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sustainable energy for everyone

The potential for recovering and using surplus heat from industry

Appendix for Final Report
For the

Heat Strategy and Policy Team
Department of Energy and Climate Change

04th March 2014

Element Energy Ltd
Ecofys BV
Imperial College (Centre for Process Engineering)

www.element-energy.co.uk

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Lotte chemical

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North Bank Growers

Ochsner

Durr Cyplan

Smart Heat

Reckmann & Jung

Danfoss

GMK

Triogen

PPSL Energy

Brugg Pipe Systems

Pipe2000

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Authors

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.

Ecofys

Ecofys has a clear mission: a sustainable energy supply for everyone. Based on our deep expertise in energy & carbon-efficiency, renewable energy, energy systems & markets, and energy & climate policy, we develop smart policies and solutions and bring them to life.

Imperial College

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.

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Contact Details:

Joris.Besseling@element-energy.co.uk

0330 119 0993

Harsh.Pershad@element-energy.co.uk

01223 852 496

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- “Base Case” Scenario and Results of techno-economic modelling
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- Sectoral assumptions and key issues
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Objectives of this document

- This document is the Final Appendix and accompanies the Final Report for DECC on the Potential for Recovering and Using Surplus Heat from Industry.
- The appendix provides further details on the main assumptions taken in the project and context for some of these.
- The appendix provides a disaggregation of results to help identify priorities for further analysis.
- The approach and datasets incorporate feedback received from Government and Industry to date where possible; however no confidential data are included in this report or within the modelling assumptions.

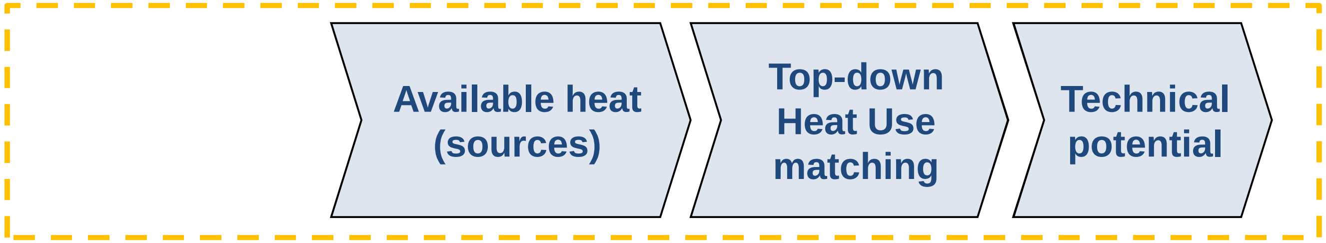
Previous approaches to estimating the technical potential for industrial heat recovery

- The most transparent and peer reviewed prior assessment of waste heat recovery in UK industry has been conducted by McKenna and Norman (2010), which estimated a technical potential of 10-20 TWh/yr based on averaged 2000-2004 data.

McKenna and Norman Model (2010)

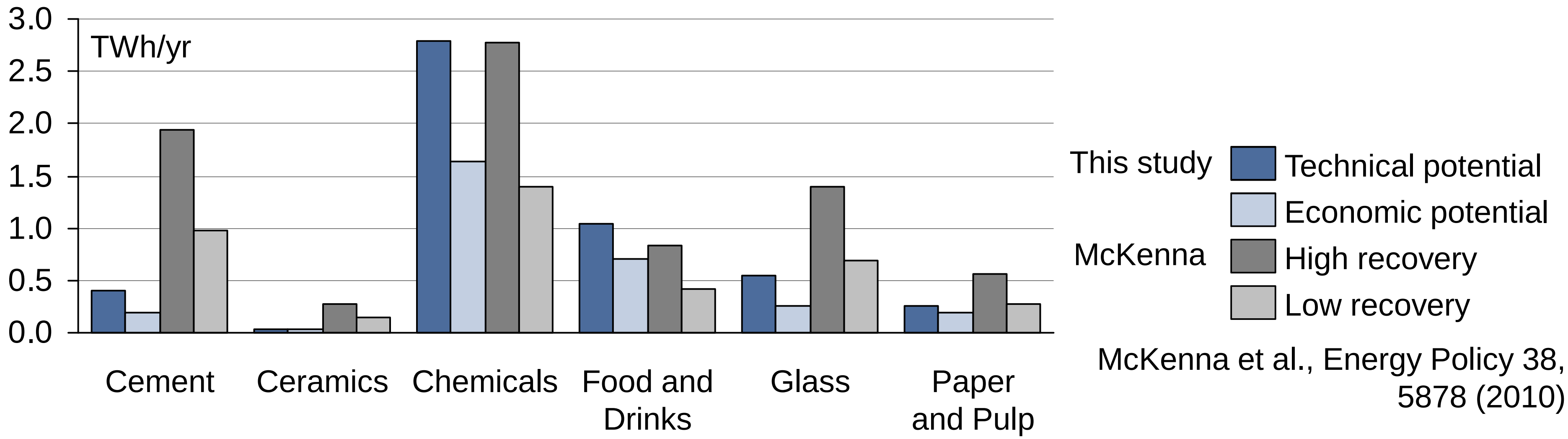
- The McKenna and Norman (2010) approach made the simplifying assumption that a fraction of recovered rejected waste heat can always be re-used, without considering the potential constraints around this. Norman and Hammond (2012) recently updated this in a recent conference paper to include greater analysis on the potential applications for re-using recovered heat.

Norman and Hammond (2012)



The total potential for heat recovery is similar in this study compared to the results obtained by McKenna and Norman, on a per sector basis

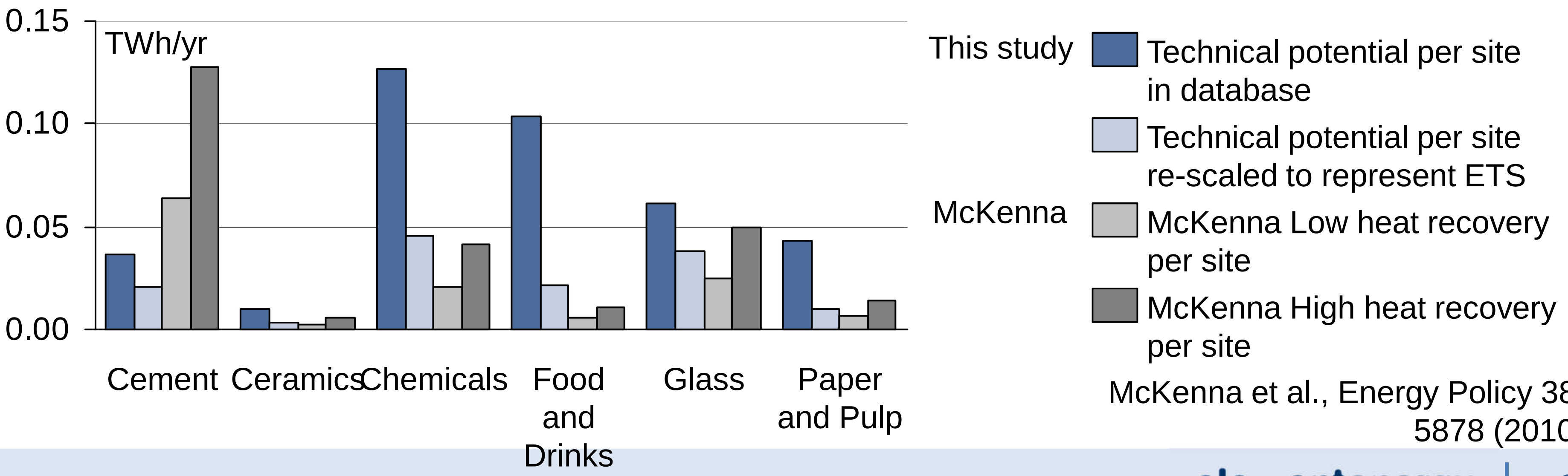
- The technical and economic potential as defined in this study do not translate directly to the high and low recovery estimates of McKenna, as set out on the previous slide. However the metrics do aim to similarly estimate the amount of recoverable heat in the different sectors.
- The results of heat recovery potential per sector show a strong similarity between the two studies.
  - The largest difference is in the cement sector. The main reason the potential is low in this study is the lack of heat sinks for most cement facilities. They are often remote from other facilities and lack significant opportunities to reuse heat on site.
  - The differences for the glass and paper and pulp sectors is mostly attributable to the limited number of sites considered in this study, as detailed further on the next slide.
- The iron and steel sector is left out of this comparison, because this study does not consider recovery from solids, which is included as source of heat in McKenna. This results in a large difference between the studies.
- The oil refining sector is left out, because that sector is not included in the McKenna study.



McKenna et al., Energy Policy 38, 5878 (2010)

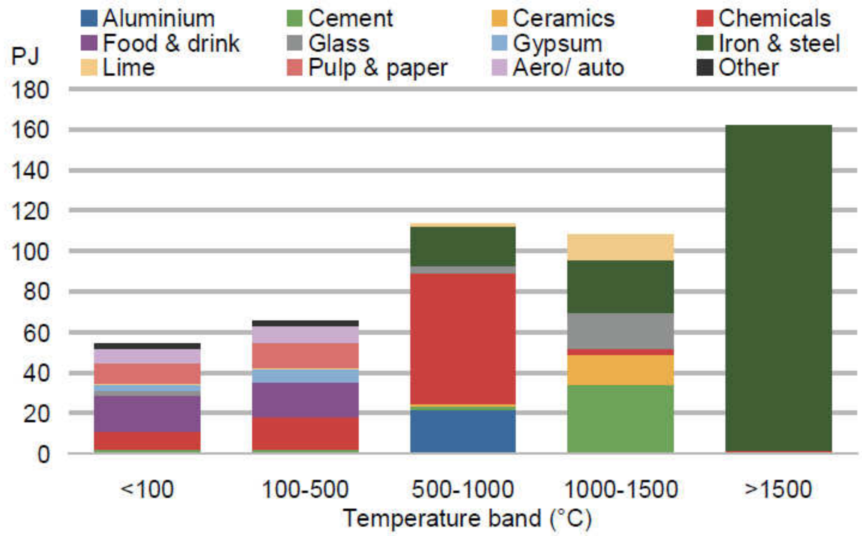
The estimate of the potential for heat recovery per site shows similar agreement between the two studies

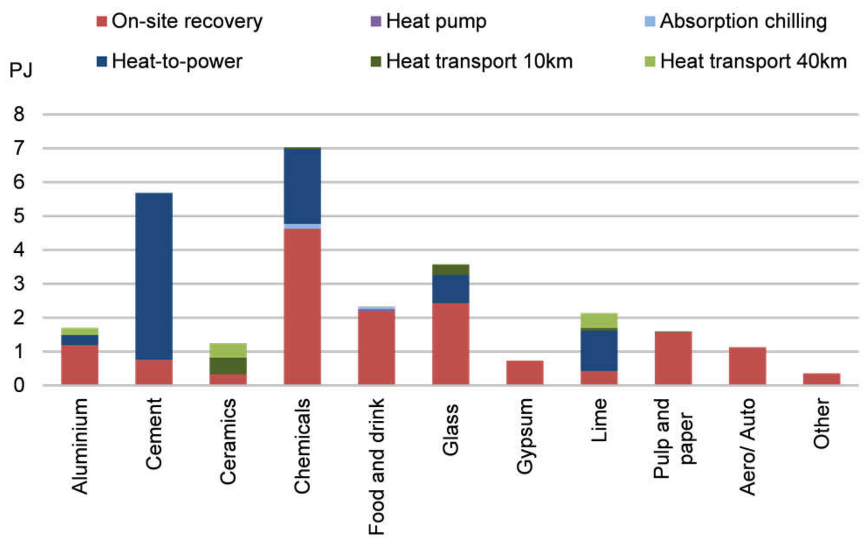
- The number of sites taken into account in the McKenna study is significantly higher than for this study.
- By rescaling the heat recovery potential per site for this study to reflect the fact that only the largest few sites are considered, the heat recovery per site can be compared with the study by McKenna. These metrics show a strong agreement between the two studies. The main exception is still the cement sector.
- This reflects the fact that the limited potential in this study is mainly due to the lack of heat sinks. This results in both a total and a per site low heat recovery estimate
- The glass and paper and pulp total estimates differ significantly (previous slide), while the per site estimates are vin good agreement. This reflects that the differences in the total estimate, are mainly due to the limited number of sites that are considered.



McKenna et al., Energy Policy 38, 5878 (2010)

Prior studies have identified that the potential for heat recovery and re-use varies considerably between sectors.





Upper panel (heat demand by manufacturing sector, excluding CHP)

Lower panel (potential heat recovery application by re-use)

Both figures generously provided by Dr. Jonathan Norman.

Norman, J.B., 2013. *Industrial Energy Use and Improvement Potential* (PhD). University of Bath

N.B. These data do not form inputs to the present study as considered out of date, as based on ETS Phase I data. Norman has not reported analysis of what measures are implemented.

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To understand the economic potential, it is essential to understand project level economics through source-sink-technology matching.

- A literature review reveals only a few papers that examine quantitatively the overall UK potential for waste heat recovery and re-use from industry or even sector-specific estimates.
- The analysis by Norman and colleagues at Bath University provides a useful approach for understanding the UK technical potential, without the need for excessive site level modelling.
- However to meet DECC's requirement for a transparent estimate of the UK economic potential, it is necessary to develop a new approach that allows individual projects to be identified and economic benefits to be ranked and combined.

This Model

8 industrial sectors

(+ Power to be added)

Available heat (sources) and heat demands (sinks) → **Source-sink matching** → **Technical potential** / **Economic potential** / **Commercial potential**

- All models are pragmatic simplifications of a complicated reality, they are designed to aid understanding.
- Variations in modelling approaches and/or database assumptions could lead to alternate estimates of the potential.

The new approach provides a transparent and flexible platform that allows DECC to establish the potential for heat recovery across a wide range of scenarios.

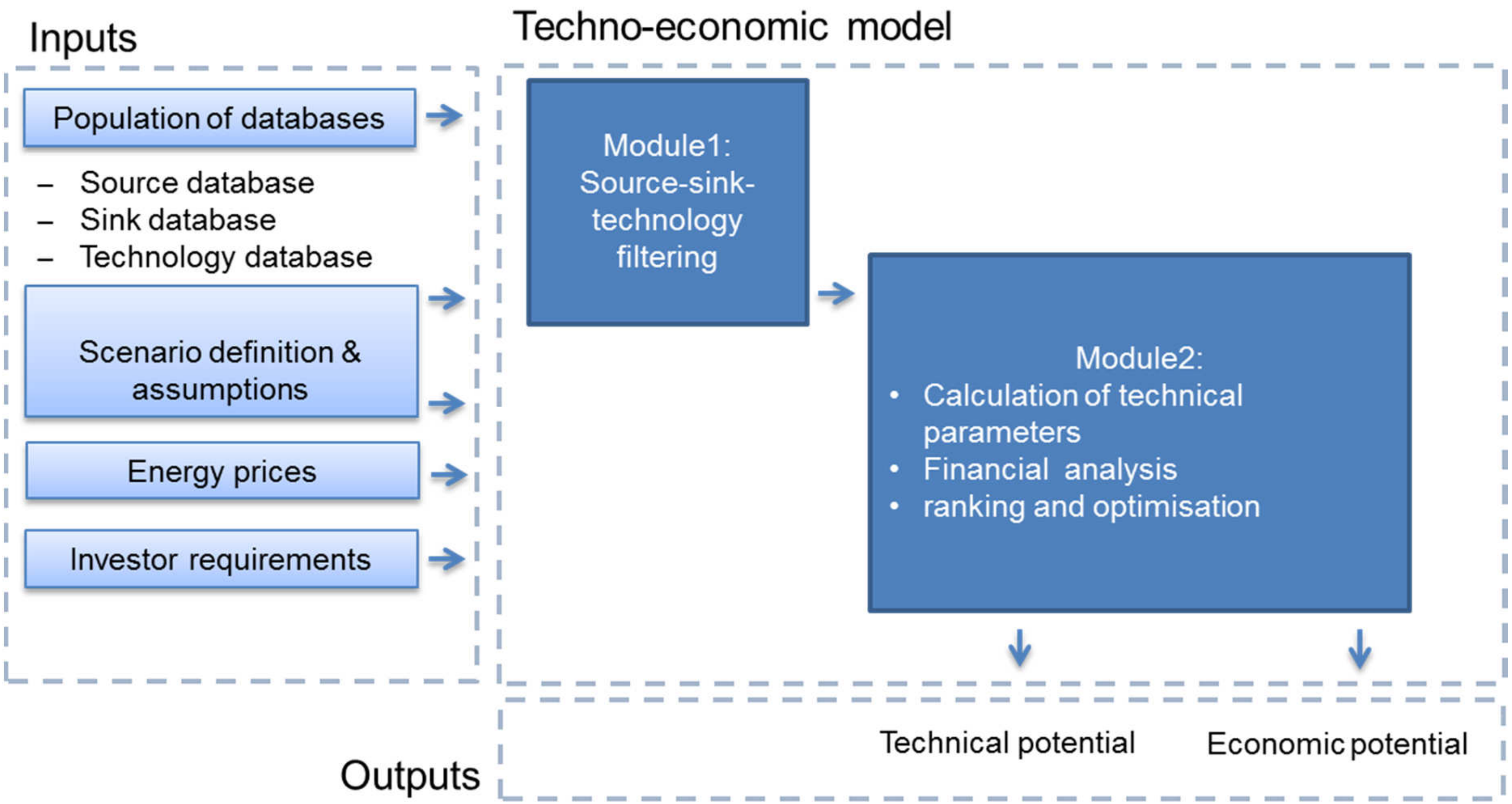
Heat consumption	Heat sources	Technical potential	Economic potential	Commercial potential
How much heat is used by industry?	How much is available for recovery?	Is there a suitable project (sink and tech for the source?	Positive business case over 25 yrs at 10% discount rate?	Payback <2 yrs

Source: waste heat stream available for recovery
Sink: heat demand available*

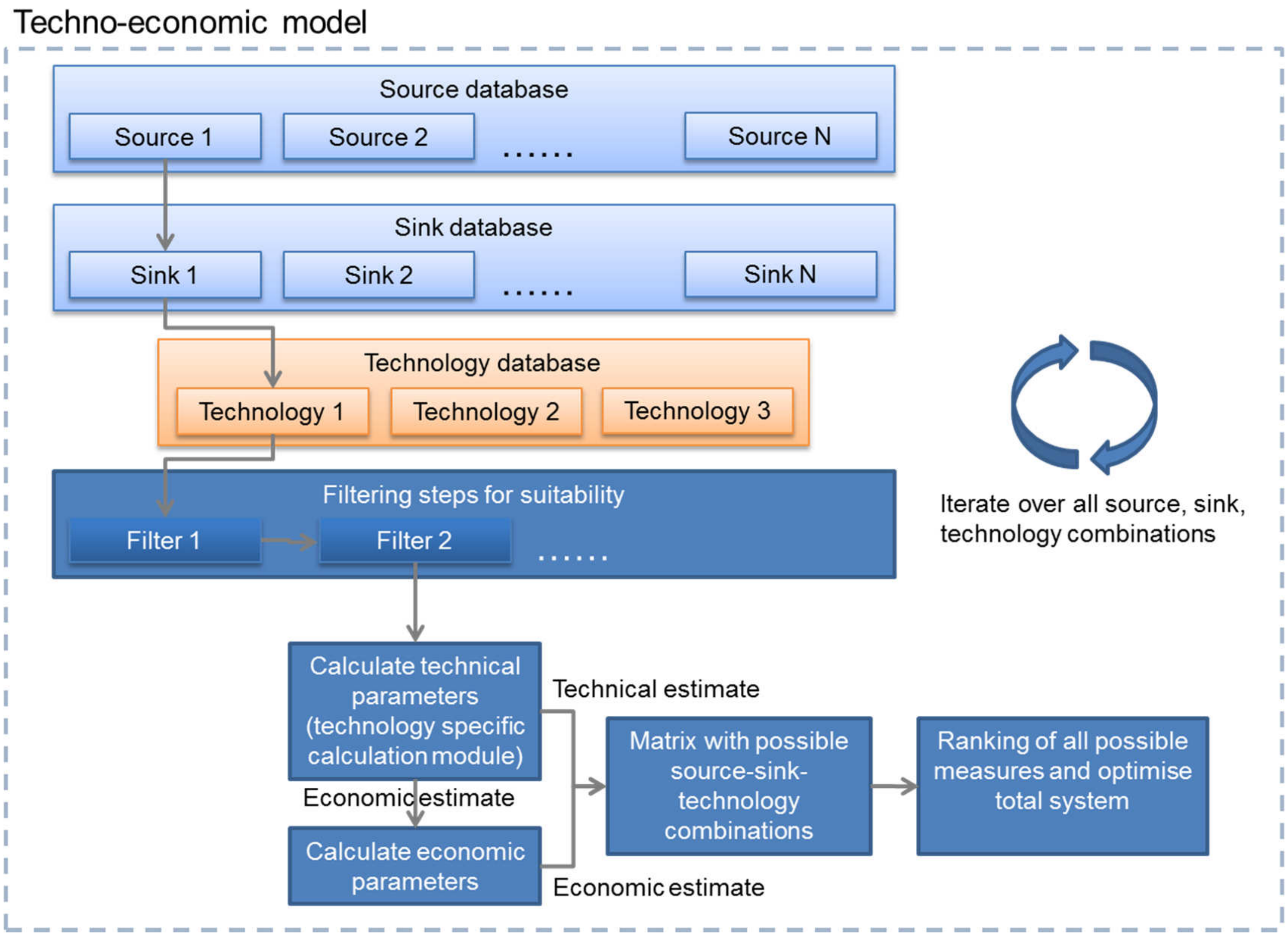
*available to correct for some heat demand that is already provided through heat recovery.

- **Heat consumption**
  - Total amount of heat used by industry
- **Heat sources**
  - Fraction of total heat consumption rejected in a waste stream which may reasonably be available for recovery (but not already used)
- **Technical potential**
  - Fraction of heat sources within 40km of a sink of suitable capacity, medium and temperature, taking into account availability and capability of technology.
  - Ranking based on CO_2 abated (only CO_2 saving systems included)
- **Economic potential**
  - Fraction of technical potential with a positive business case for two scenarios: private (10%), social (3.5% & air quality costs)
  - Ranking on net benefit
- **Commercial potential**
  - Simple payback within 2 years

Databases & assumptions are inputs for the techno-economic model to estimate technical & economic potential of UK industry heat recovery



Source-sink-technology combinations are filtered on suitability and matches are selected based on ranking to optimise total system



The economic potential is based on the net benefit of the individual heat recovery measures, evaluated at an annualized basis

Annual net benefit (£/yr) = Annual cost savings (£/yr) – Annual costs (£/yr)

Annual costs include

- Annualised Investment cost (based on capital cost, discount rate and economic lifetime)
- Fixed O&M cost
- Variable O&M cost
- Electricity cost

Annual cost savings are calculated from :

- Amount of primary fuel saved at sink (MWh/yr)
- Efficiency of heat generation of incumbent system
- Fuel choice (e.g. gas, coal, oil) and corresponding industrial fuel price
- Avoided environmental payments (CO_2 price, air quality, subject to scenario)
- Avoided equipment costs are excluded from the analysis

All potential measures are ranked in terms of their net benefit, and the most favourable combinations are chosen.

Modelling approach - worked example of a site with on-site heat recovery

Heat consumption? → Heat sources? → Match and rank source with all feasible technologies and sinks → Technical potential? → Economic potential? → Commercial potential?

Consider a particular heat **source #6 at a Food & Drinks plant**

Site consumes 0.3TWh of heat p.a.

Source #6/7 is water from condenser at 60ºC, with available heat flow **0.036 TWh/yr**

97 suitable sinks at 11 sites within 40 km, matched with 4 technologies: heat exchangers and heat pumps

Match with largest CO_2 abatement 30 ktCO_2 p.a.:

- on-site sink #1, water pre-heating in boilers 15-50ºC using convective heat exchanger
- heat flow **0.036TWh/yr**

Investment: £0.6m for 4.5 MW HX delivering **0.036 TWh** heat p.a. and £113k for heat transport infrastructure; O&M: £40k p.a.

Primary fuel replaced: 0.045 TWh gas p.a. at 2.1 p/kWh -> £0.95m

Net benefit £0.7m p.a. @10% disc. 20 yrs, payback 1.8 yrs

Recover 0.036 TWh/yr heat saving **8 ktCO2/yr** with **net benefit £0.7m** p.a.

Modelling approach - worked example of heat upgrading and over the fence heat delivery

Heat consumption?

Heat sources?

Match and rank source with all feasible technologies and sinks

Technical potential?

Economic potential?

Commercial potential?

Consider a particular heat **source #5 at an Oil refining plant**

Site consumes **6TWh/yr** of heat p.a.

Source #5/19 is condenser cooling water at 50ºC, heat flow **0.44 TWh/yr**

79 suitable sinks at 7 sites within 40 km, matched with 4 technologies, heat exchangers and heat pumps

Match with largest CO_2 abatement 14 ktCO_2 p.a:

- over-the-fence site, next to refinery (200m), space heating using heat pump.
- heat flow **0.05 TWh/yr**

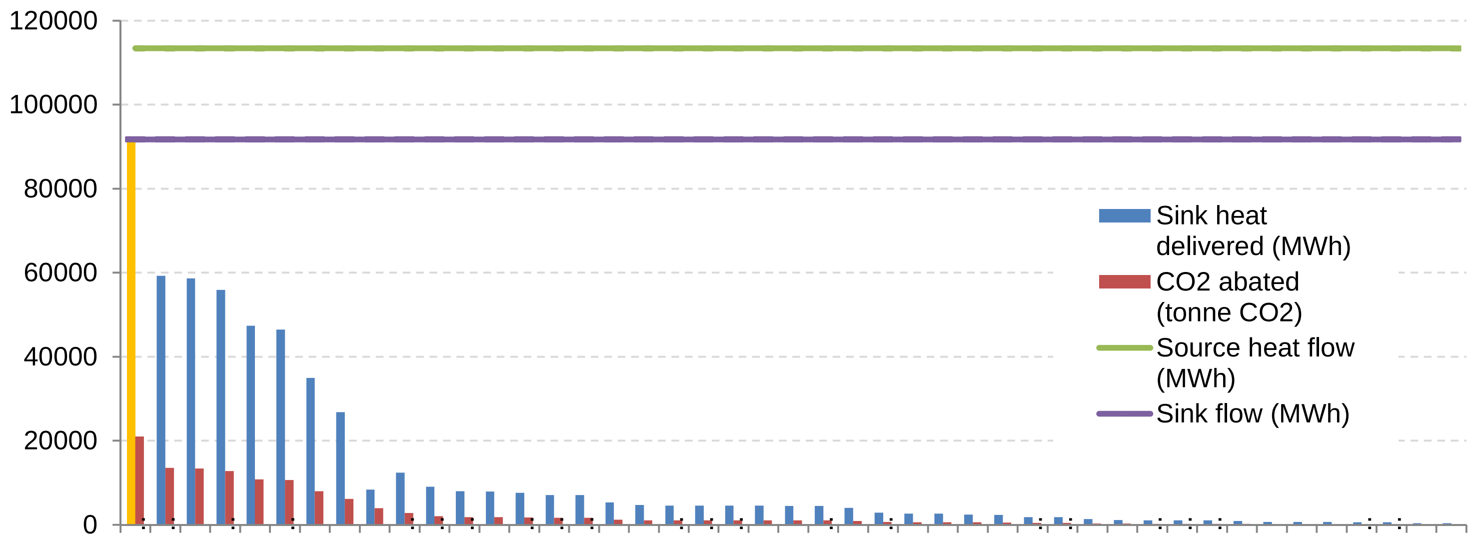
Investment: £10m for heat pump and £0.2m for heat transmission infrastructure delivering **0.06TWh** heat p.a.; O&M*(electricity)*: £1.2m pa

Primary fuel replaced: 0.08TWh oil p.a. at 3.5 p/kWh -> £2.8m

Net benefit £0.5m p.a. @10% disc. 20 yrs, payback 6.4 yrs

Recover 0.06TWh/yr heat saving 14 **ktCO2/yr** with **net benefit £0.5m** p.a.

Illustrative source-sink-technology matching



- For every source all feasible source-sink-technology combinations are analysed on the technical and economic metrics.
- The graph above provides a schematic overview of all feasible combinations with different sinks and technologies for a single source.
- These options are taken up in the total set of all feasible options and ranked on their attractiveness (depending on the chosen metric).
- The most attractive options will subsequently be selected. The yellow combination will be selected, if the source and sink corresponding to the yellow bar are not yet taken up in a more attractive option.

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Methodology caveats

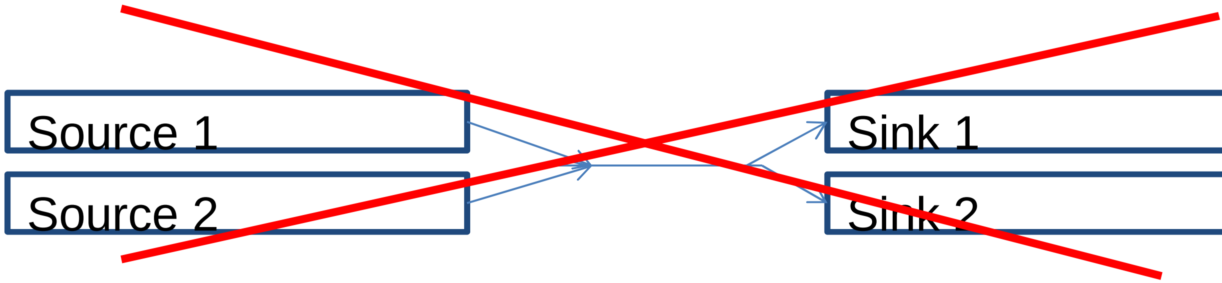
- Sectors and technologies are reduced to “archetype” properties, whereas in reality site and technology characteristics are heterogeneous.
- One source to one sink with one technology: if a source or sink has been used, both are no longer available
- Ranking of possible measures is done on “absolute” values (ie highest value measures first)
- Measures are chosen on ranking order, no optimisation
- Sites explicitly taken into account: top 88% largest EU ETS emitters
- Study considers heat intensive industry, small industrial and commercial not explicitly taken into account.
- Not actual site data: archetype processes mapped to the individual sites
  - For the avoidance of doubt, the project team has not scaled up data from individual site visits to each sector. The site visits were used to provide insight into current practices.
- Second order effects not taken into account (for example acceleration of process efficiency improvement or recovery technology development, due to higher CO_2 prices: not taken into account)
- Cost estimates based on generic cost engineering equations (costing of heat exchangers and hand factors to estimate total installed costs)
- The investment cost analysis considers the average total installed cost of a project. Project specific complexities and site specific additional integration costs are not taken into account. Trade associations have indicated that these impacts are likely to be substantial.

Methodology caveats

- Cost difference in retrofitting or new built not taken into account
- For condensing heat exchangers, only heat of condensation is utilised, convective heat is neglected
- For heat pumps heat transfer is assumed to be at constant temperature (sink and source at constant temperature; temperature increase and decrease neglected).
- For heat to power devices it is assumed that source heat stream can be rejected at respectively 40 °C and 180 ° C for low temperature and high temperature ORC
- Steam and flue gas pressure assumed to be 4 barg for heat exchanger costing. For some sectors and applications pressure will be higher, and cost increases with higher design pressures.
- For simplicity of presentation, the technical, economic and commercial potentials are presented as if accruing to the sector of the heat source. In reality the benefit from over-the-fence projects would likely be shared with the sector corresponding to the sink, and/or an intermediate energy company. This relates to the business model employed and is out of scope of the present analysis.
- The underlying absolute total CO_2 emissions from UK industrial sources have not been modelled, this project focusses only on savings related to implementing heat recovery technologies.
- Whilst the approach builds on a “bottom-up” calculation, the accuracy of the underlying databases and matching exercise is not sufficient to warrant identify favourable combinations of heat source-sink-technology at the sector or site level.
- The amount of heat already recovered and re-used within industry is out of scope of this study.

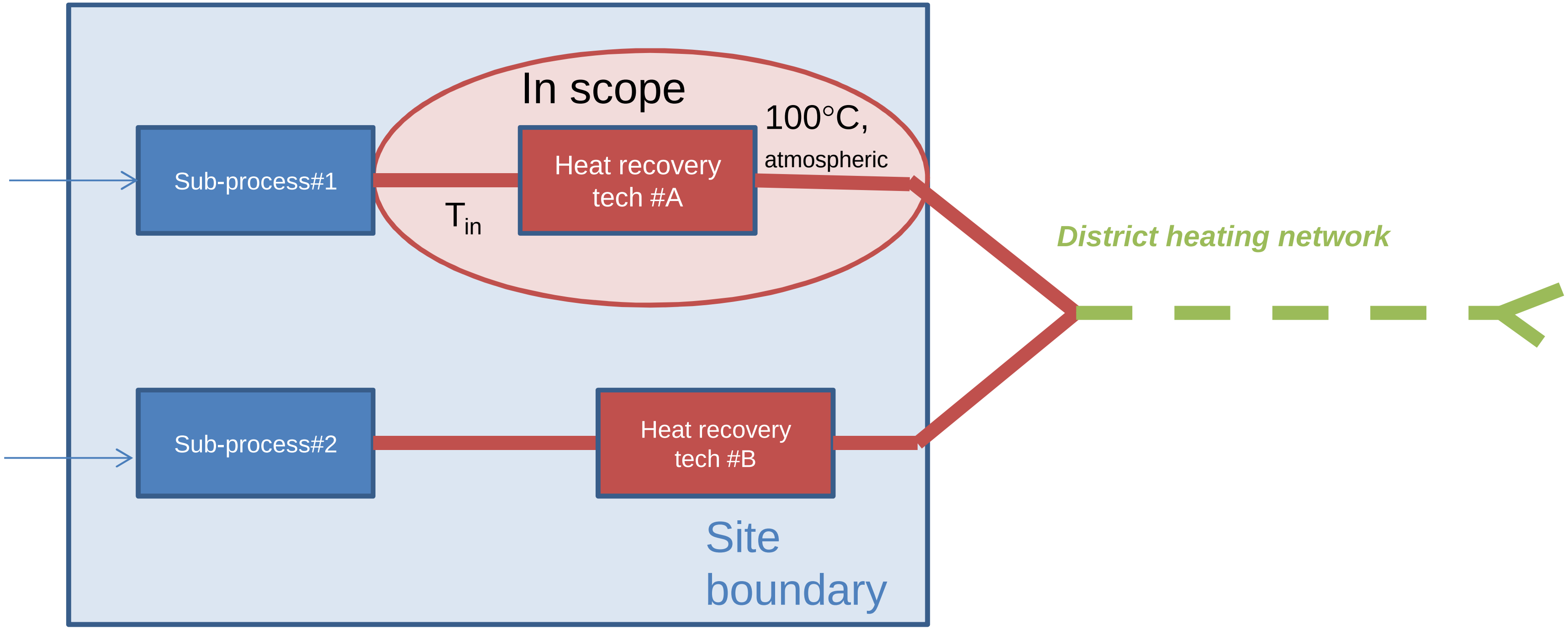
The modelling excludes integrated heat networks and plant re-design or process optimisation

- Only point-to point connections between source and sink are considered making use of a single heat recovery technology. Heat networks with multiple sources and sinks increase costs and complexity but may allow more flexibility and make better overall use of the waste heat recovered, however this is out of scope. Network optimization as in the example below and integrated networks of heat sources and sinks are not taken into account.



- Plant process reoptimisation and trade-off choices are out of scope. For example hot steam extraction from CHP plants is not considered, because this would reduce the efficiency of power generation.
- The calculation of the re-use of recovered rejected heat for power generation assumes that all sites can be connected to the electricity grid, *but excludes any a grid connection fee*.
- Avoided CO_2 payments are taken into account in profitability calculation but lifecycle CO_2 in the production and installation of heat recovery technologies, the acceleration of process efficiency and recovery technology development due to high CO_2 prices is not taken into account.

Costs for district heating option are the "gate" connection costs for each heat source to a heat network.



- The outputs of the model complement work carried out elsewhere on the potential for district heating in the UK by providing the cost of accessing individual heat streams.
- Modelling implementation; heat transfer to district heat supply at 100^{0}C atmospheric pressure
- 300 metres of on site pipeline work is assumed, with a 2/5th total installed cost factor
- Costs for the use of heat source in a district heating network exclude the aggregation of multiple heat sources, heat storage, backup, peaking capacity, transmission or distribution costs.

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There are several heat recovery technologies for UK industry, each with distinct costs, performance and relevance.

- A wide range of commercially available heat recovery technologies, including heat exchangers, heat pumps, heat to power systems, and heat transport contribute meaningfully to the overall UK technical and economic potential for heat recovery.
- The shortlisted heat recovery technologies for the analysis include regenerators (economisers), low temperature indirect contact condensation recovery systems, condensing and convective shell and tube-based heat exchangers. For a given temperature difference, the costs and efficiency for these increase with the area of the heat exchanger. Of the heat upgrading technologies, closed compression cycle and evaporative heat pumps were shortlisted. For conversion of heat to power, the study considered high and low temperature Organic Rankine Cycles.
- Transport of hot water and steam in pipeline networks is also considered. Here the critical parameters are the actual distance and the costs and heat loss per unit distance between source and sink.
- The overall fully installed project costs are assumed as 1.5x-5x the costs of the individual heat recovery technology, to reflect ancillary equipment, labour, insurance, installation, transport, project management etc., but some variability between sites should be expected.
- Individual heat recovery technologies are restricted for specific source-sink temperature and medium combinations. Additionally, some technologies will face compatibility issues, primarily because some waste streams from industrial sources are contaminated and would need clean-up prior to heat recovery.

A technology database defining the suitability, costs and performance of the most relevant commercially available heat recovery technologies has been prepared.

Technology pre-selection

Selection of heat recovery and conversion options from literature search and expert judgement

Data gathering

Literature search and expert judgement
- Data highly scattered
- Often poorly documented
- Unclear what is included
- Often outdated

Data obtained from manufacturers
- Hard to obtain on generic level

Engineering equations to scale installed costs with capacity and process parameters

Data validation & technology short list selection

- Cross reference data sources
- Use of manufacturer data to calibrate engineering equations for heat exchanger cost estimates

Technology commercial relevance

Good coverage of range of conditions employed

Technology database

Assessed, relevant parameters of technologies:
- Relevance for industrial use
- Temperature range in which technology can be operated
- Media that could be used in technology
- Efficiency indicators
- Costs of technology

The short list of technologies is based on industry relevance and ensuring operating range coverage of media and temperature

Recovery technologies	Conversion Technologies	Heat storage	Heat transport/distribution
Recuperators - (metallic & ceramic) Regenerators - Regenerating furnace - Heat wheel - Passive air preheaters - Regenerative burners - Economizers - Waste heat boilers Low temperature heat recovery - Deep economizers - Indirect contact condensation recovery Shell-and-tube heat exchangers - condensing: steam to water - condensing: steam to gas - condensing: gas to water - condensing: gas to gas - convective: gas to gas - convective: water-to-water - convective: water to gas - convective: steam to gas Plate type heat exchangers - gas-to-gas - water-to-water Plate-fin heat exchangers - gas-to-water	Heat pumps - Closed compression cycle - Evaporate heat pump - water-to-water - gas-to-water - Absorption heat pump - Absorption heat transformer - Open compression cycle - Mechanical vapor compression Heat to power - Rankine cycles - Traditional steam cycle - Kalina cycle - Organic rankine cycles - Screwed expander - Turbine - Low temperature - High temperature	Hot water storage (tanks)	Steam distribution Hot water transport

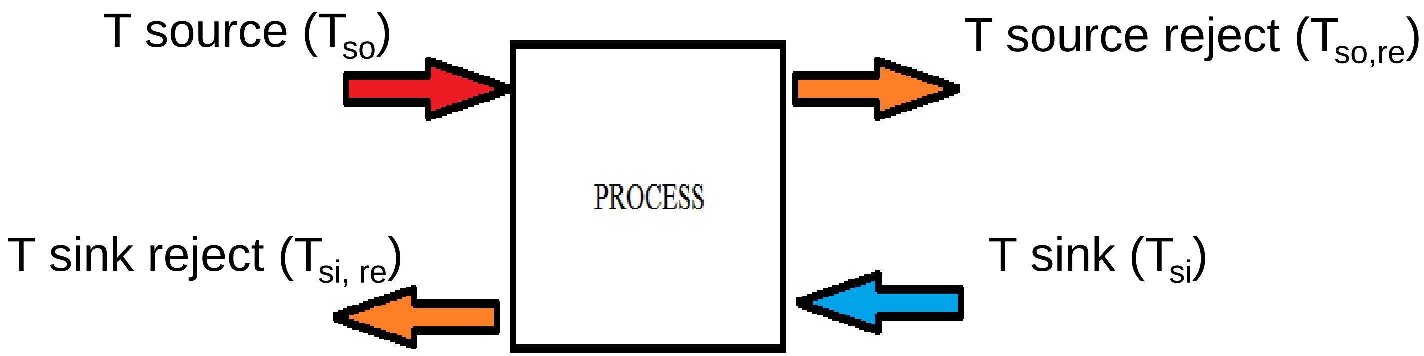
Black – Included in analysis
Grey – Excluded from analysis

Heat Recovery Technologies– Heat Exchangers (HX)

- **Operating principle/ function**: to transfer heat from one medium (fluid) to another. Basic component can be viewed as a tube with one fluid running through it while the second fluid flowing by on the outside.
- **Classification**: typically according to flow arrangement (parallel-flow and counter-flow) and type of construction (plate, plate-fin, shell-&-tube, etc.)
- **Technology readiness level (TRL)**: high

Parameter	Plate HE	Plate-fin HE	Shell-&-tube HE condensing	Shell-&-tube HE convective
Temperature in	100°C – 650°C 50°C – 250°C	60°C -90°C	100°C – 500°C	40°C – 500°C
U-value **(k**W/m²K**)**	0.06 – 0.28	0.06	0.11 – 0.85	0.11 – 0.57
Media	Steam-to- steam water-to-water	steam-to-water	Steam-to steam Steam-to-gas Steam-to-water Gas-to-steam Gas-to-gas Gas-to-water	Water-to-gas Water-to-water Water-to-steam Steam-to-steam Steam-to-gas Gas-to-gas Gas-to-steam
Costs	£180 /m²	£4/m²	£180-220/m²	£170-180/m²
Project cost factor	3.5	3.5	3.5	3.5

Key equations for heat exchangers



Governing equations:

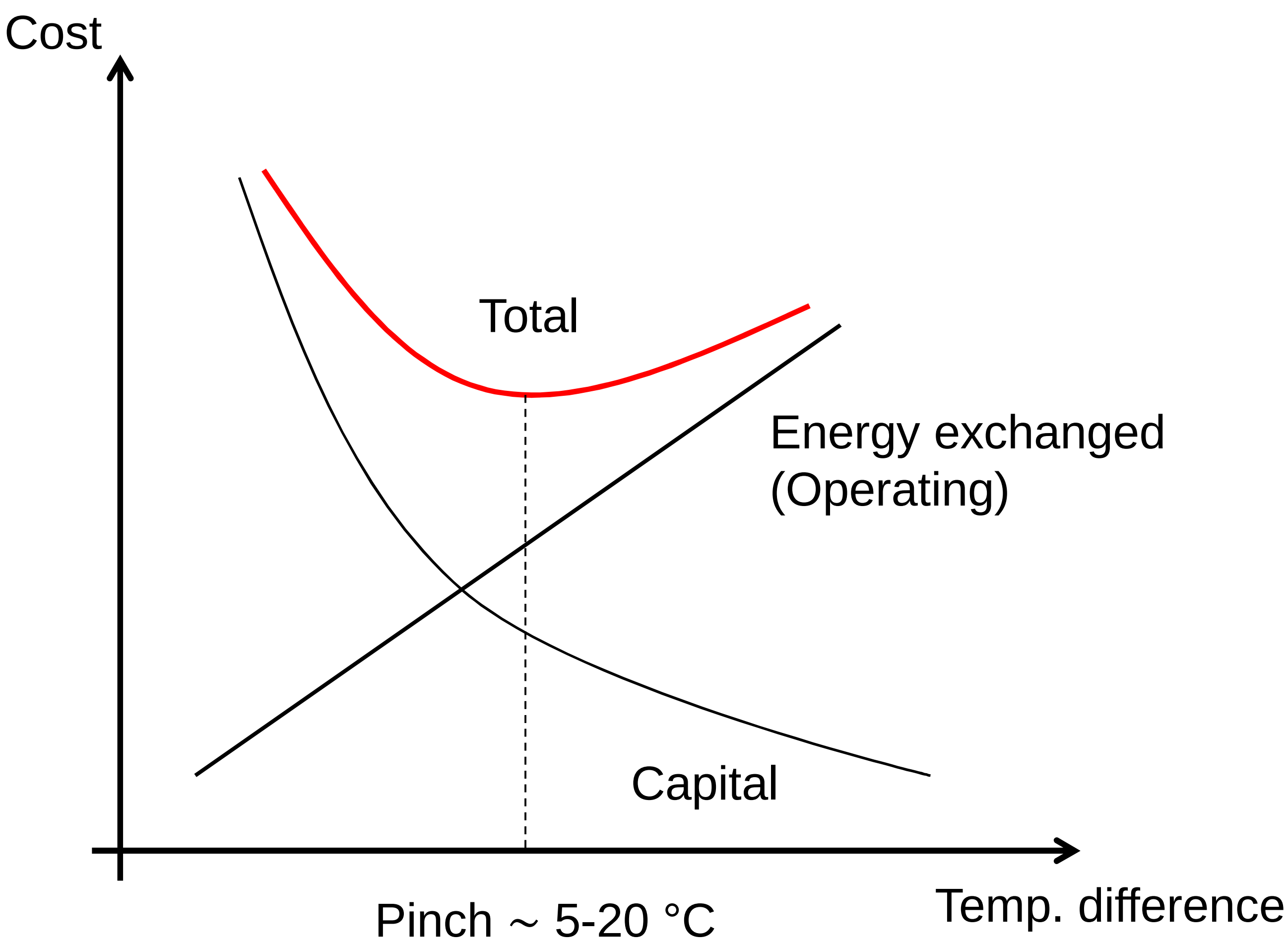
- Logarithmic mean temperature; $\Delta T_{LM} = ((T_{so}-T_{si,\ re})-(T_{so,\ re}-T_{si}))/\ln((T_{so}-T_{si,\ re})/(T_{so,\ re}-T_{si}))$
- Heat exchanger surface area; $A = Q_{transfer/}(\Delta T_{LM} * U)$, where U is the heat transfer coefficient
- Engineering cost equations; Couper, Chemical Process Equipment, Selection and Design, 2010

$$\text{Cost (\$2010)} = 1.218 * f_d * f_m * f_p * C_b$$

Assumptions:

- $C_b = \exp[8.821 – 0.30863(\ln A_{ft}) + 0.0681(\ln A_{ft})^2)$, where A_{ft} is the heat exchanger surface area in ft^2.
- Shell and tube heat exchangers ($f_d = \exp[-0.9816+0.0830(\ln A_{ft})]$
- cs/304L stainless steel (f_m=1.9)
- pressure <4bar(g) (f_p=1.00)

There is typically a cost optimal size for a heat exchanger.



- Process optimisation can be very resource and data intensive and was not carried out in this study.
- Different sectors and sites and processes will adjust pinch values to meet sectoral or local optimisation criteria.
- Here a simplifying "one-size-fits-all" assumption of 10 °C for the pinch was used.

Heat Recovery Technologies– Heat Pumps (HP)

- **Operating function**: transfer of heat energy against a temperature gradient;
- **How it works:** the HP compresses a refrigerant (volatile evaporating & condensing) to make it hotter on the side to be warmed & releases the pressure at the side where heat is absorbed (closed cycle). In open cycle systems, waste vapour is compressed to a higher pressure and thus a higher temperature, and condensed in the same process giving off heat (e.g. Mechanical vapour recompression systems (MVR, mechanical compressor) or thermal vapour recompression (TVR, steam ejector)
- **Classification**: two main types – compression and absorption heat pumps.
- **TRL**: high

Parameter	Compression HP		Absorption HP
Temperature (min input)	35°C	30°C	50°C
Temp (max output)	110°C	110°C	110°C
Efficiency*	COP: 5	COP: 3.3	Heat out/heat in : 1.6
Media	water - water	gas - water	water - water
Costs (equipment)	£200/ kW_{th}	£370/ kW_{th}	£230/ kW_{th}
Project cost factor	2.5	2.5	2.5

*Typical efficiencies for reference, the efficiency used in the analysis is based on the thermodynamic analysis of the source and sink temperatures

Key equations for heat pumps

Reference: Dr. Christos N. Markides

Governing equations:

- $COP_{therm\ lim} = T_{reject}/(T_{reject}-(T_{source}))$
- $COP_{current} = 0.97801*\ln(COP_{therm\ lim} -2)+1.5479$
- $W_{electric}= Q_{source} / (COP -1)$, where $W_{electric}$ is the required electric power and Q_{source}, the source heat that can be transferred from the source to the sink
- $Q_{sink} = COP * W_{electric}$, where Q_{sink} is the heat delivered to the sink

Assumptions:

- Assumed heat transfer at constant temperature (sink and source at constant temperature; temperature increase and decrease neglected).

Heat Recovery Technologies– Organic Rankine Cycle (ORC)

- **Operating principle/ function**: an organic, high molecular mass fluid with a liquid-vapour phase change, or boiling point, occurring at a lower temperature than the water-steam phase change, is pumped to a boiler where it is evaporated, and then passed through a turbine/screwed expander where it is re-condensed.

- **Classification**: use of technology (turbine or screwed expander) and temperature (low/high)

- **TRL**: medium

Parameter	Turbine ORC (low temperature)	Turbine ORC (high temperature)
Temperature	90-150°C	300-550°C
Efficiency	gross: 10 % net: 8 %	gross: 18-20 % net: 16 - 17%
Media	exhaust gas, steam, hot water or thermal oil	exhaust gas, steam, hot water or thermal oil
Costs (equipment)	€ 2500 / kW electricity	€ 2900 / kW electricity
Project cost factor	2.0	2.0

Source: average values of obtained manufacturer data

Key equations for heat to power conversion

Governing equations:

$\eta_{current}$ is approximated by Chambadal-Novikov efficiency

- $\eta_{current}$= Q - 2*$T_{reject}^{0.5}$*$\dot{m}_{source}$*C_p*($T_{source}^{0.5}$ - (T_{reject}+$T_{approach}$)$^{0.5}$))/Q

Assumptions:

Assumed that source heat stream can be rejected at respectively 40 ^{o}C and 180 ^{o}C for low temperature and high temperature ORC.

Heat Recovery Technologies– Heat Distribution

- **Operating principle/ function**: Transport of a heat carrier from heat source to heat sink using piping and ducting. When the heat carrier is close to atmospheric pressure additional energy is required for pumping. Heat losses depend on distance, diameter and insulation value of the piping.
- **Classification**: Two main types – steam transport and hot water transport (typically used in district heating)
- **TRL**: High

Parameter	Steam	Hot Water
Temperature	100 – 140 °C	50 – 90 °C
U-value	0.82 K/km	0.4 K/km
Medium	Steam	Hot Water
Costs (equipment)	£740k/km	£188k/km
Project cost factor	2 (assuming only above ground civil work)	5 (assuming under ground civil work)

Source: manufacturer data

Implementation of heat distribution

- Heat loss is modelled by temperature drop over supply line (heat source temperature), provided by U values
- Heat loss in the return line is neglected

- Additional heat exchanger at sink taken into account, characterised by U values;
  - Condensing vapour to flowing liquid, 0.8517 (kW/m2.K)
  - Liquid to liquid, 0.2839 (kW/m2.K)
  - Liquid to gas, 0.11356 (kW/m2.K)

- For on site source-sink combinations, a limited amount of heat transport infrastructure is required, the following is assumed for all on site source-sink combinations, as well as for district heat delivery to the fence of a facility;
  - 300m pipeline
  - Project cost factor 2/5th of normal cost factor

- Production of district heat: heat transfer to district heat supply at 100^{0}C atmospheric pressure

Heat Recovery Technologies– Hot Water Storage

- **Operating principle/ function**: Storage of hot water in tanks to create a day/night buffer between supply and demand for heat.
- **Classification**: Glass lined steel hot water tanks insulated with rigid polyurethane
- **TRL**: High
- **Relevant parameters of assessed heat storage systems:**

Parameter	
Temperature	50-90°C
U-value	0.08 kW/m^2
Media	Hot water
Costs (equipment)	£36/kWh
Project cost factor	3

Source: manufacturer data

Overall project costs for heat recovery projects can be double the cost of the underlying technologies

- **Equipment cost data**
  - Indicated cost data are main equipment costs
  - Cost estimates are averages of the data received from manufacturers for respective technologies
- **Project cost factor**
  - The total project costs consist of direct costs (main equipment and other equipment and material), on-site pipework, and indirect costs (transport, insurance, installation, commissioning, project management). Costs related to any specific complexities resulting from local site conditions (i.e. redesign of existing facilities, compatibility etc.) are not taken into account.
  - The cost factor represent the ratio between the total project costs and the main equipment costs.
  - Total project costs, especially for retro-fit applications, are highly dependent on specific situations on an industrial plant (more complicated to implement recover technology). The project cost factor is therefore subject to a high degree of uncertainty. On an aggregated level project cost factors can provide a reasonable estimate of the total costs. Project cost factors for different technologies have been estimated based on expert knowledge and manufacturers.

Technology	Project cost factor (assumption)
Heat exchangers	3.5
Compression heat pumps	2.5
Absorption chillers	2.5
ORC	2
Hot water storage	3
Steam distribution	2
District heating systems	5

* The assumption of an average cost factor represents a simplification, potentially impacting some sectors disproportionately.

Limitations of technology representation are inherent for generic representation of diverse cases and of data gathering process

- **Limitation to implementation & use of technologies**
  - Technological performance and efficiency of some technologies still need improvement to become more attractive for industrial investment
  - Implementation of waste heat recovery technologies requires enough available space at industrial sites
  - Temporal and distance limitations: heat supply and demand not at the same time requiring storage equipment or far apart requiring transport of heat.
  - Economics of scale: equipment costs favor large-scale heat recovery systems and challenges for small-scale units

- **Limitation to technology data gathering for the study**
  - Data in literature is highly scattered, often poorly documented, unclear about what is included and often outdated
  - Manufacturer data proved hard to obtain on the generic level we need for this study
  - Efficiency and costs are strongly dependent on size and specific application conditions (temperature, pressure, etc.) Generic efficiency and cost estimates for heat exchangers or heat pumps are therefore very uncertain, and subject to a large uncertainty.
  - Moreover, market for industrial use of recovery technologies is highly individual due to specific needs in industrial application (rather custom-made design than serial production)
  - Costs can therefore only be used at the aggregated level of this model and are not fit to assess individual project costs

Technology development is taken into account in performance improvement and cost reduction for the different technology classes

Cost reduction (learning rates)

- Reference: McDonald, “Learning rates for energy technologies”, Energy Policy 29 (2001) 255-261. Combined with in-house analysis of capacity growth over time.
- Heat exchangers cost reduction: 0.25%/decade
- Heat pumps & heat to power devices cost reduction: 0.5%/decade

Performance improvement, impact on governing equations:

- Heat pumps: $COP_{future} = COP_{current}+(COP_{therm\ lim}-COP_{current})*0.5*(Year-2010)/(2050-2010)$
- Heat to power devices: $\eta_{future}= \eta_{current} +(\eta_{therm\ lim} – \eta_{current})*0.5*(year-2010)/(2050-2010)$

Performance improvement impact on operating range of heat pumps; increase of maximum delivery temperature

- 2010 = 110^{o}C
- 2020 = 130^{o}C
- 2030 = 150^{o}C
- 2040 = 165^{o}C
- 2050 = 180^{o}C

There are a number of technologies, which are currently developed, that could contribute to future improvements in heat recovery

- **These technologies are not included explicitly in the modelling.**

  Rather, the modelling takes into account general improvements for certain types of technologies. The following examples could be the technologies that in practice deliver those improvements.

- Heat recovery and reuse considered to be of interest in the time period 2020 – 2050
  - Stirling engine
  - Improved Organic rankine cycle
  - Ad/absorption chiller
  - Thermofluidic oscillator

- **Stirling engine: converts heat energy to mechanical work via the compression and expansion of a working fluid**
  - Relatively efficient and quiet – appropriate for application within urban environments
  - Most efficient in relatively cold countries
  - High potential for use in electricity generation, micro-CHP units and water pumping
  - Fuel flexible: can use both waste heat and "dirty fuels" – e.g., landfill gas as available
  - Currently cost competitive on a small scale (≤ 100 kW)
  - Scope for improvement
    - Corrosion resistant materials
    - Improved working fluids

Future technologies

- **Absorption refrigerator: uses a low boiling point refrigerant as a working fluid to provide cooling**
- **Adsorption chiller is similar, except that the refrigerant is sorbed onto a solid material (e.g., zeolites or metal organic frameworks)**
  - Appropriate for use where waste-heat utilisation is preferable to direct use of electricity
  - Vapour cycles have a relatively low coefficient of performance and are therefore only appropriate when waste heat is considered to be available at a very low cost
  - Scope for improvement
    - Improved working fluids in terms of heat capacity, toxicity and GWP

Future technologies

- **Improved Organic Rankine cycle (ORC): converts low temperature waste heat to mechanical work and then to electricity via a Rankine cycle**
  - Use a high MW, low boiling point (i.e., lower than H_2O at 1atm) organic working fluid
  - Appropriate for use in a wide range of industries and geothermal sources
  - Scope for improvement
    - Optimisation of working fluid selection and design for a specific waste heat source

Future technologies

- **Thermofluidic oscillator: a novel heat engine which is capable of converting extremely low grade waste heat to mechanical work**
  - Operates via the phase change of a organic working fluid
  - Can exploit very low temperature differences, e.g., 30ºC
  - No moving parts – exceptionally quiet
  - Potential applications include agricultural irrigation and utility distribution
  - Scope for improvement
    - Optimisation of working fluid selection and design for a specific waste heat source

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Assumptions - financial

Private scenario	
Discount rate	10%

Social scenario	
Discount rate	3.5%
Air quality cost	DECC IAG tables, Dec 2012

All scenarios	
Amortisation period	20 yr
Gas, coal, oil prices	DECC IAG tables, Dec 2012 (industrial)
CO_2 prices	DECC IAG tables, Dec 2012
Electricity prices	DECC IAG tables, Dec 2012 (industrial)

Assumptions - technical

Technical parameters	
Wet steam enthalpy	400 kJ/kg
Wet steam temperature	373 K
Flue gas enthalpy	230 kJ/kg
Flue gas dew point temperature	313K
Minimum approach temperature	10 K
Maximum heat transport distance	40 km
Electricity CO_2 emission factors	DECC IAG tables, Dec 2012 (grid average)
Fuel CO_2 emission factors	DECC IAG tables, Dec 2012
Source & sink waste heat availability & demand development	The source and sink heat flows reduce because of process and energy efficiency measures at constant product output level, i.e. the output of all industries in terms of product is kept constant at todays level. The decadal benchmark for change of process and energy efficiency, and distances to benchmarks, are based on a combination of semi-public and expert opinions

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An overview of UK industry heat demand

- UK industry consumes about 17% of the final energy consumption of the UK economy (25Mtoe, 290 TWh in 2011)
- About 80% of the industrial energy demand is for heating purposes
- Most heat (44%, 9 Mtoe) is used for low temperature processes. High temperature processes use 22% (4.5 Mtoe).
- Drying and separation processes (3.6 Mtoe) and space heating (3.1Mtoe) make up for the rest.
- The division over the type of processes differs considerably per sector. Food and drinks use mainly low temperature processes, whereas non-metallic minerals and iron and steel are dominated by high temperature processes.
- Source: Dukes database

Four generic approaches are used to translate available waste heat streams from archetype processes to sites

Approach 1
Site unit production main challenge

- Archetype: waste heat / unit production
- Unit production / site /year

→ Waste heat / site

Approach 2
Annual UK production for EU ETS sites main challenge

- Annual UK production
- CO_2 emissions per site and sector, large industrial (EU ETS)

→ Archetype: waste heat / unit production
→ Calculate site unit production with CO_2 proxy*: sector energy use x (CO_2 site/ CO_2 sector)

→ Waste heat / site

Approach 3
CO_2 as proxy for site size, within a specific industry sector

- Energy use per sector, large industrial (DUKES)
- CO_2 emissions per site and sector, large industrial (EU ETS)

→ Archetype: waste heat / unit energy in
→ Calculate energy input per site with CO_2 proxy: sector energy use x (CO_2 site/ CO_2 sector)

→ Waste heat / site

Approach 4
Large data requirement & sector specific detailed information

- Process emissions
- Fuel split
- Efficiency
- Load factor
- Temperature profile
- CHP H:P ratio

→ Archetype: waste heat / unit energy in
→ Back calculate energy input per site from CO_2 emissions EU ETS (Bath approach)

→ Waste heat / site

* The use of a publicly available proxy avoids using confidential or commercial sensitive site-specific data in the analysis.

Industrial heat sources – Limitations of approach

As agreed with DECC, 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. By including cross-cutting heat flows, e.g. heat recovery from air compressors, and by including generic heat flows in the chemical and food and drink industry, we tried to accommodate for this.
- As there are large differences between one industrial site and another, translating the archetype heat sources to actual sites is not straightforward. One needs to know to what extent unit operations are being applied at actual sites. This information is not always public or up-to-date. Nevertheless, we collected data on this area for different sectors and applied estimations in our ‘point-source’ database.
- The approach is highly data-intensive. Because of time and budget constraints we needed to limit the level of detail in some cases. For instance, for the most heterogeneous sectors (food & drinks and chemicals) an approach based on generic thermal processes was taken.
- 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 justifiable. Correction factors were applied were appropriate to account for lower emissions with CHP installations.
- 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 database. The database has value at more aggregated level where it is expected that site differences are averaged out.

Approaches used per sector

Industrial Sector	Approach
Iron and Steel	1 & 2
Chemicals	3
Food and Drinks	3*
Paper and Pulp	2
Cement	2
Glass	2
Ceramics	2
Power	4**
Oil Refining	2

*For food and drinks a division has been made between the sugar industry and the rest of the food & drinks industry
** For the power sector we used actual production capacities per site and an average load factor to estimate the production per site

The sectors vary strongly in their degree of homogeneity, diversity of sources and major waste heat sources.

Sector	UK sector process heterogeneity	Functional unit	Diversity of waste heat source characteristics	Major waste heat sources
Iron & steel	++	tonne steel	+++	Hot solid steel (hot rolling), coke oven gas, off-gases from BOF/EAF furnaces
Pulp & paper	++	tonne paper	+++	Exhaust air from drying machines, water discharges
Cement	+	tonne clinker	+	Hot gases from kilns (various temperatures)
Oil refining	++	barrel of oil processed	+++	Cooling water and low temperature flue gases
Chemicals	++++	kWh final energy input	+++	Cooling and process water, furnace and boiler exhaust, condensates
Glass	++	tonne glass	+	Melting furnace exhaust gas (differentiated types)
Food & drink	++++	kWh final energy input	+++	Condensates from evaporation/distillation/cooling, flue gases from baking and drying
Ceramics	++	tonne product	+	Hot gases from firing process in kilns
Power	+++	kWh electricity	+	Cooling water, gas turbine exhaust gas

A large number of processes have been taken into account, in order to achieve a representative bottom up approach for the source and sink database population

Sector	Number of processes considered
Iron & steel	12
Pulp & paper	3
Cement	4
Oil refining	19
Chemicals	5
Glass	4
Food & drink	7
Ceramics	1
Power	6

Illustrative source database extract showing selected properties of the 5 processes in the Chemicals sector:

Industrial Sector	Process Type	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/functional unit)	Temperature Range (low/medium/high)	Temperature Value (Celsius)
Chemicals	Processing Furnace Exhaust	Processing Furnace Exhaust	GAS	0.07	LOW	200
Chemicals	Boiler exhaust	Boiler exhaust	GAS	0.075	LOW	200
Chemicals	Condensate	Condensate	WATER	0.025	LOW	90
Chemicals	Process water	Process water	WATER	0.063	LOW	50
Chemicals	Condenser cooling water	Condenser cooling water	WATER	0.133	LOW	50

Industrial heat sinks

Modelling assumptions for industrial heat sinks:

- High temperature processes are modelled as:
  - Furnaces: heat sink is combustion air preheating.
  - Steam boilers: heat sinks are water preheating and combustion air preheating.
- Low temperature processes are modelled as water boilers. Heat sinks are water preheating and combustion air preheating.
- Drying processes* are modelled as industrial air heaters. Heat sink is air preheating.
- Space heating processes are modelled as water boilers. Heat sinks are water preheating and air preheating.

*In the pulp and paper sector drying processes are modelled as steam boilers. A large fraction of the energy consumption in the pulp and paper sector is used for drying. These processes are in practice steam driven.

Industrial heat sinks

For each type of end consumption type, heat sinks and temperature levels are defined:

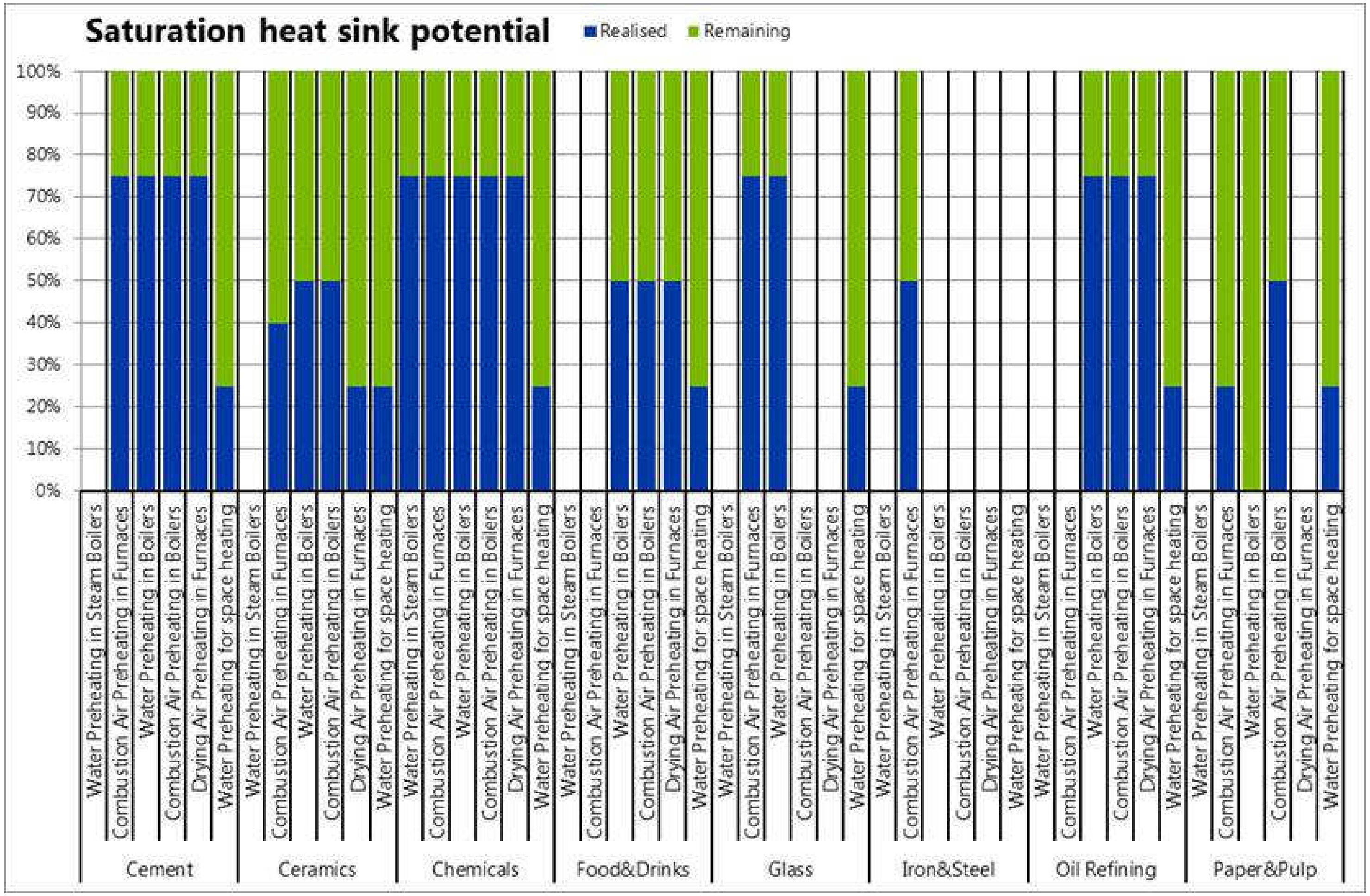
Process Type	Sub process Type	Heat Sink Description	Sink Temperature (Celsius)	Target Temperature (Celsius)	Temperature Intervals Defined (Celsius)
High Temperature Processes	Furnaces	Combustion air preheating	20	900	20-50/50-100/100-150/150-250/250–650/650–900
	Steam Boilers	Water preheating	15	100	15-50/50-70/70-100
	Steam Boilers	Combustion air preheating	20	250	20–250
Low Temperature Processes	Hot water boilers	Water preheating	15	90	15-50/50-70/70-90
	Boilers	Combustion air preheating	20	250	20–250
Drying	Low temperature drying	Air preheating	20	250	20-50/50-100/100-150/150-250
	Medium temperature drying	Air preheating	250	650	20-50/50-100/100-150/150-250/250–650
Space Heating	Space heating	Water preheating	15	90	15-50/50-70/70-90
	Space heating	Combustion air preheating	20	250	20–250

Dominant industrial heat sinks identified in each sector

Process Type	Sub process Type	Heat Sinks Descriptions	Iron and Steel	Pulp and Paper	Cement	Glass	Ceramics	Oil Refining	Food and Drinks	Chemicals
High Temperature Processes	Furnaces	Combustion air preheating	+		+	+	+			+
	Steam Boilers	Water preheating								+
	Steam Boilers	Combustion air preheating								+
Low Temperature Processes	Boilers	Water preheating		+	+	+	+	+	+	+
	Boilers	Combustion air preheating		+	+	+	+	+	+	+
Drying	Low temperature drying	Air preheating		+	+		+	+	+	+
	High temperature drying	Air preheating		+	+		+	+	+	+
Space Heating	Space heating	Water preheating		+	+	+	+	+	+	+
	Space heating	Combustion air preheating		+	+	+	+	+	+	+

The categories are based on standard categories reported in DUKES, which in several sectors overlay poorly with actual site practices.

Accounting for existing heat recovery and re-use on-site practice.

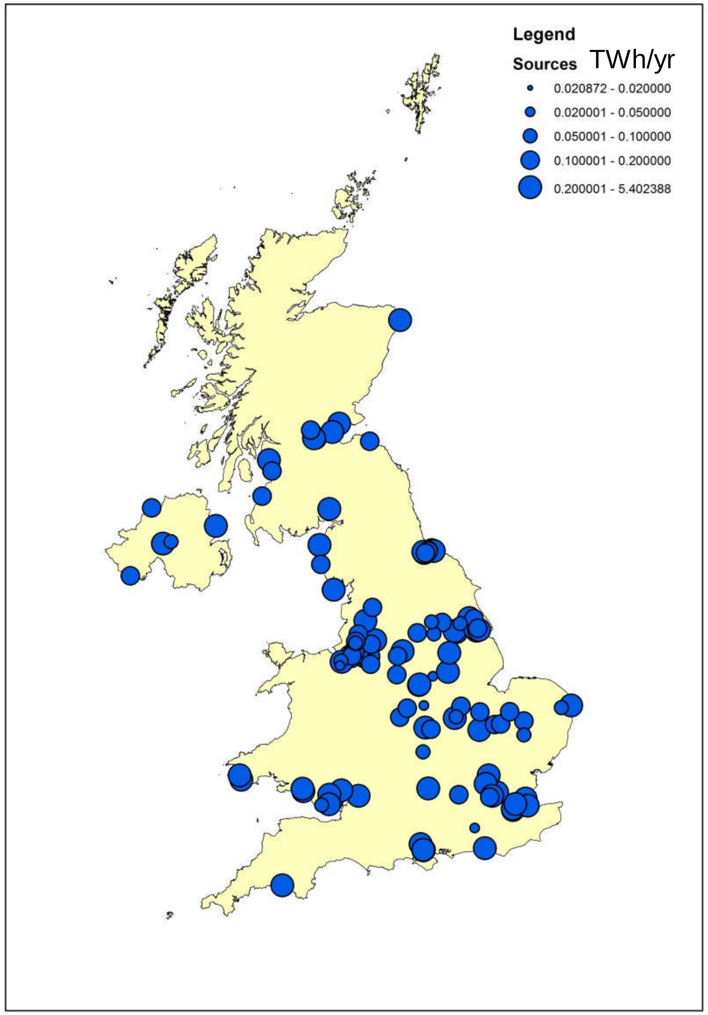


Assumed different 'sink saturation factors' as % of the heat sink that is already supplied with waste heat as common practice in industry, i.e. a proxy for the level of heat integration. Obviously this depends on the sector, as well as the type of the heat sink.

467 industrial waste heat source streams and 1090 industrial heat sinks are included in the source and sink databases, covering 73 unique sites.

Sector	No. of sites	No. of heat sources	No. of heat sinks	% of sectoral EU ETS emissions
Iron & steel	3	31	18	98
Refineries	8	144	96	97
Chemicals	22	110	484	82
Cement	11	22	198	95
Food and drinks	10	65	90	52
Pulp & Paper	6	18	60	56
Glass	9	18	72	76
Ceramics	4	4	72	24
Total Industry	**73**	**467**	**1090**	**85%**
Power	**47**	**47**		

The underlying databases can be expanded and refined over time as data become available or industrial activity changes.



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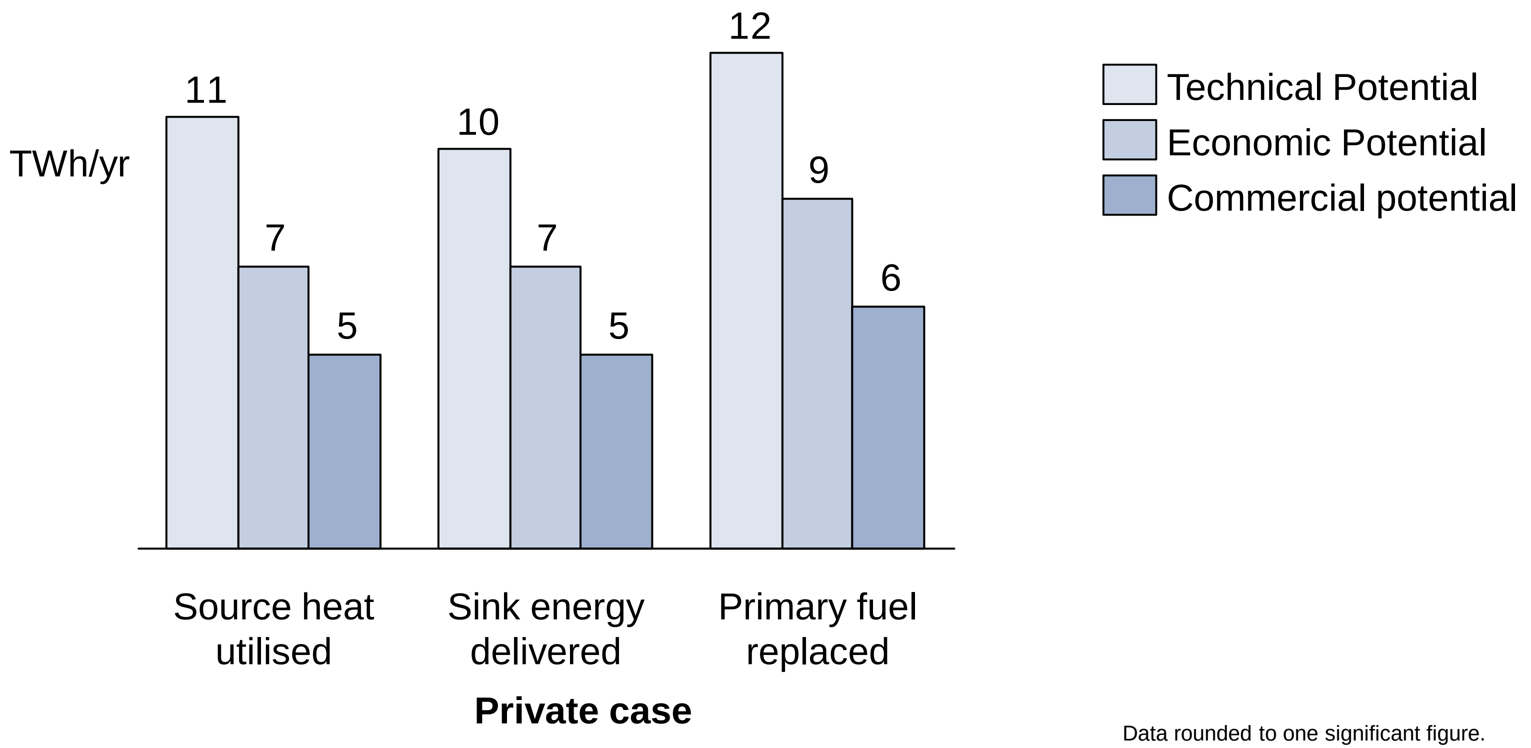
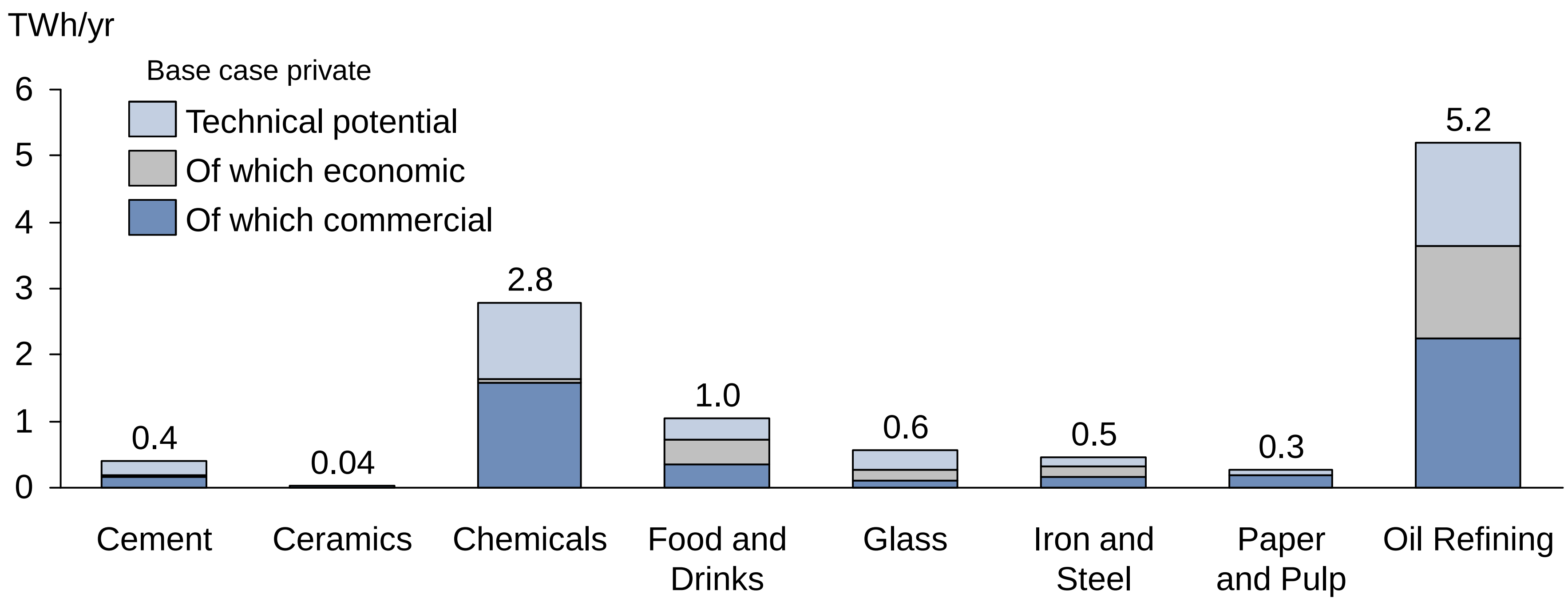
There is a need to agree appropriate definitions for reporting the amount of industrial waste heat recovered.

- Different metrics give rise to different absolute levels of recoverable waste energy available for re-use
  - Because of the (in)efficiency of some energy conversion technologies
  - Because of upgrading low grade heat using electricity to higher grade heat, with heat pumps.
- The convention in this report is to present the amount of energy in the waste heat source stream.



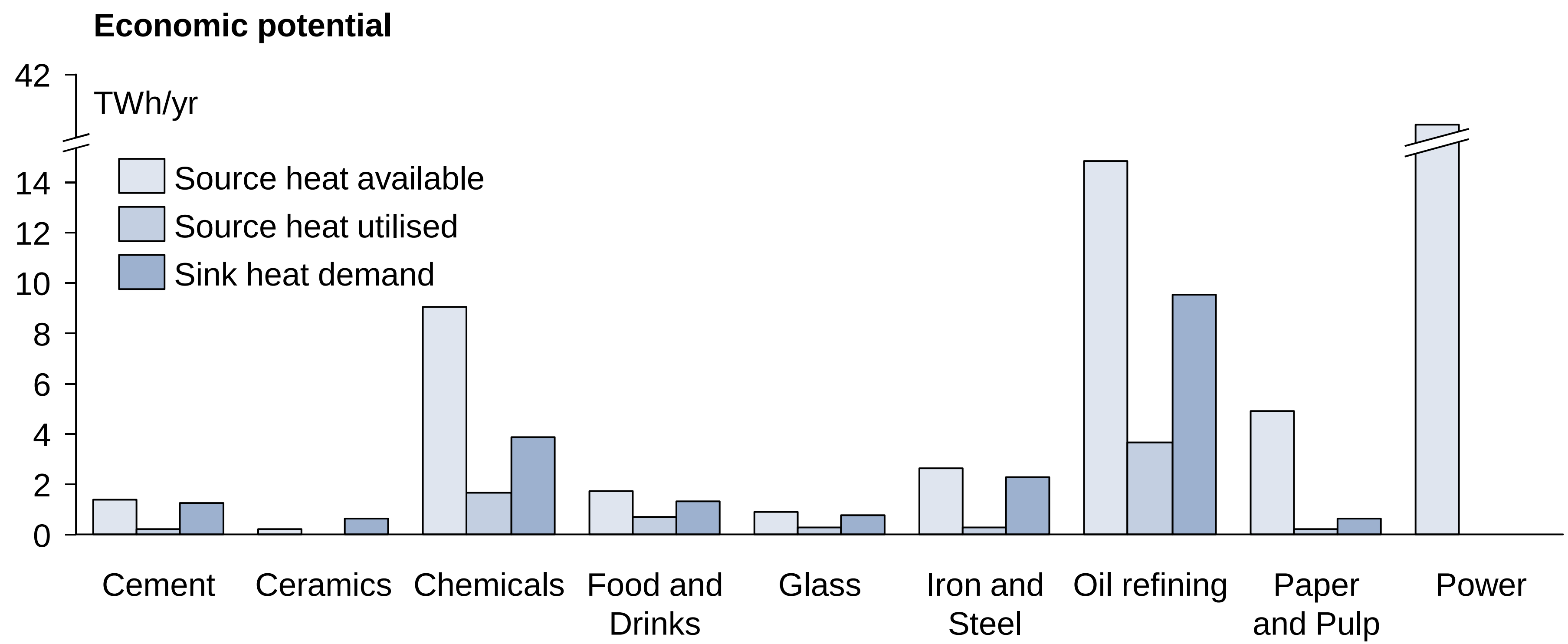
Data rounded to one significant figure.

All sectors examined have heat recovery options which are commercially viable. The sectors with the largest potential for industrial heat recovery are oil refining and the chemicals sector.



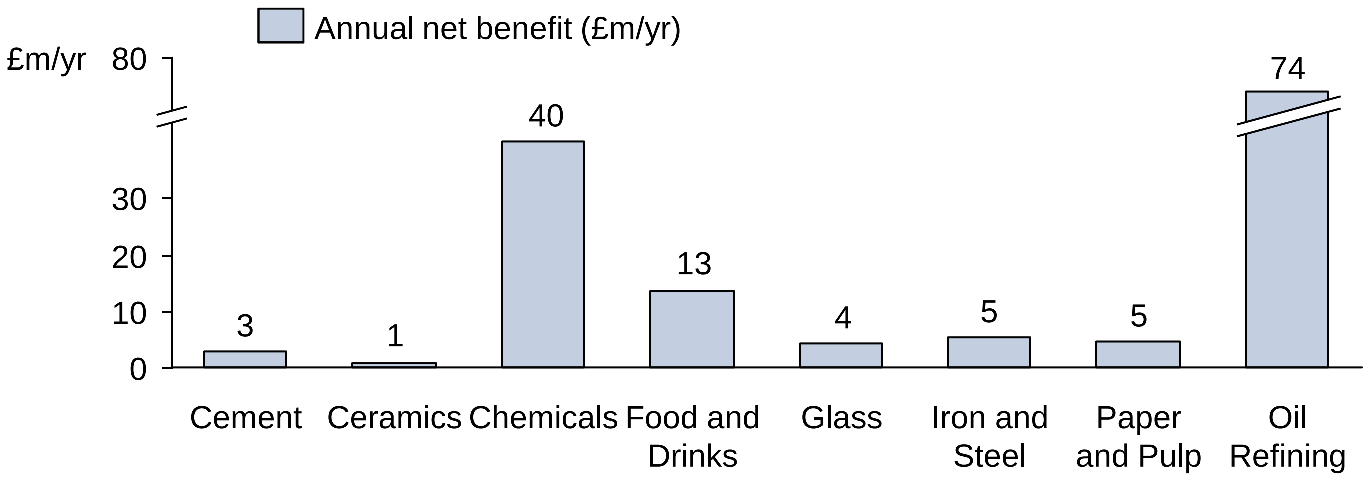
- On average 45% of the technical potential meets the commercial requirement for payback within 2 years, but the ratio varies strongly between sectors. Most of the commercial potential is attributable to the deployment of heat exchangers for on-site water pre-heating, and to a lesser degree combustion air preheating.
- Heat recovery in the some industries (especially food and drink) may be restricted due to batch processes, the fouling from contaminants in the heat stream, or the need to maintain controlled conditions. Obviously these issues would **reduce** the remaining potential below that identified here.

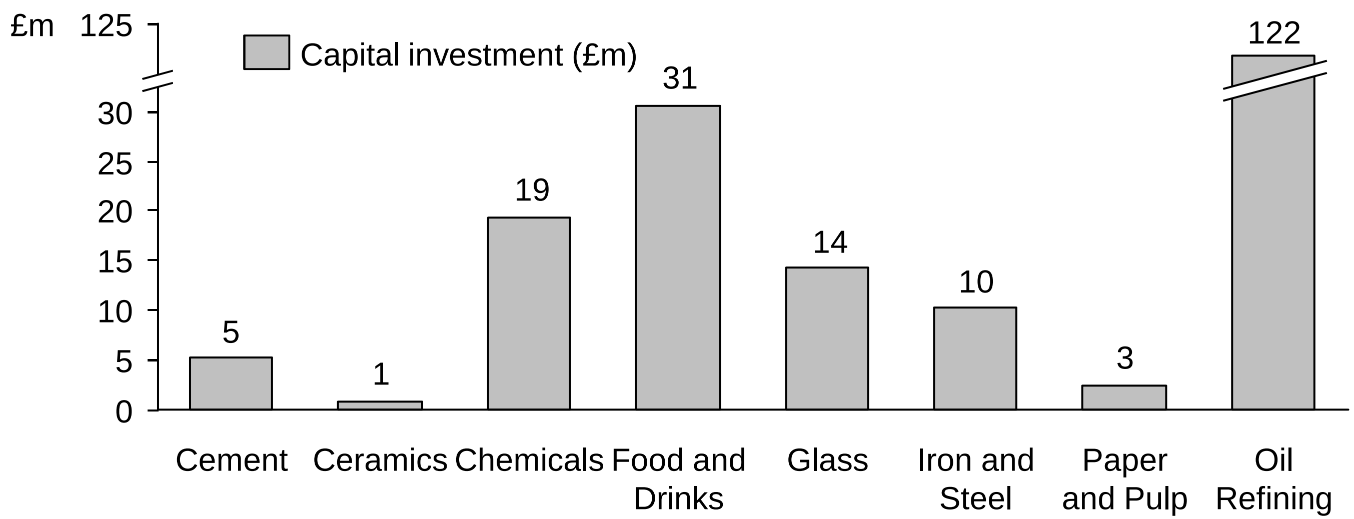
For most sectors, sink heat demand is lower than source heat availability.



- Lack of low grade heat demand is also one of the main bottlenecks in rejected heat reuse, according to many industry stakeholders.
- In the power sector particularly many low grade waste heat reuse options (air preheating etc), are already utilised as common practice.
- The available source heat in the power sector is the rejected heat available at current conditions. Increase of heat supply by process changes or lower electricity production is not considered in this study.
- Where sink heat demand is higher than source heat utilised this would imply that the remaining sink demand continues to be met through existing methods, i.e. not the heat recovery options identified in this study.

The oil refining and chemicals sector represent the largest share of the total annual net benefit

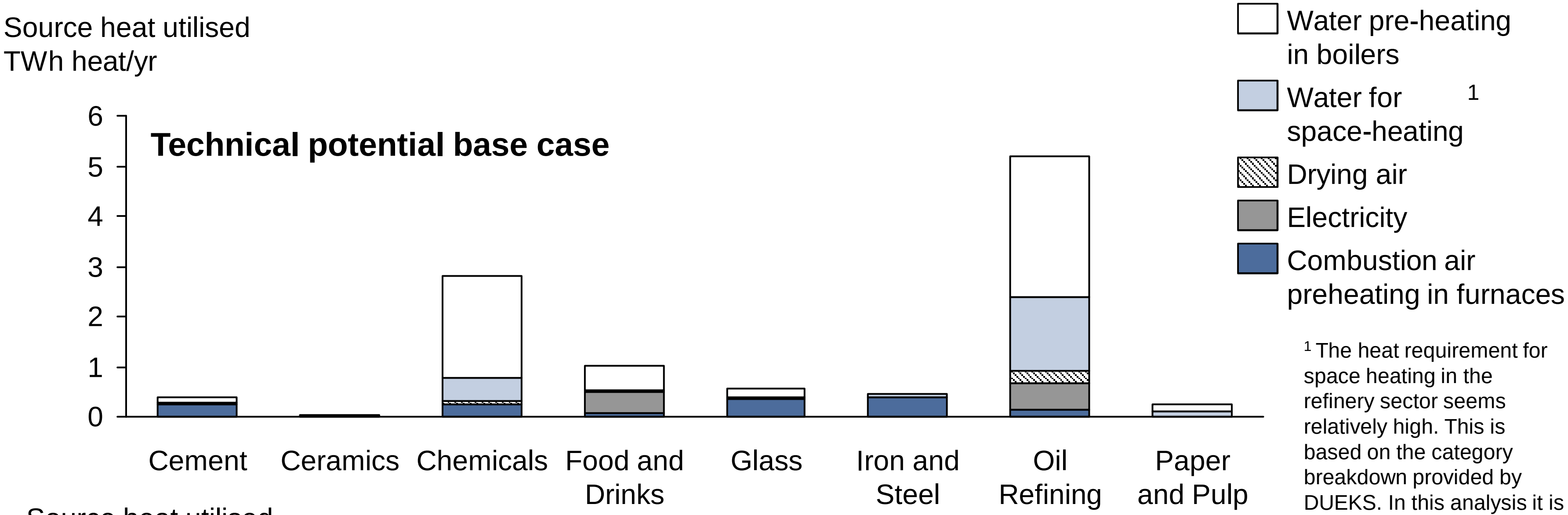


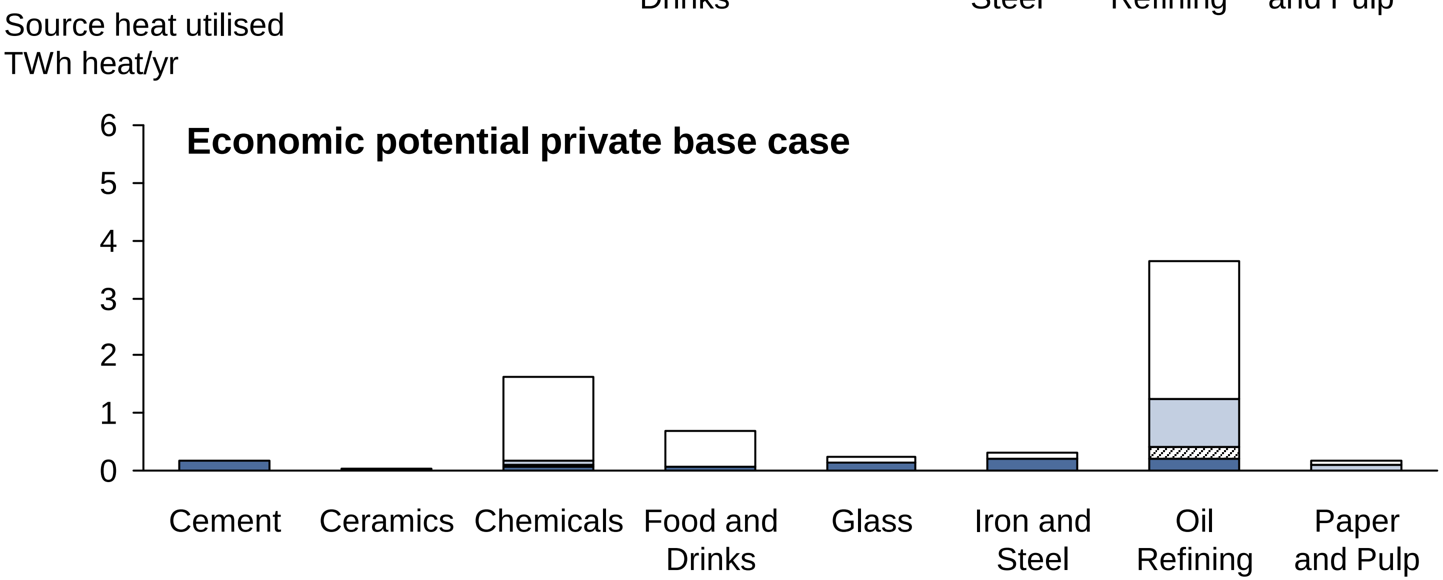


N.B. Capital investment refers to equipment and installation only, it excludes costs such as downtime and costs related to site specific integration complexities.

Potential risks, complexities or interaction of heat recovery with other site processes are not considered.

Main applications of recovered heat in sink sectors are in combustion air preheating and boiler water pre-heating.

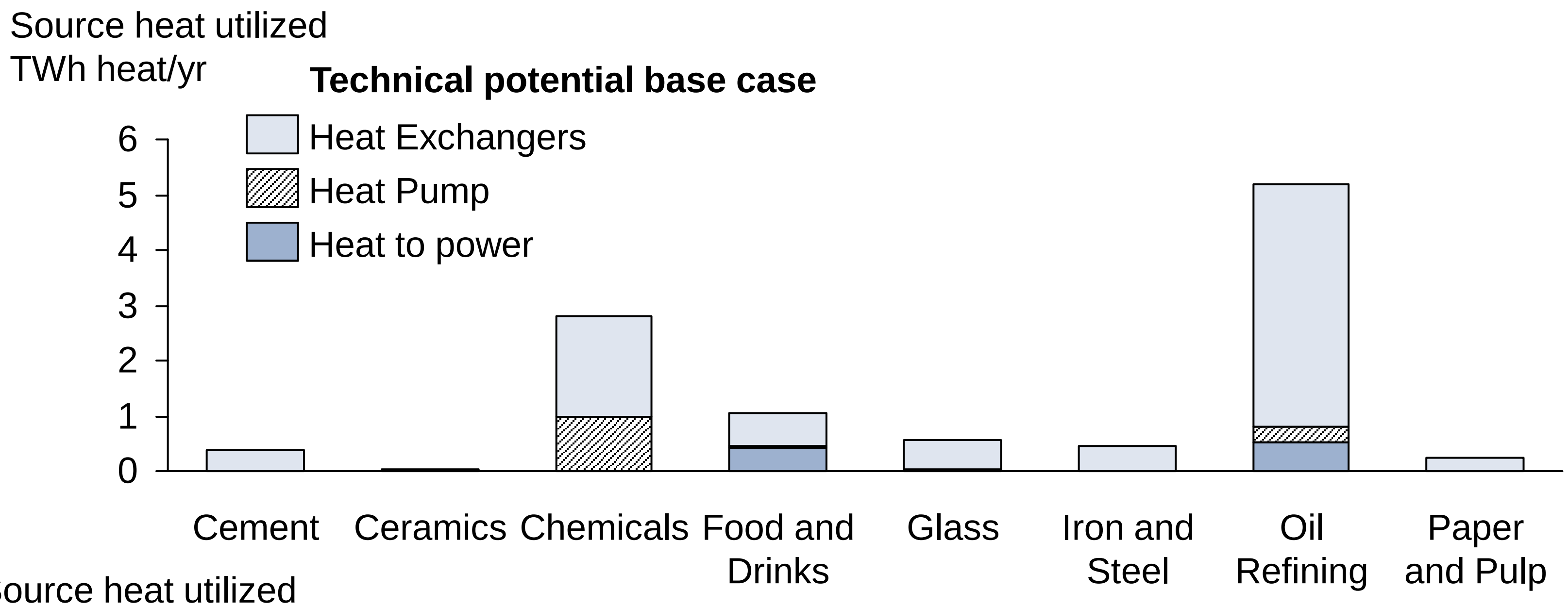


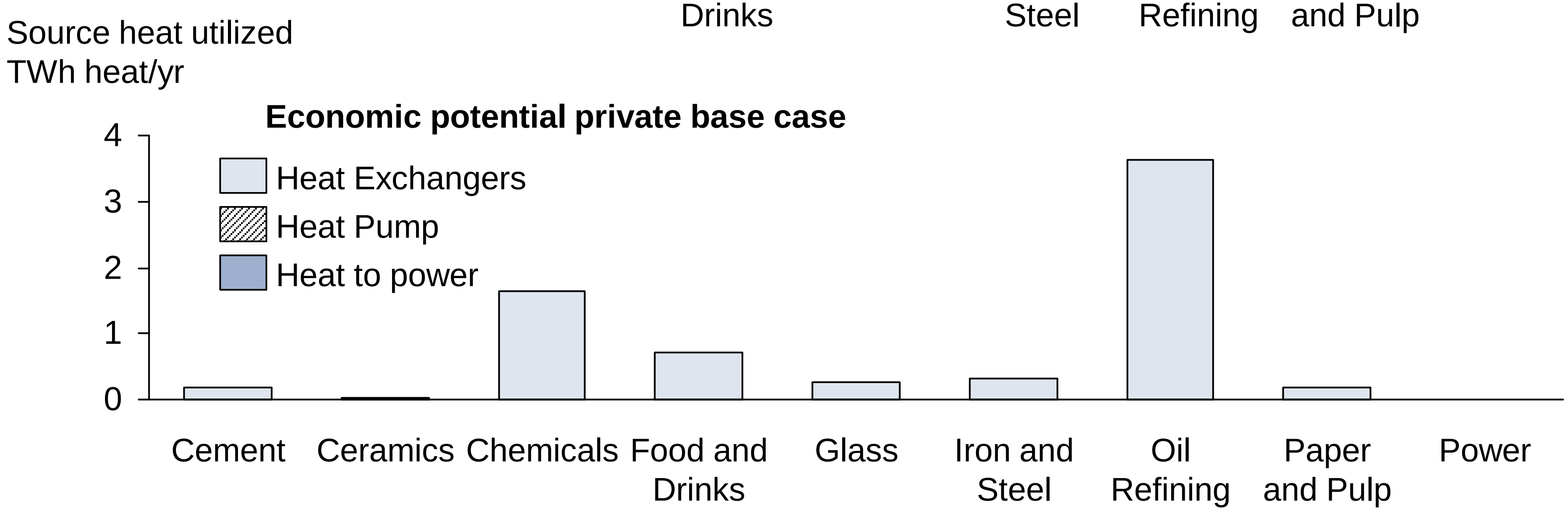


[1] The heat requirement for space heating in the refinery sector seems relatively high. This is based on the category breakdown provided by DUEKS. In this analysis it is assumed that the heat required for “space heating” in DUKES is heat required for warm water applications (ie produced in warm water boilers), no delivery to building heating facilities is taken into account.

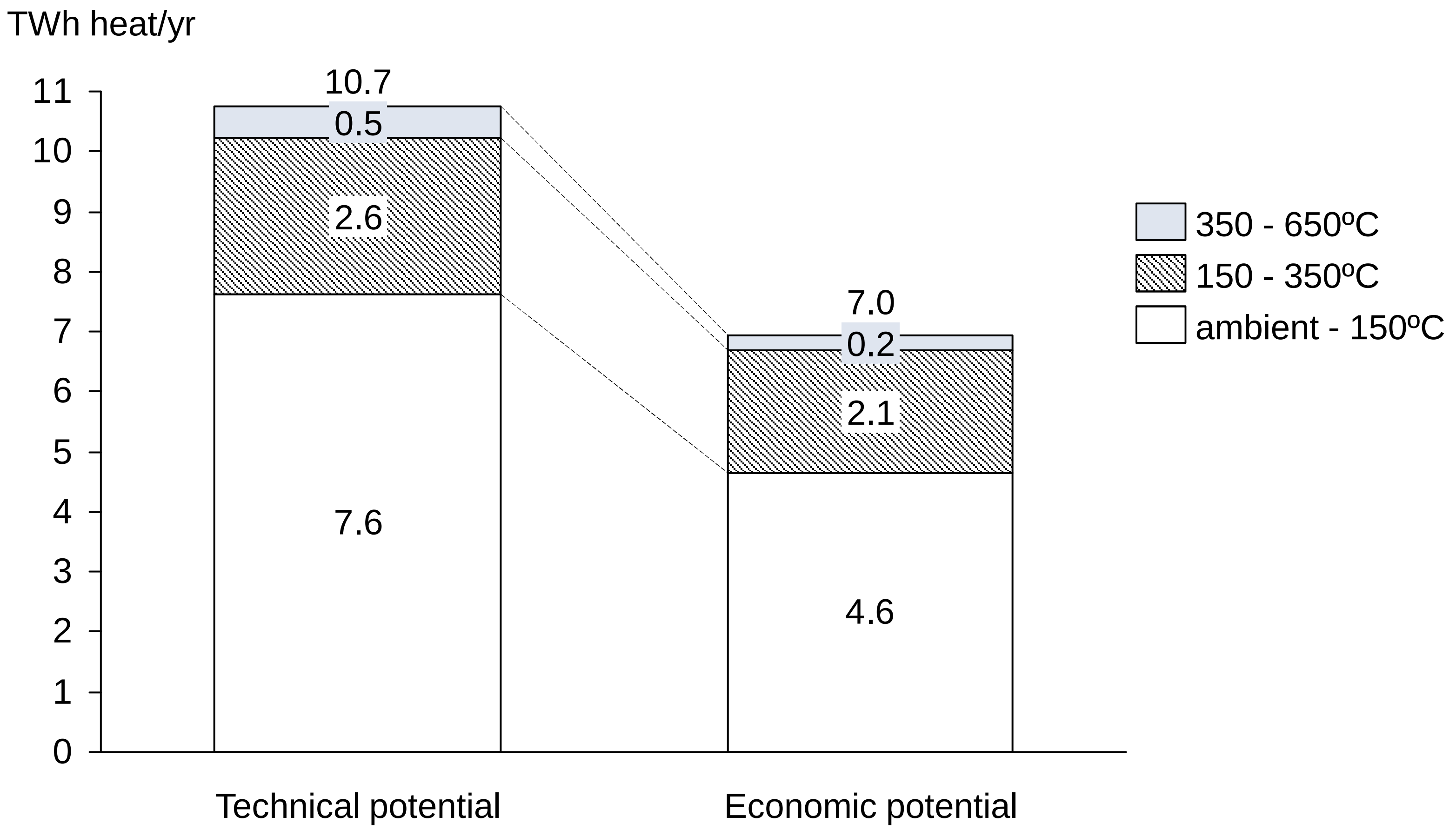
Note that the definitions of processes identified here correspond to the archetype representation, and do not necessarily correspond with actual site practice

Heat is mainly recovered and reused using heat exchangers, especially for the economic measures. Technical measures include heat upgrading with heat pumps and heat to power devices as well.





Heat sources: largest contribution to heat recovery potential is from low temperature sources, relative contribution of low temperature sources reduces the most going from technical to economic potential

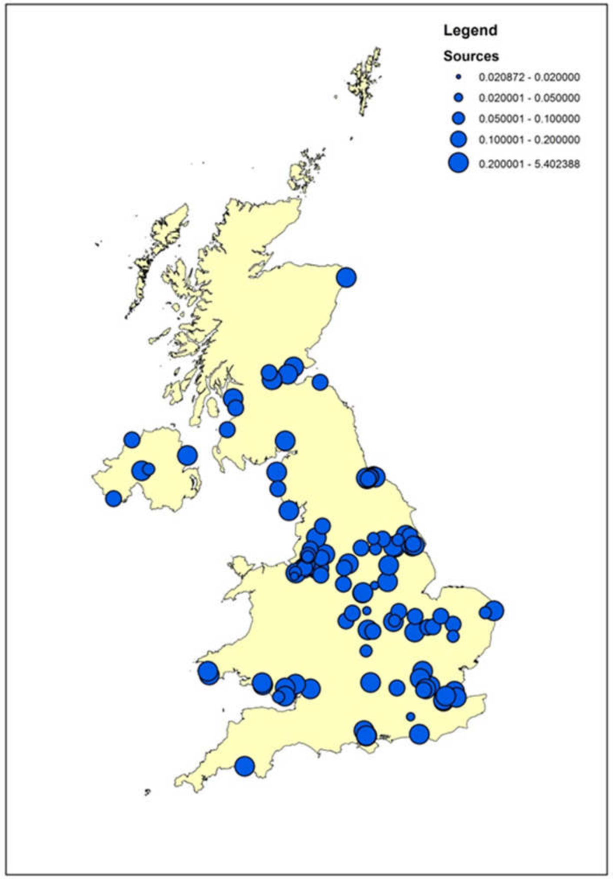


The economic potential is limited primarily by the ability to match source and sink energy demands.

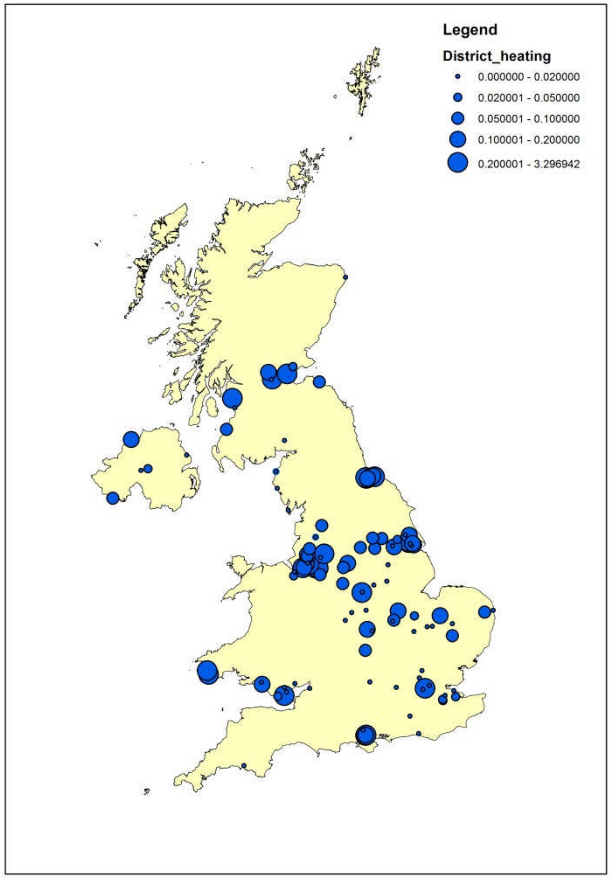
- Of the *ca*. 167 TWh/yr heat consumed by UK industry, around a quarter (48TWh/yr) has been identified as potential waste heat streams in the heat source database. The 48 TWh/yr figure refers to streams that are not already included within heat recovery projects.
- It is possible to identify source-sink-technology combinations which re-use around a quarter of the energy available as potential waste heat streams - the “technical potential” (10.7 TWh/yr) which only allows combinations that lead to a net CO_2 saving. The other part is limited by sink demand, competition between sources for the same sinks, mismatch in source and sink supply and demand, technology effectiveness or technology limitations (e.g. recovery of heat from hot solids).
- The “economic potential” is further constrained by the need for positive economics using a discount rate of 10%. In practice a large part of the technical potential is also economic (7.0 TWh/yr), because the majority of projects that make sense technically are sufficiently viable even at 10% discount rate.
- Trade associations and site visits have confirmed that the majority of commercial site managers would use a “simple payback” rule as the basis for investment decisions in heat recovery technologies. The range varies between companies and sectors (1-4 yrs), with 2 years being most common. With this more stringent requirement, the commercial potential is 70% of the economic potential.

Heat available for recovery and distribution of technical and economic potential

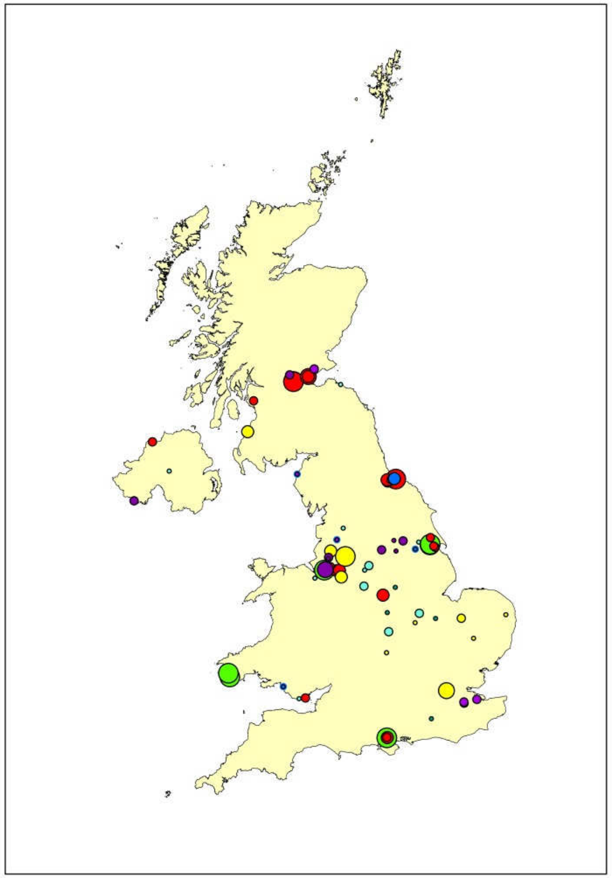
Sources in database (TWh/yr)



District heating potential (TWh/yr)



Economic potential per sector (TWh/yr)



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  - Optimisation parameter
  - Energy intensity in period to 2050
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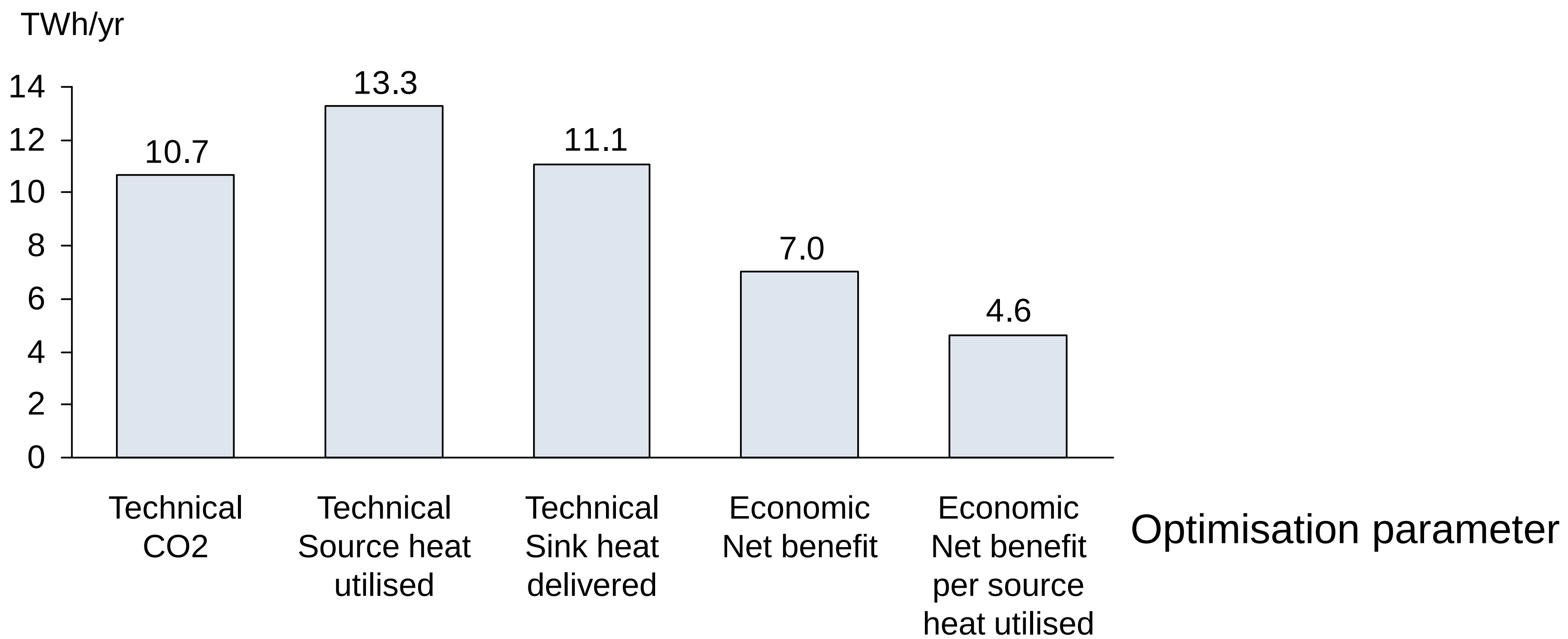
- Industrial carbon capture and storage

The model allows source-sink-technology combinations to be ranked across energy, CO_2, and economic criteria.

- Given DECC focus on CO_2, the baseline techno-economic model results were presented on the basis of source-sink-technology combinations ranked on the basis of CO_2 saving.
- However the model allows the user to optimise on the basis of source heat utilised, amount of sink heat delivered, the net economic benefit or the net benefit per source utilised.
- The model shows that technical and economic potential depend (albeit weakly) on the KPI chosen. This implies the policies designs will need to be evaluated to maximise impact.



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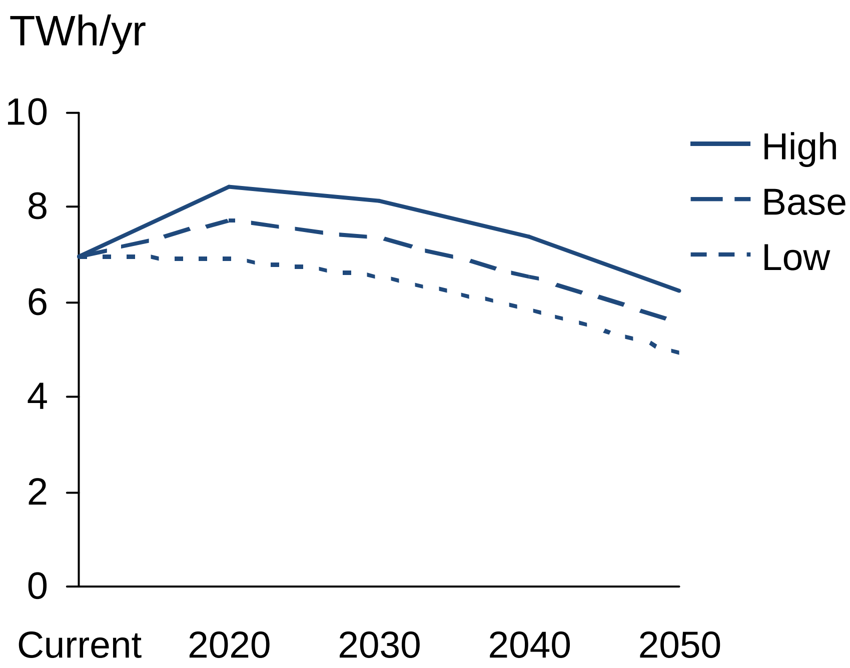
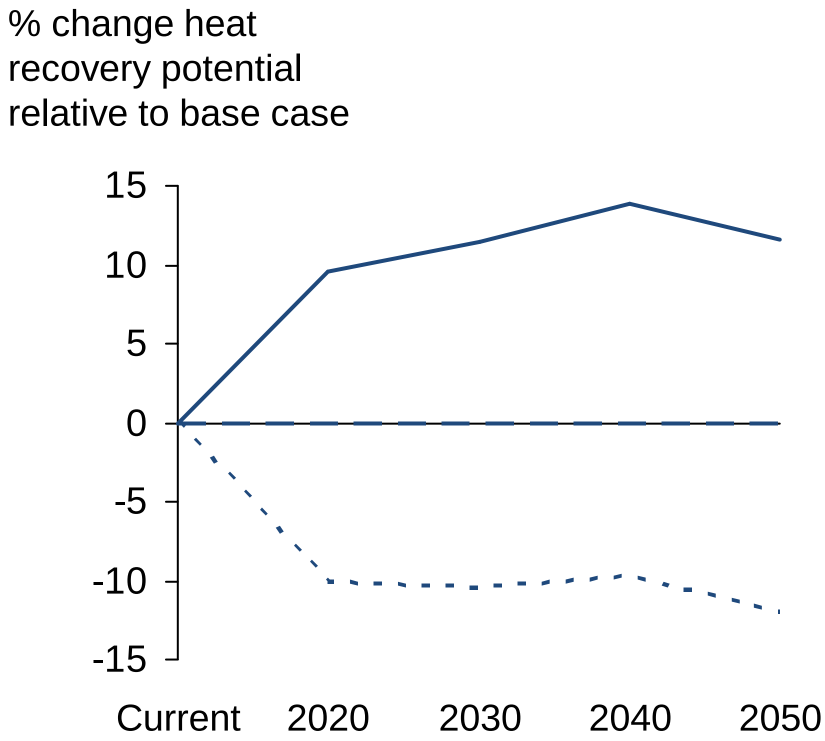
High and low scenarios for the development of industry heat intensity, show a ±10%-15% impact on the base case heat recovery potential

Sensitivity scenarios for the economic potential for the level of industrial energy heat intensity, absolute levels



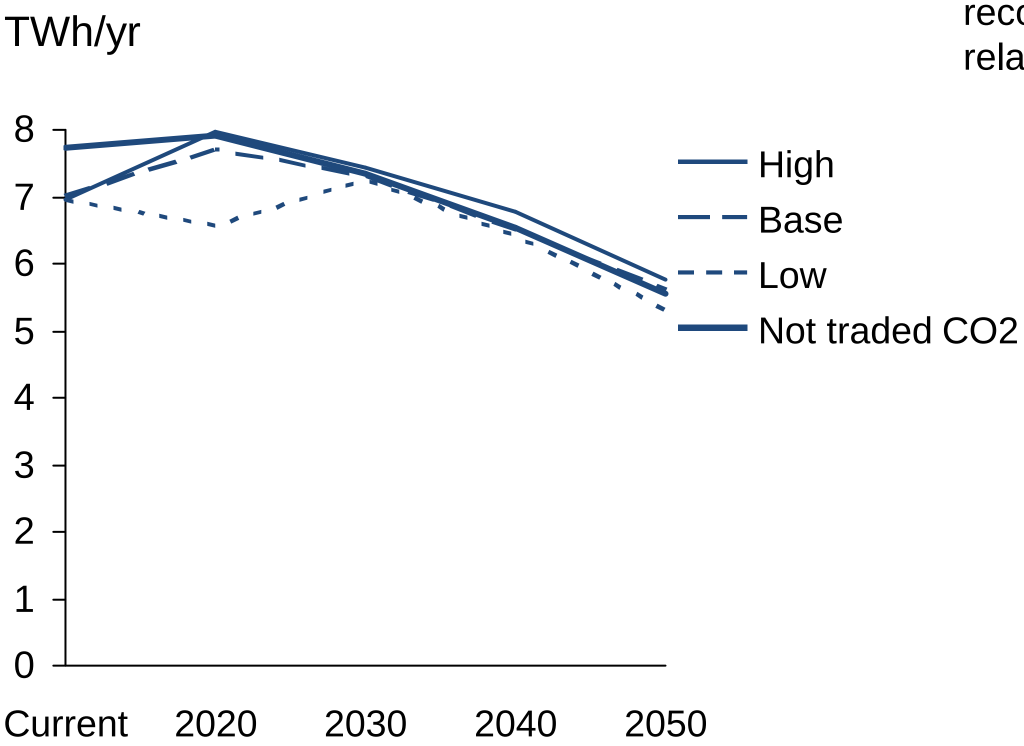
High and low sensitivity scenarios for the economic potential for the level of industrial energy heat intensity, relative to the base case



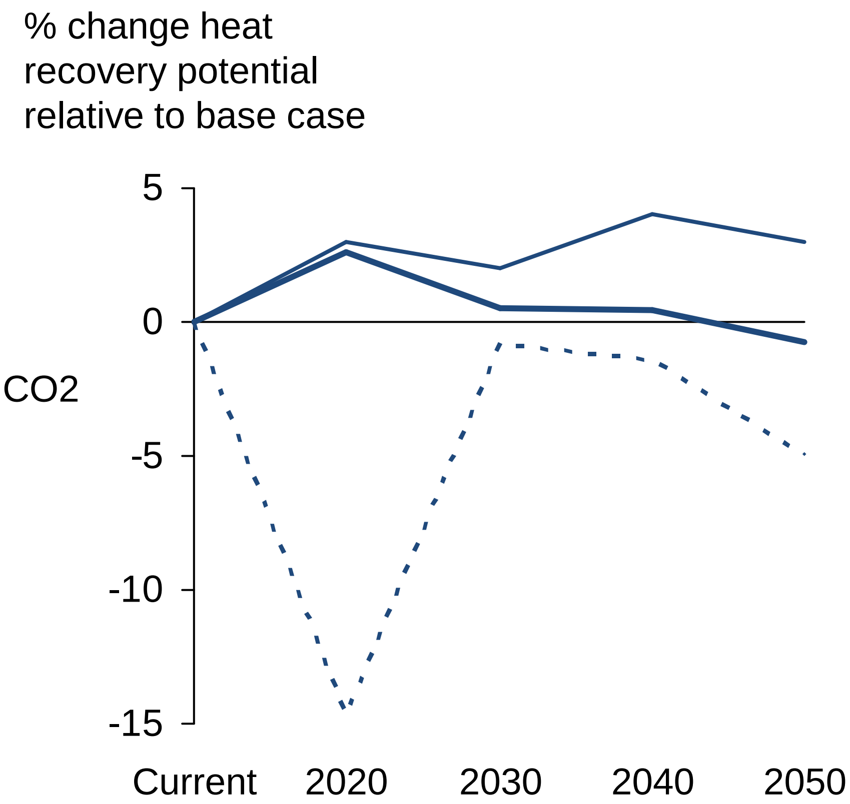
Industrial energy heat intensity scenarios reflect changes in process and energy efficiency, at constant industrial output.

High and low scenarios for fuel prices has limited impact on the potential for heat recovery, but impact on net benefit is significant

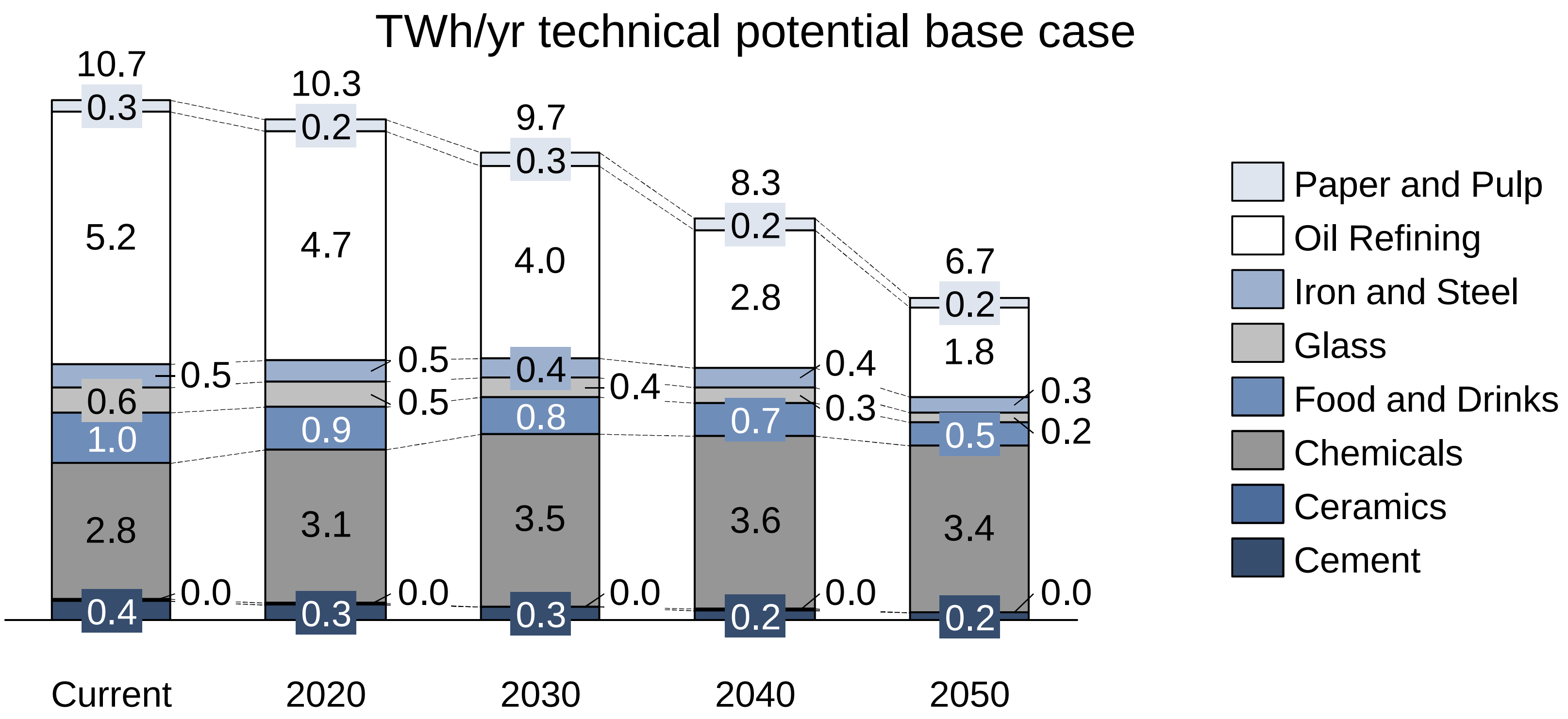
Sensitivity scenarios for the economic potential for the level of fuel prices, absolute levels



High and low sensitivity scenarios for the economic potential for the level of fuel prices, relative to the base case

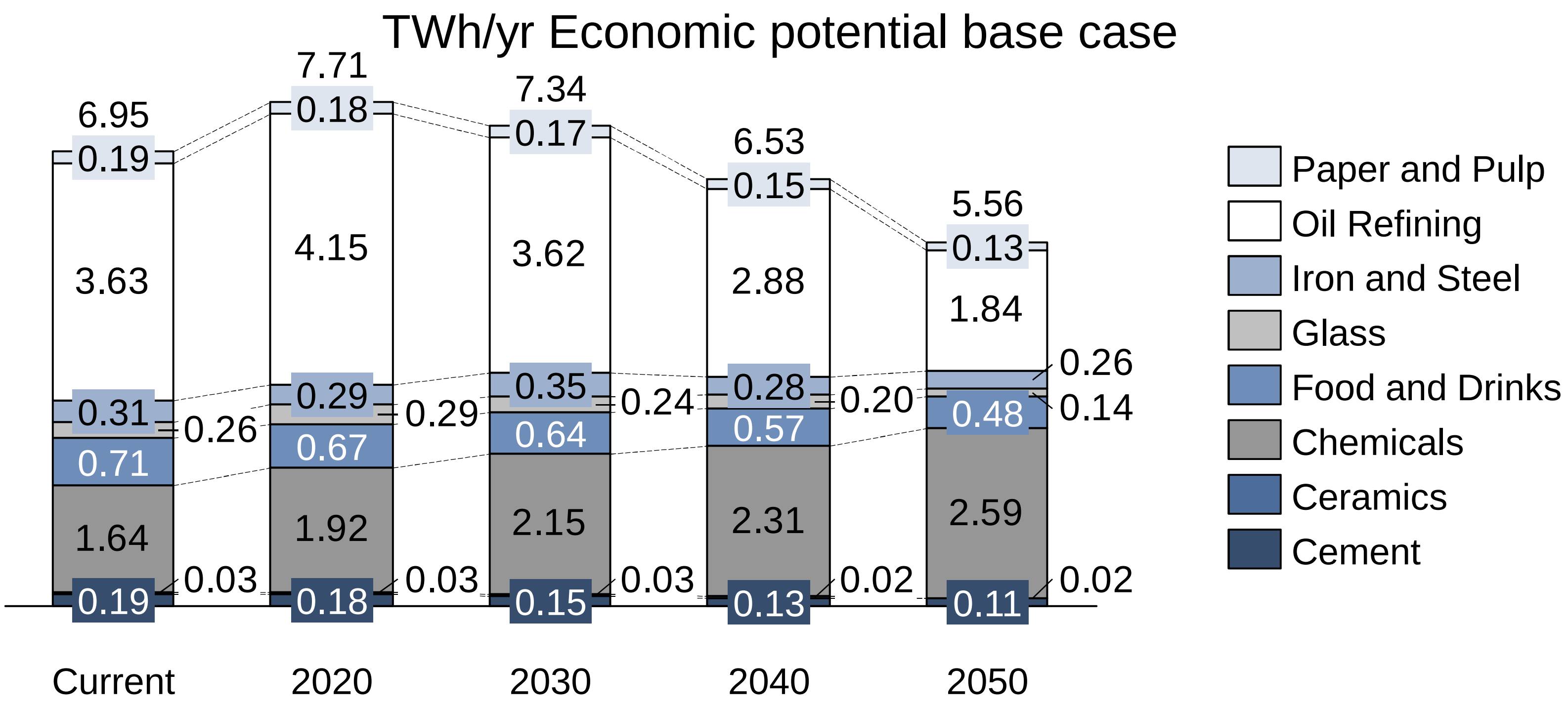


Strong decrease in technical potential due to lowering impact on rejected heat by increases in process and energy efficiency



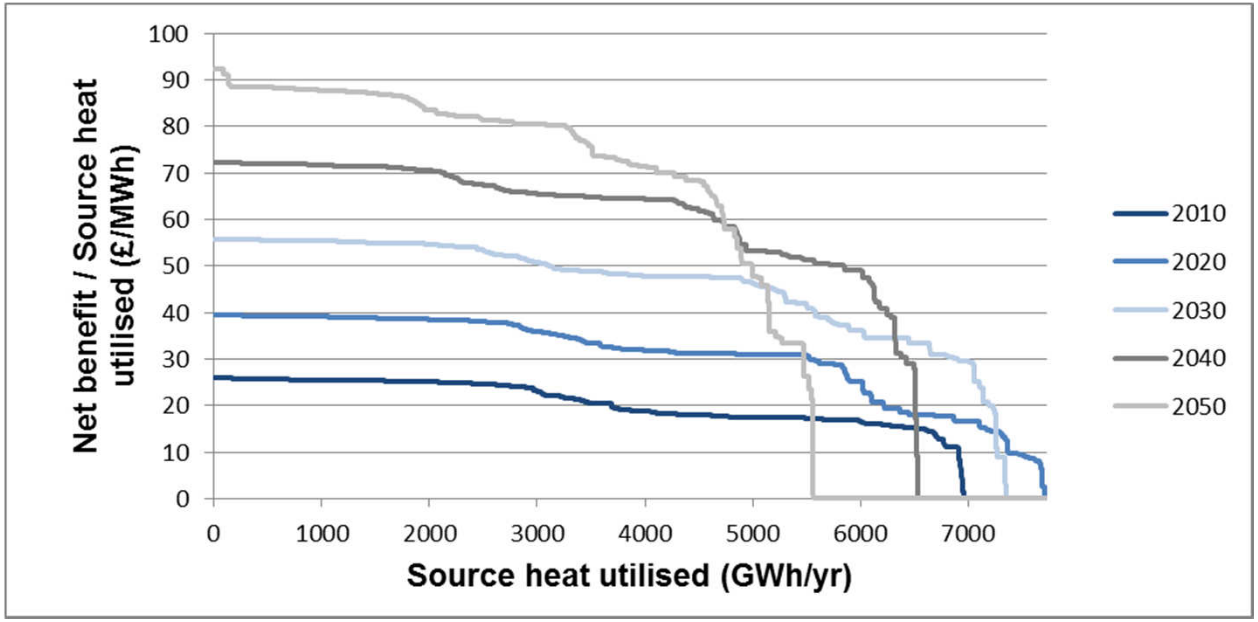
- Strong reduction in oil refining heat recovery potential, is due to increases in process and energy efficiency that reduce the amount of waste heat and low grade heat demand
- Increase in chemicals sector due to less competition from refining sector to supply the same sinks
- Potential is calculated for every decade separately, assessing positive net benefit investments in each year, assuming base case availability of heat sources and sinks. i.e., no reduction of source and sink capacity due to additional implementation of heat recovery measures in earlier years, other than the base case process and energy improvement efficiency.

Relative decrease of economic potential is lower than the technical potential, due to offsetting effect of higher prices



- Further increase in economic potential chemicals sector, relative to increase in technical potential, beyond 2020, due to increases in counterfactual fuel prices
- Potential is calculated for every decade separately, assessing positive CO_2 reduction investments in each year, assuming base case availability of heat sources and sinks. i.e., no reduction of source and sink capacity due to additional implementation of heat recovery measures in earlier years, other than the base case process and energy improvement efficiency.

Development of the net benefit abatement curves over time show the opposing effect of higher prices and increases in efficiency



- Increases in process and energy efficiency reduce the amount of heat that is available and can be recovered, resulting in a lower economic potential.
- Higher counterfactual fuel prices increase the net benefit of the available measures per decade.

- Potential is calculated for every decade separately, assessing positive CO_2 reduction investments in each year, assuming base case availability of heat sources and sinks. i.e., no reduction of source and sink capacity due to additional implementation of heat recovery measures in earlier years, other than the base case process and energy improvement efficiency.

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- The recovery of waste heat for re-use in cooling
- A note on heat networks
- Disclaimer

Approach & Issues

Straw man data	Data validation	Updating technology database	Technology database
Gathering of data on heat sources and sinks per sector from literature search and expert judgement	Site visits were performed to test the straw man data on real sites and to get expert insights on the straw man data. Trade association shared information and recent publications, asked members for input. Sector experts from the consortium partners validated and updated the straw man data.	The technology database was updated using the inputs from the data validation Site visit reports were validated and approved by sector and site experts. Useful comments that came back in this second round were still incorporated in the database	Assessed, relevant parameters of heat sources and sinks: - Origin of heat source (process) - Temperature - Medium - Heat flow - Complexity of heat recovery - Heat sink saturation factor

Trade associations are keen to emphasise diversity within sectors.

Within each heat intensive industrial sector, trade associations are keen for the Project Team to emphasise to DECC the underlying **diversity** in the following factors that will drive the potential for heat recovery:

- Impacts of heat costs or heat savings on commercial margins/competitiveness.
- The degree to which heat flows are measured and reviewed.
- Fuel type(s) used, fuel flexibility, and fuel purchase agreements.
- The processes for heat generation and their corresponding investment cycles.
- The nature of waste heat streams (size, composition, pressure, temperature, medium, temporal profile).
- The nature of heat sinks available on site (size, temperature, medium, temporal profile)
- Ownership, decision-making process, investment criteria (payback models, risk appetite, capital available), UK and global reach.
- Technical capacity in-house to manage energy-related decisions and knowledge of heat recovery technologies in particular.
- Location, in particular local terrain and the proximity to significant heat sources and sinks.
- Dynamics, i.e. the degree to which any or all of the above are expected to change over time.
- Investments in energy efficiency or CO_2 reductions to date, in progress, or planned.

Methodology caveats

- One source to one sink: if a source or sink has been used, both are no longer available
- Ranking of possible measures is done on “absolute” values (ie highest value measures first)
- Measures are chosen on ranking order, no optimization
- Industry flatline assumed
- Sites explicitly taken into account: top 88% largest EU ETS emitters in the UK
- Study considers heat intensive industry, small industrial and commercial not explicitly taken into account.
- Not actual site data: archetype processes mapped to the individual sites
- Second order effects not taken into account (for example acceleration of process efficiency improvement or recovery technology development, due to higher CO_2 prices: not taken into account)
- Especially cost estimates very simplified
- Limited number of technologies taken into account.
- Complexity and costs related to actually installing at a site not taken into account
- Cost difference in retrofitting or newbuilt not taken into account
- No process optimization taken into account
- Small sinks not taken into account

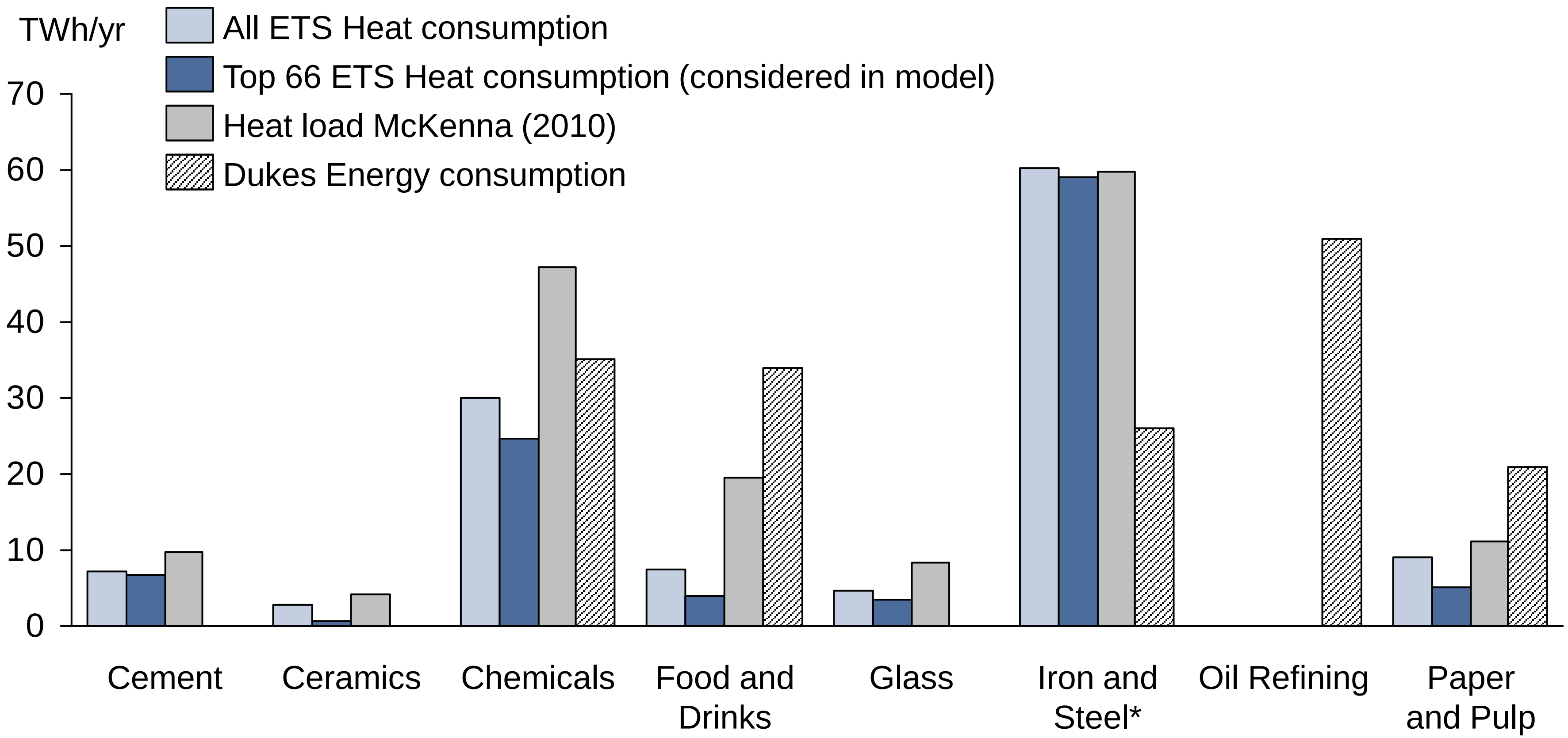
There are considerable source and sink data challenges for policymakers.

- There is no readily useable dataset of industrial heat use, and the project confirmed expectations that reliable, up-to-date data on heat flows within existing industrial emitters is challenging to obtain.
- Commercial confidentiality and competition constraints prevent public disclosure of quantities produced, process descriptions, and product energy intensities at individual sites, even where the required data have been measured and recorded. For other sites, data on heat flows are not well captured.
- Therefore it has been necessary to draw on indirect data sources to estimate heat flows for this study.
- However, indirect data sources are at various levels of relevance, coverage and accuracy. The indirect sources included in this study comprised trade journals, academic journals, trade association data, benchmark assessments, reported CO_2 emissions, expert judgements and data from individual companies. There is a high risk that the errors and biases in the readily available datasets may skew analysis.
- As an example, most UK heat intensive industry sites have typically evolved over several decades through incremental changes. Since the site layouts and process descriptions correspond weakly to the new build representations common in the literature, analysis based around idealised site heat flows will necessarily be limited.
- The team believes that this study establishes for the first time a transparent database of heat sources and heat sinks within UK heat intensive industry; this can be progressively refined to improve decision making by policymakers as required.

There are heat recovery opportunities available in each of the main heat intensive sectors.

- The dominant heat sinks in industry are air and water pre-heating using heat exchangers, for which there are some opportunities in all eight sectors.
- The techno-economic modelling identified examples of where on-site re-use of waste heat is expected to meet already commercial payback requirements (up to 6 TWh/yr identified in the base case).
- Some of these “fast payback” options are known from the project site visits and trade association discussions to have already been implemented. The heat sources database has been corrected for these known implementation.
- Likewise, some of the heat sinks have already been supplied to waste heat to a certain degree. We have included a heat sink saturation factor to account for this. Unfortunately, the degree to which heat sinks have already been saturated is not monitored. Hence this is based on information from site visits and expert judgements.
- The commercial potential of 6 TWh/yr could likely be increased to 9 TWh/yr with financial and organisational support, and up to 28 TWh/yr if there is widespread adoption of heat networks involving industrial heat users.

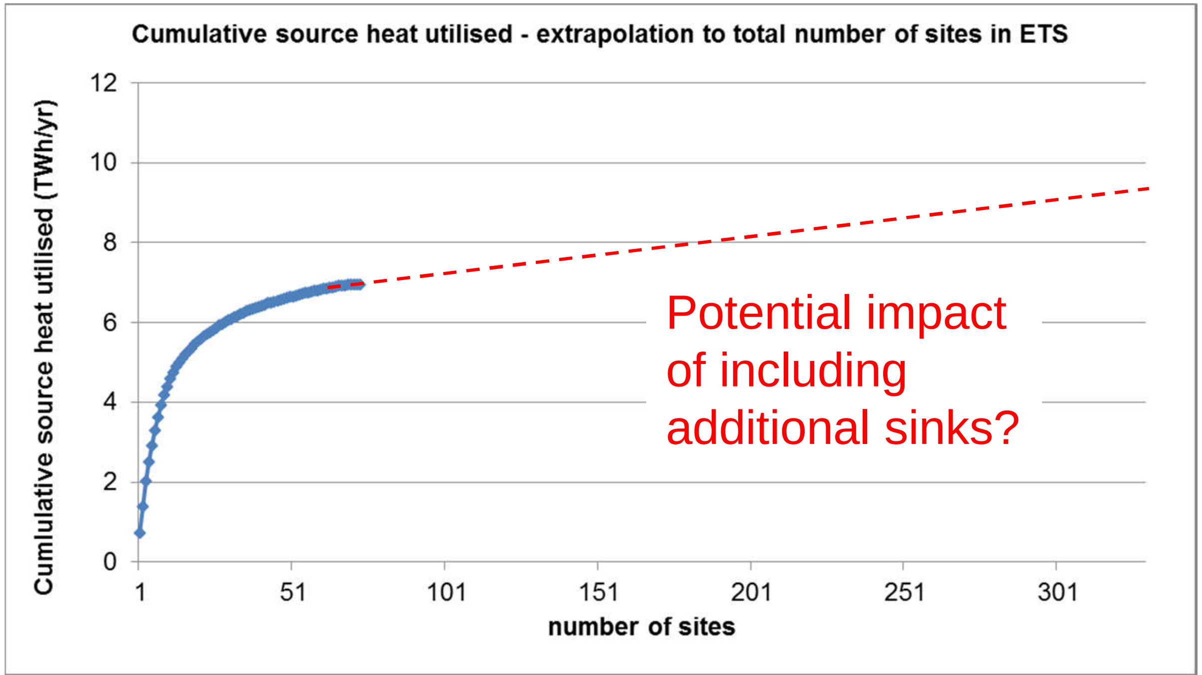
Focus on large sites for national estimate results in high coverage of large-site industries, but lower for industries with more smaller sites



*Compared on a unit production (tonne steel basis), relative to heat load McKenna

McKenna *et al*., Energy Policy 38, 5878 (2010)

Extrapolation of economic potential results to all UK ETS sites shows diminishing contribution of more smaller sites, upto ~10 TWh/yr



Sector	No. of sites	% of sectoral EU ETS emissions
Iron & steel	3	98
Refineries	8	97
Chemicals	22	82
Cement	11	95
Food and drinks	10	52
Pulp & Paper	6	56
Glass	9	76
Ceramics	4	24
Total	**73**	**85%**

- The diminishing contributions provides additional support for the focus on the largest sites for a national estimate of the available potential
- The projected additional potential is mainly from sectors that have a lower representation in the base case estimate, especially Food&Drinks, Pulp&Paper and Ceramics.

Chemicals

Chemicals – Sector Description

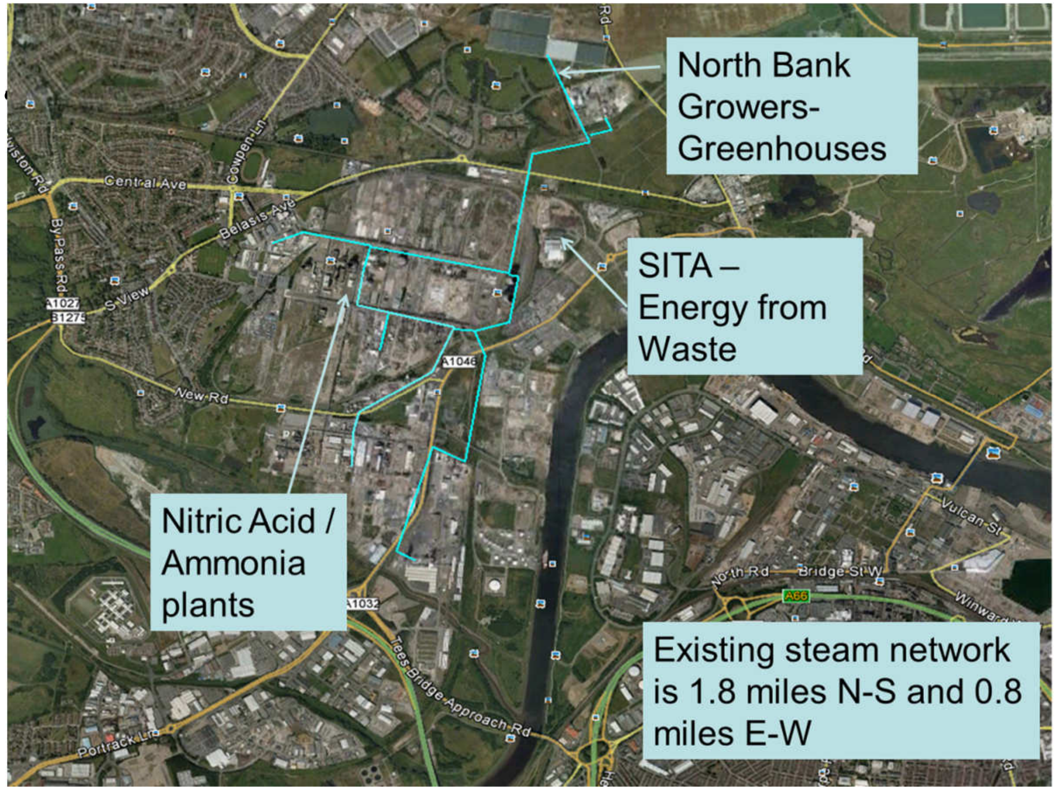
1. Sector context
   The chemicals industry comprises many different products, ranging from (in)organic bulk chemicals to small volume special products.
2. Description of main processes
   Due to the wide ranges of different chemicals produced, various combinations of processes take place in the chemical sector, therein forming new substances in various types of reaction vessels. Special corrosion-resistant equipment at elevated temperatures and pressures with the use of catalysts produce chemicals that are separated by a variety of techniques, such as (fractional) distillation, precipitation, crystallization, adsorption, filtration, sublimation, and drying.
3. Energy intensity / CO_2-emissions
   In 2012, the largest consuming industrial sub-sector in the UK was the chemicals sector, being responsible for 4,102 ktoe (16 per cent of total industrial energy consumption). Between 1990 and 2011, energy intensity in the chemical sector fell by 47 per cent, more than offsetting the increased output in that period. The UK is 25 per cent less energy intensive than the EU average. Between 2000 and 2009 the UK has reduced energy intensity by 53 per cent compared to the EU average of 23 per cent.
4. Heat recovery
   Main sources of rejected heat in the chemical sector are low temperature cooling water and low temperature exhaust gas from boilers.

Chemicals – Sector Description

5. Potential on-site heat recovery measure
   Additional reject heat recovery potential is expected to be limited. Generally, on many larger sites, optimalisation of heat flow integration, by e.g. pinch analyses is continuously taking place.
6. Availability of over-the-fence options (proximity to nearby sites)
   The UK chemical manufacturing industry is largely centred in the north of England. Commodity chemicals and petrochemicals are being produced on Teesside, which creates significant opportunities for feeding a DHS for the inhabitants of Middlesbrough and surroudings, with a population of over 100,000.
7. Indication that sector uses different investment criterion than 2 year payback
   No such indication.
8. Identified barriers to implementing waste heat recovery projects
   Long-term commitment of DHS, economics of investing in DHS (payback generally >2 years).

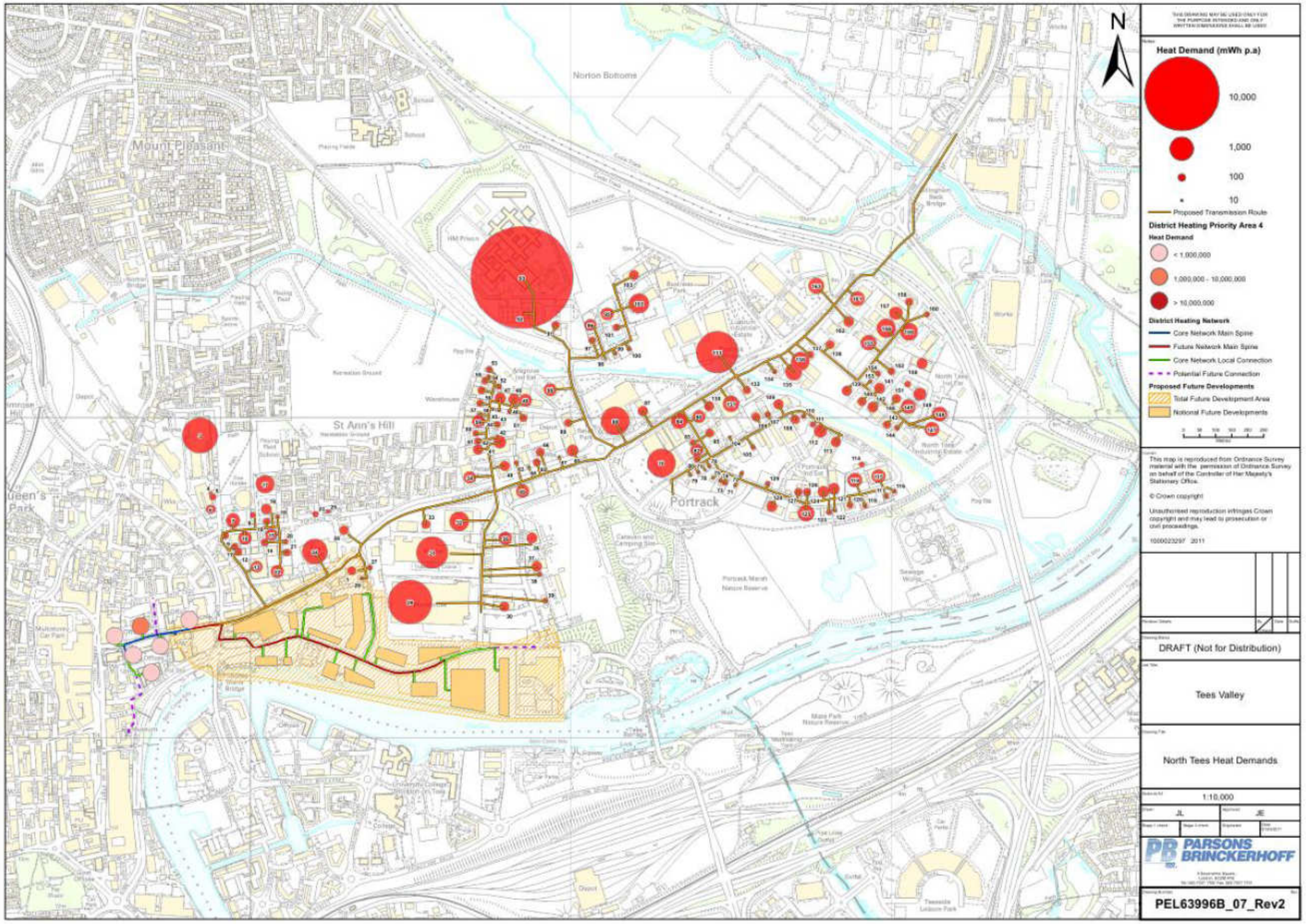
Existing heat recovery in the chemicals sector: a chemical plant in the Tees Valley already supplies heat to multiple users via a network

As an example, in the Tees Valley there is already an industrial heat (steam) network with capacity ca. 0.2 TWh/yr connecting GrowHow's fertiliser plant (a heat source) with at least five heat users in close proximity (less than 4 square miles).



Source: GrowHow (Presentation to Element Energy 2nd July 2013)

There is potential to expand provision of heat network to integrate multiple heat intensive industrial sites in the Tees Valley.



PB Power report for One North East (2011) A District Heating Utility for the Tees Valley

Industrial heat sources – Chemicals

Identified heat sources for the chemical sector

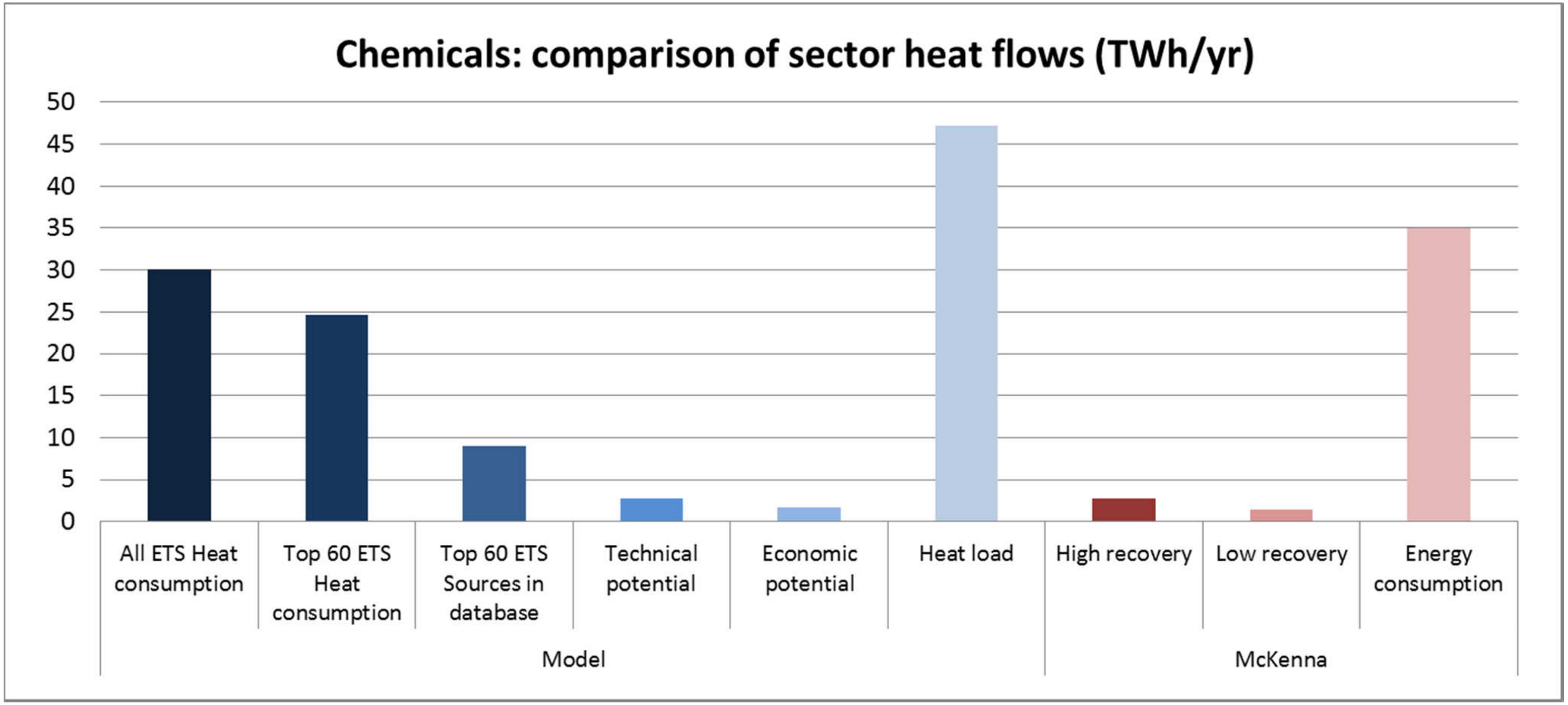
Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/kWh energy input)	Source Temperature (°C)
Chemicals	Processing Furnace Exhaust		Processing Furnace Exhaust	GAS	0.07	200
Chemicals	Boiler exhaust		Boiler exhaust	GAS	0.08	200
Chemicals	Condensate		Condensate	WATER	0.03	90
Chemicals	Process water		Process water	WATER	0.06	50
Chemicals	Condenser cooling water		Condenser cooling water	WATER	0.13	50

- Constructing a bottom-up model covering the majority of production routes, would have been too time-consuming for this project. Instead, we focused on the main heat using processes that are common in most chemical plants.
- The functional unit is kWh energy input, derived from DUKES, as a product based functional unit would not work because of the heterogeneity of the sector.
- The division over the process types is based on generic sources of rejected heat according to Crook, A. (1994). Temperature levels are typical values for the generic heat sources considered. Rejected heat flows are corrected with progression of an energy efficiency index, specifically for the UK chemical sector (obtained from DECC statistics)
- The CIA (Chemical Industries Association) did not acknowledge the above method to represent the waste heat potential of the chemical sector. However, due to no proposed alternative approaches in obtaining an estimate, the method was operationalised and subsequent estimations of waste heat potential have been compared with estimations from earlier studies such as McKenna (2010).

Sites included in modelling – Chemicals

Site name
Wilton Olefins 6 (Cracker)
Grangemouth Olefins
Winnington CHP (Brunner Mond)
Fife Ethylene Plant
Lostock Sodium Carbonate Manufacturing site
Teesside Hydrogen Plant
Cassel Site
Cellulose Acetate Flake Production Unit
Weston Point CHP Station
Runcorn Halochemicals Manufacturing
NPOWER COGEN (HYTHE) LIMITED
DSM Dalry
Shell UK Ltd Fife NGL Plant
Dow Corning Cogen Plant
INEOS CHP PLANT
Acordis UK Grimsby power station
Fawley
BASF, Seal Sands
Invista UK Power Facility
BP Chemicals Ltd, Hull
Millennium Inorganic Chemicals Ltd
North tees Aromatics

Chemicals



McKenna *et al*., Energy Policy 38, 5878 (2010)

Feedback from the Chemicals Industry Association (1/2)

- In view of the number of assumptions, the report provides a welcome objective quantification of the potential.
- For chemical projects, the installed cost factor for heat exchangers is ca. 4-5, possibly due to needing to use more expensive materials of construction and additional instrumentation in the chemical sector.
- Heat exchangers in the chemical industry use pressures higher than 4barg with a corresponding impact on cost.
- Steam and flue gas conditions are limited by the potential for acid corrosion.
- Air and water preheating are well understood and it is expected that almost all commercially viable projects would already have been implemented.
- The use of Phase 2 EU ETS has created a bias towards standalone heat supply by boilers and CHP. This means some potential heat sources are omitted, eg; while though ethylene crackers were by exception included in Phase 2, other direct heat equipment starting with ammonia furnaces were not.
- Opportunities to refine allocation of installations between sectors in future work.
  - As the cellulose acetate plant is now closed so the associated Derwent generator is no longer associated
  - The NGL plant is upstream and should be considered part of the energy sector.
  - Grangemouth CHP and Grangemouth power station are listed in the refinery and power sectors but partly serve the downstream petrochemicals processes at Grangemouth.
  - The Stanlow Refinery installation permit also covers the downstream petrochemicals processes which use part of the output from the CHP.

Feedback from Chemical Industries Association (2/2)

- Opportunities for heat recovery may not be economic if they can only be implemented during a shutdown.
- In the chemicals sector (and in other sectors) there can be technical barriers to implementation of heat recovery such as concerns over fouling, expensive materials of construction (to minimise corrosion) etc. The presence of solids adds huge complexity and requires a tremendous amount of research, the need for a lot of scientific evaluation and design and high capital costs.
- 5-10 km radius may be more realistic for over-the-fence heat networks than 40km.
- Commercial or liability issues associated with supplying heat offsite to a 3rd party heat users are significant potential barriers.
- Funding and cultural challenges for district heating are significant.
- Long term investment is difficult amid the current policy uncertainty, and trust plays a crucial part. There is currently a weighting for projects with a payback of up to 2 years.
- Possible mechanisms for addressing barriers include:
  - Support for R&D and demonstration projects to assist learning.
  - Incentives to support higher payback opportunities.
  - Funding for district heating infrastructure.

Cement

Cement – Sector Description

1. Sector context
   The UK cement sector consists of 6 companies with in total 13 sites. Of this, 11 are included in the quantitative modelling. Typical UK cement production is 10 million tpa.
2. Description of main processes
   Cement production can be divided in two basic steps. (1) Clinker is made in a rotary kiln at temperatures of 1450°C and (2) Clinker is then ground with other minerals to produce the powder we know as cement. Raw materials are limestone (for lime), clay, marl or shale (for silica, alumina, and ferric oxide) and other supplementary materials such as sand, pulverised fuel ash (PFA), or ironstone (to achieve the desired bulk composition). More and more low and zero carbon waste fuels are being used. Most of the plants in the UK are of the dry process type (grinding mineral components without addition of water).
3. Energy intensity / CO_2-emissions
   Typical cement kiln sites use 50-55% coal, 35-40% waste-derived fuels (meat and bonemeal, tyres, sludge), variable biomass, but relatively little gas use. Most (60%) of the CO_2-emission of cement production is in fact process-related due to the decomposition of the $CaCO_3$. Since 1990 an absolute reduction of 54% in emissions have been achieved, based on efficiency, fuel switching and changes in output. This is equivalent to 29% as expressed per tonne of product.
   http://cement.mineralproducts.org/documents/MPA_Cement_2050_Strategy.pdf
4. Typical energy consumption is 3-4 GJ of fuel/tonne and 90-120 kWh of electricity per tonne of cement produced. Dry processes consume about 13% less electricity and 28% less fuel than a wet process. Energy represents a huge proportion of the operation costs of a cement work – approximately 34%[1] of the gross-value added (GVA) for cement, of which electricity accounts for 59%[2] of the energy costs or 20% of the total GVA.

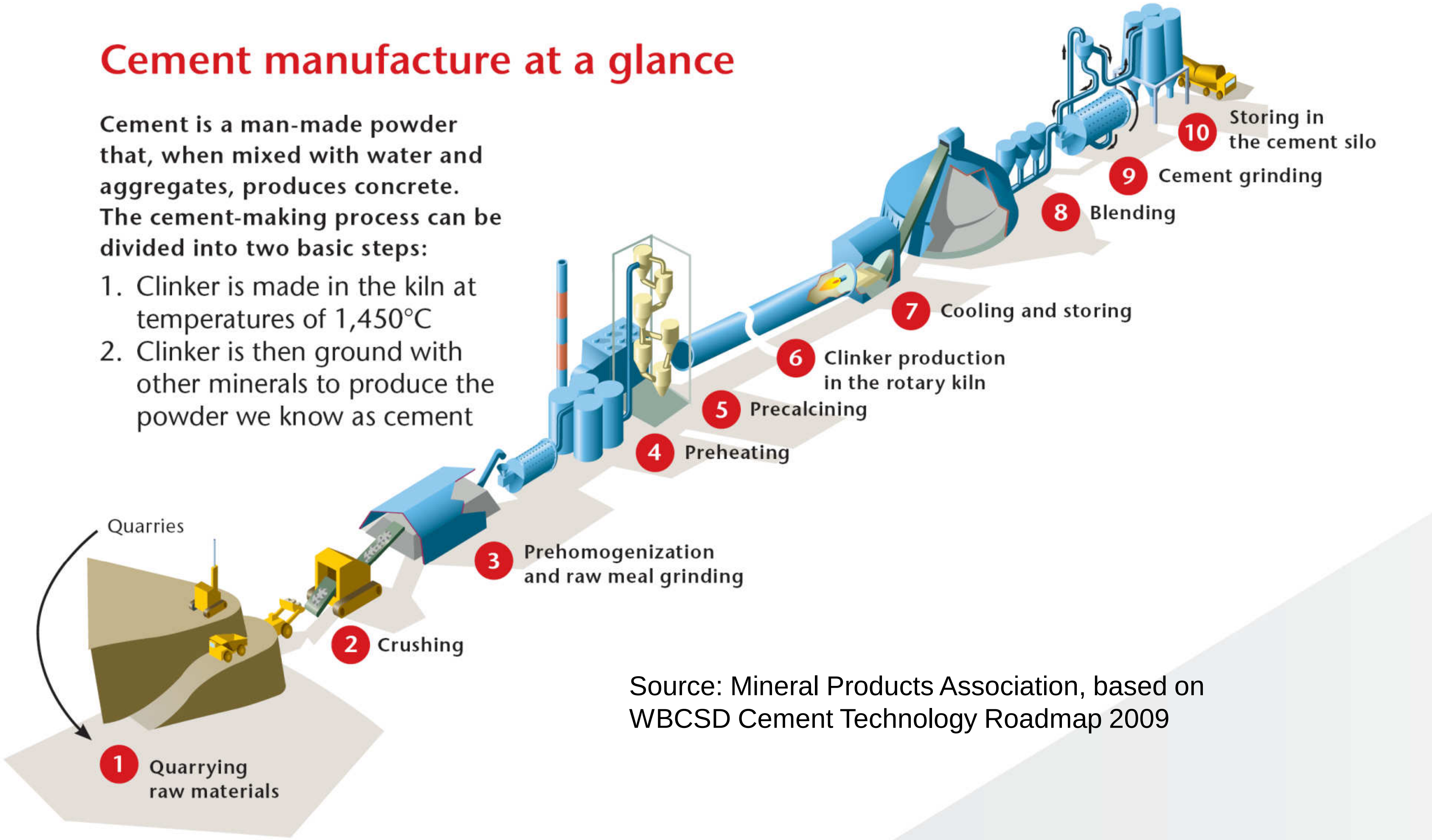
[1] *DECC, The Future of Heating, meeting the challenge 2013*

[2] *Based on the Digest of UK Energy Consumption (DUKES) and DECC IAG 2013 price curves*

Cement – Sector Description

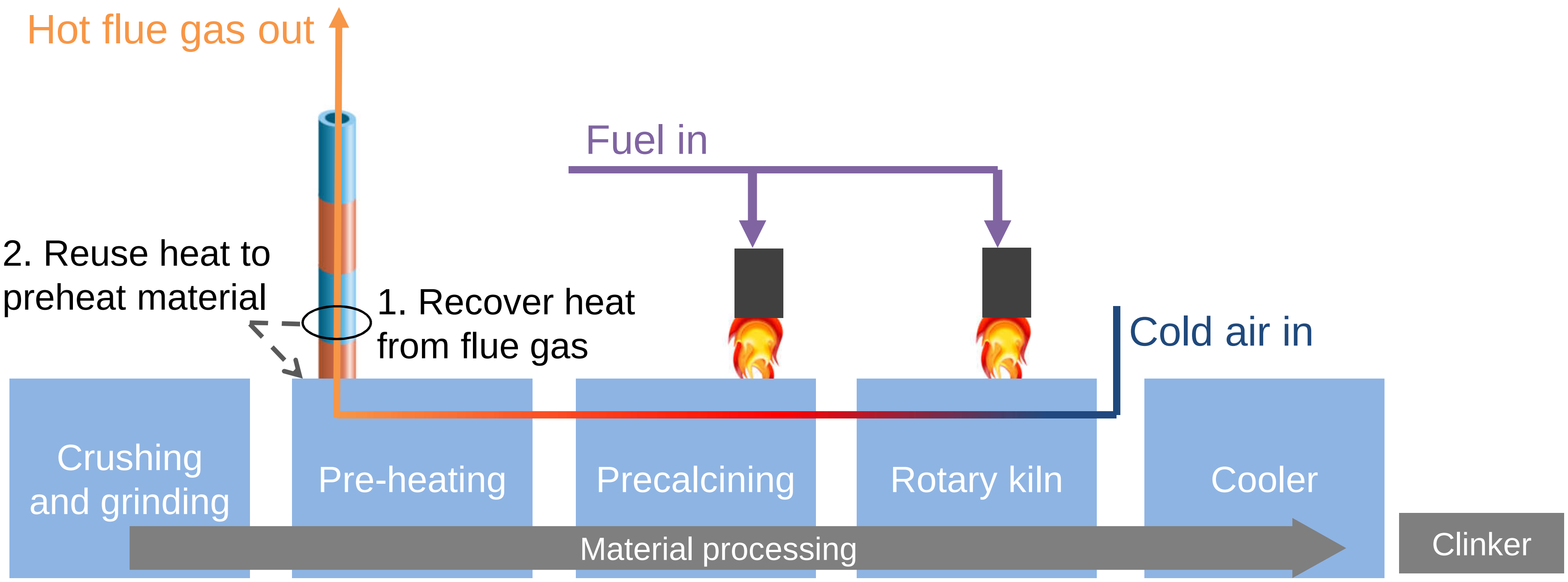
5. Heat recovery
   The rotary kiln is the major energy user. Main “reject heat” sources are from: top end of the rotary kiln (exhaust gases typically passed through 4 or 5 pre-heat chambers to re-capture the reject heat and use for the raw-material pre-heating and pre-calcining of the carbonates into oxides), or heat from the clinker as it drops out from the furnace (used for feeding to the silo pre-heaters, drying the raw materials, superheating exhaust from wet-scrubbers). Already uses the secondary grater-cooler heat for superheating the exhaust from the wet-scrubber
6. Potential on-site heat recovery measure
   Additional reject heat recovery potential is expected to be very limited. Clinker grate cooling could be used for the generation of electricity using waste heat.
7. Availability of over-the-fence options (proximity to nearby sites)
   Due to the nature of cement works, being located near to quarrying operations in largely rural locations, there are few of such sinks close to cement works.
8. Indication that sector uses different investment criterion than 2 year payback
   No such indication.
9. Identified barriers to implementing waste heat recovery projects
   MPA see that current legislation acts as a major disincentive to re-capturing and re-using any reject heat for electricity(heat will be largely derived from coal, so fossil-fuel). Hence it would be charged the various Carbon Price support taxes/ levies for fossil fuels used in power generation, and not attract any incentives such as FITs, ROCs or RHI (other countries, such as Norway and Germany, make it attractive for cement and others to generate electricity from waste-gases. This is much less so in UK).

Illustrative rotary kiln-based cement manufacturing



Source: Mineral Products Association, based on WBCSD Cement Technology Roadmap 2009

Example existing heat recovery measure at a cement plant



Heat recovery is employed extensively in cement plants. The hot flue gas is usually used to preheat the crushed and ground base materials in various stages.

Industrial heat sources – Cement

Identified heat sources for the cement sector

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/tonne of clinker)	Source Temperature (°C)
Cement	Kilns	Dry Kiln - Preheater	Waste heat in the exhaust gas from the kiln	GAS	192	338
Cement	Kilns	Dry Kiln - Precalciner	Waste heat in the exhaust gas from the kiln	GAS	225	338

Characterisation

- The cement sector is relatively homogeneous across sites in terms of unit operations.

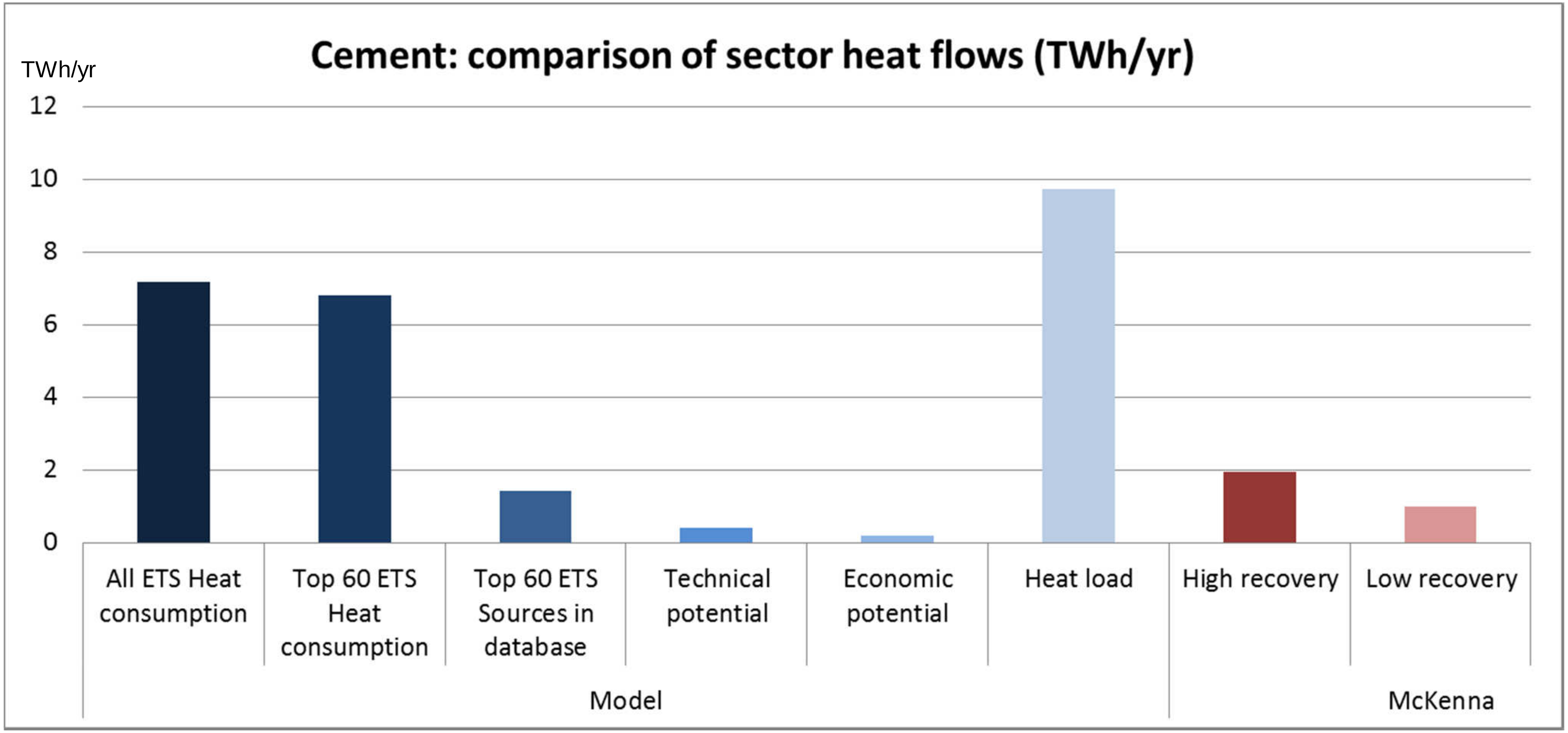
Methodology

- We used ‘tonne of clinker’ as the functional unit to define the heat flows (kWh rejected heat/functional unit)
- Different types of kilns have substantially different rejected heat flows as a fraction of energy input as well as exhaust temperature levels. These have been differentiated. Specific energy consumption of kilns according to IEA (2010)
- Unit operations, heat flows and temperature levels derived from DOE (2008)

Sites included in modelling – Cement

Site name
Rugby Works
Lafarge Cement UK PLC site 1
Ketton Works
Lafarge Cement UK PLC site 2
Tunstead Cement
Ribblesdale Works
Lafarge Cement UK PLC site 3
South Ferriby Works
Lafarge Cement UK PLC site 4
Lafarge Cement UK PLC site 5
Padeswood Works

Context for technical and economic potential for heat recovery and re-use in the UK cement sector



McKenna et al., Energy Policy 38, 5878 (2010)

Ceramics

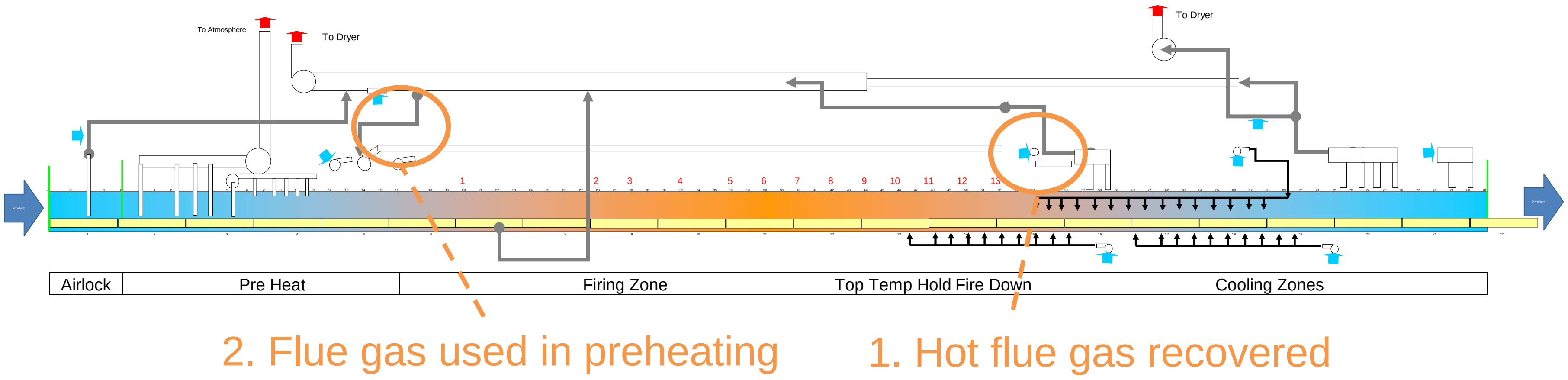
Ceramics – Sector Description

1. Sector context
   The UK ceramic industry manufactures products such as domestic and commercial tableware and giftware, sanitaryware, wall- and floor-tiles, bricks, clay roof tiles, and clay pipes. Brick production consumes approximately half of the total energy used by the whole ceramics sector. There are some 55 operational brick works in the UK, making approx 1,500 million bricks pa.
2. Description of main processes
   Clay is extracted in quarries, after which it is stockpiled before being used to make bricks through the following key steps: (1) clay preparation (crushing/grinding with additives) – (2) forming (either extrusion or soft mud process) – (3) drying (most dryers rely on recovered heat from the kiln to provide the bulk of their heat requirements for water evaporation) – (4) <u>firing</u>: dried bricks are fired in kilns at temperatures between 900°C and 1100°C, which changes the chemical make-up of the clays, thereby strengthening it and giving it the desired appearance. The main kiln types are tunnel kilns (continuous operations), intermittent kilns (batch operations), continuous chamber kilns (series of intermittent kilns) – (5) inspection and packaging.
3. Energy intensity / CO_2-emissions
   Most of the energy consumed in a brickworks (and most of the carbon emitted) is the result of the firing process. Drying is also energy intensive, but requires less fuel to be directly supplied as heat is recovered from the kilns for use within the driers. Natural gas is favoured because of its clean burn characteristics and easier maintenance. Electricity makes up around 8 per cent of the energy consumption of a typical factory and 19 per cent of the CO2 emitted (motors/fans/compressors). Specific energy consumption accounts to approx. 2 – 2.5 GJ fuel, and 0.1 – 0.25 GJ electricity per tonne of brick produced.
4. Heat recovery
   Recapturing reject heat from kiln to provide the bulk of the energy needed for brick drying (brick drying is a major energy centre; each 1 t of brick has to have approx 160 kg of water evaporated from it; therefore 158 Mt/y of bricks requires the evaporation of 25.3 Mt/y of water.) However many such opportunities have already been implemented.

Ceramics – Sector Description

5. Potential on-site heat recovery measure
Several internal energy savings to reduce heat requirements for brick making (improve tunnel dryer, reduce kiln car losses, combustion air pre-heating for burners, fix leakage of under car cooling air at kiln exit, use cooling energy for drying purposes. Further, heat losses from dryer exhaust, from kiln, other).
In general, most likely use is to pre-heat the water used for mixing the clay plus brick additives prior to its extrusion. Secondary effect is less water in the brick, which reduces dryer energy requirements. CHP is mentioned as option. Significant heat recovery is already implemented.
6. Availability of over-the-fence options (proximity to nearby sites)
The opportunities for export of heat to adjacent sites or locally via a DHS are broadly similar to other sites considered for the same opportunity. UK brick manufacturing locations tend to be up to 10 kms from small- to medium city areas.
7. Indication that sector uses different investment criterion than 2 year payback
Tend to use 2 years as bare maximum, in practice even 2yr payback might be difficult to justify.
8. Identified barriers to implementing waste heat recovery projects
UK Government policy decisions are considered to be fragmented and difficult to understand, and overlap with EU-ETS. Further, the impact of consultation exercises is not known, no longer contributing to energy benchmarking such as EEBPP.
There is limited trust in Government interventions (most interventions seen as “sticks”, largely taxes or legislation, whilst little positive incentives or “carrots”). Lastly, limited cash availability for investment due to the sector’s fragile nature and low profit margins (see 7.)

Example existing heat recovery at a ceramics plant



Different types of kilns are used in the ceramics sector, depending on the nature of the process (continuous vs batch specialty products)

Continuous processes provide the best opportunities for heat recovery. The above depicted brick tunnel kiln layout is illustrative for continuous production. Heat is usually recovered from the end of the firing zone and reused for drying the input materials

Image provided by Weinerberger and Ceramics Federation

Industrial heat sources – Ceramics

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/tonne of product)	Source Temperature (°C)
Ceramics	Firing	Continuous kiln - Tunnel	Waste heat in the flue gas from the kiln	GAS	228	165

Characterisation

- The ceramic sector is very homogeneous across sites in terms of unit operations. The vast majority of installations in the UK are brick manufacturers (McKenna, 2009)

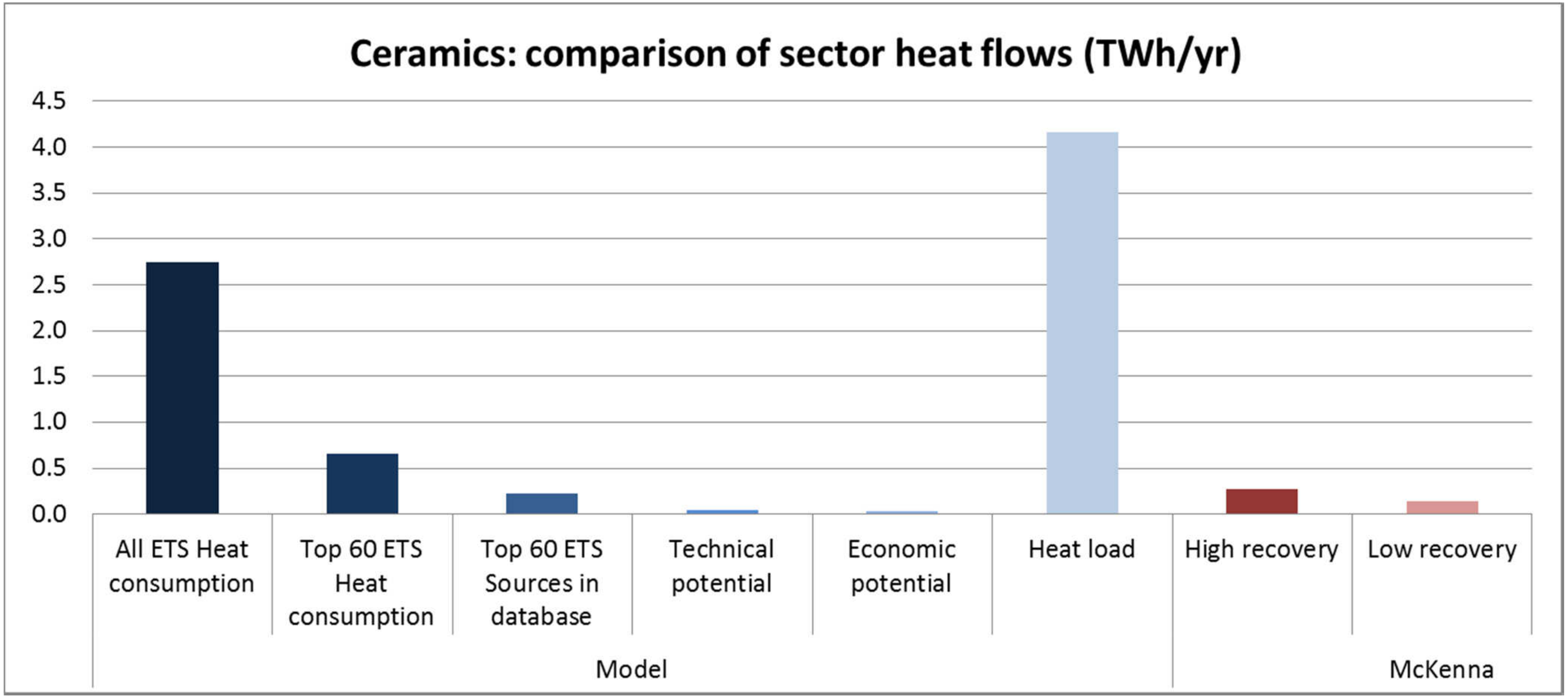
Methodology

- We used 'tonne of product' as the functional unit to define the heat flows (kWh rejected heat /functional unit)
- Specific energy consumption in kilns according to BREF document (EC, 2007)
- We assume that 35% of the energy input for the firing process is lost is lost as waste heat in the flue gas (MacKenna,2009). We estimate that 30% of the energy input for the firing process is lost is lost as hot air in the cooling section of the tunnel kiln.

Sites included in modelling – Ceramics

Site name
Hanson - Whittlesey
Hanson - Desford
Ibstock Brick Ltd Dorket Head Factory
Warnham Brickworks

Ceramics



Ceramics: comparison of sector heat flows (TWh/yr)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
All ETS Heat consumption
Top 60 ETS Heat consumption
Top 60 ETS Sources in database
Technical potential
Economic potential
Heat load
High recovery
Low recovery
Model
McKenna

The European Ceramics Industry Association's 2050 roadmap includes significant roles for heat recovery in the future.

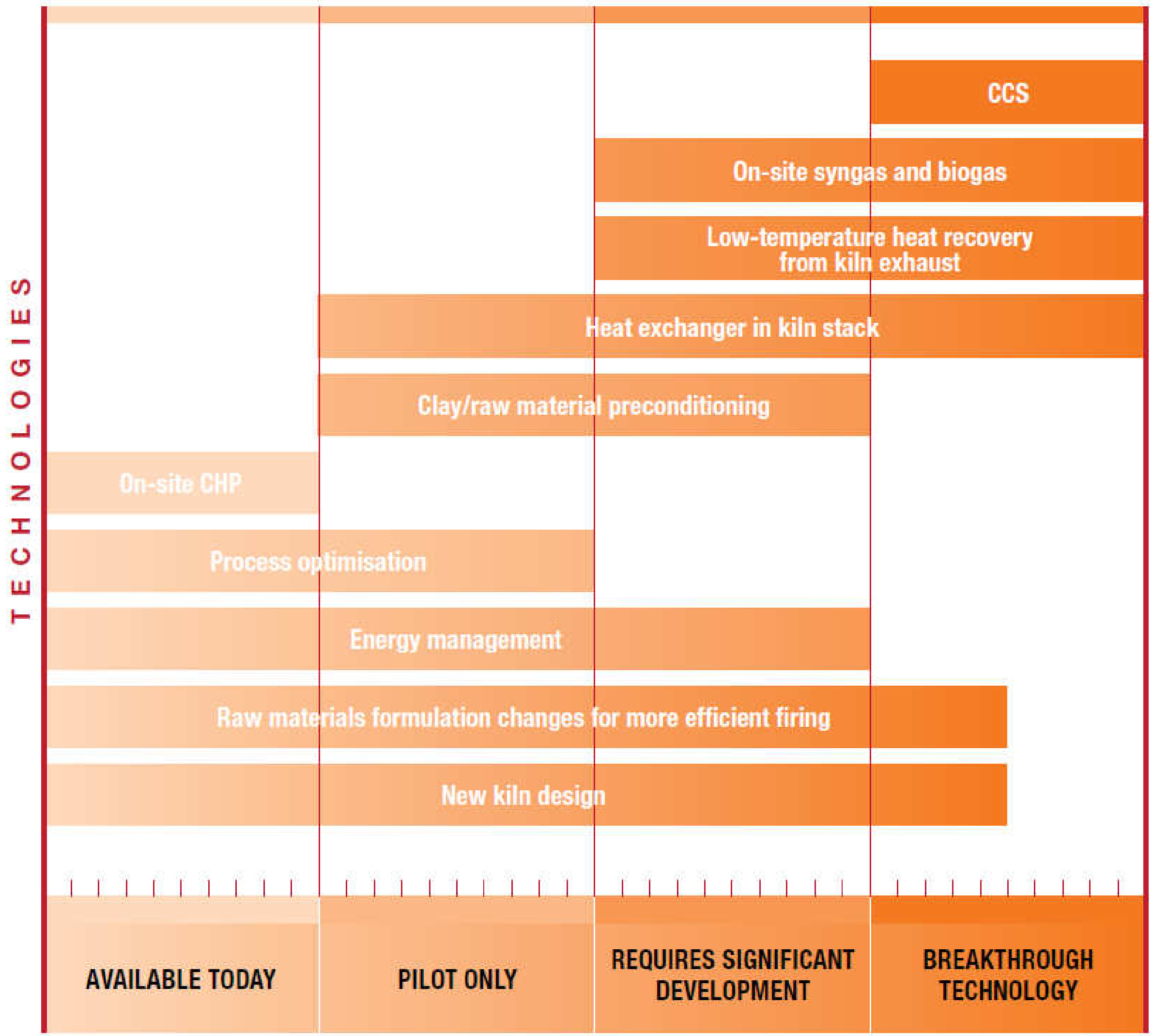


Image from Cerame-Unie
Paving the way to 2050

Food & Drinks

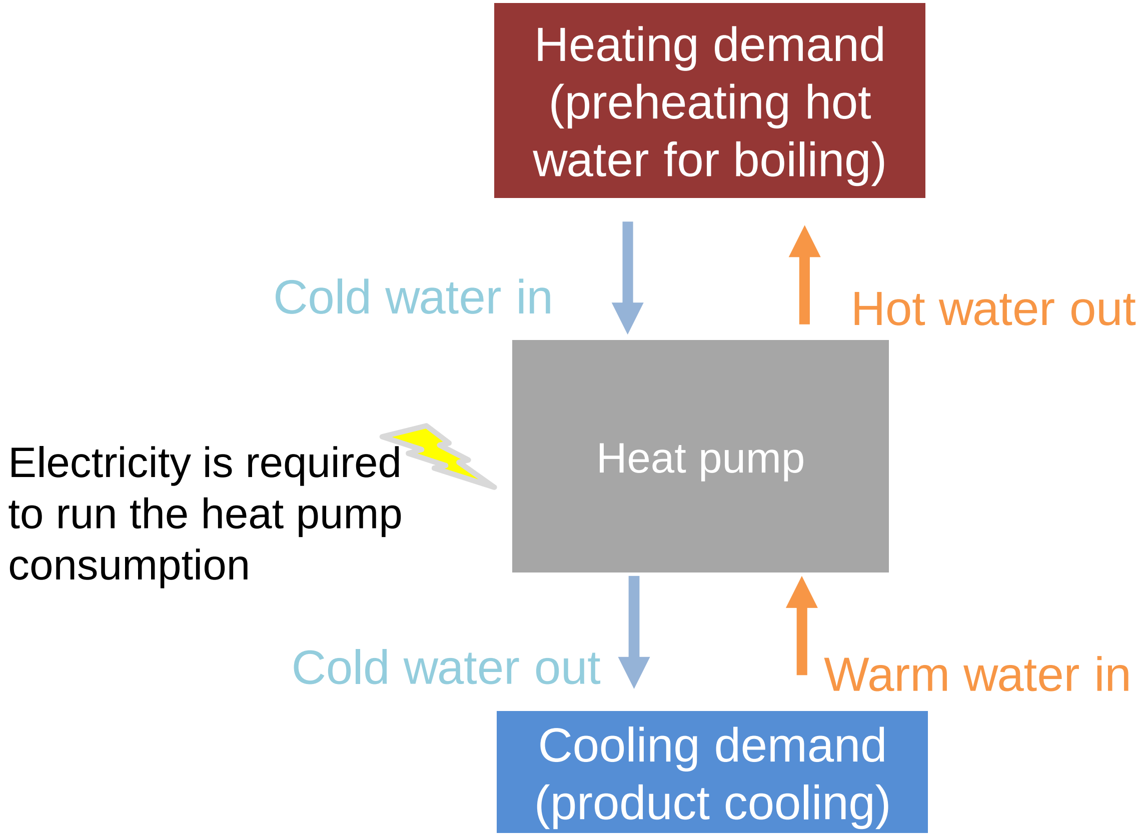
Food and Drinks – Sector Description

1. Sector context
   The food and drinks sector is very heterogeneous in terms of processes and type of product output across sites. For this reason, we have defined generic unit operations.
2. Description of main processes
   Due to the wide variety of products, several unit operations are found in the Food & Drinks sector. This ranges from product heating/cooking to evaporation to wash water /CIP (clean-in-place; a method to clean interior of equipment) operations.
3. Energy intensity / CO_2-emissions
   Energy use can be broken down into different unit operations identified by FDF (Trade Assocation for larger part of Food & Drinks sector). The majority (~75%) of energy use for EUETS installations is consumed by product heating/cooking, baking, drying and evaporation operations. The remainder is used for frying, wash water/CIP, pasteurisation/sterilisation, space heating and domestic hot water uses. More than 80% of the required heat is produced by CHP, steam boilers and direct fired ovens. Hot oil heats, direct fired dryers and other installations account for the last 20%. Of course, this greatly various per subsector (e.g. tea and ground coffee knows 60% of heat provided by direct fired dryers).
   In terms of CO2 emissions, the subsectors sugar, ambient food, baking and cereal, confectionary and frozen and chilled account for 50% of total sector emissions (2008).
4. Heat recovery
   Main heat sources are low temperature condensate from evaporation, distillation and cooking processes as well as low temperature exhaust gases from boilers.

Food and Drinks – Sector Description

5. Potential on-site heat recovery measure
   Boiler (economizers) / Direct fryers (recup. burners, waste-heat boilers) / Thermal oil fryers (recup. burners, waste-heat boilers) / glazer (waste gases fryer) / Indirect heat recovery from electricity units (refrigeration, freezing, chillers, compressors).
6. Availability of over-the-fence options (proximity to nearby sites)
   In general, food and drinks operations tend to be close to urban areas, which could lead to several low grade heat needs in the direct surrounding. Also, several other operators that might be close to a F&D facility could use low grade heat for certain boiler units. The assessment of these opportunities need to take place on a site-by-site basis due to the high heterogeneity of the sector.
7. Indication that sector uses different investment criterion than 2 year payback
   Due to the limited size of many F&D operations (relative to other industrial sectors), payback criterions tend to be less than 1 year
8. Identified barriers to implementing waste heat recovery projects
   Heat-recovery is not considered core business, so many operators are not sure what they can do with heat. Also, many tend not to consider retrofit unless it can pay back for itself within 1 year. Usually, core activities give more immediate pressures. With respect to heat delivery, the risk and longevity seem to be experienced differently, with questions like what if heat customers close, relocate or otherwise change their minds, or as heat supplier. Also, it is considered that sales of waste heat might act as a disincentive/ barrier to standard energy efficiency due to the lock-in of supplying waste heat to a 3rd party. Not all sites employ heat metering or have specialist site energy managers.

Illustrative case study of a heat recovery option in the food industry



Heat recovery is used in the food and drinks sector. An innovative example is to use a heat pump to simultaneous cooling to a cooling demand and heating to a heat demand. Typical constraints in food and drinks facilities to use heat recovery extensively are extensive batch processes, (food) contaminants in effluent streams or hygienic requirements in the processes.

Industrial heat sources – Food and drinks

Characterisation

- The food and drinks sector is very heterogeneous in terms of processes and type of product output across sites. For this reason, we have defined generic unit operations.

Methodology

- We used ‘kWh of final energy consumption’ as the functional unit to define the heat flows (kWh rejected heat/functional unit)
- Final energy consumption in the food and drinks sector (from DUKES database) is allocated into the generic unit operations (boilers, baking, drying, evaporation, distillation, cooking, cooling water, refrigeration, air compressors) based on expert estimations.
- Rejected heat flows from each unit operation are calculated as a fraction of the energy input. Temperature levels are typical values for the generic unit operations considered.
- A differentiated analysis is done for the sugar sector given its weight among food and drinks sites under ETS.

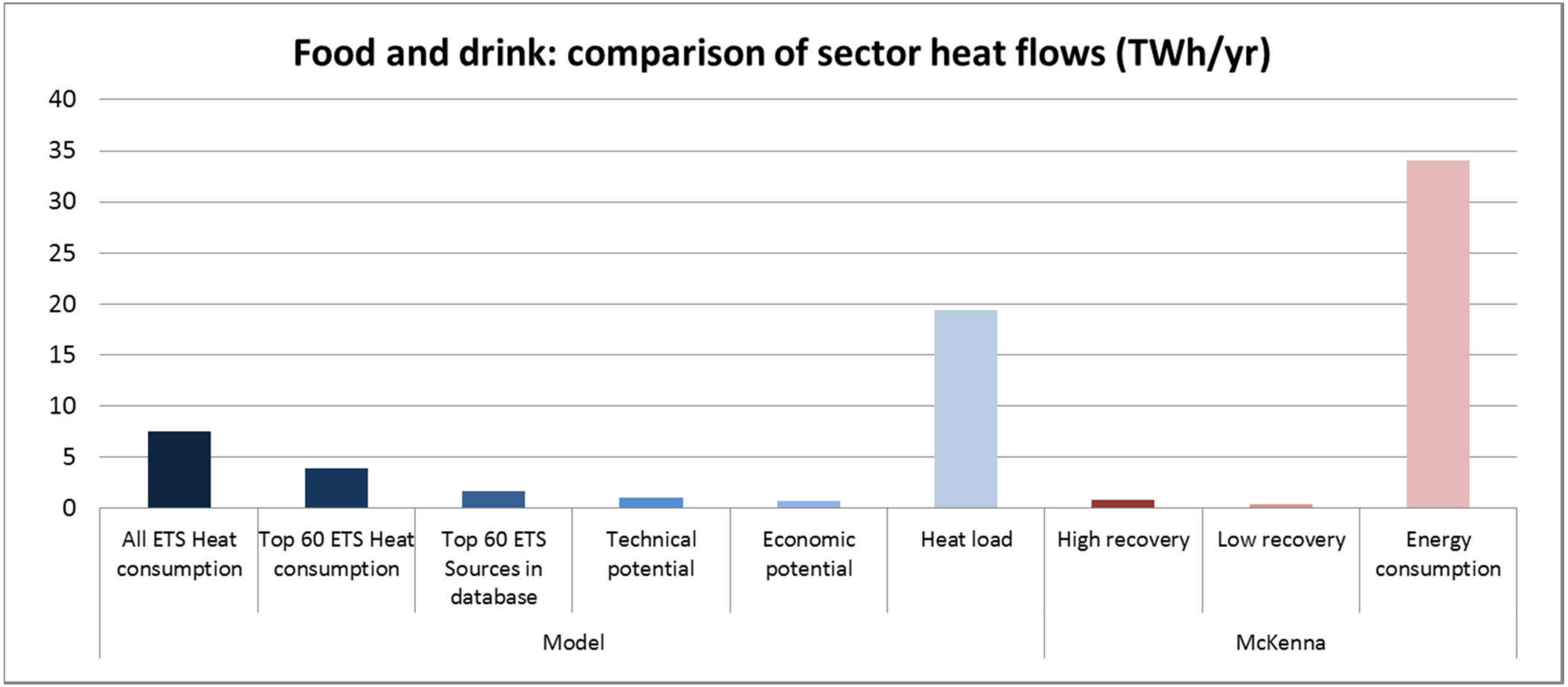
Industrial heat sources – Food and drinks

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/functional unit)	Source Temperature (°C)
Food & drinks	Boilers		Flue gases boilers	GAS	0.025	145
Food & drinks	Baking		Flue gases ovens	GAS	0.018	170
Food & drinks	Drying		Air / vapours	GAS	0.035	125
Food & drinks	Evaporation / Distillation/Cooking		Condensates	WET_STEAM	0.125	90
Food & drinks	Cooling water		Condensates	WATER	0.081	100
Food & drinks	Refrigeration		Condensor	WATER	0.126	60
Food & drinks	Air compressors		Cooling air	GAS	0.022	50
Food & drinks	Boilers		Flue gases boilers	GAS	0.019	145
Food & drinks	Baking		Flue gases ovens	GAS	0.000	195
Food & drinks	Drying		Air / vapours	GAS	0.054	125
Food & drinks	Evaporation / Distillation/Cooking		Water vapour	WATER	0.281	50
Food & drinks	Cooling water		Condensates	WATER	0.081	100
Food & drinks	Refrigeration		Condensor	WATER	0.027	60
Food & drinks	Air compressors		Cooling air	GAS	0.004	50

Sites included in modelling – Food and drinks

Site name
Wissington Sugar Factory
Bury St Edmunds Sugar Factory
Manchester Sweetners
Tate and Lyle Sugars
Cantley Sugar Factory,
Roquette UK Limited - CHP Plant
British Salt Ltd. Middlewich Site
Kraft Foods - Coffee
The Girvan Distillery
H.J. Heinz – Kitt Green

Food and Drink



McKenna et al., Energy Policy 38, 5878 (2010)

Insights from the Food and Drink Federation on energy use

During stakeholder discussions, the FDF has highlighted:

- Considerable sub-sector heterogeneity in terms of processes used (see table).
- Thermal processes include steam boilers, CHP, hot oil, direct fired ovens, direct fired dryers, and cooling.
- Actual site process and production data are confidential.
- Overall sector energy use and energy cost competitiveness impacts are substantial, even if individual food and drink manufacturing sites are not always as large as sites in other manufacturing sectors.
- Many electrical systems also used.
- Mix of data reporting mechanisms
    - 7 TWh/yr under CCA and ETS
    - 9 TWh/yr energy use under the CCA but not EU ETS
    - 3 TWh/yr under ETS but not CCA.

Process	ETS energy use (excl. sugar)
Product heating/cooking	37%
Evaporation	10%
Drying	11%
Baking	18%
Frying	5%
Wash water and CIP	9%
Pasteurisation and sterilisation	5%
Space heating	5%
Domestic hot water	2%

Glass

Glass – Sector Description

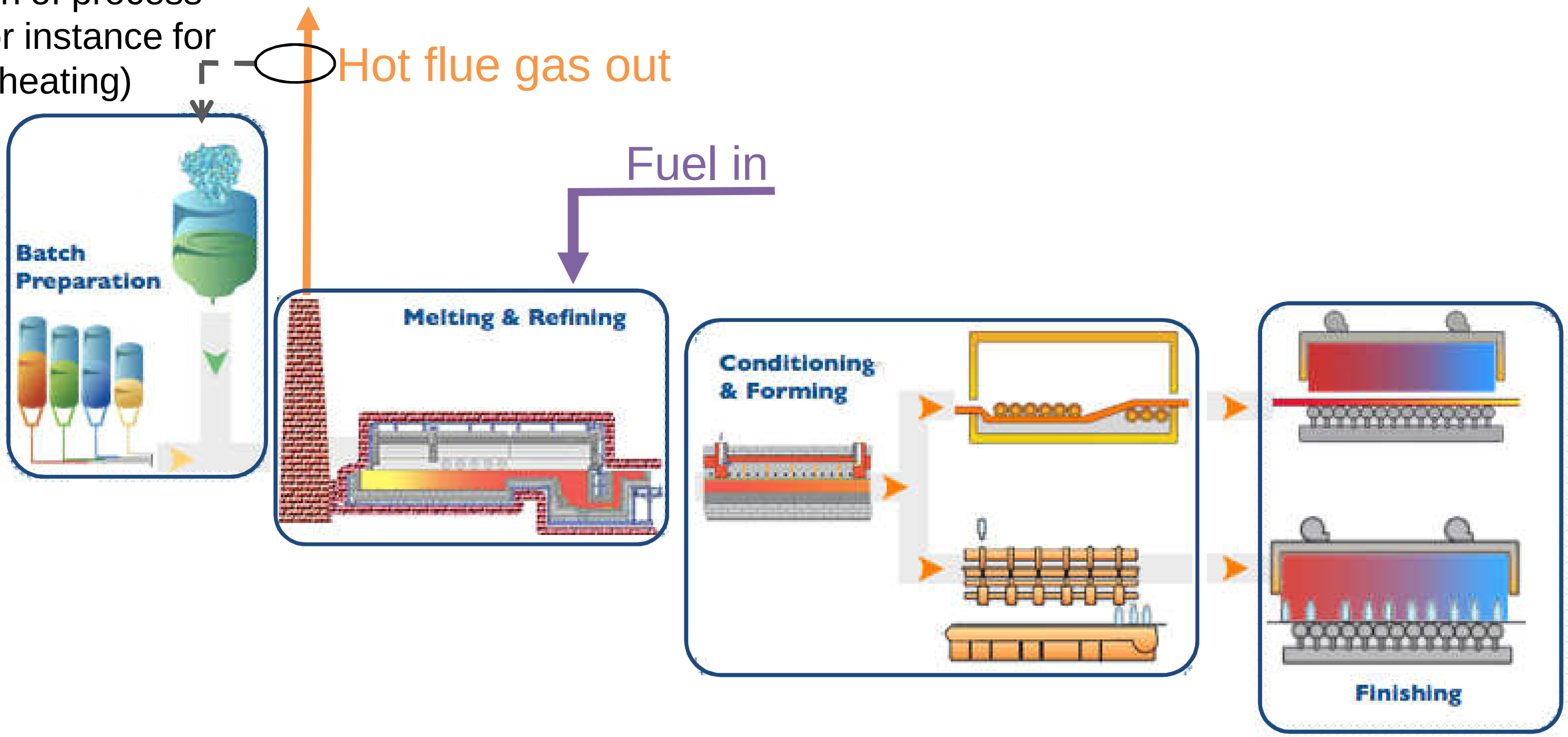
1. Sector context
   The UK glass industry (all sectors) produces an estimated 4 million tonnes of glass per year, divided as follows in the generalised subsectors of Container, Flat, Fibre and Domestic (including Crystal and Special Glass). Container glass, mainly bottles and jars, accounts for around 60% of all UK glass production. The UK container industry presently comprises six manufacturers producing a total of 2.3 million tonnes of container glass in 2010. The flat glass industry, fuelled by demand for building and automotive glass, represents the second largest sector in the UK glass manufacturing industry (3 companies produce 1.3 million tonnes (2010)). Larger facilities tend to be flat glass facilities and smaller facilities container glass. So container glass and flat glass account for 90% of total UK glass production.
2. Description of main processes
   Flat glass: feeding raw materials (mixture of silica sand, soda ash and lime and so on) – melting furnace (1,600+ °C) – refining furnace (bubble removal, temperature lowered to 1,100 – 1,300 °C, suitable for forming) – float bath (smooth and uniform flow over molten tin for formation) – annealing (slow glass cooling) – cutting (according to shipment sizes).
   Container glass: batch processing system (raw materials' housing) – melting furnace (1,600+ °C) – forming process (blow and blow process or press and blow process) – forming machines (hold and move parts that form container) – internal treatment (improve chemical resistance) – annealing (in a annealing oven called Lehr for slow cooling, time depending on thickness) – cold end (inspection, packaging, labelling).
3. Energy intensity / CO_2-emissions
   Energy is a major consideration in glass making. It is one of the largest operational costs (gas accounts for 36% of the GVA costs and electricity a further 10%). Nearly all the gas is used in the melting furnace; electricity is used throughout for fans, pumps, bag-filtration, motors – including the IS machines, compressors, electric-lehrs, conveyors and packing, laminating process and magnetron coating process.

Glass – Sector Description

4. Heat recovery
   Waste heat is generally recovered from the firing process, via regenerators. Regenerators comprise two large ceramic blocks that are used in tandem. Cold air is passed through the first (hot) regenerator. This pre-heats the air prior to it mixing with the gas and burning, reducing the quantity of gas needed for firing. The flame is used to melt the batch and heat the molten glass to approx 1400-1500°C. Exhaust gases (CO_2, H_2O and "ballast" N_2) exit via the second regenerator, heating up the ceramic blocks. The waste gas exits the bottom of the second regenerator at approx 400-500°C then pass to waste gas treatment and onto the chimney stack. Every 20 minutes the process is reversed and the pre-heated regenerator #2 is used to pre-heat the air, and the now cooled regenerator #1 recaptures the heat from the glass-tank. The regenerator system recaptures approx 50% of the heat from the process.
5. Potential on-site heat recovery measure
   Compressor waste heat recapture for space heating of "Cold-end" buildings, co-gen of electricity from waste gas exiting the exhaust flue, batch or cullet pre-heating (pass the hot exhaust gases through the batch hopper which allows the raw materials pick up some of the heat either indirectly (via tubes) or directly (intimate contact between waste gases and batch raw material)), heat from the float process, clean hot-air from the bag filters, Lehrs (as heat sink).
6. Availability of over-the-fence options (proximity to nearby sites)
   As *some* larger glass facilities tend to be located in fairly built-up areas and established industrial areas, with many industrial and commercial buildings within some km's of sites, potential heat export opportunities might arise.
7. Indication that sector uses different investment criterion than 2 year payback
   No such indication.
8. Identified barriers to implementing waste heat recovery projects
   UK Government policy (fragmented/inconsistent, wish to be involved with policy consultation earlier on), no incentives for recapturing reject heat ("sticks", byt no "carrots"), long paybacks and competition for investment, cultural issues (e.g. waste heat not being core activity).

Example existing heat recovery measure at a glass plant

Reuse heat in waste heat recovery boiler for the production of process steam (for instance for cullet preheating)



Heat recovery is employed extensively in glass plants. The hot flue gas from the smelting process is often used in waste heat recovery boilers to produce process steam. This can be used to preheat cullets (crushed recycled glass) or provide space heating.

Adapted from the Industrial Efficiency Technology Database (http://ietd.iipnetwork.org)

Industrial heat sources – Glass

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/tonne of glass)	Source Temperature (°C)
Glass	Glass Melting Furnaces	Regenerative	Waste heat in the exhaust gas from the furnace	GAS	316	500
Glass	Air Compressors	Air Compressors	Cooling air	GAS	68	40

Characterisation

- The glass sector is relatively homogeneous across sites in terms of unit operations.

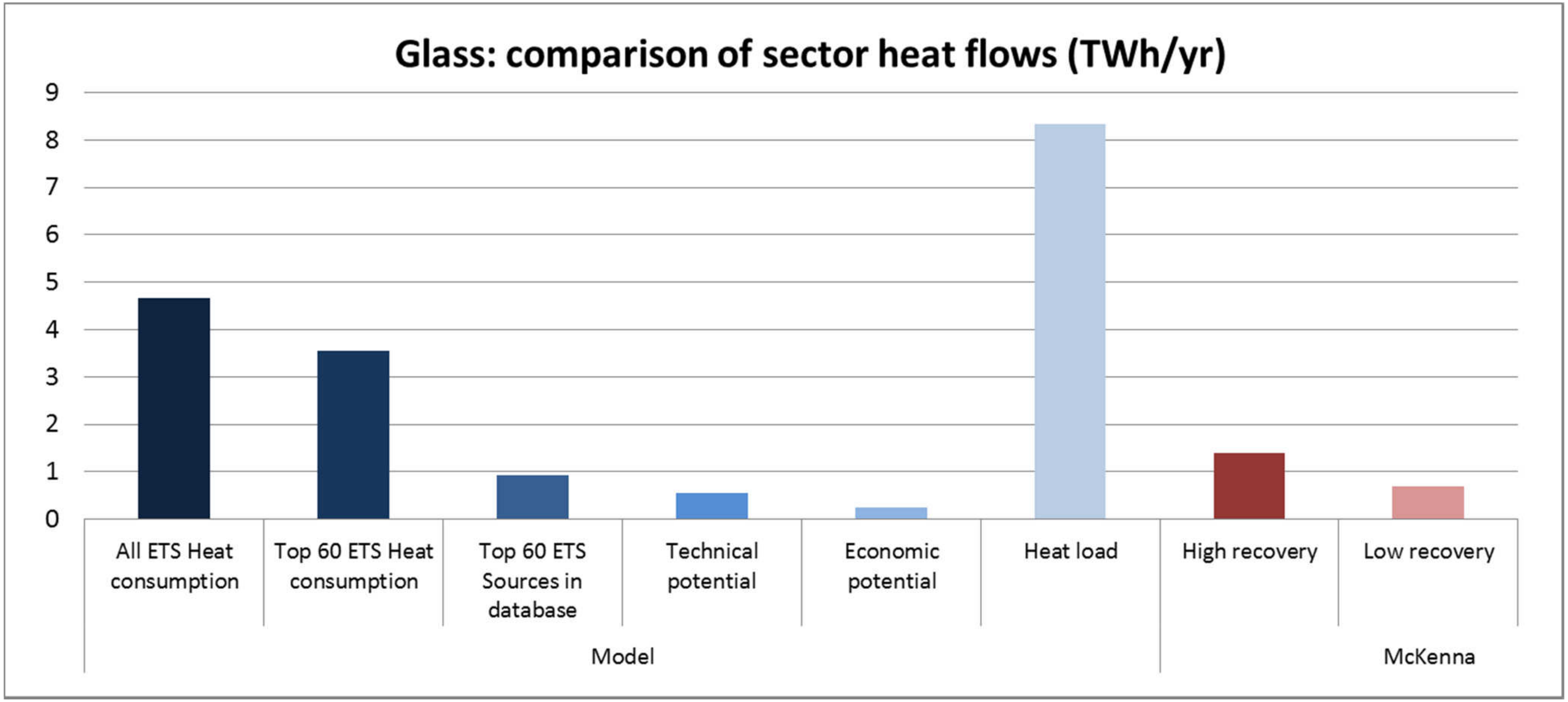
Methodology

- We used ‘tonne of glass’ as the functional unit to define the heat flows (kWh rejected heat /functional unit)
- Different types of glass melting furnaces have substantially different rejected heat flows as a fraction of energy input as well as exhaust temperature levels. These have been differentiated. Specific energy consumptions for different types of glass furnaces derived from BREF document (Joint Research Center, 2013)
- Selection of unit operations based on DECC (2013)
- Rejected heat flows as a fraction of energy input obtained from DOE (2008)

Sites included in modelling – Glass

Site name
Quinn Glass Elton
O-I Alloa Plant
PUKL Cowley Hill
Guardian Industries UK Limited
Redfearn Glass Limited
Quinn Glass
Ardagh Glass - Wheatley
Saint-Gobain Glass UK Ltd
PUKL Greengate Site

Glass



McKenna et al., Energy Policy 38, 5878 (2010)

British Glass (Trade Association) Feedback on options for waste heat recovery

Heat recovery opportunity	Container glass	Flat glass
Electricity generation	Barriers include high capex, space requirement, need for high heat volumes, difficult for companies to fund and trial technologies. Suggest establish a mechanism to reduce risk, e.g. Energy Technology Support Unit (ETSU) and/or financial incentive	Expect high potential using steam or organic Rankine cycles. Barriers include high capex, long payback, lack of UK availability of equipment and maintenance services in the UK, back pressure risk. Noted that implementation in France and Germany where electricity reward price is available
Pre-heating raw material – batch and cullet	Potentially valid at some sites. Interprojekt, Zippe, and Sorg have commercial designs of preheaters and energy savings of 10%-20% are possible. The technology has been implemented on a few container furnaces in Europe; but it must be noted that European recycling rates are higher than in the UK. The greater availability of cullet makes the technology more financially viable.	Low level preheating is already carried out in some cases. Potential risk of segregation of raw materials during transport to the furnace (causes melting problems). Cullet preheating is not attractive for flat glass. Cullet percentages in flat glass are typically much lower than in container glass. Flat glass manufacturing requires cullet with very low levels of contamination to preserve quality and reduce waste & energy use.
Space heating	Some space heating is already in place. Direct space heating is not traditionally used in glass manufacturing. Using a waste heat boiler generating steam or hot water can be a more flexible and cost effective solution.	
Over-the-fence heat network	Potential interest only if Government or third parties funds and manages any network into which a glass factory can plug into. Pipeline capex is high. Little willingness to enter into long-term contracts, which may have a seasonal demand.	

Other issues identified by British Glass:

- Temperature range for heat recovery limited by acid gas dew-point
- Pollution (dust) control systems such as bag filters and electrostatic precipitation installed between regenerator exit and the chimney sack under current integrated pollution regulations, and there may be future needs to control Nox using techologies that operate at 300-450 °C. These significantly impact availability of waste heat.
- Need to consider furnace investment cycles (10-20 yrs).

Iron & Steel

Iron & Steel – Sector Description

1. Sector context
   The UK iron and steel sector can be subdivided into three subsectors; Integrated (only 3 sites - Teesside Scunthorpe and Port Talbot), minimills (only a couple of sites) and Others (miscellaneous plants on Teesside, Corby, Hartlepool, S. Wales, and some in the Midlands and Scunthorpe, as well as several small re-rollers and annealers). In terms of heat recovery significance, focus is on Integrated and Minimills. In 2012, about 7.5 million tonnes of crude steel was produced in Integrated Steelworks, and 2 million tonnes in Minimills (electric arc furnaces). 2012 was atypical as Tata was rebuilding the blast furnace at Port Talbot and SSI were ramping up production in Teesside.

- Description of main processes
  There are two process routes for making steel in the UK today: through an *Electric Arc Furnace* and through the *Basic Oxygen Steelmaking* (BOS) process.
  The key component in the BOS is the Basic Oxygen Converter, however before this process can begin a blast furnace is required to create a charge of molten iron. The raw materials for producing molten iron are iron ore, coking coal and fluxes (materials that help the chemical process) - mainly limestone. Blended coal is first heated in coke ovens to produce coke (carbonisation), after which it is allowed to cool. Iron ore lumps and pellets, coke, sinter and possibly extra flux are carried to the top into the blast furnace. Hot air (900 degrees C) is blasted into the bottom of the furnace, from which oxygen combusts with the coke forming CO, which flows up through the blast furnace, removing oxygen from the iron ores on their way down, thereby leaving iron. The heat in the furnace melts the iron, and the resulting liquid iron flows out at the bottom of the furnace, towards the BOS vessel in which scrap steel has been charged first. Then very pure oxygen is blown at high pressure, which combines with the carbon, separating them from the metal, leaving steel.
  Unlike BOS, the EAF is charged with "cold" material (recycled steel goods at EOL, or direct reduced iron (DRI) and iron carbide, as well as pig iron). The cold material is fed into the furnace, after which electrodes are lowered into it. An electric current is passed through the electrodes to form an arc. The heat generated by this arc melts the scrap. As with the basic oxygen process, oxygen is blown in to the furnace to purify the steel.

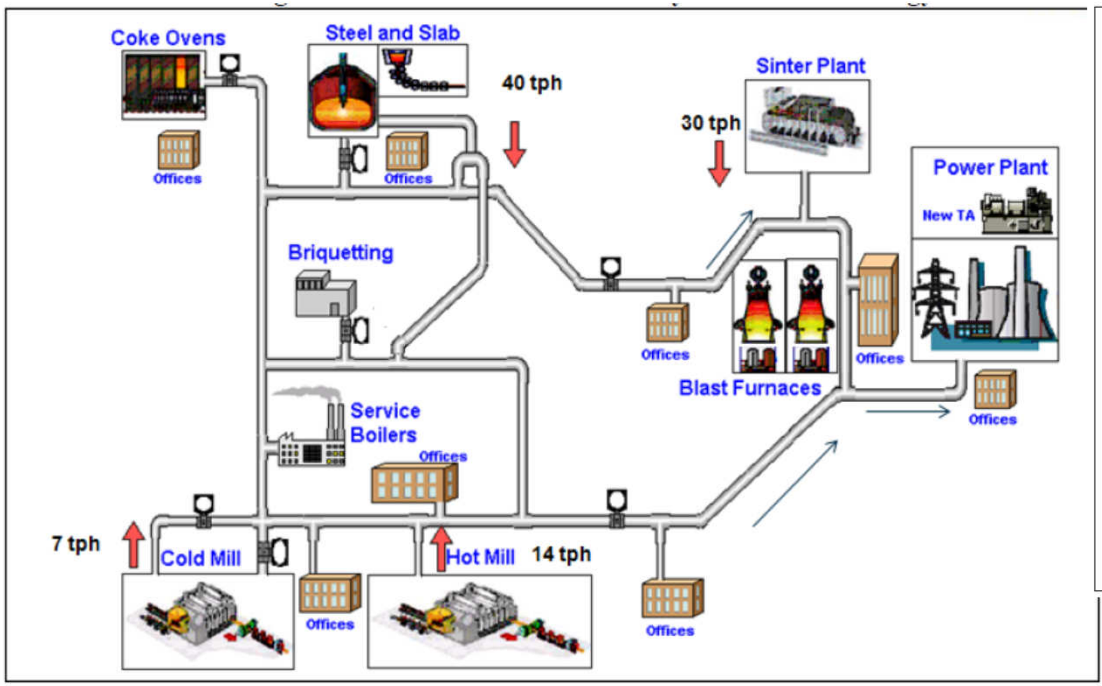
Iron & Steel – Sector Description

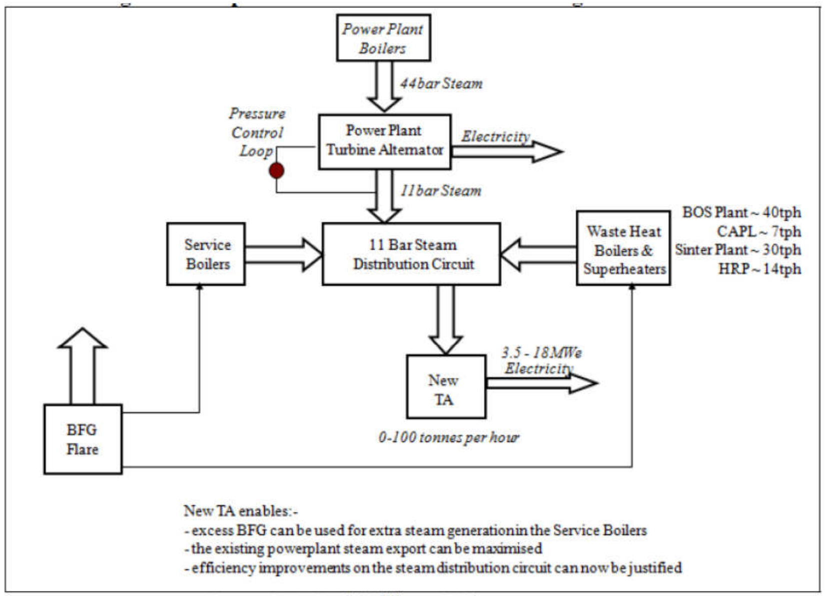
3. Energy intensity / CO_2-emissions
   Since the 2000s, the energy requirements are about 20 GJ per tonne of steel produced. Since 1973, there has been a steady decline from over 30 GJ/tonne.
4. Heat recovery
   Some plants have reduced BOS gas flaring. This gas is then captured and could supply a power station , while coke oven gas has supplanted natural gas use elsewhere, possibly in the reheating furnaces, which is probably the largest energy consumer after the blast furnaces.
5. Potential on-site heat recovery measure
   Heat recovery from coke oven gas cooling / from water quenching of cokes / from exhaust gases in reheating furnaces / from sinter plant / from the blast stove exhaust to pre-heat combustion air and gas / blast furnace slag / from steel slab / from ladle pre-heat off gases / from hot strip mill furnace / from continuous annealing process line
6. Availability of over-the-fence options (proximity to nearby sites)
   Steel works in the UK tend to be close to medium to large cities (10k to over 600k inhabitants), the heat demand of which could be significant with respect to waste heat availability (e.g. water at 90 deg C).
7. Indication that sector uses different investment criterion than 2 year payback
   Investment projects with (10%-discounted) payback of 4-5 years would only be considered for essential replacements, not for waste heat recovery projects, for which the 2 year payback is likely to be more suitable.
8. Identified barriers to implementing waste heat recovery projects
   For DHS, monopoly is considered a serious issue. Controlling the price of heat to the community is sensitive, and incentives are probably required to enable local governments to invest in district heating. For on-site, selection of suitable heat exchanger equipment is considered difficult, with very high costs and auxiliary equipment with parasitic power consumption counteracting the savings from recovered heat. Furthermore, technical issues may arise (e.g. leakage of inflammable gases from rotary heat exchangers).

Case study (1/2): Heat recovery at an integrated steelworks using a turbine alternator.

- A case study exploring the potential for waste heat recovery to contribute to overall site efficiency has recently been published by Cardiff University, reflecting an engineering analysis of concepts that may be applicable to the integrated blast furnace steelworks.
- At such a site is essential to consider energy use holistically, to avoid the risk that efficiency measures lead to increased flaring of unused gases, i.e. with no net reduction in site CO_2 emissions.
- The analysis identified opportunities for steam turbines (5-12 MWe) for power generation using excess heat. This includes waste heat sources with backup provided from the site's existing, but under-utilised, 20km steam distribution network (to minimise the risk of lack of steam supply).
- For the centralised heat recovery investment strategy identified, revenues (or avoided costs) would be in the region £5m/yr, with simple payback in the region 3 yrs. CO_2 savings are in the order 53kt/yr.
- However, discussions with industry reveal that the current make up of financial incentives (such as the renewable heat incentive) create a (potentially perverse) incentive for import of heat from a biomass CHP plant into industrial site that already has considerable supply of surplus heat, rather than use or export of the site's waste heat.

Case study (2/2): Heat recovery at an integrated steelworks from a new turbine alternator.





tph = tonnes of steam per hour; TA = Turbine Alternator; BOS – basic oxygen steelmaking; BFG – blast furnace gas; CAPL continuous annealing process line

Source: Williams, C (2012) Waste heat recovery strategy – presentation given at the Works Energy Strategy Review Meeting, Port Talbot UK, September 2012; cited in Williams *et al*. Utilising Waste Heat for Steam Generation within an Integrated Steelworks: A Methodology for Power Generation and CO_2 reduction (2013) ACEEE Summer Study on Energy Efficiency in Industry.

See also http://www.tatasteeleurope.com/en/news/news/2011/2011_investment_CAPL

Industrial heat sources – Iron and Steel

Characterisation

- The iron and steel sector is relatively homogeneous across the three large integrated sites in terms of unit operations.
- Electric Arc Furnaces not considered in the present study.
- Waste heat sources in the iron and steel sector are diverse and spread along a large number of unit operations.

Methodology

- We used ‘tonne of steel’ as the functional unit to define the heat flows (kWh rejected heat/functional unit)
- Unit operations, heat flows and temperature levels derived from DOE (2008)

Industrial heat sources – Iron and Steel

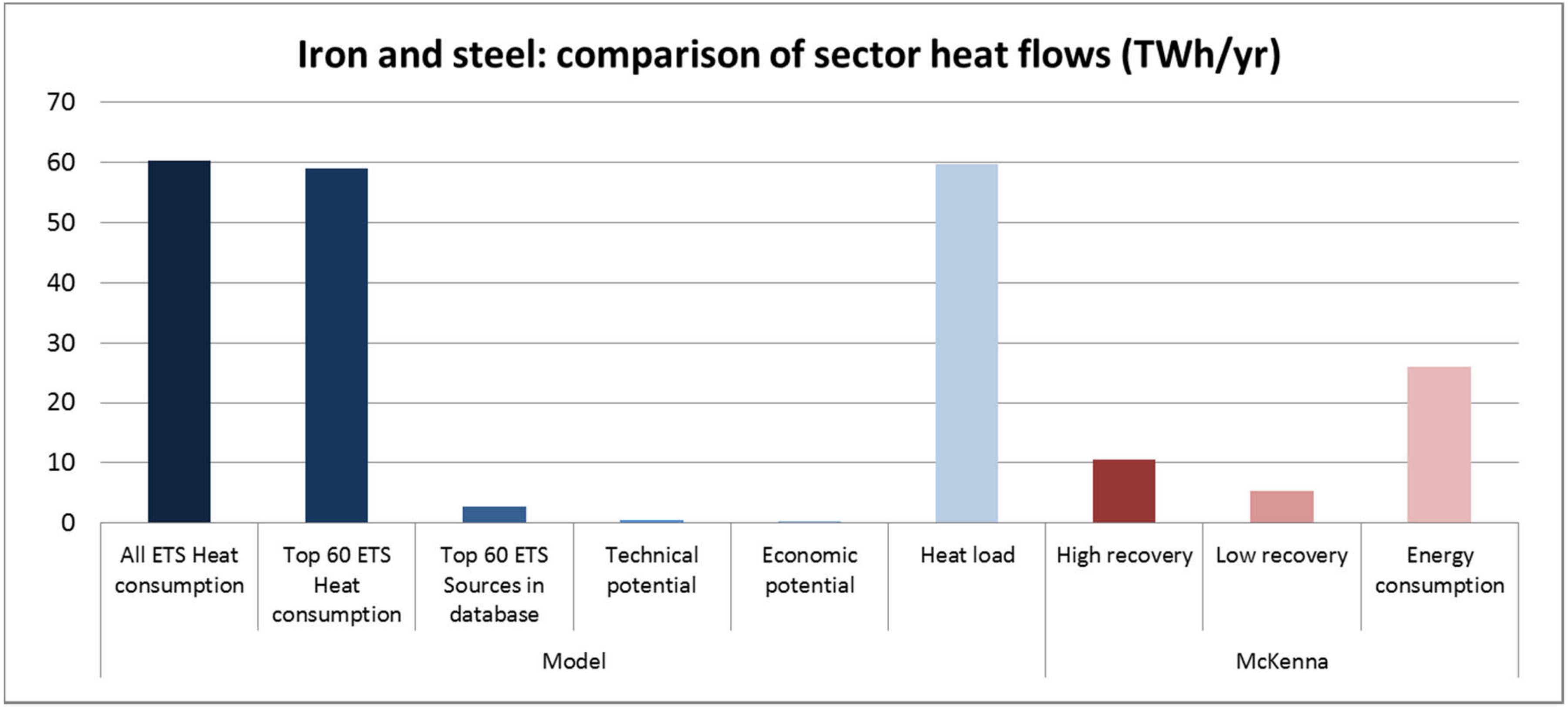
Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/tonne of steel)	Source Temperature (°C)
Iron and Steel	Coke Ovens	Coke Ovens	Sensible heat in the coke oven gas	GAS	82	980
Iron and Steel	Coke Ovens	Coke Ovens	Exhaust gas from combustion of coke oven gas	GAS	58	200
Iron and Steel	Coke Ovens	Coke Ovens	Heat recovery from hot radiant coke	SOLID	62	800
Iron and Steel	Blast Furnaces	Blast Furnaces	Sensible heat in the blast furnace gas	GAS	28	100
Iron and Steel	Blast Furnaces	Blast Furnaces	Exhaust gas from blast stoves	GAS	82	250
Iron and Steel	Blast Furnaces	Blast Furnaces	Heat recovery from hot BF slag	SOLID	100	1300
Iron and Steel	Basic Oxygen Furnaces	Basic Oxygen Furnaces	Heat recovery from BOF off-gases	GAS	141	1700
Iron and Steel	Basic Oxygen Furnaces	Basic Oxygen Furnaces	Heat recovery from hot BOF slag	SOLID	6	1500
Iron and Steel	Electric Arc Furnaces	Electric Arc Furnaces - no scrap preheat	Heat recovery from EAF off-gases	GAS	44	1200
Iron and Steel	Electric Arc Furnaces	Electric Arc Furnaces - with scrap preheat	Heat recovery from EAF off-gases	GAS	6	204
Iron and Steel	Steel Casting	Steel Casting	Heat recovery from hot cast steel	SOLID	352	1600
Iron and Steel	Hot Rolling	Hot Rolling	Heat recovery from hot rolled steel	SOLID	1395	400

Sites included in modelling – Iron and Steel

Site name
Port Talbot Steelworks
Scunthorpe Integrated Iron & Steel Works
Teesside Integrated Iron & Steel Works

* Electric arc furnace only locations are not included in the present analysis.

Context for the technical and economic potential for waste heat recovery from the Iron and Steel sector.



- As previously, the technical potential refers to matched potential, i.e. where source-sink-technology combinations can save CO_2, the economic potential to those combinations which save money at 10% discount rate.

McKenna et al., Energy Policy 38, 5878 (2010)

Paper & Pulp

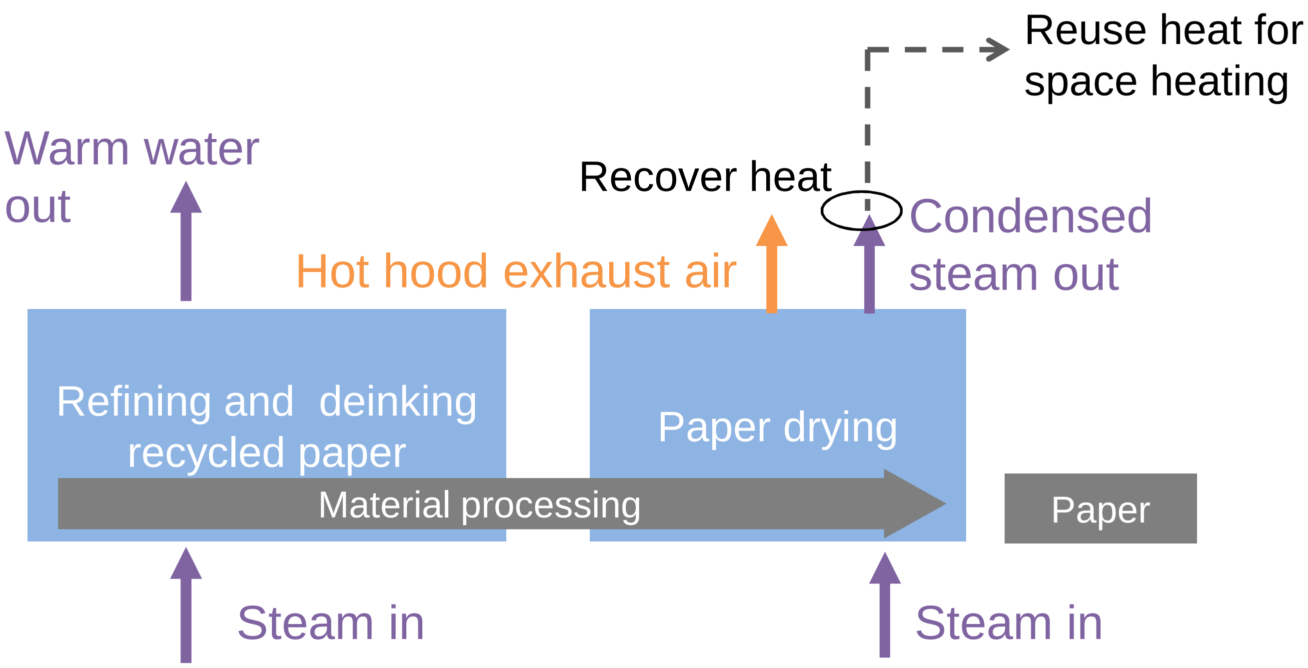
Paper & Pulp – Sector Description

1. Sector context
   There are 51 pulp and paper mills in the UK, of which 16 have CHP that account for 65% of product tonnage produced. Of the 50 paper mills, the 10 largest account for 70% of production. 73% of paper manufactured in the UK is from recycled paper. Energy consumption patterns at paper mills in the UK can vary from 24/7 360 dpy to only 10 hours per day 5 days per week.
2. Description of main processes
   The main processes are pulping, screening, fractionation, blending and paper drying. With the exception of drying, all the processes are carried out at a little above ambient temperature. Heating is only required at start-up and the temperature is determined solely by parasitic heat gain from electrical equipment. Paper drying is by far the largest user of energy on the site. Heat for drying is obtained from steam, extracted from e.g. a CCGT cycle or produced by a steam boiler. Additional heat output could be obtained from other sources, e.g. sludge incinerators.
3. Energy intensity / CO_2-emissions
   Industry norms are approx. 1,000 – 1,600 kWh thermal and 330 – 520 kWh electricity per tonne of paper. Certain specialist papers, however, could require a total energy input as high as 22,000 kWh per tonne. Figures tend to be very site specific. There is a trend towards higher electrical consumption and lower thermal consumption as packaging paper becomes thinner and processes advance.
4. Heat recovery
   Heat recovery is commonly practised around CHP, steam boiler and/or alternative heat producers on-site, mostly in terms of condensate recovery and flue gas economisers. There appears to be limited scope for heat recovery around the wet processes prior to the paper dryers. There is some heat recovery from the paper drying machines, which sometimes is used for space heating purposes (pulping at 40°C from pumps).

Paper & Pulp – Sector Description

5. Potential on-site heat recovery measure
   Further recovery of heat from the exhaust hoods of the paper machines could reuse the heat from moist air at a temperatures of around 100 – 120°C. Relatively large heat exchangers would be needed to recover this heat. Air-air heat exchange would be used for pre-heating ventilation air in the paper machine hall. Air-water and air-glycol heat exchange would be used where there is a demand respectively for space heating and process heating (e.g. in cold climates). Water is discharged at a low temperature (around 30°C) at several different point sources in the mill. Heat recovery of this low-quality heat is possible but expensive.
6. Availability of over-the-fence options (proximity to nearby sites)
   Paper mills are all near sources of water because historically used for transport and now used as a water carrier. For that reason, paper mills tend to be located a relatively short distances from urbanised areas, providing over-the-fence possibilities for DHS.
7. Indication that sector uses different investment criterion than 2 year payback
   Short time horizons of the business and the consequently short payback requirements for energy saving projects (preferably 2 years with an absolute maximum of 3 years).
8. Identified barriers to implementing waste heat recovery projects
   Long-term (20yr) guarantees for over-the-fence heat delivery expected to be difficult – there's little future visibility on site viability. A trend towards light weighting leads to more electrical and less thermal energy consumption. In UK, limited demand for heat, bad experience with heat network.

Example existing heat recovery at a paper plant



Heat is recovered in (recycled) paper production facilities in several steps. There is some opportunity to reuse heat in the stage where recycled paper is refined and deinked. Significant heat is recovered from the paper drying stage. Condensed steam from the paper drying stage is sometimes used for space heating.

Industrial heat sources – Pulp and paper

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/tonne of paper)	Source Temperature (°C)
Paper and Pulp	Water discharges	Refining/De-inking/Paper Machine	Rejected heat in waste water	WATER	761	30
Paper and Pulp	Papermaking	Paper Drying	Waste heat recovery from paper drying	GAS	1068	85
Paper and Pulp	Air Compressors	Air Compressors/Vacuum	Exhaust air from vacuum machines	GAS	270	160

Characterisation

- The pulp and paper sector can be considered a papermaking sector as, there is only one virgin pulp mill in the UK (DECC, 2013)

Methodology

- We used ‘tonne of paper’ as the functional unit to define the heat flows (kWh rejected heat /functional unit).
- Rejected heat flows from paper drying process derived from draft BREF document (EC, 2013). Heat flows from water discharges estimated on the basis of average reported water consumption (Malmberg, 2011) and average water temperatures reported by sector experts.

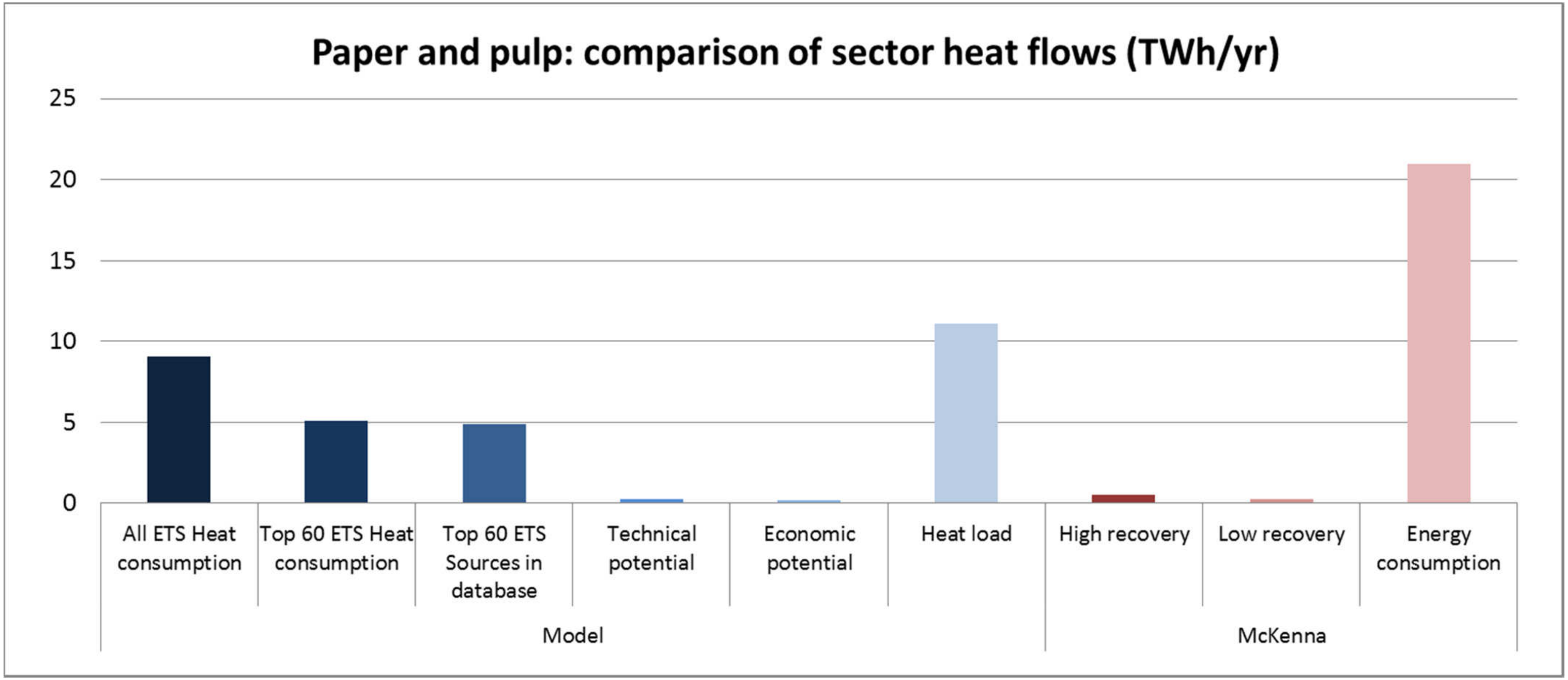
Sites included in modelling – Pulp and Paper

Site name
Kemsley CHP Plant
Tullis Russell Papermakers
Aylesford Papermills Cogen Plant
Smurfit Townsend Hook
Workington CHP Plant (Iggesund Paperboard)
Blackburn Mill CHP

Feedback from the Confederation of Paper Industries

- The following feedback was received from the CPI on the sources database as listed in the draft report. This would be useful to consider in future heat recovery potential studies focussed on this sector.
  - Kemsley – the CHP was designed to supply three large mills but one closed in 2007 and the other two amalgamated in 2009-10. The heat consumption at the mill is now less than it was pre-2007.
  - Tullis Russell – the mill has decommissioned its coal-fired plant this summer and is commissioning a large biomass CHP which will provide all its energy. This will clearly affect fossil energy efficiency.
  - Aylesford – the CHP was designed to supply two large mills but one closed in 2009 so the plant has been running at a significantly lower load since then. Smurfit Townsend Hook – the mill is shut down for 15 months and is being completely rebuilt. Presumably opportunities will be taken during the rebuild for additional heat integration.
  - Iggesund - the mill decommissioned its gas-fired CHP in February and is now running a large biomass CHP which will provide all its energy. This will clearly affect fossil energy efficiency.
  - Blackburn CHP – the paper mill which this plant was built to supply closed down in 2008. Since then the CHP has been run by its utility owner solely to generate electricity – there is no customer for the heat any longer.

Paper and Pulp



McKenna et al., Energy Policy 38, 5878 (2010)

Refineries

Refineries – Sector Description

1. Sector context
   The members of UKPIA (UK Petroleum Industry Association) run the seven major operating refineries in the UK. Since the refinery closures in 1997, 1999, 2009, and most recently 2012, UK refining throughput has fallen from its late 90s' peak of 97 million tonnes of crude oil. UK refining throughput was around 69 million tonnes in 2012 – an 8% drop compared to 2011. Over 80% of product output is petrol, diesel, jet fuel, gas oil and fuel oils.
2. Description of main processes
   Refinery operations can be broken down into five main processes: (1) distillation (separates crude oil into different refinery streams)– (2+3) conversion and reforming (quality improvement and yield adjustments to meet market demand) – (4) desulphurisation (reduces sulphur in the streams) – (5) blending of the refinery streams (to produce final products).
   The starting point for all refinery operations is the crude distillation unit (CDU). Crude oil is boiled in a fractioning column, which breaks the crude down into more useful components. The crude oil enters the column near the bottom and is heated to around 380°C. The lighter fractions are vaporised and rise up the column. As they rise, they are cooled by a downward flow of liquid and condense at different points. This enables fractions with different boiling points to be drawn off at different levels in the column.
3. Energy intensity / CO_2-emissions
   Refineries emit around 30% of the UK's industrial CO2 emissions and are included in the EU ETS. The total emissions for the last 20 years account to 15 – 20 Mte pa.
   Refineries use the equivalent of between 5 and 6% of throughput as fuel, to provide energy to refine crude oil into products for consumers. The additional energy that is required for more recent cleaner transport fuels, has been offset by improved energy efficiency, thereby remaining at 5 – 6% of throughput as fuel. Approx. 75% of the energy input is from direct firing of oil and gas, 20% from steam, derived also from oil and gas, and 5% from electricity. More than two thirds of the energy input is rejected to cooling systems and thence to the atmosphere.

Refineries – Sector Description

4. Heat recovery
   Heat recovery is practiced to a greater or lesser extent within the individual blocks of process plant. The extent to which heat recovery is achieved depends both on the technical potential and the age of the plant. There is some heat recovery between processes, where an intermediate product at high temperature is directed to a downstream process before cooling.
5. Potential on-site heat recovery measure
   In general, condensate is not recovered for return to the boiler plant. This is partly a question of capital cost but, more importantly, a matter of risk to the process, where the accidental return of contaminated water would have potentially disastrous effects on the high pressure steam boilers. Combustion and heat exchange systems are generally designed for a minimum flue temperature of 250°C in order to minimise the risk of damage from combustion products arising from sulphur bearing feedstock. Some stacks could be hotter than this target figure and fuel savings in the order of a couple of per cents might in theory be achievable.
6. Availability of over-the-fence options (proximity to nearby sites)
   There exists some energy infrastructure integration with adjoining chemical plants. There remains the theoretical potential for recovery of heat into a future district heating system. The practical limit for economical heat distribution is about 10 – 15 km. Generally, within that range from refineries, smaller cities tend to be located with 10-30 k inhabitants, thereby limiting the availability of significant heat demands.
7. Indication that sector uses different investment criterion than 2 year payback
   No such indication.

The total heat consumption of the refining sector is some 46 TWh/yr (DECC heat strategy). The economic and commercial potential for heat recovery (not taking into account any barriers, see next slide) are 8% and 5% respectively.

Sector heat consumption	46 TWh/yr	
Economic potential heat recovery	3.6 TWh/yr	(8%)
Commercial potential heat recovery	2.2 TWh/yr	(5%)

Refineries – Sector Description

- Identified barriers to implementing waste heat recovery projects
  Availability of capital is a particular issue when currently annual capital expenditure on the site is typically 2.5 times the annual profit generated. Priority has to be given to environmentally led projects, some of which can present opportunity to improve energy efficiency. All UK refineries are struggling to meet costs and current margins are insufficient to pay for changes brought about by legislation. For this reason the focus generally is on low cost efficiency improvement projects such as insulation, steam traps etc. A number of barriers have been identified, that are specifically relevant for the refinery sector. These can have significant cost impacts on the realisation of heat recovery projects;
  - Many waste heat streams are not available as a single stream, but consist of many small and widely distributed streams integrated in the refining process. This poses significant complexities in recovering heat from these streams.
  - Additional retrofit costs can be very significant, especially where extensive equipment integrated into the refinery processes require replacement.
  - Extensive retrofits can require long downtime of units, resulting in missed revenues and additional complexities and costs to ensure downstream supply
  - Operational risks due to heat integration of units, carries inter unit operability risks, especially regarding unavailability.
  - In the UK, limited to no new built refineries are expected in the near term, hence all heat recovery project would be executed in the context of existing units.
  - In order to utilise low temperature heat sources, especially co-location with other low temperature heat demands and district heating networks are seen as the most feasible options.

UK refinery sites typically comprise (and are close to) multiple heat intensive processes.

- The degree of process heat integration or independence reflects a balance of cost optimisation and operability (including flexibility).
- In all UK refineries there is a large degree of heat usage optimisation and recovery within process units, using various types of heat exchangers.

Image kindly provided by Ineos showing the Grangemouth complex.

Industrial heat sources – Oil refining

Characterisation

- The oil refining sector is relatively homogeneous across sites in terms of unit operations.
- Waste heat sources in the oil refining sector are diverse and spread along a large number of unit operations.

Methodology

- We used ‘barrel of oil processed’ as the functional unit to define the heat flows (kWh rejected heat /functional unit)
- Unit operations and rejected heat flows from unit operations are derived from Energetics, Incorporated and E3M (2004)[1]
- For steam systems we model the rejected heat as hot water. For fired systems we model the rejected heat as 80% hot (cooling) water and 20% hot flue gases.

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/boe)	Source Temperature (°C)
Oil Refining	Distillation	Atmospheric Distillation	Waste steam from atmospheric distillation	WATER	7.7	70
Oil Refining	Distillation	Atmospheric Distillation	Hot flue gas from atmospheric distillation	GAS	3.3	150
Oil Refining	Distillation	Atmospheric Distillation	Hot water (coolers) from atmospheric distillation	WATER	3.3	70
Oil Refining	Distillation	Vacuum Distillation	Waste steam from vacuum distillation	WATER	6.3	70
Oil Refining	Distillation	Vacuum Distillation	Hot flue gas from vacuum distillation	GAS	0.9	150
Oil Refining	Distillation	Vacuum Distillation	Hot water (coolers) from vacuum distillation	WATER	3.7	70
Oil Refining	Coking	Delayed Coking	Hot flue gas from delayed coking	GAS	2.7	150
Oil Refining	Coking	Delayed Coking	Hot water (coolers) from delayed coking	WATER	10.9	70

[1] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program. Energy Use, Loss, and Opportunities Analysis: U.S. Manufacturing and Mining. (December 2004). Prepared by Energetics, Inc. and E3M, Incorporated

Industrial heat sources – Oil refining

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/barrel of oil)	Source Temperature (°C)
Oil Refining	Cracking	Fluid Catalytic Cracking (FCC)	Hot flue gas from fluid catalytic cracking	GAS	7.3	150
Oil Refining	Cracking	Catalytic Hydrocracking	Waste steam from stripping	WATER	12.5	70
Oil Refining	Cracking	Catalytic Hydrocracking	Hot flue gas from catalytic hydrocracking	GAS	14.3	150
Oil Refining	Combination/Rearrangement of Hydrocarbons	Catalytic Reforming	Waste steam from stripping	WATER	15.6	70
Oil Refining	Combination/Rearrangement of Hydrocarbons	Catalytic Reforming	Hot flue gas from catalytic reforming	GAS	3.2	150
Oil Refining	Combination/Rearrangement of Hydrocarbons	Catalytic Reforming	Hot water (coolers) from catalytic reforming	WATER	12.6	90
Oil Refining	Combination/Rearrangement of Hydrocarbons	Alkylation	Waste steam from stripping	WATER	61.2	70
Oil Refining	Combination/Rearrangement of Hydrocarbons	Alkylation	Hot water (coolers) from Alkylation	WATER	27.6	90
Oil Refining	Combination/Rearrangement of Hydrocarbons	Isomerisation	Waste steam from stripping	WATER	39.7	70
Oil Refining	Treating	Catalytic Hydro-treating	Waste steam from stripping	WATER	9.5	70
Oil Refining	Air Compressors	Air Compressors	Cooling air	GAS	0.7	40

Sites included in modelling – Oil refining

Site name
Esso Petroleum Company Ltd
Stanlow Refinery
Valero Energy Ltd
Humber Refinery
Grangemouth Refining
Total Lindsey Oil Refinery
Murco Petroleum Milford Haven Refinery
Grangemouth CHP LTD

Power

The UK power market is dynamic over the long term

- DECC has agreed that analysis of the power sector within this study is only at the level of a sensitivity analysis to the core project analysis of waste heat recovery from manufacturing industry.
- Thermal power generation can theoretically provide waste heat for use in industry or in heat networks. Nuclear, coal, gas and biomass-fired power stations are relevant. [CHP stations already deliver heat and are therefore excluded from analysis of supply of “waste” heat. The potential for CHP is analysed in depth elsewhere (e.g. DECC, CHPA). Renewable electricity from wind, PV, wave, tidal, hydro etc. does not generate useful heat.]
- The majority of existing UK coal and nuclear thermal generation fleet is due to close within the next decade because of environmental constraints and intrinsic age. Retrofit of the surviving nuclear stations in any future waste heat network is considered unlikely for technical reasons.
- The characteristics (location, capacity, temperature, medium) of waste heat sources available from future nuclear and coal or gas CCS plants are difficult to foresee – if integration with a heat network is planned then it would be more effective to design this from the outset rather than retrofit.
- The study anticipates biomass and gas-fired power stations provide the majority of the sources of waste heat from thermal power generation. However, following electricity market reform, the future electricity market beyond 2020, and unabated gas power stations are likely to operate at ever decreasing load factors (and with limited predictability) as the penetration of renewable electricity generation increases.
- To facilitate the sensitivity analysis we have prepared a shortlist of potentially relevant gas and biomass power stations based on previous Element Energy and Ecofys datasets and combining this with DECC’s base case scenario for future power generation, and we have made the simplifying assumption of an 60% average load factor.

Power – Sector Description

1. Sector context
   Most electricity is generated at large power stations connected to the national transmission network. However, electricity can also be generated in smaller scale power stations which are connected to the regional distribution networks. There are many companies in the electricity generation sector, from large multinationals to small, family-owned businesses running a single site.
2. Description of main processes
   Electricity generation by nuclear, coal-fired and gas-fired major power plant (MPP) or stations use steam as the energy transfer medium for electricity generation process. Laws of thermodynamics limit the amount of useful energy that can be extracted from the steam cycles , in practice to 40% (modern coal-fired power station) to 60% (modern combined cycle gas turbines (CCGT)). The lost energy is transferred to a cooling medium (typically water) as low temperature, low grade heat. This rejected heat is an unavoidable feature of electricity production using the steam cycle.
3. Energy intensity / CO_2-emissions
   Most of the UK's electricity is produced by burning fossil fuels, mainly natural gas (47% in 2010) and coal (28%). The volume of electricity generated by coal and gas-fired power stations changes each year, with some switching between the two depending on fuel prices. Nuclear reactors provide ~16% of UK electricity needs. Renewable technologies use natural energy to make electricity. Fuel sources include wind, wave, marine, hydro, biomass and solar. It made up 7% of electricity generated in 2010 - this will rise as the UK aims to meet its EU target of generating 30% of its electricity from renewable sources by 2020.
   Emissions from the electricity sector have fallen by 16% since 1990 and are expected to continue to fall. By 2020, zero carbon technologies (renewables and nuclear) are expected to produce 40% of UK electricity.
4. Heat recovery
   On-site: waste heat from the condenser to pre-heat the combustion fuel and air (improving efficiency)
   Over-the-fence: The Isle of Grain gas-fired power plant sells heat via local DHS, primarily to a neighbouring liquid natural gas (LNG) terminal. The reject-heat-warms the LNG into to gaseous natural gas, prior to injecting into the UK gas grid. Some analyses to assess opportunities for local heat without resulting demand have been carried out.

Power – Sector Description

5. Potential on-site heat recovery measure
   On-site potential is considered very limited to none, as efficiency optimisations are continuously investigated at most power plants.
6. Availability of over-the-fence options (proximity to nearby sites)
   The theoretical quantity of rejected heat produced by each category of electricity plant could in principle be recaptured and used, for example by industrial processes that can use low grade heat or by district heating schemes.
7. Identified barriers to implementing waste heat recovery projects
   Technical
   Although there is a lot of reject heat generated by UK MPPs, most of it is at low (non-useful) temperatures. Secondly, heat does not come off at one point of the power plant but numerous points, which would necessitate multiple gather points.
   The only case where a considerable temperature delta is available is for open-cycle gas turbines (OCGTs). However, a CHP scheme is impractical because the engines are seldom run (low load factor as uncompetitive in the electricity market).
   Economical
   The plant has to be designed to allow for lower flow rates – which adds some capital costs and results in some unavoidable power reduction. Retrofitting is more difficult. As more heat is generated for extraction and export, there is a systematic loss of power generation.
   Location
   Most power plants are a long way from substantial industrial or domestic heat demands, and the heat available is generally far larger than any conceivable local demand. Heat can be transported, but a combination of: (1) high capital costs, (2) transmission losses, and (3) the existing arrangements of potential end-users make the long-distant demand for heat uneconomic.
   Contractual
   Long term lock-in with purchase contracts, guaranteed supply of the heat to the third-party (regardless of own power generation needs), compatibility with legislative drivers (such as EU ETS or CCA reporting).

Industrial heat sources – Power

Characterisation

- We used ‘kWh of electricity produced’ as the functional unit to define the heat flows (kWh rejected heat /functional unit)

Methodology

- We have distinguished 5 subsectors depending on the type of fuel input: coal, nuclear, biomass, waste to energy and gas.
- We have distinguished 3 types of thermal cycles with differentiated rejected heat flows as a fraction of energy input: conventional Rankine cycle, open cycle gas turbines and combined cycle gas turbines.
- In consistency with other parts of the project, no plant redesign is assumed
- In reality it would make sense to consider altering process design (e.g. use of cooling towers) to produce higher grade heat initially, rather than tapping into the low grade heat available.

Industrial heat sources – Power

Industrial Sector	Process Type	Unit Operation	Heat Source Description	Heat Source Medium	Heat Supply Flow (KWh/kWh electricity produced)	Source Temperature (°C)
Power	Conventional Steam Cycle Plants - coal plants		Heat in the cooling water out of the condenser	WATER	1.4	30.0
Power	Conventional Steam Cycle Plants - biomass		Heat in the cooling water out of the condenser	WATER	1.8	30.0
Power	Conventional Steam Cycle Plants - nuclear		Heat in the cooling water out of the condenser	WATER	1.4	30.0
Power	Conventional Steam Cycle Plants - waste to energy		Heat in the cooling water out of the condenser	WATER	1.4	30.0
Power	Open Cycle Gas Turbines		Heat in the exhaust gas of open cycle GT	GAS	1.4	500.0
Power	Combined Cycle Gas Turbines		Heat in the cooling water out of the condenser	WATER	0.7	40.0

Sites included in modelling – Power

Site name
PETERHEAD
STAYTHORPE-C
CONNAHS QUAY
GRAIN
TEESSIDE
SALTEND
BALLYLUMFORD
DIDCOT
SEABANK
SEVERN POWER
SOUTH HUMBER BANK
IMMINGHAM CONOCO
BARKING
LANGAGE
BAGLAN ENERGY
MARCHWOOD POWER
KEADBY POWER
CORYTON INTERGEN
ROCKSAVAGE
RYE HOUSE-II
MEDWAY
KILLINGHOLME-A
LITTLE BARFORD
GREAT YARMOUTH

Site name
BRIGHTON
ENFIELD POWER
COTTAM CDC
DEESIDE
COOLKEERAGH
CORBY
ROOSECOTE CENTRICA
DERWENT (SPONDON)
GRANGEMOUTH CHP
FAWLEY NPC
GREENWICH
SELLAFIELD
FORT DUNLOP HEARTLANDS
Stevens Croft
SAICA Paper Mill
Elean Business Park Biomass Plant
Thetford Biomass Power Station
Wilton International
Caledonian Papermill
Ely
Slough Heat and power
UPM Caldedonian
UPM Shotton

Outline

- Background
- Description of techno-economic modelling approach
- Modelling limitations
- Technology assumptions
- Fuel and electricity assumptions
- Approach for generating source and sink database
- “Base Case” Scenario and Results of techno-economic modelling
- Results from sensitivity analysis
  - Optimisation parameter
  - Energy intensity in period to 2050
- Sectoral assumptions and key issues
- Industrial carbon capture and storage
- The recovery of waste heat for re-use in cooling

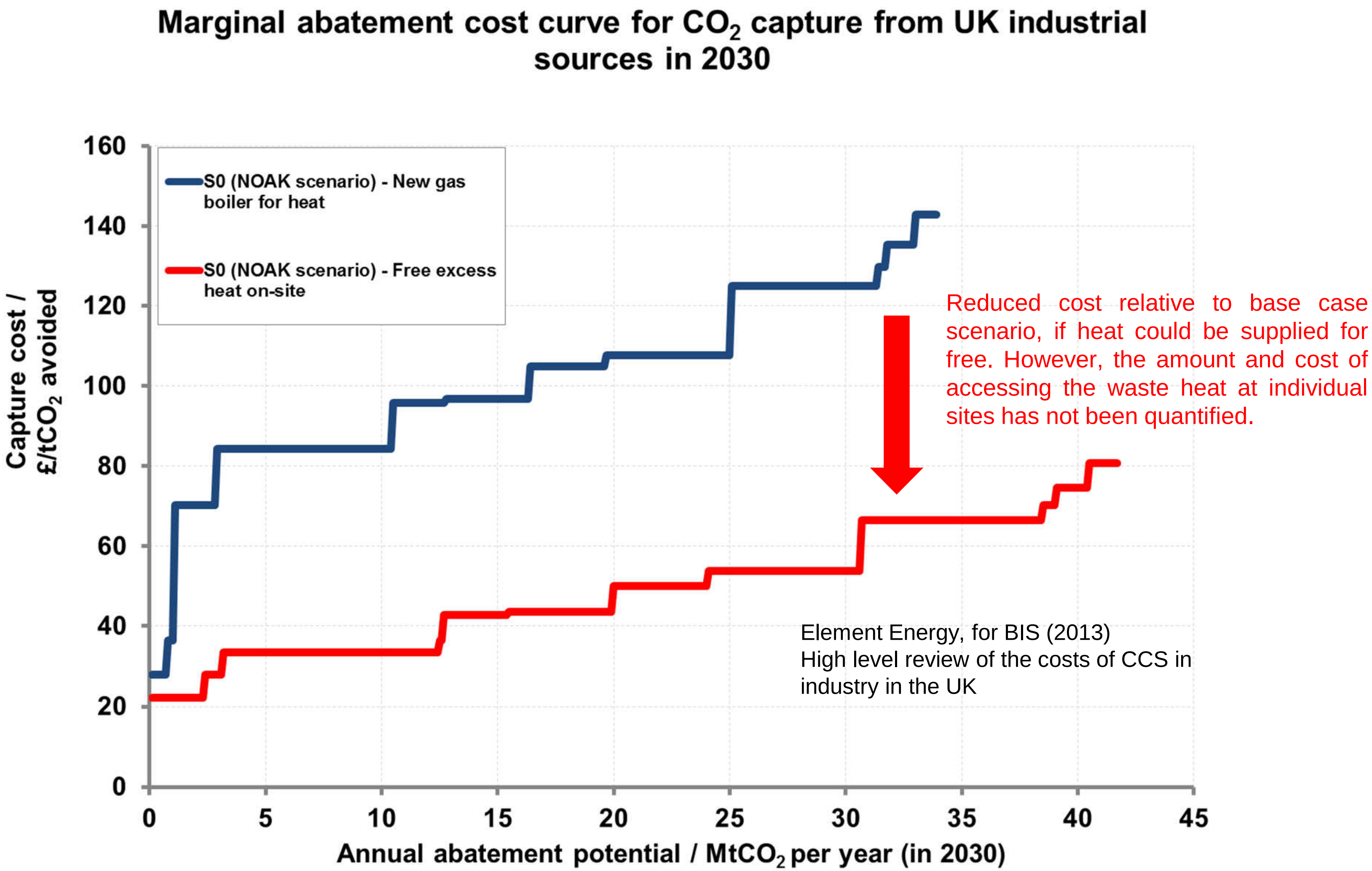
Opportunities for waste heat recovery and re-use with Carbon Capture and Storage

There are no full-chain industrial CCS projects in the UK, and only a limited number of (weakly) analogous projects worldwide. Likely configurations are difficult to pin down and could be site dependent. For several sites and CO_2 capture technologies, industrial capture would require a supply of heat.

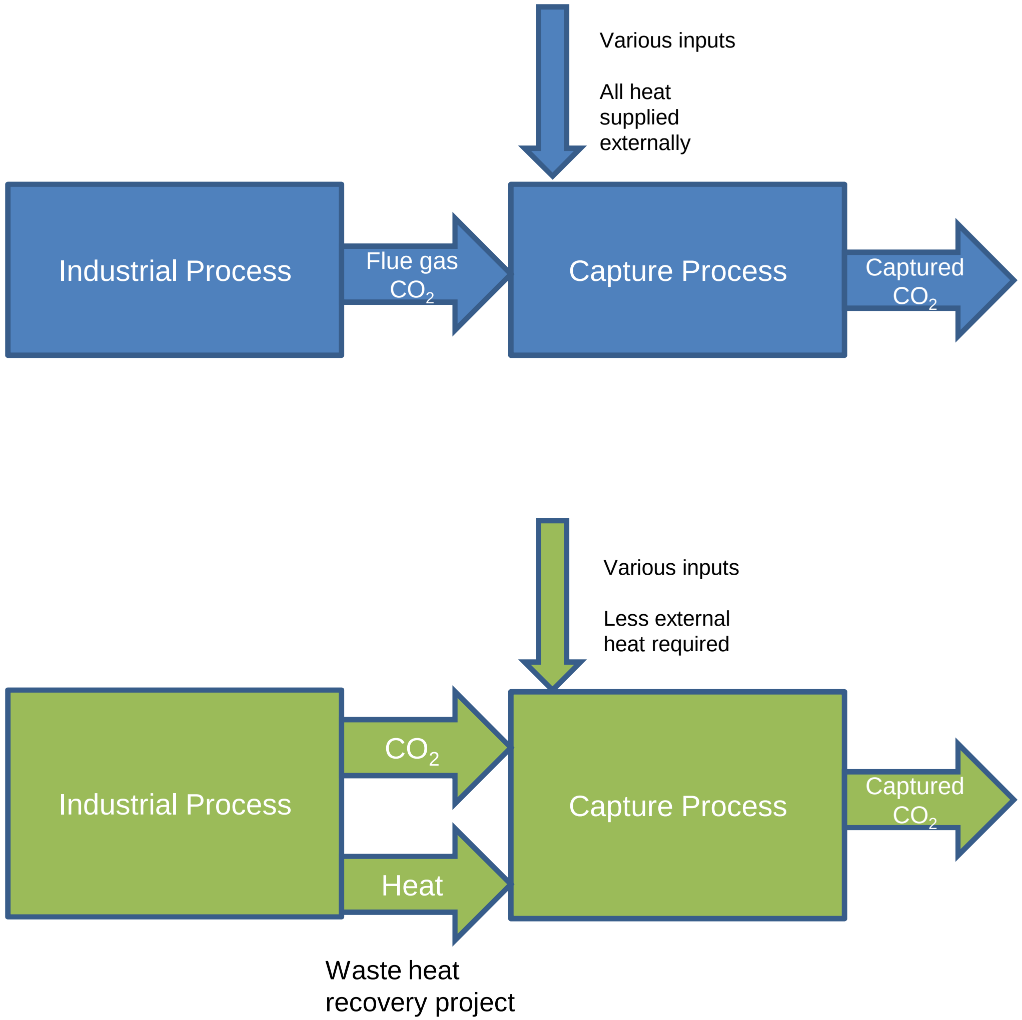
Several high-level opportunities are identified as interaction points between the market for waste heat recovery and re-use and implementation of carbon capture and storage technology:

- Biomass, Coal, and Gas Power CCS projects could supply waste power and heat for industrial sites directly or as part of larger heat networks.
- Waste heat sources from industrial processes could reduce fuel requirements for on-site or over-the-fence carbon capture processes.
- Waste heat from industrial carbon capture processes could reduce fuel costs for on-site or over-the fence industrial processes.
- Alternatively for regulatory, commercial or operational reasons, capture plants may be run independently of base industrial plants.

The first analysis of potential impacts was considered in a recent report for BIS on the costs of industrial CCS in the UK.



The techno-economic modelling approach provides an opportunity to quantify at high level how much heat is available to reduce the fuel costs for industrial CCS



For several sites and CO_2 capture technologies, industrial capture would require a supply of heat.

This can be supplied externally but in some cases integration using waste heat from the same or a nearby site can:

- Reduce fuel costs
- Increase site operational complexity and reduce flexibility

Most implementation solutions would likely rely on backup boiler provision for heat, so that capex savings may be low relative to fuel savings.

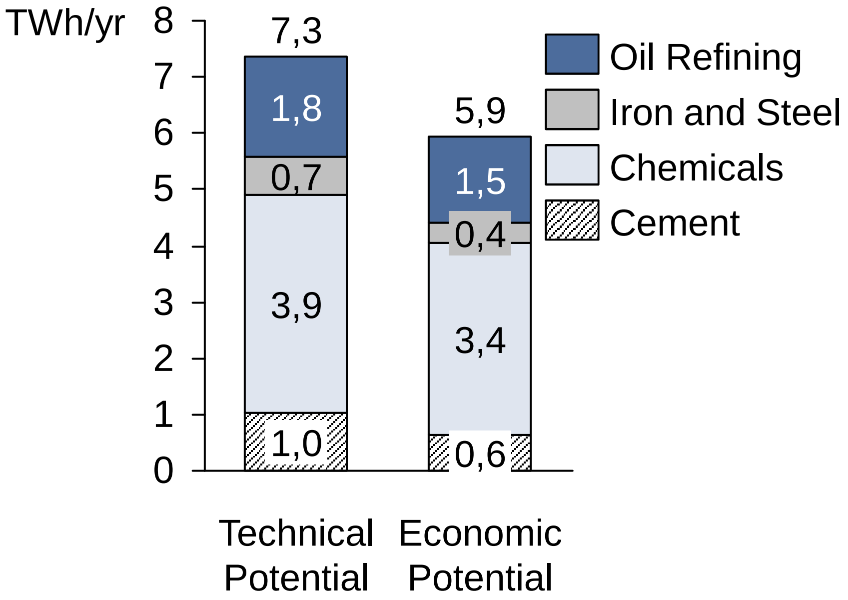
Some simplifying assumptions for understanding the potential relevance of waste heat for industrial CO_2 capture.

- Consider CCS retrofit in UK industry as per Element Energy et al. for BIS (2013)
- Assume 2030 carbon and energy prices
- Assume post-combustion amine scrubbing capture for all sectors, with ca. 3 GJ/tCO_2 heat needed in 2030 (this is a plausible improvement beyond today's MEA based processes, but neglects significant stream and capture technology-specific variations)
- Assume this corresponds to a single water sink that can start at 60°C and go up to a maximum of 100°C.
- Assume scenario without waste heat integration leads to "vented" rather than captured CO_2
- Allow combinations that do not supply *all* the heat, just use waste heat to reduce fuel costs CO_2 impacts, although assume a gas boiler as backup and to supply remaining heat.
- For ease of interpretation delete all other sinks in the sink database other than industrial CCS have been deleted.

The model identifies 5.9 TWh/yr could be delivered economically to reduce the costs of industrial CO_2 capture.

Highlights of the modelling are:

- Technical potential estimated at 7.3 TWh/yr
- Economic potential estimated at 5.9 TWh/yr
- Combined potential CO_2 saving of 1.5 $MtCO_2$/yr in the economic potential case
- Annual cost saving of £176m/yr
- 80% of the theoretical economic potential for heat recovery with application in CCS is concentrated in 12 sites (out of 50)



- There is significant uncertainty is which sites actually implement CCS, their scale, technologies and the timing of this.
- Food and Drink, Glass, Ceramics and Paper sectors excluded as considered unlikely to implement CCS in 2030.

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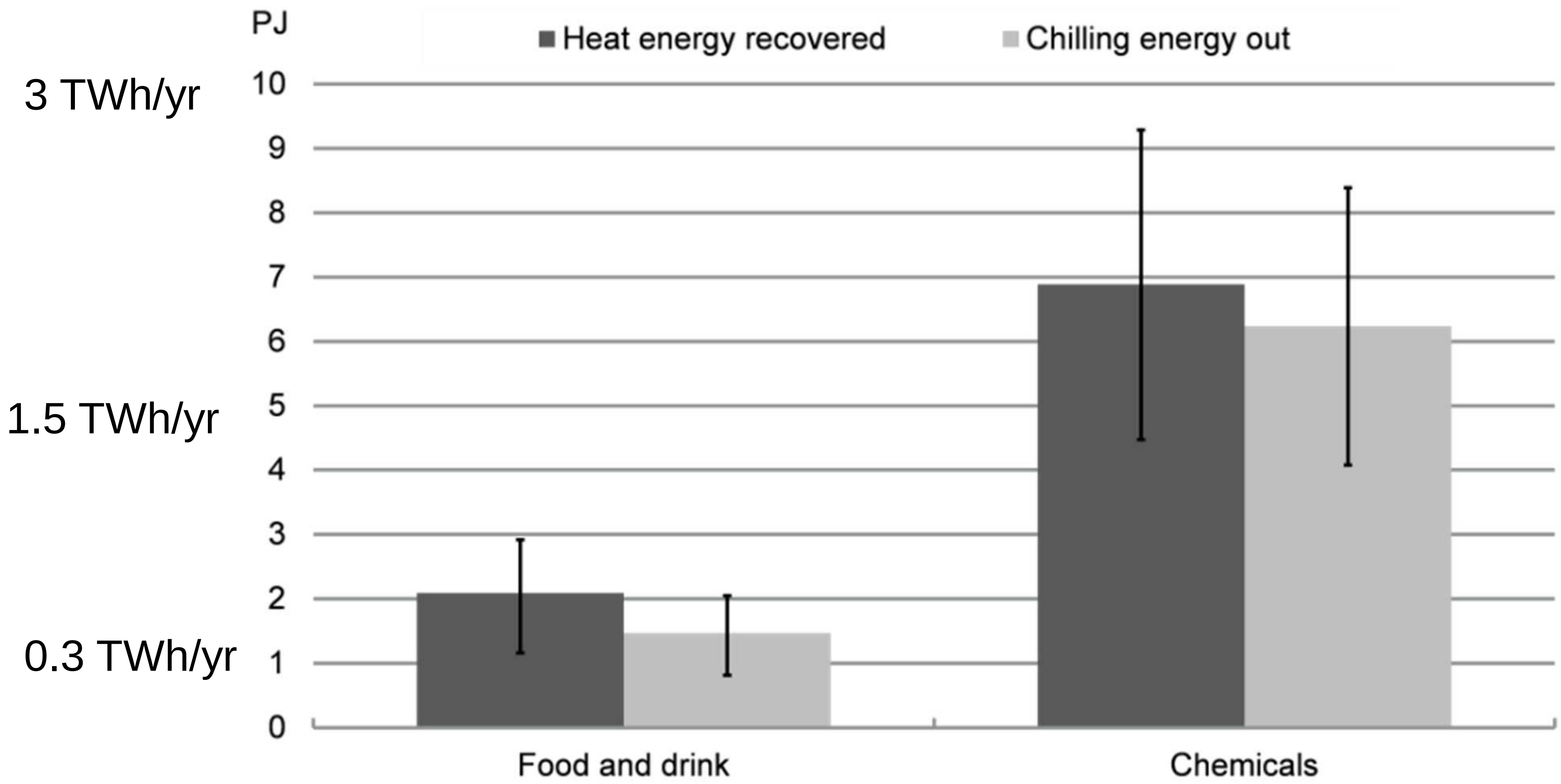
- Industrial carbon capture and storage
- The recovery of waste heat for re-use in cooling
- A note on heat networks

There is a lack of data to allow quantitative analysis of the potential for industrial waste heat recovery for cooling within this study.

- The team researched the literature on industrial cooling loads and consulted with industry on data availability.
- There is no existing public database with temperature, energy and location data on cooling that allows source-sink-technology matching. Creating this dataset would itself be a significant undertaking.
- In the absence of data on cooling loads, no quantitative analysis of heat recovery potential related to cooling was carried out in the techno-economic modelling.
- Instead we reproduce information identified in the literature.
- The most relevant literature has been published by Bath University*, who have analysed the potential to provide cooling from waste heat in industrial sectors using top-down assumptions on feasibility.
- These assumptions are based on ETS Phase I data (so may be out of date) and to our knowledge have not involved industry feedback.
- Waste heat can be utilised to provide cooling using absorption heat pumps. Two key parameters are :
  - Chemicals, mainly double-effect chillers due to relatively higher temperature, resulting in an overall COP of 0.9
  - Food and Drinks, mainly single-effect chillers due to relatively lower temperature, resulting in an overall COP of 0.7

**Norman, J.B., 2013. Industrial Energy Use and Improvement Potential (PhD). University of Bath.*

A technical potential for industrial heat recovery for cooling was previously estimated at 2.5 TWh/yr (source energy) i.e. 2 TWh/yr delivered energy using a top-down approach.



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Norman, J.B., 2013. Industrial Energy Use and Improvement Potential (PhD). University of Bath.

Further information on absorption and adsorption chilling

A good review describing the basics of absorption chilling, and the potential application for industrial heat recovery with application in absorption chilling in Northern Ireland, with a specific analysis of the food and drink processing industries is:

Nicol (2009) Absorption cooling – technical investigation of absorption cooling for Northern Ireland, for Invest Northern Ireland

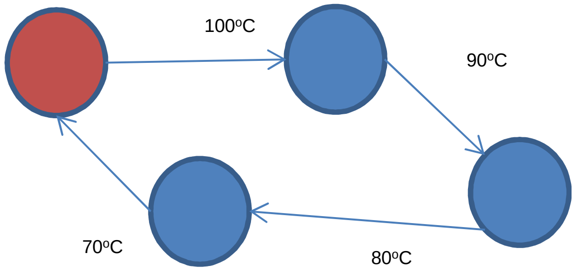
This can be downloaded from:

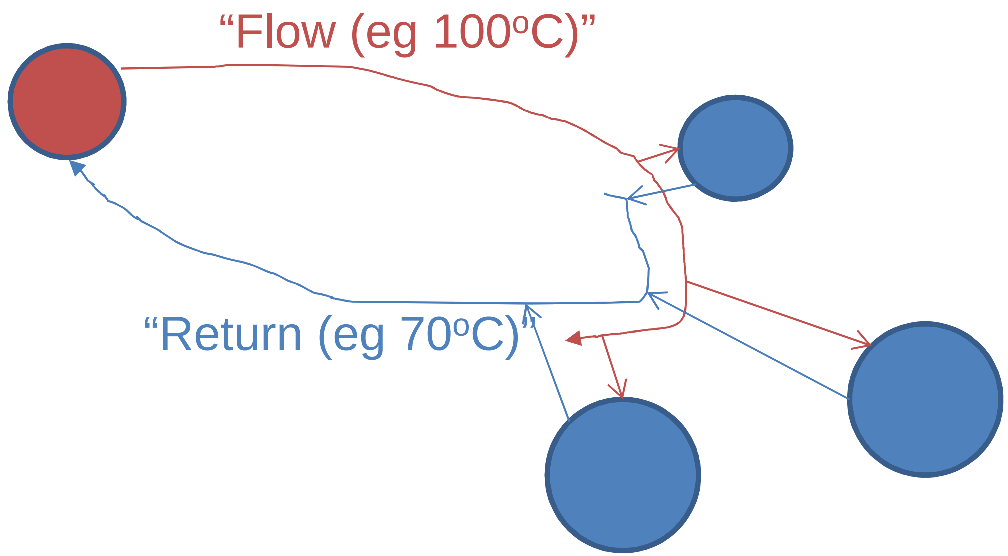
http://www.investni.com/absorption_cooling_technical_investigation_for_northern_ireland_17-may-2009-v2_draft.pdf

Outline

- Background
- Description of techno-economic modelling approach
- Modelling limitations
- Technology assumptions
- Fuel and electricity assumptions
- Approach for generating source and sink database
- “Base Case” Scenario and Results of techno-economic modelling
- Results from sensitivity analysis
- Sectoral assumptions and key issues
- Industrial carbon capture and storage
- The recovery of waste heat for re-use in cooling
- A note on heat networks
- Disclaimer

Optimal heat network design with multiple nodes requires significant understanding of site operational issues and potential trade-offs.





- Concern in "series" supply: fluctuations in demand at each sink node (blue) will cause temperature fluctuations and there affect supply of heat to downstream nodes
- Can be simpler to design but operability and control is complex

- "Parallel" supply is more complex to design but should be more flexible to operate (assuming nodes are in close proximity).

- In either series or parallel case, the results of source- sink-technology matching may be significantly different compared to the "point-to-point" solutions identified in this study.

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Disclaimer

Obtaining a first transparent estimate for the technical and economic potential for industrial heat recovery in the UK has been extremely challenging, and has required a large number of simplifications and assumptions. 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.