, such as fulfilling corporate social responsibility (CSR) objectives; and the presence of an individual champion for energy issues holding a decision making position within a company can also influence the uptake of opportunities [27].

The analysis undertaken in the current study is inherently uncertain. When examining a number of sites in this manner, the analysis may not accurately identify all site-level opportunities, although it is likely to be indicative of the overall potential for the technology. Since the collection of the data used in the current study, there has been a reduction in industrial energy use [43], linked to the post-2008 economic recession. Some sites have closed, particularly in the aluminium, cement and paper subsectors [4]. However, the analysis presented here is still thought to give a reasonable assessment of potential, especially considering the large uncertainties represented via the variability in the range of input parameters.

The estimations of energy saving potential here seem to be broadly in agreement with those of a study by Campana *et al.* [19] that recently assessed the potential for ORC use in energy-intensive industries in the EU. That study assessed the savings based on the expected ORC output per unit of physical throughput (taken from energy audits), the capacity of plants, and a range of load factors [19]. A comparison can be made between the results for the cement and steel sectors from Campana *et al*. [19] with those of the current study[5]. It was estimated by Campana *et al.* [19] that the output from ORC plants installed in the UK cement sector would be 0.45-0.72 PJ/yr, whereas here the technical potential (thought to be the best comparison with the results of Campana *et al.* [19]) was estimated at 0.41-1.20PJ/yr; for the steel sector the corresponding values are 0.85-1.36 PJ/yr and 1.01-2.85 PJ/yr respectively. The results of these two comparisons are reasonably close given the different methodologies employed and the different time periods (Campana *et al.* [19] based their estimations on industrial activity in 2012). By focussing further work on the steel and cement subsectors, along with the chemicals subsector, the majority of economic potential found by the current study could be assessed in further detail (see Fig 6).

[5] Campana *et al.* [19] also assessed opportunities in the oil and gas industry, which was not included in this analysis, as well as the glass industry, which, although included in the current analysis was assumed to have surplus heat available at too high a temperature for the use of ORC systems.

It is not possible to directly compare the results here to those of Element Energy [5] in detail. Although the Element Energy study covers the UK, and includes an assessment of ORC technology, this assessment is within a broader analysis of heat recovery technologies. In that study [5] heat-to-electricity conversion was not assessed when another technology was preferred. Element Energy [5] also cover a smaller number of sites (seventy-three, including multiple sources and sinks at each site) than the current study, but considers these sites in rather greater detail. Heat to electricity technology (including ORCs) was found to have a technical potential to recover 3.2 PJ/yr of heat within the 'Food and drink', 'Oil refining' and 'Pulp and paper' subsectors of industry [5]. None of this potential was assessed as being economically or commercially viable.

5. Concluding remarks

It is characteristic of many energy saving technologies to have technical and economical limitations on their installation that constrain the potential energy savings to less than the thermodynamic potential for savings. In the current assessment it was found that all ORC systems that were technically viable should be economic over their lifetime: this potential totals 5.5 PJ/yr of electricity generation in the mean case. However, if the ORC is required to payback over a target period that is representative for energy efficiency technologies, the potential savings fall to 3.5 PJ/yr in the mean case - although this result is largely dependent on the input parameters used, particularly the price of electricity and the target payback period. These parameters are subject to considerable uncertainty, especially when undertaking an assessment of many sites. The majority of the energy savings potential that is economic over the target period was found to be located at a relatively small number of sites in the steel, cement, and chemicals subsectors. A comprehensive study of those subsectors would add more detail to the broad assessment undertaken here. The gap between the economic potential for a technology and the realised opportunities, or market trend potential, can be understood by considering the drivers and barriers to the installation of the technology. Hidden costs may be a key barrier to the take-up of ORC technology.

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The authors' names are listed alphabetically.

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