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

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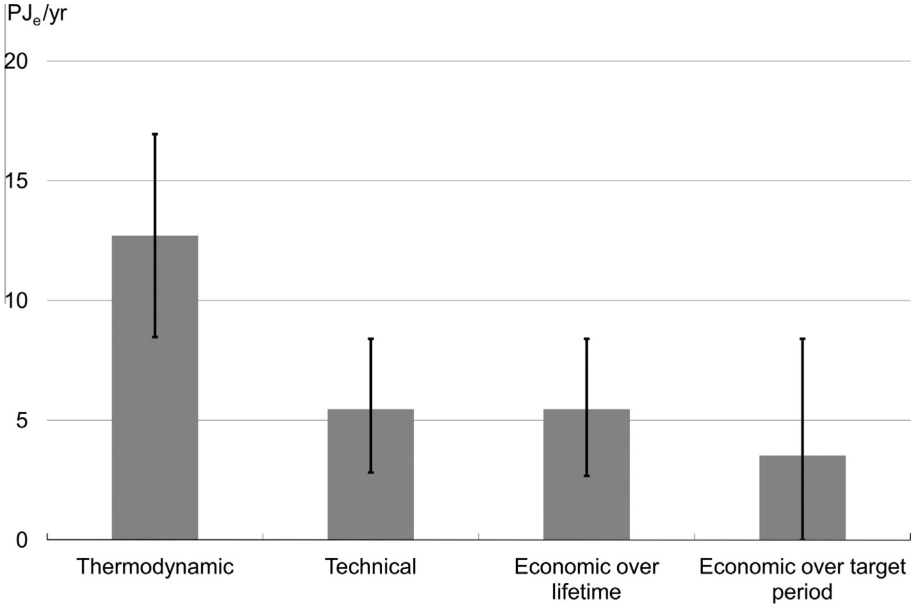
HIGHLIGHTS

- 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.

GRAPHICAL ABSTRACT



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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

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Industry
Barriers
Manufacturing

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.

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 2000 to 2004 with the surplus heat available being based on the mean for these years.

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[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.

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