The potential for recovering and using surplus heat from industry

Final Report

for

DECC

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Led by

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Element Energy

Element Energy Ltd is a technology consultancy providing a full suite of services in the low carbon energy sector. Element Energy's strengths include techno-economic analysis and forecasting, delivering strategic advice, engineering and the design of strategies for the coordinated deployment of low carbon infrastructure.

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Imperial College London is Europe's leading science university. Since its foundation in 1907, Imperial has had a particular focus on the application of science for the needs of industry and government. Imperial's *Department of Chemical Engineering*, founded in 1912, is the largest chemical engineering department in the UK.

Dr. Paul Stevenson (Larksdown Environmental Services Ltd.) and **Dr. Robert Hyde** (RHEnergy Ltd.) are independent industrial energy efficiency experts and provided valuable input into this work.

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While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report. There is considerable uncertainty around the development of industrial heat recovery. The available data are extremely limited and analysis is therefore based around hypothetical heat recovery scenarios. The information and models developed for this study have been provide an understanding at UK-level understanding of opportunities, and should not be relied on for analysis at the level of individual sectors, technologies, or projects. The authors assume no liability for any loss or damage arising from decisions made on the basis of this report. The views and judgements expressed here are the opinions of the authors and do not reflect those of the UK Government or any of the stakeholders consulted during the course of this project.

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Abstract

Recovery and re-use of industrial waste heat is an attractive concept that could simultaneously reduce energy costs and CO_2 emissions. This study has developed a novel approach to quantifying the opportunity, involving the creation of an innovative techno-economic model that links energy and carbon prices and investor priorities with first-of-a-kind databases of industrial waste heat production, process heat use, and heat recovery technologies.

Innovative databases describing “archetypal” characteristics of the waste heat sources and heat sinks at 73 of the largest UK industrial sites were initially developed and populated using literature sources. The contents of the databases were then refined through expert review, feedback from ten trade associations, and insights gained from 11 site visits and discussions with individual companies.

Overall the databases identify 48 TWh/yr industrial waste heat sources, i.e. around one sixth of overall industrial energy use.

The technical potential is defined based on the projects that together deliver the highest CO_2 saving, taking into account “competition” between sources for sinks and technology efficiency. The model identifies a technical potential of 11 TWh/yr (2.2 $MtCO_2$/yr) from *ca*. 250 potential individual combinations of heat sources, heat sinks and heat recovery technologies including heat exchangers, heat pumps and heat-to-power technologies. This figure is at the lower end of previous estimates, but consistent with an independent study by Bath University. The technical potential includes on site measures and heat recovery projects that connect heat sources with heat sinks at nearby sites.

The economic potential is identified as those NPV positive projects which together provide the highest total NPV, and is estimated at 8 TWh/yr and 1.9 $MtCO_2$/yr (3.5 % social discount rate) or 7 TWh/yr and 1.6 $MtCO_2$/yr (private discount rate, 10%).

To put these figures into context, the economic potential of 7 TWh/yr reflects 2.4%[1] of overall UK industrial heat energy use and *ca*. 4% of heat energy use within the leading eight heat intensive sectors (164 TWh/yr excl. power[1]). 1.6 $MtCO_2$/yr reflects 0.3% of the UK’s overall direct CO_2 emissions (479 Mt/yr in 2012[2]). If implemented, a reduction by 1.6 $MtCO_2$/yr would contribute *ca*. 2% of the targeted Carbon Plan reduction (*ca*. 70% by 2050 in industrial emissions from a current sectoral level of 120 Mt/yr[3]).

Based on industry feedback, a narrower “commercial” potential is also defined as those projects which provided simple payback within two years of investment. This commercial potential is identified as 5 TWh/yr, or 1.1 $MtCO_2$/yr, and derives mostly from use of heat exchangers to connect heat sources and heat sinks at the same site.

As a separate analysis, a supply cost curve is identified for connecting 28 TWh/yr from the industrial waste heat sources in the database in potential district heat networks.

Sensitivity analysis is used to understand the factors driving the technical and economic potential. Opportunities and challenges to improve the accuracy of the analysis, particularly to provide greater resolution are discussed.

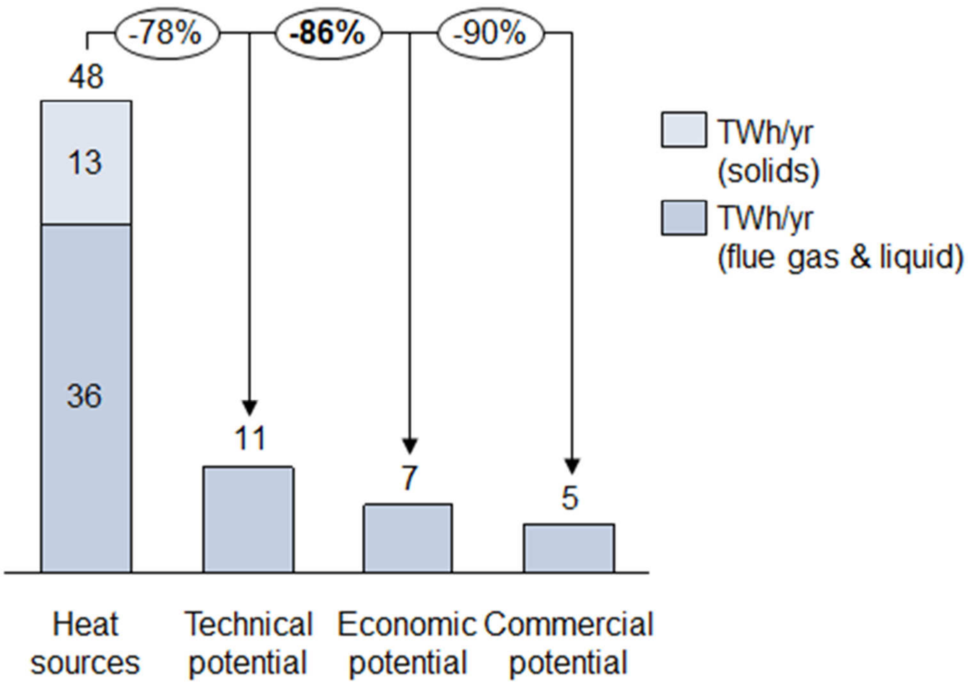
[1] Digest of UK Energy Consumption (2011)
[2] DECC statistical release, 2012 UK greenhouse Gas Emissions
[3] DECC, the future of heating (2012)

Contents

Executive Summary

In its paper, “The Future of Heating: Meeting the Challenge”, The Department for Energy and Climate Change (DECC) committed to assessing the potential for recovery and re-use of industrial waste heat to contribute to meeting the UK’s energy challenges and legally binding CO_2 reduction target.

The potential for heat recovery is governed by multiple factors. These include the characteristics of waste heat source(s) and heat sink(s), the compatibility of sources and sinks (i.e. temperatures, capacity, timing, location), the available heat recovery technologies (costs and efficiency), energy/carbon prices, investor priorities and site- or industry-specific issues. To understand these drivers, databases of industrial waste heat sources, heat sinks and heat recovery technologies have been constructed based on literature data and updated following discussions with industry.



A novel techno-economic model framework identifies a potential for industrial heat recovery in the UK in the range of 5TWh/yr to 28TWh/yr, consisting of hundreds of source-sink-technology combinations. The lower range of this estimate consists of measures that already comply with commercial payback requirements, while the higher end of this range would require significant development of heat networks and district heating, in order to be realised.

The analysis identifies a *technical potential* of 11 TWh/yr from heat sources, based on projects that are projected to save 2.2 $MtCO_2$/yr. The technical potential includes contributions from on-site heat re-use, over-the-fence supply to another large industrial user and conversion to power. All heat-intensive industrial sectors examined (refineries, iron & steel, ceramics, glass, cement, chemicals, food and drink, paper and pulp) contribute to this potential. The technical potential is sensitive to industrial heat demand and supply, and CO_2 savings are also sensitive to assumptions on avoided fuel use.

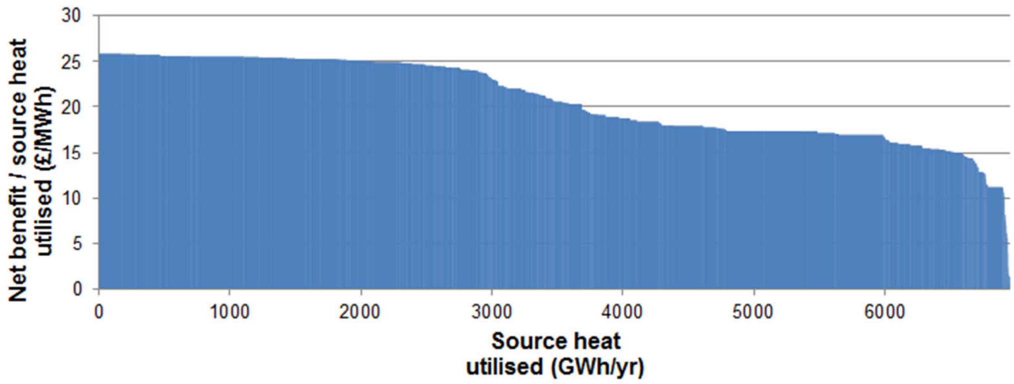


Figure 1 A marginal benefit supply curve for the economic potential. From left to right, projects with decreasing £/MWh net benefit.

The *economic potential*, which considers only those projects where net annual benefits outweigh annual costs, is 8 TWh/yr (social real discount rate of 3.5%) or 7 TWh/yr (private real discount rate of 10%), with corresponding CO_2 saving of 1.9 Mt/yr and 1.6 Mt/yr, respectively. This represents the first estimate of the economic potential for industrial waste heat recovery at a UK level.

To put these figures into context, the economic potential of 7 TWh reflects 2.4% of overall UK industrial heat energy use (*ca*. 291 TWh/yr[4]) and *ca*. 4% of heat energy use within the leading eight heat intensive sectors (164 TWh/yr excl. power[4]). 1.6 $MtCO_2$/yr reflects 0.3% of the UK's overall direct CO_2 emissions (479 million tonnes per year in 2012[5]). If implemented, a reduction by 1.6 $MtCO_2$/yr would contribute *ca*. 2% of the targeted Carbon Plan reduction (*ca*. 70%) for industrial CO_2 emissions (currently *ca*. 120 Mt/yr) by 2050[6].

The projected benefit from upfront capital investments of £205 m would be *ca*. £145 m/yr based on primary fuel and avoided CO_2 payments. Models are invariably simplifications of a complex reality, but if correct, this positive result would suggest that waste heat recovery could improve the profitability and thereby competitiveness of heat intensive industries. The majority of the economic potential is found in on-site measures where waste heat streams can be further used to pre-heat inputs (beyond business as usual).

Discussions with manufacturing industry experts identified multiple constraints to delivering this economic potential:

- challenging commercial investment criteria such as the need for rapid payback for "non-core" investments such as heat recovery
- hidden costs related to acquiring information, equipment downtime for retrofit
- the increasing complexity and risks for processes that are integrated through heat recovery measures.
- conflicting process demands, such as pollution control measures, which might restrict the potential for heat recovery

A *commercial potential* is identified as 5 TWh/yr (1.1 $MtCO_2$/yr) for projects which meet the constraint of payback within two years, but which are currently not widely implemented.

4 Digest of UK Energy Consumption (2011)
5 DECC statistical release, 2012 UK greenhouse Gas Emissions
6 DECC, the future of heating (2012)

Further understanding of this lack of implementation would require investigation of barriers to uptake, which are outside the scope of this report.

Although some individual towns have examined the contribution of heat intensive businesses within district heat networks quantitatively, there has not to our knowledge been a systematic assessment of the economic potential for the supply of waste heat from industry. An initial supply curve is developed identifying that 28 TWh/yr could be supplied at a cost of up to £90/MWh for supply of 100°C water at the facility gate (i.e. excluding transmission and distribution), assuming no fundamental plant redesigns. This can support further national evaluation of the potential for district heating that seeks to link potential supply with demand. A sensitivity analysis shows that the contribution from industrial waste heat is modest compared to that potentially available from the power generation sector (even with conservative assumptions on heat supply from the power sector).

These figures represent a best first estimate of the existing economic potential for industrial heat recovery in the UK today. Looking ahead towards 2050, some improvements in technologies can be expected (i.e. reduced costs, greater applicability, or greater performance) that could increase the technical potential for waste heat recovery. Rising energy and carbon prices would also increase the economic potential. However changes in the supply or demand for waste heat through improved industrial process efficiency and/or changes in industrial output for individual sectors or sites are likely to be more significant over the period to 2050.

A programme of site visits to industrial users identified that public efforts to facilitate industrial waste heat recovery and re-use would be broadly welcomed by industry. However, diverse barriers are identified that would need to be explored in any future work to understand how policymakers could best intervene. Industry perceptions were that, although there was some heterogeneity between sites, the most commercially attractive heat recovery projects have already been implemented.

The long-term contract challenge facing developers and contracted parties within over-the fence and district heat networks are understood within the energy sector (for example by CHP providers), but would seem to be amplified for industrial suppliers and users. This is partly because individual sites have limited certainty of operation. Several of the industrial sites considered in this study have already been included in previous studies of heat networks, prepared by local authorities or others. However, few of the companies visited expressed a strong desire to diversify their current business activities to become lead heat suppliers to third parties under existing market arrangements. This implies that intervention in the form of organisational support and/or financial incentives would be required to realise societal benefits from any “over-the-fence” heat network solutions.

1 Introduction

1.1 The opportunity

UK industry consumes about 20%[7] of the final energy consumption of the UK economy (291 TWh in 2011[7]) and generates 32%[8] of the UK's heat-related CO_2 emissions, mostly from fossil fuels. There has been a strong downwards trend on industrial CO_2 emissions, and UK manufacturing industry has a good reputation for energy efficiency (see DECC Heat Strategy 2012).

73% of the UK industrial energy demand is for heating[7]. The Digest of UK Energy Statistics (DUKES) suggests of this nearly half is used for low temperature processes and 22% is used for high temperature processes. Drying and separation processes (42 TWh/yr) and space heating (36 TWh/yr) make up the rest. The technical potential for industrial waste heat recovery has previously been estimated at 10-40 TWh/yr. This implies a significant potential for reducing fuel demand, thereby increasing energy security, reducing costs, and CO_2 emissions.

The most heat intensive industries are cement, ceramics, iron and steel, glassmaking, chemicals, refineries, paper and pulp, and food and drink. Together these sectors employ around 2% of the UK workforce (around 600,000 people), and contribute £50 bn/yr to the UK economy (4% of the UK's GVA)[8]. Their products are, by and large, traded globally.

Since energy costs can represent up to 40% of total production costs for these sectors, measures to improve site energy efficiency or reduce CO_2 emissions, could also reduce operating costs and improve competitiveness of the UK businesses. Many heat intensive businesses are either part of industrial clusters in regions facing socio-economic challenges and/or are significant local employers. Therefore improved competitive position through reduced costs may strengthen these clusters and support a "rebalancing" of the economy.

1.2 Prior Literature

The first estimate for UK industrial heat recovery potential appears to be from the Carbon Trust's work in 2008. On the basis of commercially confidential data and analysis, a potential of 40 TWh/yr surplus heat from industrial processes has been referenced, but given the confidential nature of the analysis this cannot be substantiated. It is not clear if this estimate linked heat supply with the potential for heat recovery.

The first transparent assessment of the potential for industrial heat recovery was prepared by Bath University. McKenna and Norman (2010) categorised heat supply and demand into broad temperature bands and quantified energy available based on EU ETS site CO_2 emission and other public data. The potential is concentrated in a limited number of "heat-intensive" sectors and indeed sites. Of 180 TWh/yr industrial heat consumption identified in that study, technically feasible savings of 10-20 TWh/yr were identified. Norman and Hammond (2012) have recently updated this work considering the temperature of heat sources and scenarios for the re-use of the surplus heat including on-site re-use, heat

[7] Digest of UK Energy Consumption (2011)
[8] DECC, the future of heating (2012)

pumps, heat to power generation, and heat for chilling (in the food and drinks and chemicals sectors), and heat transport networks.[9]

The above studies have focussed on the overall energy that can be re-used. To our knowledge no prior study has sought to quantify the economics of industrial waste heat recovery at the UK level economic potential for industrial waste heat recovery and re-use. This creates an important gap in understanding for policymakers and wide stakeholders keen to take advantage of the technical potential identified.

1.3 Scope

In May 2013, DECC issued an ITT for Consultants to provide DECC with an understanding of the technical and economic potential for the recovery of rejected heat from heat intensive industries and the potential for this to supply low carbon energy within the UK energy system. This should consider new and existing industrial sites, and cover the period from now up to 2050. The focus should be on re-using heat on site, but also consider use of heat by other industries (including carbon capture), conversion of the waste heat to electricity, use in cooling, or supporting residential/commercial heat networks. Key outputs required include energy profiles, exergy, temperatures, transfer medium, location, CO_2 savings, costs and benefits (e.g. £/kWh). The approach taken should combine literature review, modelling, industry consultation, and site visits, within a short timetable (4 months).

A team led by Element Energy, and comprising Ecofys, Imperial College, London, RH Energy and Larksdown Environmental Services, was awarded the project in June 2013. The proposed approach combined literature review, the creation of Excel-based databases and a techno-economic model to characterise heat recovery potential, and a programme of discussions with industry and site visits to “groundtruth” understanding,

1.4 Structure of this report

This draft final report represents the primary deliverable from the project. Stakeholders are encouraged to direct feedback on the draft report to Harsh.Pershad@element-energy.co.uk.

The remainder of this document is structured as follows:

Section 2 describes the key concepts associated with industrial heat recovery, and drivers of the overall technical potential.

Section 3 introduces the project methodology, agreed with DECC at the outset of the project.

Section 4 discusses heat recovery technologies

Section 5 presents from the results of the techno-economic modelling.

Section 6 summarises the main conclusions from the analysis.

[9] A comparison between the findings in this study and those of Bath University is provided in the Appendix.

Section 7 discusses opportunities to improve the quality of the analysis.

Section 8 provides a Glossary of key terms

Section 9 provides a list of useful references

In addition this draft report is accompanied by an extensive technical appendix which provides further details on

- The modelling approach
- Key assumptions
- Breakdown of results
- Sectoral issues and opportunities

2 Concepts and drivers of industrial waste heat recovery

Much of the energy required for industrial processes is ultimately emitted again to the environment in the form of heat. Where the emission is related to a flow of hot gases or liquids, then technologies exist to recover some of this heat. As well as understanding whether the capacity of these streams matches demand on a simple energy (MWh) or flow (MW) basis, it is essential to consider the “exergy” available. The exergy corresponds to the amount of useful work that can be obtained from a heat stream, and is limited by thermodynamics. The concept of exergy explains that two heat streams with the same energy content, but a different exergy value, provide different opportunities for useful reuse. In practice most actual heat recovery technologies fall short of the thermodynamic limits, although there has been improvement in technology performance over time.

In this study an available waste heat stream is designated a heat source. A low grade heat demanding process is termed a sink. The main characteristics of both sources and sinks are their temperature, medium, mass flow rate and availability over time.

This study considers the match of available waste heat to (low grade) heat sink demand, based on the following factors:

1. Temperatures of heat sources and heat sinks
2. The heat flow rate (or capacity). The amount of heat supply and heat sink demand.
3. The medium of the source waste stream and sink heat demand
4. The distance between heat source and heat sink
5. Timing of heat supply and demand
6. The composition of the waste stream and potential complexity associated[10].

A number of technologies are considered that can be used to recover and reuse waste heat. The main distinction between types of technologies, are technologies used in heat conversion on the one hand (from a high grade source to a low grade sink), and heat upgrading (from a low grade source to a higher grade sink).

Heat upgrading includes heat pumps (which increase the fluid temperature) and heat to power devices which generate electricity. Heat exchange devices are usually passive while the heat upgrading devices are usually active devices, requiring also ancillary electricity for instance to drive motors. In general specific costs for heat pumps and especially for heat to power devices are higher than heat exchangers per unit of energy input.

A second dimension regarding technology application is the location of the source and sink. In this study a distinction is made, for reference, between the following:

[10] Many exhaust streams are contaminated or containing fouling particulates of some form. Resulting issues can be clogging and abrasion of devices, and corrosion or deposit formation when temperatures are reduced below dew points of certain components when heat is extracted form a stream. These aspects can limit the possibility to recover heat from some sources, or significantly increase the associated costs when for instance corrosion resistant materials are required. Additionally these issues provide operational risks, which provide a barrier to implementation. The latter is outside the scope of the present study.

- On site reuse; both source and sink are on the same site, not necessarily the same process or facility
- Over the fence; delivery from a source to a sink at another industrial facility.
- Heat to power; the assumptions is made that all power produced can be fed to the grid, at no additional cost, i.e. every site has a suitable grid connection.
- District heat production; considers the production of district heat and delivery to the fence of the industrial facility. Availability and delivery to a specific district heat network (or other district heat demand) is not taken into account.

The economic feasibility of heat recovery measures depend on three main aspects.

- Investor key performance metrics;
- Energy and carbon prices; these impact the revenues by avoiding primary fuel use and the ongoing costs through power ancillary power consumption.
- Project costs; investment costs are a significant driver, especially given the short payback requirements. Project costs are very site and facility specific, especially where heat recovery projects are integrated in existing facilities.

3 The development of an innovative techno-economic model

This section describes the modelling approach taken, and the implications of the approach on data sources, their quality and the main project assumptions used.

The most transparent prior assessment of waste heat recovery in UK industry to date has been conducted by McKenna and Norman (2010), which estimated a technical potential of 10-20 TWh/yr. The McKenna approach makes the simplifying assumption that a fraction of recovered rejected waste heat can always be re-used, without considering the potential constraints around this. In reality, recovering of waste heat is constrained by the ability to re-use this and any heat recovery technology is only worth considering if economic.

Therefore to obtain more insight into the value of heat recovery, it was deemed essential to develop a new approach. The new approach explicitly identifies potential heat recovery projects at potential sites and the CO_2 savings, costs and benefits of these, and allows these data to be aggregated to provide a UK-level picture.

Before introducing the modelling approach, the section first introduces two parameters that are the desired modelling outputs:

- The "**technical potential**" combines projects with the largest CO_2 abatement.
- The "**economic potential**" combines projects with the largest net benefit.

Further distinctions are made in the economic potential. The "social" case adopts a Treasury 3.5% real discount rate. The "private" case is modelled as 10% real discount rate (e.g. an Energy Service Company). Following discussions with industry, a "**commercial potential**" is also defined which includes measures that provide simple payback of capital invested within two years.

The main key investment metrics defining the economic social, private and commercial potentials are provided in Table 1.

Table 1 Key investment metrics for the social and commercial potential scenarios.

	Economic potential		Commercial
	Social	Private	
Discount rate	3.5%	10%	
Amortisation period (yr)	20	20	
DECC carbon price	Yes	Yes	Yes
Air quality costs	Included	Excluded	Excluded
Simple payback time (yr)			2

3.1 Techno-economic model

To gain greater insight into the economic potential for heat recovery in UK industry, it is important to understand project costs and benefits, which in turn depend on how well heat sources are matched with sinks and heat recovery technologies.

Novel databases describing heat sources, heat sinks and heat recovery and conversion technology data sets are created to form the basis of the techno-economic model[11]. The main structure of the inputs, outputs and the techno economic model is shown in Figure 2.

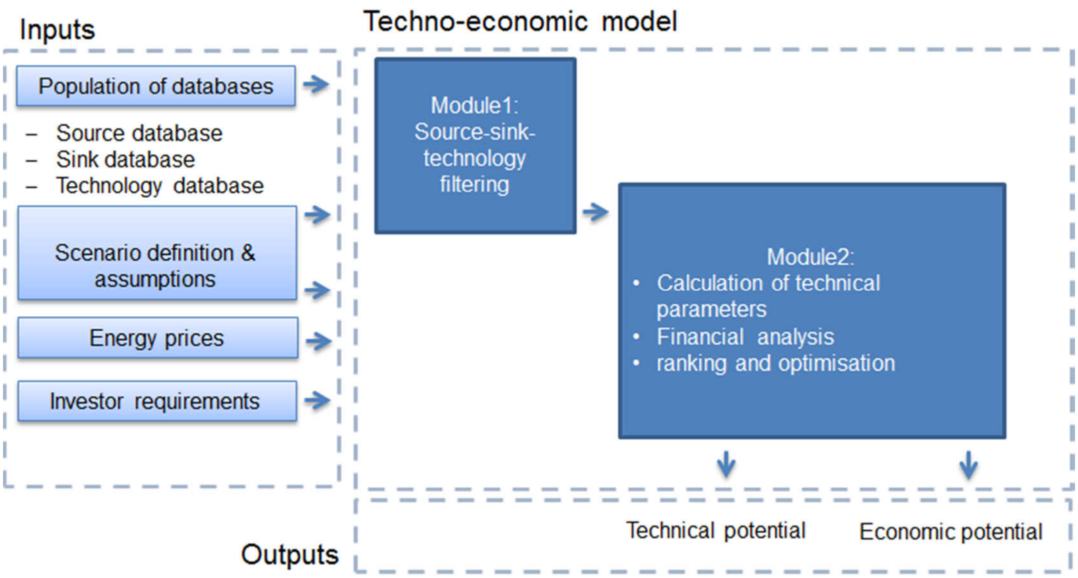


Figure 2 Main structure of the inputs, outputs and the techno-economic model

The first calculation module contains the filtering steps, this process is depicted in more detail in Figure 3. All combinations of source, sink and technology are filtered on the following criteria.

- Temperature; absolute value of source sink, their difference and compatibility with the selected technology
- Distance; the maximum distance between a source and a sink is defined in the model (default 40 km "straight line" distance)
- Medium; source and sink medium, and compatibility with the selected technology
- Seasonal match in source availability and sink demand

In the second calculation module the technical parameters are calculated, the financial analysis is performed and measures are optimised for either technical or economic potential, which are depicted in more detail in Figure 3.

Not all combinations of heat source, heat sink and heat recovery technology are feasible or practical, and only a small fraction of those identified are "optimal". The structure of the techno-economic model and the interactions of the databases and the calculation modules are depicted in more detail in Figure 3 (and further details are provided in the Appendix).

[11] At DECC request, the approach taken is implemented in Excel with short run-times (*ca.* 15 minutes per scenario on a conventional PC).

In the Financial module both the annualised net financial benefit and simple payback are calculated. The annual net benefit is based on the annualised investment cost and the opex and revenues in the snapshot year of the analysis. The annual revenues consist of the avoided fuel and CO_2 cost at the sink, and in the "social" case, also include avoided air quality costs.

Net benefit (£/yr) = Avoided annual fuel cost + Avoided CO_2 cost – Annualised investment cost – Annual opex

The simple payback time is the number of years until the cumulative undiscounted avoided fuel, CO_2 cost and operating costs exceed the cumulative investment.

All feasible combinations of sources-sinks and technologies are stored in a matrix. Following financial assessment, all possible measures are ranked and a selection is made that maximises total CO_2 abatement (technical potential) or overall system net benefit (economic potential). Importantly, although there will sometimes be competition for a source from multiple sinks, and for a sink from multiple sources, this final selection assumes every source or sink ensures conservation of energy, i.e. every source or sink is only used once.[12]

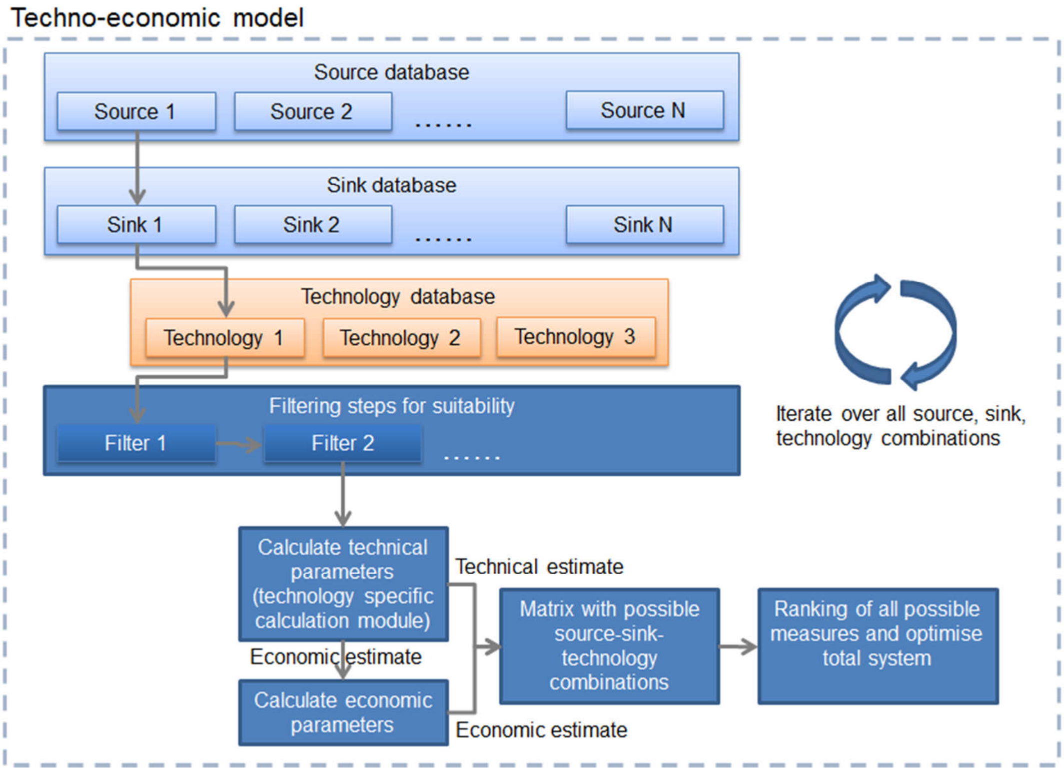


Figure 3 Main structure of the techno-economic model, indicating interaction of the databases and the calculation modules.

[12] In reality of course, "optimal" configurations may not be chosen, and in some cases it will be possible to connect multiple sources and sinks through integrated rather than point-to-point heat networks. In such cases, the "optimum" combination of heat source and sinks could be substantially different from the combinations identified here. See Appendix.

3.2 Database population

The model builds on six databases covering heat sources, heat sinks, technologies, investor criteria and energy/carbon prices and fuel carbon intensity:

Both the source and sink databases are built from “archetype” databases and “site” database[13]. Archetype and site databases were initially identified from a global literature review, and then updated following discussions with UK industry and expert review.

The archetype database contains data on available rejected heat flows per unit production for representative processes and sub-processes. Since details of actual processes are commercially sensitive, representative data have been used for different sectors. The heat flows are characterized on the level of sub-processes on heat carrier medium (wet/dry steam, water, gas, solid), temperature ranges, mass flow and a compatibility factor. The compatibility factor gives an indication of the complexity to recover the heat and is used in the calculation of the costs of heat recovery. Parameters that determine the complexity of decoupling are contamination of heat flow, whether the waste heat stream has to be recovered from inside a process or is available at the outside and whether the heat flow is made up of many smaller flows or consists of one larger flow. Archetype source data derived initially from public sources and experts were reviewed with Trade Associations and site visits with selected individual businesses, and subsequently updated in light of feedback received.

The “site” database scales the archetype data based on assumptions of output at site level. Ideally this would use actual production data. However, since site specific data on e.g. production volume and energy demand are confidential, the best available published proxy data were initially identified and approximate site outputs inferred.

A saturation factor indicates to what extent this sink is already supplied by recovered heat as a sector average. Archetype sink data, including saturation factors, were initially populated with data from public sources and experts, and then subsequently updated in light of feedback from trade associations and insights from visits to individual businesses.

Source and sink databases are described further in the Appendix.

The technology database contains data on heat recovery technologies, heat conversion technologies, heat transmission technologies and heat storage technologies. To account for developments in efficiency and costs, and to be able to include new technologies, separate databases are provided covering current performance and a scenario for performance in 2020, 2030, 2040 and 2050.

The technology database draws on three different types of data sources:

(i) International literature on heat recovery technologies, both generic and specific. A bibliography can be found in section 9.

(ii) Manufacturers of technologies were approached to supply data on specific technologies. Particularly costs data, that are hard to find in the open literature, have been gathered by this approach.

[13] To maximise flexibility for future DECC model users, no background IP, and to respect commercial confidentialities, all data in the databases necessarily derived from public sources and updated through discussions with industry to reflect general sectoral practice.

(iii) Cost engineering equations were used to be able to scale costs to the size of the equipment. The parameters used in the costs engineering equations were matched with the data obtained from the manufacturers as a reality check.

3.3 Characteristics of UK industrial waste heat supply and demand

3.3.1 UK industrial heat sources and heat sinks

The total energy in waste heat sources in the database is identified as 48 TWh/yr and 20 TWh/yr in sinks. These databases contain 73 sites, for which in total 467 sources and 1091 sinks are included.

What is immediately apparent is the higher absolute level of heat sources than sinks within the largest industrial emitters. This suggests that the available demand for low grade heat is likely one of the key limiting factors for the reuse of heat, i.e. local demand is likely to be quickly saturated. This would require external sink options such as heat networks and heat to power conversion. This is also consistent with the experience of industrial players, who often indicated in site visits that although waste heat is available, there is limited low grade heat demand.

To understand the supply of waste heat and the characteristics of sinks, Figure 4 differentiates heat sources and heat sinks into differentiated temperature bands and the medium in which heat is available (sources) or required (sinks). The waste heat source bands are ambient-250°C (low),250-500°C (med), and >500 °C (high). The heat sink bands are ambient-150°C (low), 150-250°C (med), and >250 °C (high).

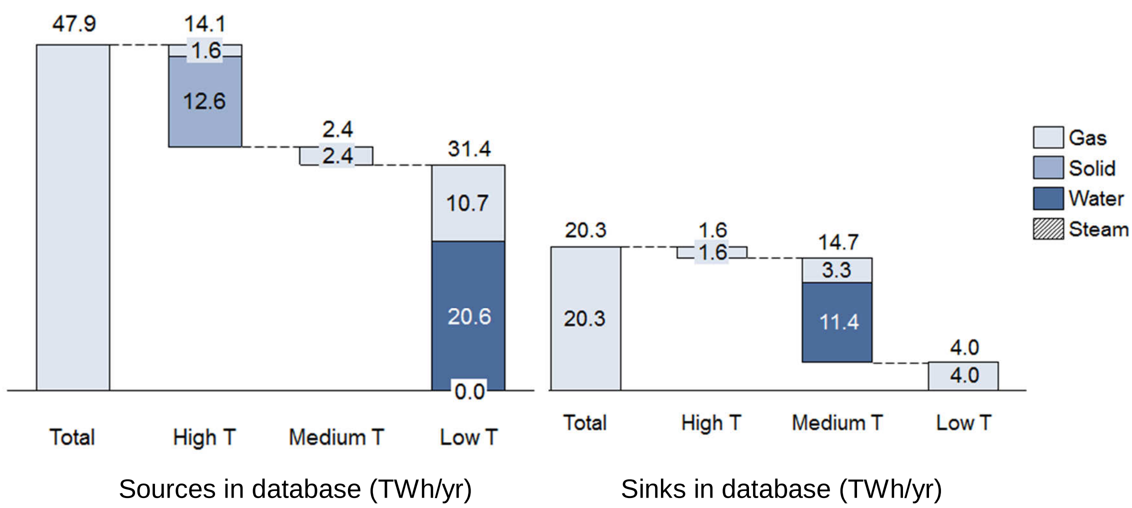


Figure 4 Breakdown of source and sink heat flows in database (data rounded where necessary)

Inspection of Figure 4 reveals that the majority of energy in waste heat sources is found in low grade streams (31TWh/yr out of a total of 48 TWh/yr). Although 14 TWh/yr is available from high temperature heat sources, the majority of this is from hot solids (primarily iron/steel from blast furnace steel production), for which heat recovery is challenging. In contrast only 1.6 TWh/yr is available as hot flue gases. Low grade waste heat sources are not relevant for conversion to electricity.

Within the sinks database, 4 TWh/yr is found in low temperature sinks 0-150 °C out of a total of 20 TWh/yr in all sinks. These sinks can be supplied by sources in all three temperature bands.

Opportunities for expanding the source and sink databases are described in section 7.

3.3.2 Time profiles

To understand potential issues around matching heat supply and demand over short and long timescales, industry was consulted to understand most common current UK practices.

As expected, manufacturing processes involving high temperature furnaces, i.e. iron and steel, ceramics, glass and cement production typically plan around 10-40 years with mostly continuous operation. This implies steady supply of heat but few and infrequent windows of opportunity for major interventions. Refineries and chemical plants have more heterogeneous heat use. In some cases maintenance is staggered, i.e. parts of large sites are repaired (or even re-built) at different times and so different parts can be in operation (or shut down), with corresponding impact on energy flows.

Some paper manufacturing plants can operate continuously or in batches, but typically the presence of several machines smoothes overall site energy use. In contrast, the food and drink industry is characterised by high variability in timing and location, for example:

- Heavy use of batch, rather than continuous production, processes, implying daily and weekly variation in heat supply and demand.
- Some products are produced to meet seasonal or promotional requirements and therefore volumes, temperatures and the composition of waste streams can be highly variable. This could raise the cost of heat recovery.
- Over the last decade several hundred individual sites have opened, closed or underwent significant refurbishment.

Some businesses close for significant (though usually predictable) periods in winter, when heat supply for heat networks may be most valuable. Across all the heat intensive industries sectoral output can follow economic cycles (i.e. output changes over years), with some individual sites impacted disproportionately.

The seasonal availability and demand for heat has been taken into account in the analysis. The impact of batch processes, or requirements for back up, heat storage, or supporting heat production have not been taken into account.

3.4 Applicability and limitations

Any techno-economic modelling approach necessarily involves a number of simplifications and assumptions.

It is important to stress that the novel databases on heat sources and heat sinks generated here were created to provide an estimate of overall national potential, and become much less accurate when disaggregated (e.g. to produce sectoral insights); especially they should not be relied on for individual site or project assessments. Likewise, the heat recovery technology database represents these technologies at a fundamental level, i.e. not at the level of individual products from specific manufacturers.

The UK heat intensive industry is highly heterogeneous, at sectoral and especially site level, and there is likely to be significant variability and uncertainty around individual input data.

Recognising the novelty of the approach proposed here, the Consultants employed an extensive and multi-pronged data quality control programme for analysis. This comprised:

- Extensive literature review, by technology and sector experts
- Review of key assumptions and outputs with eleven trade associations, four academic experts and technology manufacturers
- Ten industrial site visits (covering each of the eight sectors), with each visit involving site energy managers, industrial process energy efficiency experts, industry representatives, and other members of the project team.
    - The site visits were intended to ground truth assumptions on current UK practice, given that some literature may be out of date or not UK-centric.
    - The site visits were also used to develop case studies which were reviewed by the sites or trade associations to ensure the Consultants had a correct understanding of site energy producing and consuming processes, and the opportunities and constraints for heat recovery.
    - The contents of these case studies are confidential, due to site commercial sensitivities.

The project has identified that accuracy is strongly constrained by the need to respect commercial confidentiality of individual businesses (and in some cases avoiding breaching competition law constraints), particularly related to energy use and production levels.

However, the approach taken allows the component databases of heat sources, heat sinks, heat recovery technologies, energy and carbon prices, and investor priorities to be refined in the future.

3.4.1 Model applicability and limitations

The model is developed for the specific purpose of estimating the UK-wide potential for the recovery and reuse of industrial heat. In particular, the analysis is not designed to provide site-, sector- and technology-specific assessments. Hence, using this model should not be used for site, sector or technology-specific analysis. Specific modelling assumptions and limitations are described in the appendix – highlights are:

- The modelling assumes a single source-sink-technology combination, i.e. point-to-point rather than integrated heat networks.
- These combinations are selected on the basis of maximum CO_2 saved (technical potential) or greatest annualised benefit (economic potential), whereas in reality investors are unlikely to identify optimal configurations.
- The ‘archetype’ representation of sources, sinks and technologies may significantly mis-represent opportunities at actual sites (i.e. no site- or product-specific issues are taken into account).

- The business-as=usual assumption is that industrial output is constant at site level and plant processes are unchanged. In reality, sites and processes may change significantly for various reasons, but including maximising energy efficiency and minimising CO_2 emissions.
- The modelling of heat to power and heat pump technologies assumes on-site availability of electricity and no grid connection costs.
- Avoided annual CO_2 emissions corresponding to reduced primary energy use are taken into account, however lifecycle CO_2 impacts of the production and installation of the heat recovery technologies are not considered.
- Financial analysis is performed on an annualised basis for the designated lifetime, as this provides the most flexibility when the actual year of implementation is not known.

3.4.2 Limitations to the database population approach

As described above, the approach taken is "bottom up", i.e. the databases are intended to represent, in a highly simplified manner, individual heat processes at individual industrial sites. The bottom-up approach has the following limitations:

- The total potential can be under-estimated as the focus is on the largest heat flows per sector.
- Another reason that the potential can be under-estimated is that the study only considers heat intensive industry. Small industrial and commercial sectors are not taken into account.
- The selection of sites was done on the basis of CO_2-emissions as reported in the ETS registry. All sites in the top 80% largest EU ETS emitters are taken into account. In sectors were the coverage of selected sites in the total sector emissions was too low, additional sites were included in the database.
- The study does not use actual site energy data as the availability is limited and, restricted by commercial or competition issues. Instead proxy data based on archetype data on heat sources and sinks and allocation of sector production volumes to a site based on public CO_2-emission data. Site data are therefore not representative for the actual sites and should not be used as such.
- As there are large differences between one industrial site and another, translating the archetype heat sources to actual sites is not that straightforward. One needs to know to what extent unit operations are being applied at actual sites. This information is rarely public and up-to-date.
- The number of sites examined, and level of detail were subject to overall project time and resource constraints, and this resulted in the need to use generic models in some sectors.
- To aggregate the bottom-up information to sector information the relative share of the heat flows in the total of the sector is required. We used CO_2-emissions from the ETS-database as a proxy. As there is a correlation between CO_2-emission and direct fuel use, this is pragmatic, but is highly complicated by the role of CHP, chemical transformations, and the mix of energy sources used.

Consistent with other attempts to analyse the potential for energy or carbon reduction in the diverse and large industrial sector, at a granular level individual sites are likely to be mis-represented within the databases. The databases have value at more aggregated level where it is expected that some site or process differences are averaged out.

4 Characteristics of heat recovery technologies

4.1 Overview

For the purpose of this study we have classified the technologies for recovering and utilising heat into:

- technologies that recover heat from a primary flow and make it available as heat of a lower quality in a secondary flow. Typical examples are heat exchangers, recuperators and regenerating furnaces.
- technologies that recover heat from a primary flow and upgrade this to a form of energy of higher quality, using another energy source as input. Typical examples are heat pumps, bringing the temperature of the heat flow to a higher level, absorption chillers that transform heat into cold, and organic rankine cycles, transforming the heat to electricity.
- technologies that transport the recovered heat to another place, like hot water pipes and steam distribution systems.
- technologies that store the heat for use at another time, like seasonal storage and hot water tanks for day/night storage.

Combinations of technologies from different groups are often required. For instance, a heat exchanger combined with a steam distribution system to bring the heat from the heat source to the heat sink. For on-site use of heat we have assumed an average transporting distance of 300 metres. If the heat is used over-the-fence, the actual distance between the source and sink, as identified in the point-source database, is being used.

The characteristics of a heat recovery technology depend largely on the application, e.g. temperature and pressure (for gas phase) of the heat source, type of use of the heat and contamination of the heat flow. We have tried to capture these characteristics on a high level and realise at the same time that at specific applications the situation may be quite different. For many industries specific technologies have been developed. An example is the regenerative furnace in the glass industry used to pre-heat combustion air with the heat of the furnace exhaust.

4.2 Technologies taken into account in the model

<u>Heat exchangers</u> have been modelled as convective or condensing heat exchangers. Condensing heat exchangers capture the latent heat of water vapour and are typically used for wet steam heat sources. Convective heat exchangers recover heat from dry gaseous streams and liquid streams. The efficiency of a heat exchanger is determined by its U-value which is determined by several factors such as the heat media involved and material of the heat exchanger. For modelling purposes we have used average U-values. Heat exchangers normally also use some power for pumping requirements.

The database characterises <u>heat upgrade</u> technologies as (evaporative) <u>heat pumps</u> and <u>rankine cycles</u>. The efficiency of heat pumps is described as its coefficient of performance

(CoP), which is the ratio of heat output to work input. The CoP is influenced by the temperature lift. Typical CoP-values for an evaporative heat pump lie in the range of 3-5 and for an absorption heat pump at 1.5-3.

Rankine cycles are being used to convert heat to mechanical work, which can in turn be used to generate electricity. A widely applied example is the steam rankine cycle, used in power stations to convert high temperature steam into electricity. Technologies that can convert heat from a lower temperature (90-500°C), into electricity are the organic rankine cycle (ORC) and the Kalina cycle (which employs a solution of two fluids with different boiling points as working fluid). The efficiency of converting heat to electricity in an ORC ranges from about 8% for lower temperatures to 18% for higher temperatures. Kalina cycles can be more efficient than ORCs but due to their complexity are more suited for larger applications.

Heat transport by pipeline is widely used and mature technology for on-site, over-the-fence and for district heating. The limiting factor is the distance heat can be transported without significant losses of the enthalpy and against reasonable costs. The heat losses per kilometre are larger at elevated temperatures. Thicker and/or more expensive insulation can reduce the losses but at much higher costs. In the model we distinguish between steam pipes and hot water pipes.

4.3 Cost factors

Total installed costs of a technology consist of the equipment, transport and installation costs, civil works (e.g. ground work and piping), transaction costs. Manufacturers tend to give equipment costs only, which are only part of the total installed costs. Where accurate data of total installed costs was not available, these have been estimated with the hand factor methodology. Hand factors provide average ratios between equipment cost and their contribution to the total installed costs for different types of equipment. This is an established methodology in cost engineering, which is often used for early stage (i.e. conceptual) cost estimates. It should be recognised that the uncertainty and variability is high at this stage (e.g. factor 2-3). It frequently takes several man months’ worth of effort to narrow cost and benefit uncertainties down to the +/-10% level for any individual site.

Scaling of the costs with the capacity is done using cost engineering functions described in the Appendix. The cost engineering functions result in a range for the costs, depending on the complexity of recovering the heat. Factors that are taken into account are the quality of the waste heat stream (degree of contamination), access to the heat source without much interference with the process and the degree of concentration of the heat flows (single flows easier to recover than multiple flows).

Operation and maintenance costs have been estimated on the basis of literature and manufacturer information. In the case that a high variation in operation and maintenance costs can be expected, we worked with average values. An example are heat exchangers for which operation and maintenance costs depend heavily on the environment. In some corrosive environments piping might have to be replaced every few years, whereas in more friendly environments the equipment can run for ten years without much problems.

DECC’s published energy and carbon price assumptions, and fuel intensity data are used to populate the remaining databases (see appendix).

4.4 Future development of heat recovery technologies

Over time, but primarily related to global cumulative installed capacity, most energy technologies have seen reductions in cost, improvements in performance and a broadening of application. Learning rates vary between technologies and markets, and are challenging to predict reliably. Of the technologies examined, heat exchanger technologies are most mature and only limited further improvements are anticipated. Heat pump and heat to power technologies are less mature and some cost reduction, performance improvement and applicability to wider conditions should be expected. Performance is always ultimately limited by thermodynamics.

The Appendix describes scenarios for technology cost and performance improvements, and the impacts of using these on future technical and economic potential.

5 Results of modelling

The model allows the UK potential for technical, economic and commercial viable heat recovery to be quantified across different scenarios. In the following sections the differences between these will be outlined. Sections 5.1 and Section 5.2 provide more detail on the technical and the economic potential respectively for heat recovery in the UK industry.

Of all heat consumed by industry, some 48 TWh/yr is rejected as concentrated heat sources, 13 TWh/yr of this is in the form of heat contained in hot solids (the difference in the sum for total heat sources is due to rounding). These are not taken into account in the analysis as no technology is currently available that is suited to practically recover this heat.

The modelling analysis quantifies several steps that contribute to the reduction of the amount of heat that can be recovered, compared to the amount of heat that is rejected by industrial sources. Starting from the heat sources, the analysis provides a quantification of the available heat for several sets of criteria. The different criteria provide estimates for the technically recoverable potential, the economically recoverable potential and the commercially recoverable potential (payback less than two years).

With today's industrial output a technical potential of 11 TWh/yr of industrial waste heat can be technically recovered and re-used. Of this 7 TWh/yr is found to be economically recoverable under, under private discount rates (with today's energy and carbon prices). Only 5 TWh/yr is however commercially attractive (based on meeting a payback within two years). Figure 5 summarises the attrition of the available heat in subsequent steps from available heat sources down to commercially recoverable heat.

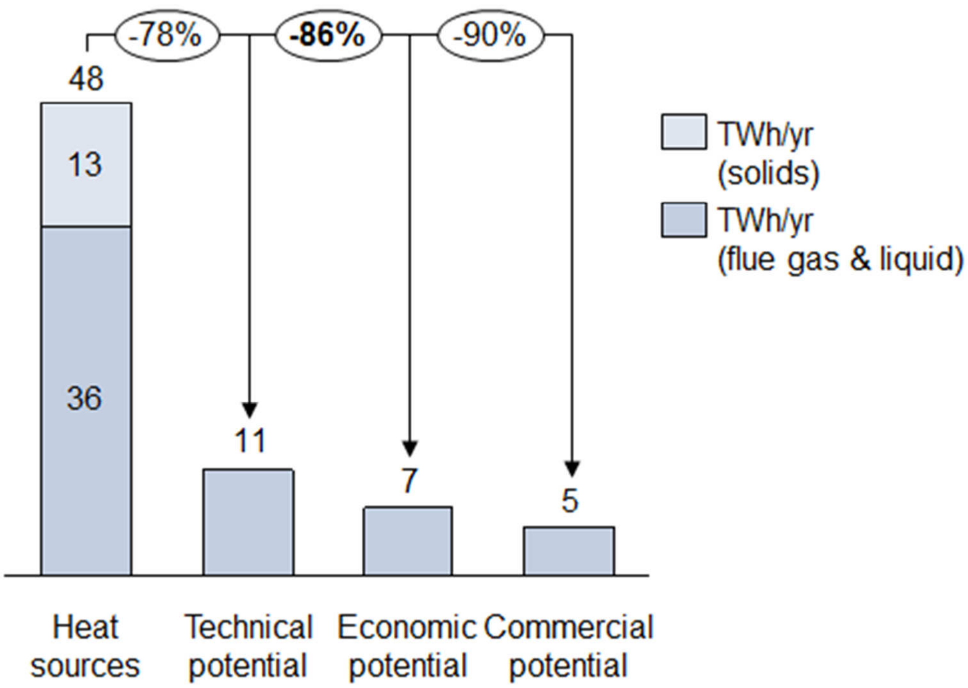


Figure 5 Potential for technical, economical and commercial heat recovery, compared to available heat sources under the base case. The economic potential refers to the Private i.e. 10% discount rate scenario.

5.1 UK technical potential for industrial waste heat recovery and re-use

The modelling identifies a technical potential of recoverable heat of approximately 11 TWh/yr, which corresponds to 2.2 million tonne of CO_2 abatement per year.

The technically recoverable heat is depicted in Figure 6, as well as the corresponding amount of abated CO_2. The factors for conversion of recoverable source heat to sink energy delivered and primary fuel replaced are depicted in the diagram on the right. Depending on technology effectiveness (especially for heat pumps and heat to power technologies) and process efficiencies the different ways of expressing the amount of recoverable heat can have different numeric values.

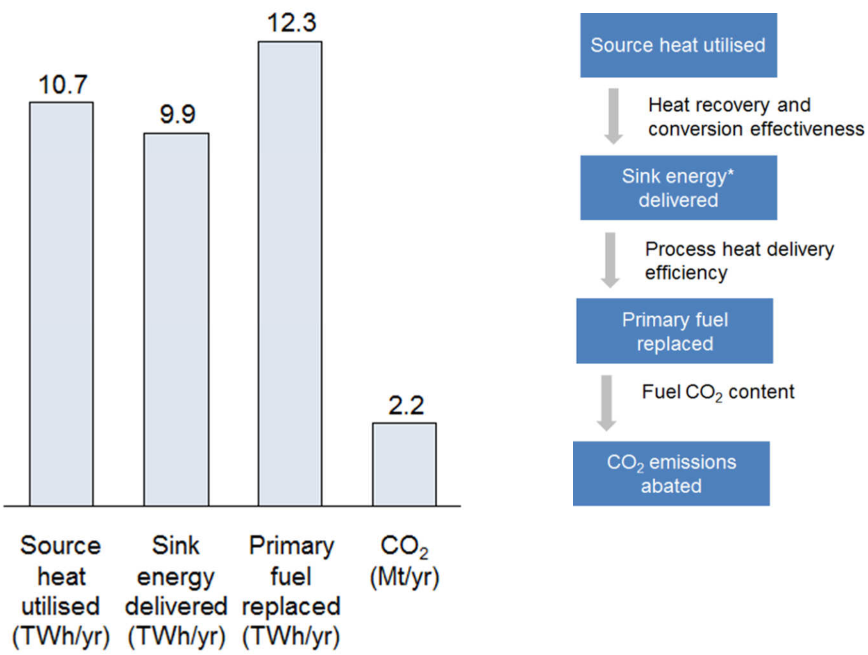


Figure 6 Base case technical potential for recoverable heat in the Base case. *Sink energy includes electricity generated from heat to power technologies.

Three main aspects that limit the amount of heat that can be technically recovered to approximately 25% of the available heat sources.

First, there is limited demand for low grade heat at industrial facilities. Many industrial facilities have rejected heat streams, but do not have significant demand for low grade heat. Often the best opportunities to use low grade heat (for instance air preheating) have been implemented already. The lack of low grade heat demand is especially apparent in the chemicals and the refinery sectors. The total source heat available, sink heat demand and technical potential to utilise source heat are depicted in Figure 8.

Two additional aspects that reduce the technical potential are mismatches in size between sources and sink (ie the amount of rejected heat vs the amount of heat demand) and competition to supply the same sinks from different sources. These aspects are less strong in cases where heat networks could realistically be developed.

Finally, there are currently no operationally implementable ways to recover heat from hot steel, which amounts to approximately 13 TWh/yr of rejected heat.

Caution should be taken when interpreting the results and using these for policymaking. In particular, the analysis is not designed to provide site and technology specific assessments. Hence, using this analysis for site and technology specific analysis is discouraged.

The relative contributions of different modes of heat reuse can be ranked in the following order:

1. Heat reuse on site
2. Heat delivery over-the-fence, to another site
3. Conversion of heat to electricity

This ranking is reflected in Figure 7, where heat re-use on the same site represents almost 61% of the technical potential. The delivery of heat from sources to sinks at other sites and the conversion of heat to electricity contribute 30% and 9% respectively.

If there is the potential for on-site re-use of heat, then this is usually more favourable in terms of CO_2 abatement potential. The estimation of the technical potential is based on maximising system abated CO_2. Heat delivery over-the-fence generally has a lower specific abatement potential than on site re-use, due to heat losses in transport and power requirements for pumping. The specific abatement potential of heat to electricity technologies is significantly lower still, due to the low heat to electricity efficiency at the low temperatures of rejected heat.

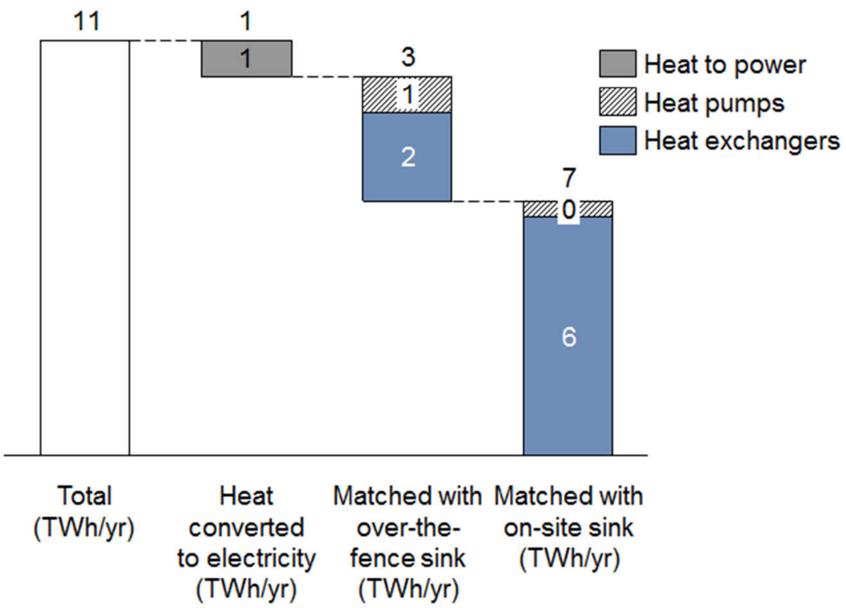


Figure 7 Application type of recovered heat in the technical potential, for different technology categories and on-site, over-the-fence and electricity-production applications. Base case. Data have been rounded where necessary.

The dominant technologies for heat recovery are heat exchangers, with heat pumps and heat to electricity technologies providing a significant lower contribution to the technical potential.

The contributions of these three technology types are depicted in Figure 7. Because the technical potential is determined by maximising the CO_2 abatement, heat exchangers are often more favourable than heat pumps or heat to electricity technologies. If there is an opportunity to recover heat through heat exchangers this often results in a higher CO_2 abatement. For heat pumps the CO_2 abatement is lower due to the electricity consumption combined with relatively low COPs, resulting from relatively high temperature lifts in industrial applications. The specific abatement potential of heat to electricity technologies is significantly lower still, due to the low heat to electricity efficiency at the low temperatures of rejected heat. The relative contribution of heat pumps compared to heat exchangers is slightly higher in over-the-fence applications.

The rejected heat is derived from a range of processes. The main application of recovered heat is preheating boiler water.

The contributions to the technical potential of different types of sources and the type of application of the recovered heat at the sinks are summarised in Figure 8a and Figure 8b respectively. The source heat is recovered from waste steam, exhaust gases and cooling water with similar contributions. Pre-heating boiler water is the dominant sink application. Although there is significant demand for further combustion air preheating, there is limited technical potential to supply this.

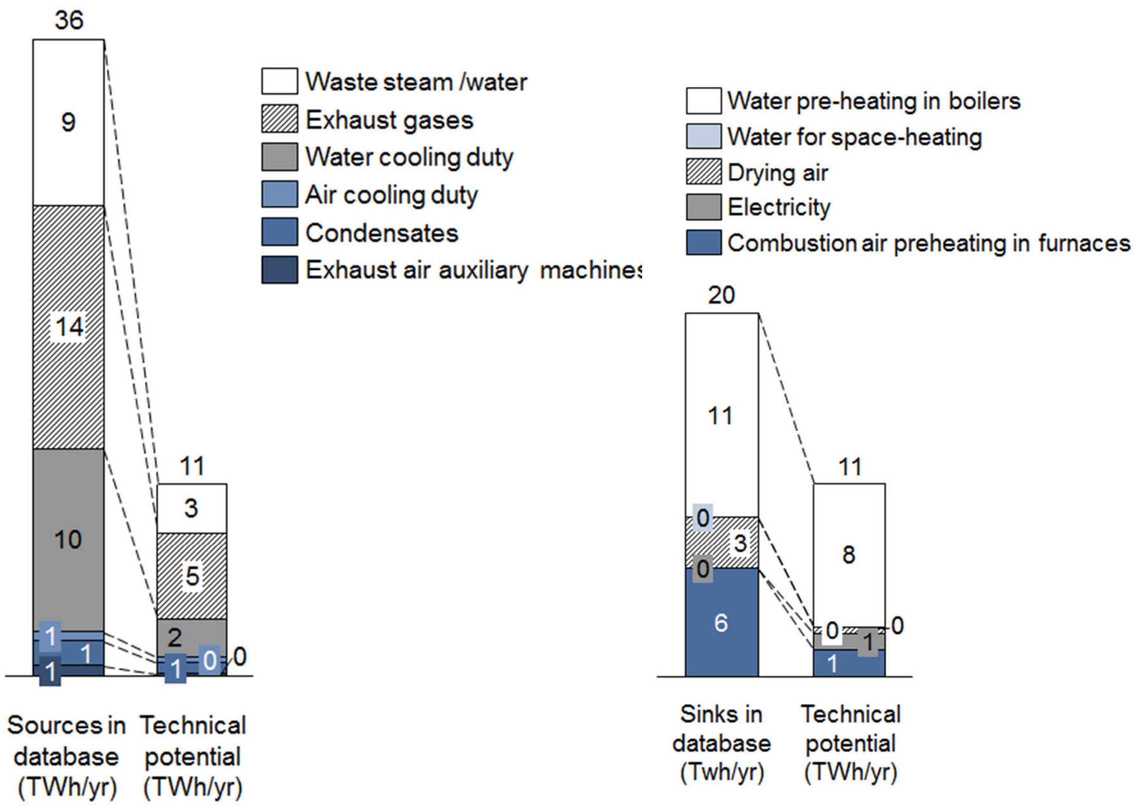


Figure 8 a) Sources heat flow in database and source heat utilised in the technical potential, per source of recoverable heat. b) Sinks heat flow in database and sink heat utilised in the technical potential, per application type. Base case. Data have been rounded.

The technical potential to recover heat is dominated by the few largest sites; 80% of the total potential for recoverable heat is provided by 35% of the sites.

The total technical potential is determined to a large extent by the few largest sites, and the larger number of smaller sites contribute relatively little to the total potential, as is indicated in Figure 9. This distribution is similar to the distribution of available waste heat (sources) over the sites. The results are consistent with the findings of Hammond and Norman (2012).

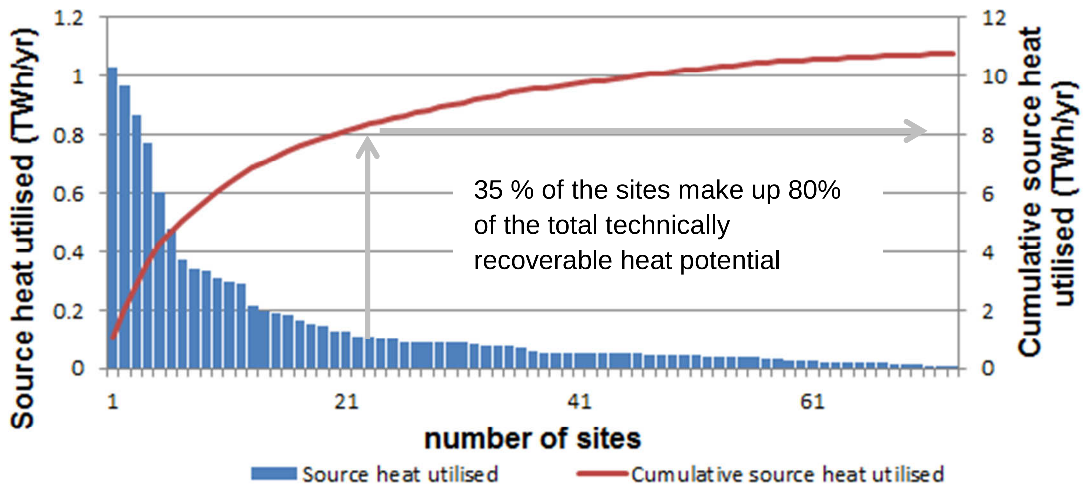


Figure 9 Absolute and cumulative contribution of individual sites to the total technical potential, source heat utilised. Base case.

Clearly there is a long tail (many sites with a limited contribution to the total recoverable potential, displayed by the right hand side of Figure 9), and the cumulative heat recovery potential will also to extend to sites which have not been modelled in this project. Inspection of Figure 9 indicates that improved accuracy at UK level could be obtained by extending the analysis beyond the limited 73 industrial sites examined thus far, but crucially also carrying out more detailed analysis on a few of the largest sites is essential.

5.1.1 Production of district heat

The potential for the production of district heat is modelled separately from the recovery and re-use of heat within industrial sites, and the results are therefore non-additive with the data presented above. The analysis quantifies the heat that could be recovered from individual processes and the costs of supplying this to a common specification at the "fence" of the industrial site. The availability of a demand for district heat and heat transmission and distribution costs beyond the fence of the industrial sites are highly geographically dependent and not taken into account in this study. Discussions with industry indicated that the level to which these opportunities have so far been examined vary strongly per site.

Industrial waste heat is not "free".

The analysis provides an opportunity to compare the costs of supply with other heat supply routes.

Some 4 TWh/yr of recovered heat can be made available for district heating at low production costs - less than £30/MWh, compared to a counterfactual heat production cost around 40 £/MWh[14]. This corresponds to approximately 0.8 Mt of CO_2 abatement. A further 24 TWh/yr and 1.7 Mt CO_2 abatement can be achieved at higher heat production costs, up to £90/MWh. (To recap, the identified potential for district heat production is non-additive with the technical or economic potential for re-use of heat within energy intensive industry).

The low production cost district heat corresponds mainly to the combination of high grade heat sources with heat exchangers. The higher production cost district heat corresponds to the combination of low grade heat that must be upgraded to the higher temperature required for district heat using heat pumps (assuming no material alteration to base industrial process design, which is a conservative assumption).

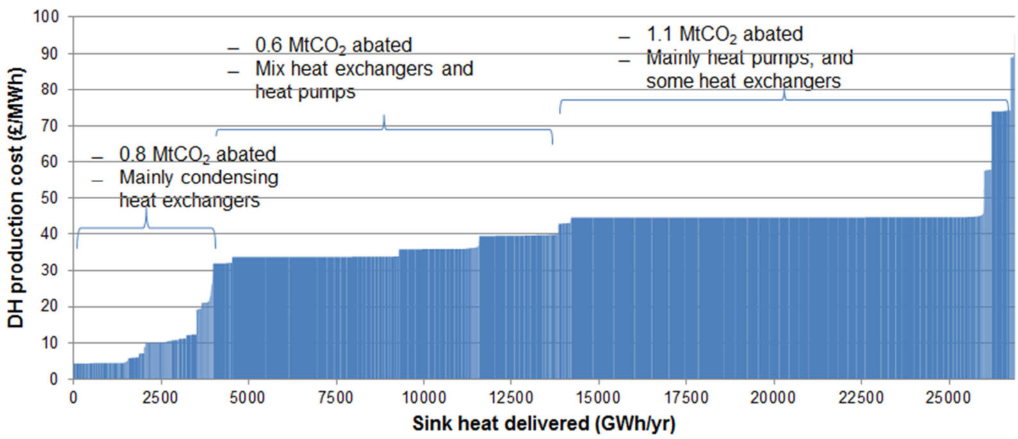


Figure 10 District heat production costs versus the capacity to deliver heat at the fence of industrial facilities, for all individual source-technology combinations. Private base case.

The power sector represents a significant additional potential for production of district heat from waste heat streams. However heat production from power plants in other more conventional ways than recovery from cooling water are likely more attractive if an appropriate district heat demand is available

A further 58 TWh/yr of district heat production from the power sector is identified, corresponding to 2.6 Mt CO_2 abatement, at a heat production cost of approximately £30 /MWh. The main source of recoverable waste heat in the power sector is very low grade cooling water. This analysis only investigates possible uses of waste heat and does not consider process changes or optimisations. Hence the only possibility to produce district heat at a temperature required for district heating systems, from low temperature cooling water, is by using heat pumps. If a suitable district heat demand is available near a power

[14] Based on heat production with a natural gas boiler (excluding district heat network investments), DECC fuel and CO_2 prices, 80% average efficiency, 70% load factor, 20yr lifetime, 10% discount rate, 60£/kWth capex cost and 5% OM cost.

station that currently doesn’t produce heat, there are likely more attractive routes to produce district heat that involve minor or larger interventions in the processes of the power plant than within the scope of the present study.

5.2 UK economic potential for waste heat recovery in industry

The economically recoverable heat and CO_2 abatement for the private and the social scenario are depicted in Figure 11. The economic potential in the social case (3.5% discount rate) is the highest in terms of both recoverable heat potential and CO_2 abatement, being 8 TWh/yr and 1.9 Mt/yr, respectively. The potential of economically recoverable heat, under private investor assumptions (10% discount rate), is approximately 7 TWh[15] which corresponds to 1.6Mt of CO_2 abatement per year. The commercial potential takes into account only those source-sink-technology combinations with a payback time less than two years. This results in 5 TWh/yr source heat utilised and 1.1 Mt CO_2 abated/yr.

The main reduction of the recoverable heat potential going from the technical to the private economic potential are the heat to power and heat pump projects. These are technically feasible but are not economic under the private base case assumptions.

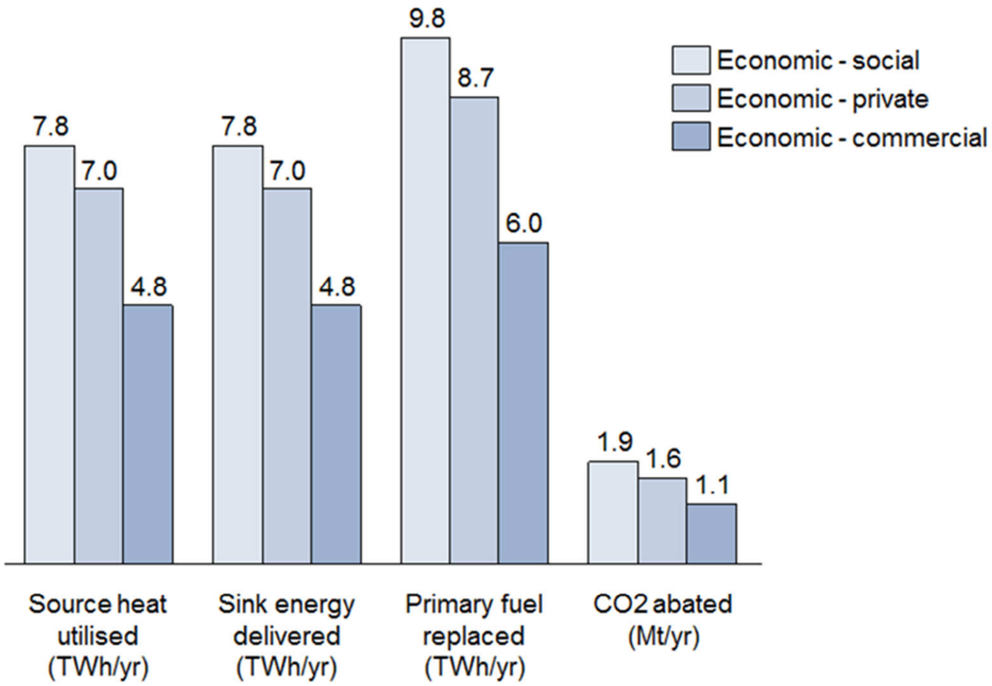


Figure 11 The economic potential for recoverable heat in UK industry, displayed for the social, private and commercial base case.

The economic potential is primarily made up of heat re-use options on site, as shown in Figure 12.

The main bottleneck that reduces the economic attractiveness of over-the-fence heat delivery are the costs for the heat transport infrastructure. While the technical potential includes also a significant number of over-the-fence heat delivery options and heat to electricity conversion, these are mostly not economically viable under the base case private assumptions. Taking into account only the commercial potential of projects with a

[15] To put these figures into context, the economic potential of 7 TWh reflects 2.4% of overall UK industrial heat energy use (*ca*. 291 TWh/yr) and *ca*. 4% of heat energy use within the leading eight heat intensive sectors (164 TWh/yr excl. power).

payback time of less than two years, the relative contribution of over-the-fence heat delivery reduces even further.

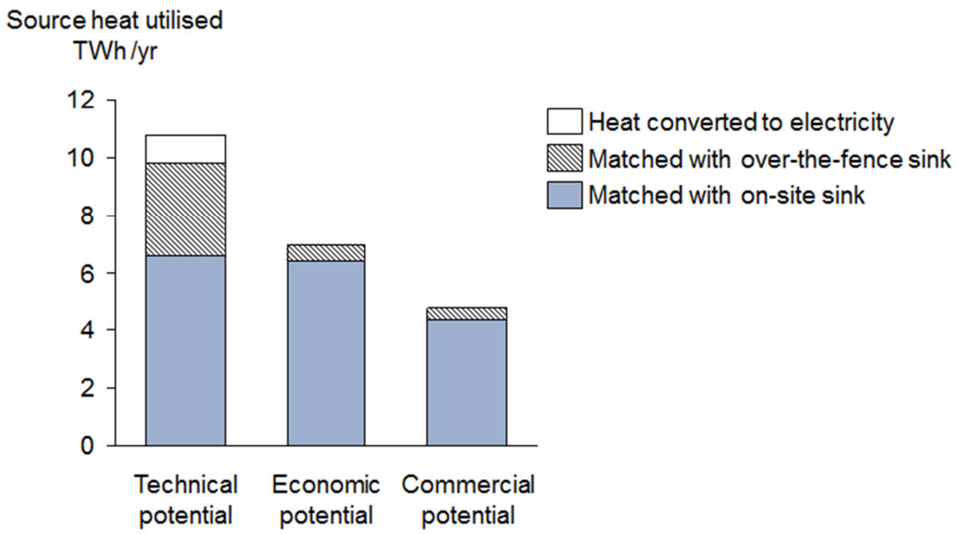


Figure 12 Application type of recovered heat in the technical, economic and commercial potential. Private base case.

The contributions to the technical and economic potentials of different types of sources and the type of applications of the recovered heat at the sinks are summarised in Figure 13a and Figure 13b respectively. The source heat is recovered from waste steam, flue gases, exhaust gases and cooling water with similar contributions. The main downward changes going from the technical potential to the economic potential, are from waste steam, exhaust gases and cooling water.

Pre-heating boiler water is, similar as in the technical potential case, the dominant sink heat application in the economic potential. Producing electricity is rarely economic.

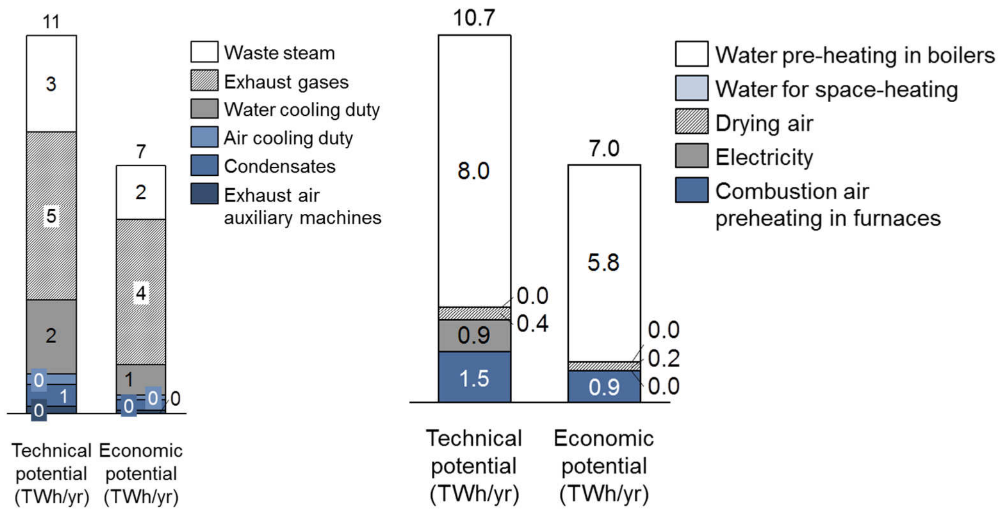


Figure 13 Source heat utilised in both the technical and the economic potential. Private base case. a) type of source of recoverable heat. b) type of application of recovered heat at sink. Private base case. Data are rounded for presentation.

Around 80% of the economic potential (as measured in terms of heat source heat utilised) identified is concentrated in 21 discrete sites, as shown in Figure 14.

This distribution is similar to the distribution of available waste heat (sources) over the sites. It would imply that a focus on these largest sites, in addition to a sectoral focus, is likely to be efficient in improving accuracy at UK level. A deeper investigation of potential heat recovery at smaller sites is required to understand the potential contribution from these, and particularly to develop a more accurate sectoral representation. This is illustrated further in the Appendix.

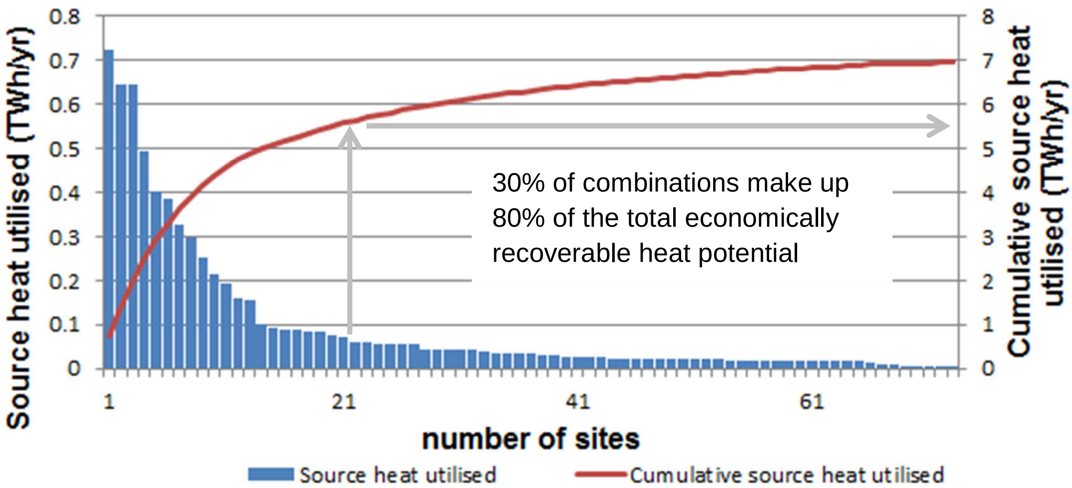


Figure 14 Absolute and cumulative contribution of individual sites to the total economic potential, source heat utilised. Private base case.

The private base case economic potential corresponds to a total capex investment of £204 million and results in total annual net benefits of £145 million/yr across UK industry.

The total potential is made up to a large extent by a few large source-sink-combinations, which is also reflected in Table 2, which shows that the median project cost and heat utilisation are significantly lower than the average. A detailed overview of the distribution of project investment costs is provided in the appendix. The total annualised capex costs in the private base case are £24 m/yr, while the annual opex costs are £13 m/yr.

Table 2 Statistical parameters representing all source-sink-technology combinations that make up the economic potential for the 73 industrial sites represented in the databases. Private base case.

Quantity		Mean	Median	Average absolute deviation	Max
Investment cost	£/million	0.8	0.3	1	18
Source heat utilised	GWh/yr	28	14	54	339
CO_2 abated	ktonne/yr	7	4	6	113

The positive net benefits for industrial heat recovery vary between £2 - 26/MWh for up to 7 TWh of source heat recovered. The average net benefit of the economic potential amounts to £18/MWh source heat utilised.

The specific net benefit per unit of source heat utilised is shown against the amount of source heat utilised per source-sink-technology combination in Figure 15. Although the estimate of the national potential carries a high inherent uncertainty on the net benefit, and underlying performance, counterfactual fuel costs and investment costs, of individual projects, Figure 15 does indicate the range of the specific benefit of heat recovery and the corresponding recovery potentials.

A number of uncertainties should be borne in mind when interpreting Figure 15. These are discussed further in the Appendix and include:

- Uncertainty in the heat that can be captured (i.e. the width of individual bars)
- Uncertainty in the net benefit (i.e. the height of the bar) resulting from a generic approach to estimating project costs and counterfactual energy costs.
- The methodology considers individual projects, rather than integrated heat networks.

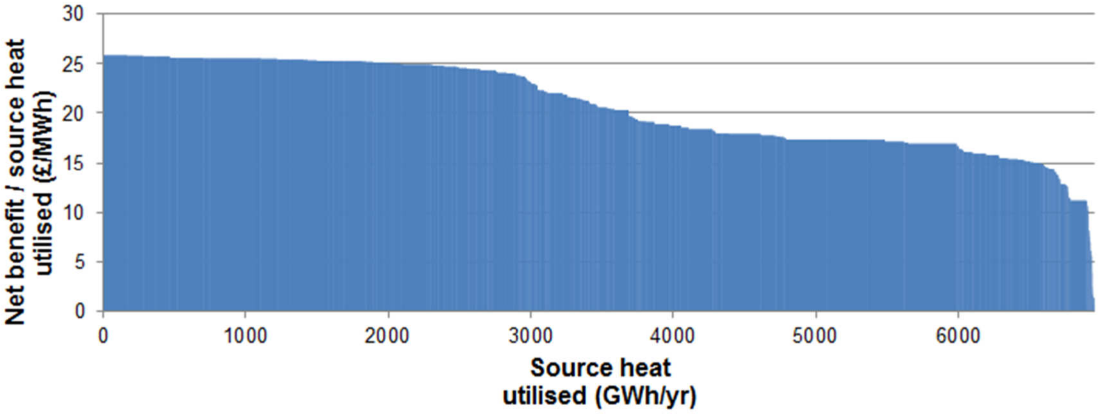


Figure 15 Marginal source heat utilisation benefit curve. The graph shows the potential for recovery and reuse of recovered heat, in terms of source heat utilised, against the specific net benefit per combination, for 256 source-sink-technology combinations. Private base case.

Industrial heat recovery provides opportunities to reduce CO_2 emissions with some 1.6 Mt/yr, while providing positive net benefits between £20-110/tonne CO_2 abated.[16]

The specific positive net benefits per abated tonne of CO_2 and the corresponding CO_2 abatement potential are depicted in Figure 16. Similar to the previous paragraph, the specific results per project are highly sensitive to the assumptions on costs and counterfactual benefits.

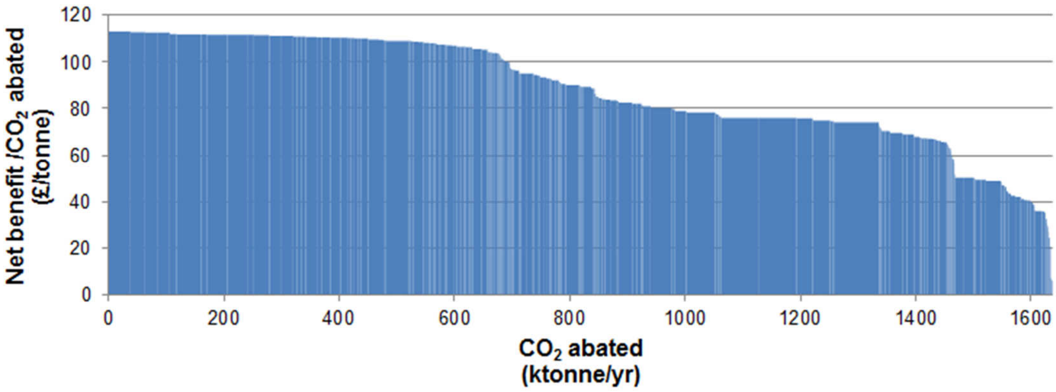


Figure 16 Marginal abatement benefit curve. The graph shows the potential for CO_2 abatement by recovering and reusing industrial recovered heat, against the specific net benefit per abated tonne of CO_2, for 256 source-sink-technology combinations. Private base case.

[16] 1.6 Mt/yr reflects 0.3% of the UK's overall direct CO_2 emissions (479 million tonnes per year in 2012). If implemented, a reduction by 1.6 $MtCO_2$/yr would contribute *ca*. 2% of the targeted Carbon Plan reduction (*ca*. 70%) in industrial emissions of 120 Mt/yr by 2050.

5.2.1 Geographic distribution of the economic potential

Figure 17 presents a map indicating the contribution to the economic potential from the large heat intensive industrial sites in the database. Although some clustering is evident, the potential is dispersed across the UK, implying opportunities are present in all Devolved Nations and English regions.

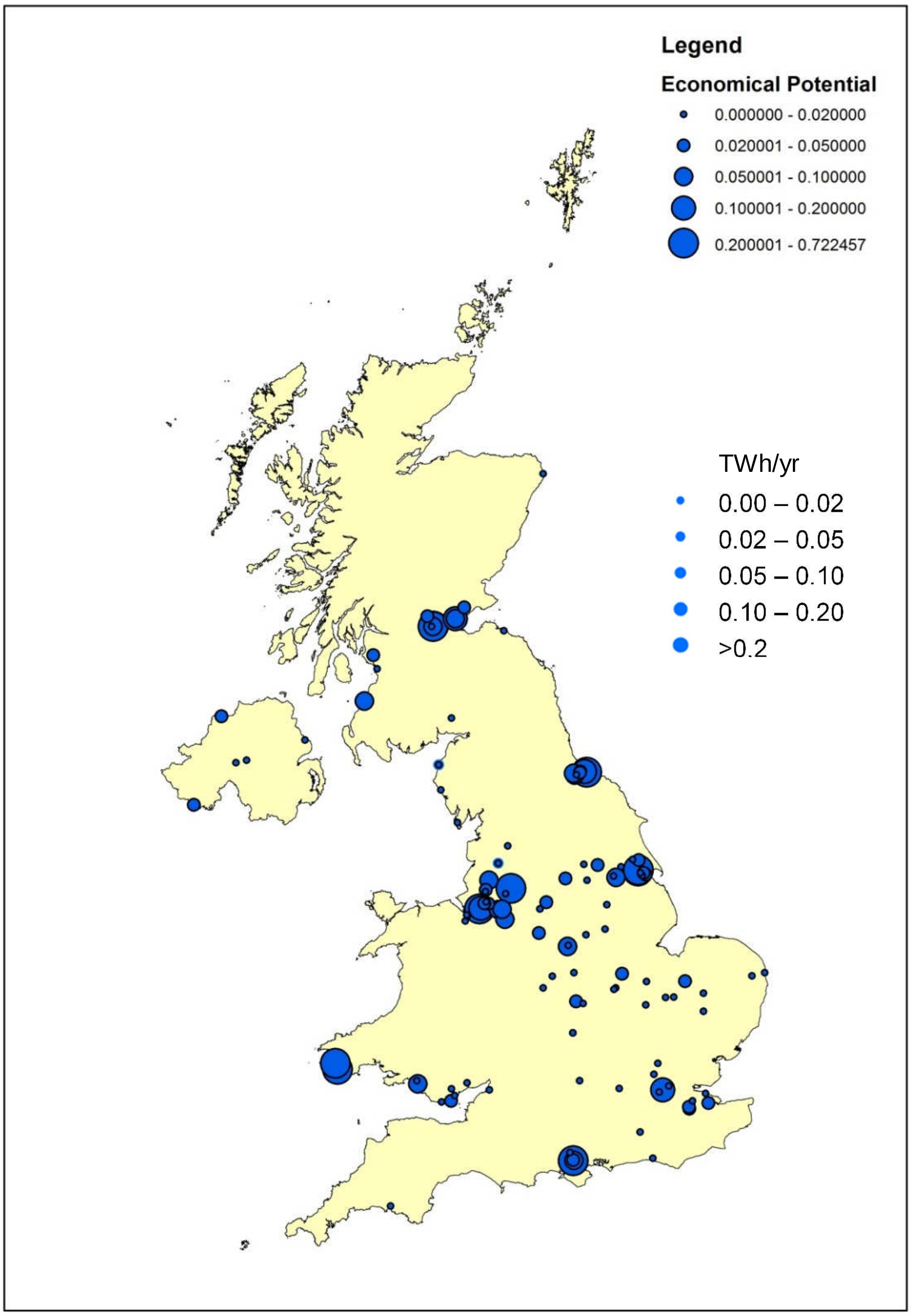


Figure 17 Map of economic potential, bubble size is proportional to TWh/yr

5.3 Sensitivity analysis of UK economic potential

By varying exogenous parameters, we found that the economic potential for heat recovery is most sensitive to the commercial requirement of maximum two year payback, fuel prices, capex changes and the amount of waste heat available from industry.

The total net benefit is strongest impacted by fuel prices, applying the non traded sector CO_2 prices and social investment criteria. The latter two parameters have a significant impact on the revenue, as expressed in Figure 19, but not sufficiently to turn the business case of many options negative, under the private economic scenario assumptions.

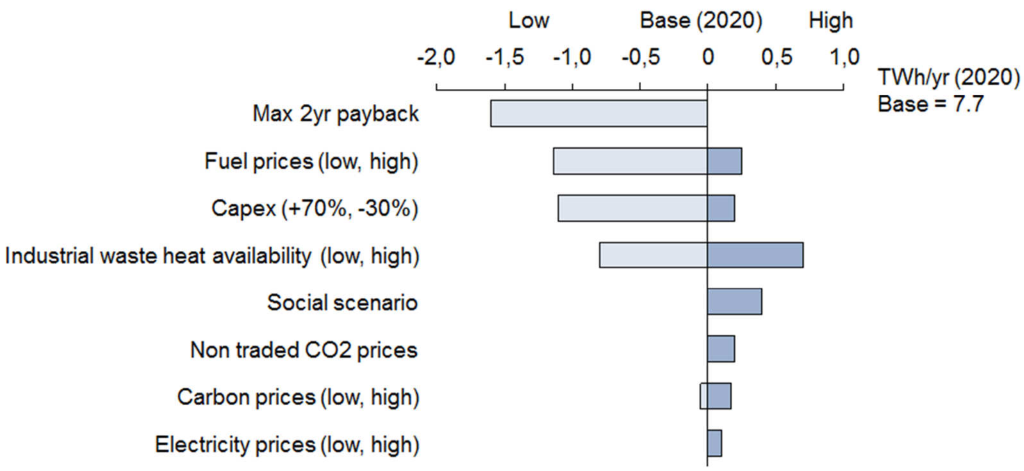


Figure 18 Impact of high and low sensitivities on the economic potential for heat recovery[17].

Low and high scenarios for industrial waste heat availability are provided in the appendix, and are based on possibilities for efficiency improvement at constant overall output. Low or high energy price scenarios for prices refer to the DECC low or high energy or carbon price scenarios for 2020. Base scenario is 2020 private economic potential base case.

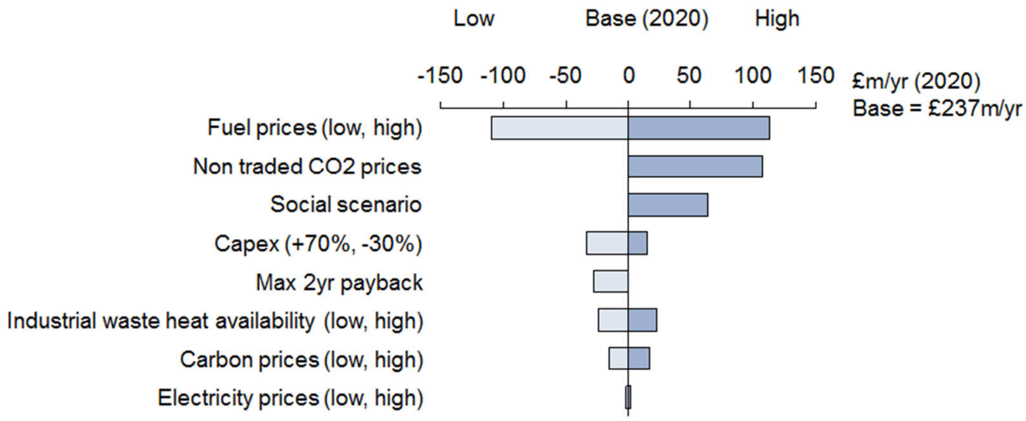


Figure 19 Impact of high and low sensitivities on the total net benefit of heat recovery measures. Low and high scenarios for industrial waste heat availability are provided in the appendix. Low and high scenarios for prices refer to the DECC low and high price scenarios. Base scenario is 2020 private economic potential base case17.

[17] The "Non traded CO_2 price" is the DECC price curve used in analysis for valuing CO_2 emissions outside the ETS, and represents the societal cost of CO2 emissions.

The impact of including the power sector in the analysis is negligible for both the economic potential for heat recovery and the related net benefit. There is however a base case technical potential for heat recovery from the power sector, which is 2.6 TWh/yr in 2020. This potential consists of upgrading low grade waste heat to a higher temperature and delivering it over the fence to another facility (although we recognise that plant redesign might significantly expand the opportunity). Both the heat pump installations and the heat transport require significant capital investments, making these options uneconomic. The opportunity in the power sector is discussed in more detail in section 5.1 on district heating.

Many factors could significantly change estimates for the technical and economic potential.

Care is taken to reduce the biases resulting from the modelling assumptions, although these can never be completely excluded. There are however a range of modelling assumptions that have an impact on the estimate of both the net benefit (£/MWh) and the total potential (MWh).

A summary of the main modelling and database assumptions that impact the estimate of the technically and economically recoverable heat are given in Figure 20.

Some of these assumptions have an incremental impact. For instance, the limitations of the 80/20 approach to data collection could be reduced by taking more sources and sinks into account; this would increase the estimate of the technical and economic potentials and will slightly reduce the estimated average specific net benefit.

Other assumptions have a potentially larger and more uncertain impact on the estimate of the potential for recoverable heat. For example, if a technology were to be developed to recover waste heat energy from hot steel, this would increase the total amount of heat that can be recovered.

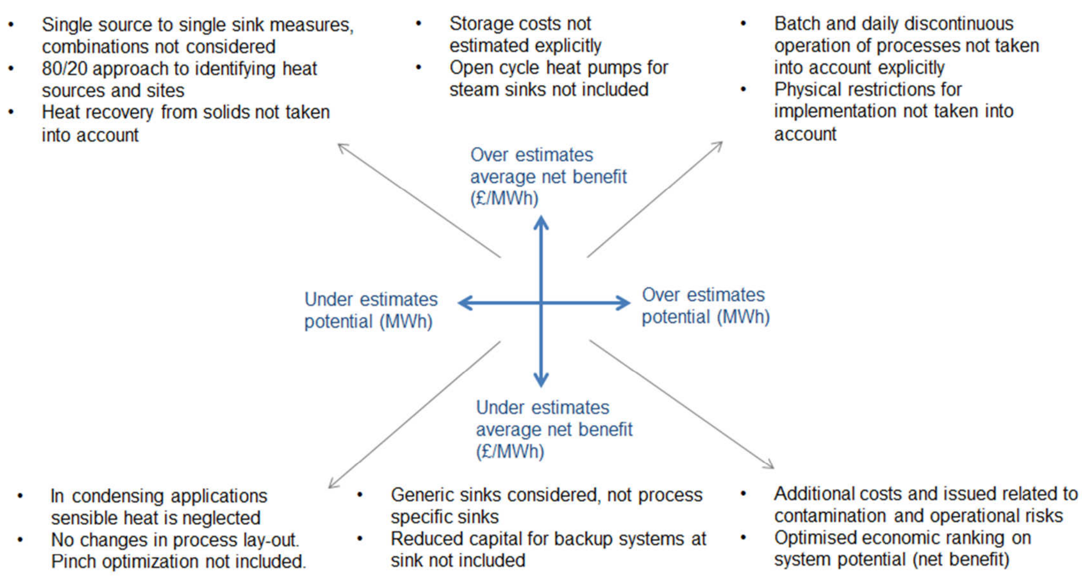


Figure 20 Impact of assumptions on estimate of potential and average specific net benefit

6 Conclusions

The project has led to the creation for DECC of novel databases of industrial heat sources, sinks and heat recovery technologies, and a novel Excel-based modelling platform that quantifies the technical and economic potential for waste heat recovery and re-use in UK heat-intensive industry. The data and modelling approach are free of constraints of background intellectual property or confidential data, and the modular structure allows for inputs to be updated, for further model development (e.g. inclusion of barriers) and for users to carry out extensive sensitivity analysis.

The analysis identifies a potential for industrial heat recovery in the UK in the range of 5 TWh/yr to 28 TWh/yr[18], arising from hundreds of source-sink-technology combinations from just 73 large industrial sites. This estimate is consistent with other publicly available estimates, which are in the range of 10 TWh/yr to 40 TWh/yr, produced using alternate approaches.

The lower end of this range (5 TWh/yr) consists of measures that already meet industry payback time requirements, but which are currently not implemented. Further understanding of this lack of implementation requires investigation of barriers to uptake.

Heat recovery projects compete with other site projects for resources. Discussions with industry indicated barriers are likely to be heterogeneous but could include lack of technology awareness, lack of data on waste heat streams, access to capital, decision making mechanisms, and real or perceived increased operational risks. An additional 2-3 TWh/yr is economic under respectively private and social investment criteria, but do not meet industry payback requirements (total of 7 and 8 TWh/yr, respectively).

The majority of the heat recovery and reuse corresponding to the commercial and economic potential is within individual industrial sites. Unlocking further waste heat recovery potential would require heat networks connecting industrial heat sources with each other or with other commercial/residential heat users. Such schemes usually involve numerous stakeholders and multiple industrial facilities. They also present commercial risks that some energy intensive businesses may be reluctant to enter into, especially individually. The amount of heat available from the electricity generation sector would likely be substantially greater than from industrial sources, so the most cost-effective solutions would require an integrated approach to energy supply.

From the sensitivity analysis, the amount of heat that can be recovered and reused economically is impacted strongest by the required investment criteria (two year payback and social scenario) and the amount of waste heat that is available from industry. The financial net benefit (i.e. £/yr) corresponding to heat recovery is more sensitive to assumptions than is the actual level of heat recovered (TWh/yr). Further discussion of sensitivities is provided in the Appendix.

[18] 6TWh/yr commercial potential and 28 TWh/yr district heat production potential

7 Opportunities for further improving understanding

The analysis thus far was developed through a combination of literature review, techno-economic modelling, discussions with ten trade associations and technology manufacturers, and expert site visits with 11 individual businesses covering the eight industrial sectors and the power sector.

Whilst the present analysis provides a step forward in understanding the potential for recovery and re-use of surplus heat in industry, there are six dimensions in which additional work could provide further insight.

7.1 Improving accuracy of estimates

More accurate representation can be achieved by a combination of one or more of the following:

- Collection of additional data to expand the sources and sinks databases to cover more sites.
    - This could include cooling loads, which are not currently modelled.
    - Some sectors are particularly under-represented.

- Develop a wider range of archetypes, and/or better use actual site-specific data, to provide a more accurate representation of site energy use, which is heterogeneous within sectors:
    - Better representation of sources and sink characteristics (temperature, quantity, etc.).
    - Include more sub-processes
    - Allow for better representation of temporal variation and the role of thermal storage.
- Understand the variability in source, sink, technology, investor and energy/carbon price characteristics and by employing a probabilistic approach for parameters, rather than deterministic approach, gain a better understanding of the distribution of potential.
- Improve technology representation, through “micro-simulation” of individual technologies applied to different sectors.
- Amend the source-sink-technology matching algorithms to allow examination of networks with multiple heat sources, sinks and/or technologies.

More challenging, but potentially of substantial impact, is to understand future, rather than historical output. Importantly estimates of heat supply and demand over long timescales (10yrs +) are needed for consideration of systems where industry is part of a heat network. However in general UK industrial site output forecasts (nor indeed current volumes) are not readily available, and for most industries unlikely ever to be reliable at site level.

7.2 Understanding barriers to delivering the economic potential

Through discussions with Trade Associations and companies, the project has identified challenges to delivering the commercial potential, beyond simply the capital and ongoing costs of heat recovery technology implementation. These include:

- Lack of data on waste heat and process-specific heat use on site (e.g. through lack of metering at some of the smaller sites).
- Real and perceived operational impacts and risks from installing heat recovery technologies. This includes concerns over fouling, requiring expensive materials for construction (to minimise corrosion). The presence of solids adds further complexity, requiring additional design evaluation and capital costs. Other aspects are availability risks from process integration of different assets.
- The decision-making process is not conducive to installing heat recovery technologies (expertise, frequency, key performance metrics such as rapid payback, budgeting processes and budget levels)
- The real or perceived fit of heat recovery solutions with industrial applications (e.g. timing constraints required downtime, design friendliness, contractual terms, technology complexity or “hassle”, technology maturity).
- Policy uncertainty regarding support or foundation for longer term investments.
- Economic impact of shut down for integrating heat recovery technologies, missed revenue, potential cost for alternative supply options.
- Non-core nature of heat recovery, particularly several industries have expressed a need to focus on core products rather than “becoming an energy services company”. This also relates to potential commercial or liability issues associated with supplying heat offsite to a third party heat user.
- Lack of communication with other existing or planned heat producers and users in close proximity.
- Uncertainty regarding the rest life time of specific facilities and long term level of sustained industry activity.

7.3 Understanding commercial confidentiality and competitiveness issues

With any model, input accuracy and relevance limits output quality. One of the practical constraints for accurate inputs encountered in this study relates to site specific parameters, particularly the quantity of heat produced or used.

Plant process and sub-process descriptions and capacities form a crucial element of competitive (dis)advantage for firms. They also form the basis of multiple commercial negotiations. From discussions during this project it is considered very unlikely that companies will voluntary provide accurate site data to be collated into a publicly accessible database, including an internal DECC database that could be vulnerable to Freedom of Information (FoI) requests. Even when third party data providers have collated some sectoral data, their re-use in a public database undermines the data providers’ business model and it will be challenging to employ these sources of data. This forces a reliance on weak proxy data such as CO_2 emissions to estimate production levels. In some cases, industry is expressly forbidden by competition authorities from divulging quantities produced, to avoid market fixing.

These commercially sensitive data are however critical for understanding accurately the potential for heat recovery and re-use. The data will be needed by heat network planners and project developers to size and cost solutions.

Any efforts to improve the technical accuracy analysis need to resolve this challenge, and therefore it would be worth exploring options for this with industry trade associations and competition authorities.

7.4 Developing an uptake model to understand the impacts of different financing models

Several trade associations and companies interviewed for this study identified that they would be more willing to consider installation of heat recovery technologies if financial support could be provided. Whilst this would be understandable for projects that are economic but fail to meet commercial criteria, the ubiquity of this feedback suggests that the analysis to date may not represent all costs incurred by industry. Indeed, hidden and missing costs are frequently observed for energy efficiency measures and the extent to which they represent a barrier to investment requires further quantitative analysis. Suggestions of financial support mechanisms from industry included tax-based instruments such as enhanced capital allowances, low interest loans, capital grants and on-going revenue support analogous to the Renewable Heat Incentive.

A technology uptake model would be a useful tool to assess the costs, benefits and impacts of any financial support, and to assist in the design of efficient support methods to realise the potential of waste heat recovery in the UK.

7.5 Understanding heat recovery technology markets

This study has focussed on understanding the fundamental *demand* for heat recovery technologies. It would be useful for policymakers wishing to understand the technical and economic potential for heat recovery in industry to also develop an understanding of the *supply* of these technologies.

Although the study identified numerous heat recovery technologies, there is no definitive market analysis in the public domain that assesses the scale, business models, supply chain and availability of the various heat recovery technologies for use in the UK in different heat-intensive industries today.

It would also be useful to understand further how the technologies, and more importantly the commercial market for these are likely to evolve over time.

7.6 Understanding of heat networks

Whilst the commercial potential is dominated by on-site use of heat exchangers, the modelling identifies that an overall potential of 28 TWh/yr heat could be supplied from industry as part of heat networks. Given the geographic spread of industry, it is important to understand the overall economics of heat supply, transmission, distribution and demand for heat networks through an integrated exercise.

The stakeholder interviews suggest that direct over the fence connection between industrial sites or to a heat network faces numerous barriers and would require a step change in public intervention to deliver.

Regarding heat delivery to other facilities, especially over-the-fence, the interconnection between facilities is regarded as a significant operational risk by plant operators. Dependence on the processes of other facilities for operations or an external heat delivery requirement impacting operations is considered both a commercial and an operational risk. The sensitivity analysis reveals that this potential is dwarfed by the potential contribution from the power sector, implying the need for an integrated approach to energy supply.

8 Glossary

CHP	Combined heat and power
COP	Coefficient of performance
DECC	Department of Energy and Climate Change
DUKES	Digest of UK Energy Statistics
EU ETS	European union emissions trading system
GVA	Gross value added
GW	Gigawatt (unit of power equal to 1,000MW)
GWh	Gigawatt hour (unit of energy equal to 1,000MWh)
ITT	Invitation to tender
Mt	Mtonne (unit of mass equal to 1000 ktonne)
MW	Megawatt (unit of power equal to 1,000kW)
MWh	Megawatt hour (unit of energy equal to 1,000kWh)
NPV	Net present value
ORC	Organic rankine cycle
TWh	Terrawatt hour (unit of energy equal to 1,000GWh)
£ m	million pound
£ bn	billion pound

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Additional references are listed in the Appendix.