Industrial Energy Use from a Bottom-Up Perspective: Developing the Usable Energy Database (Beta version)

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Introduction

This document gives background information and explains the methodology in constructing a usable energy database (UED) for the UK industrial sector. This UED details baseline energy use and emissions, and opportunities for reducing these (improvement potentials). The document should be read alongside the UED. The work is currently presented as a Beta version to allow feedback from project partners and other interested parties to be incorporated in a final version. The UED was produced to improve the representation of the UK industrial sector within the whole systems TIMES model. Due to the substantial variability in energy use within the industrial sector the approach was to undertake bottom-up studies of subsectors of industry that were important from an energy use and emissions perspective, and to supplement this with information on cross-cutting technologies that could be applied throughout industry. The subsectors chosen for bottom-up studies were:

- Iron & steel manufacture
- Chemicals manufacture
- Food & drink manufacture
- Paper manufacture
- Cement manufacture

The approach and challenges to a study of each of these subsectors was in some ways unique and is covered later in this document. However a general approach to each subsector was to identify the baseline energy use and emissions and to assess within this baseline the improvement potential offered by through the application of technologies. Improvements that could be applied immediately in the short-term, and those that offer longer-term potential through more radical change, were considered. However, in some cases, especially when examining longer-term improvement potential, information was not available at the required level to allow inclusion of technologies within the database. A recent review of research evidence for decarbonising heat in industry (Ricardo-AEA 2013a) identified a lack of evidence both technically and economically for many improvement opportunities within UK industry. This serves an example of the difficult task in collating such information to be used in the TIMES model for the UK industrial sector. The presented work is not claimed, or intended to be, complete and fully accurate. It instead offers a representation of the industrial sector to improve the previous version used in the MARKAL model, and acts as a framework to include improved and additional information as it becomes available.

The baseline year for this work was 2010[1]. For each subsector the energy flows delivered to the subsector were calculated, these are given in terms of gross calorific value (GCV, also known as higher heating value, HHV). These energy flows detailed in the baseline information can include:

- Purchased fuels, imported heat, and grid electricity.
- Subsequent transformations of energy occurring within the subsector, such as the use of combined heat and power (CHP plants).
- The final energy delivered to the processes within each subsector.

Where wastes from one part of the subsector act as fuels for another this has been represented if possible, although information was not always available. Process emissions have been detailed where possible. Emissions from the subsectors have been calculated using relevant emissions factors for the baseline year. Emissions are given in terms of carbon dioxide equivalent (CO_{2e}). The individual subsector descriptions can be referred to for a more detailed description of the baseline in each subsector.

The expected growth, or contraction, of the various outputs from industry were not considered here. Additionally measures that affect output, such as better product design to reduce material demand were not considered. Information is given in specific terms (per unit of output) to allow the calculation of parameters and resultant energy demand and emissions as output varies.

This document is split into a number of parts. First the information supplied for each of the technological improvement potential options is covered. Next the modelling of each of the subsectors studied in a bottom-up manner is discussed. For each modelled subsector information is supplied on how the baseline energy use was constructed and how technological improvement was represented. Key uncertainties and assumptions are detailed. Additional notes within the UED provide further information. Detailed information on each technology is not given here but the identified references can be viewed for more complete information. Finally the top-down view of industry is covered. This section considers how the modelled subsectors fit within industry as a whole. Also considered are cross-cutting technologies which offer improvement potential but are not specific to a subsector of industry.

[1] For Iron & steel a base year of 2007 was adopted, as detailed later in the subsector section.

Representing technological improvements

For each subsector a number of technologies were considered that offer emissions savings. For each of these technologies information is supplied to allow inclusion within the TIMES model. This section outlines the information included under each heading in the technology tables. It was not always simple to classify a technology within these general descriptions. Comments are added to the worksheets to provide clarity where required.

Note: The database groups columns to some extent for ease of navigation. When all columns are collapsed it is intended that the most important information is shown. By expanding a group the detailed information that contributes to this information is available.

Basic technology and baseline information

This introductory information defines the units of subsequent parameters.

- Technology identifier: Allows reference to the technology, particularly when referred to by other technology's entries in terms of conflicts and synergies. Note some technologies that formed an earlier version of the UED were not included in the final version due to lack of information or very high uncertainty. The technology identifiers therefore do not always run consecutively.
- Technology description: A brief description of the technology.
- Baseline applicable: The area of the subsector to which the technology relates (this may be the whole of the subsector for some technologies). Relevant information for this baseline (for example SEC and output) will be available in the baseline sheet. Although such information will also be extracted into this worksheet, as discussed below.
- Baseline output description: the primary useful output from the applicable baseline. This may be in physical, economic or thermodynamic terms.
- Units of baseline output: these vary between subsectors and baselines. They are used to define many of the other parameters later in the worksheet.
- Baseline output: the output of the baseline, in the above defined units for the base year.

Technical limitations

This section defines the maximum uptake of the technology when technical limitations are applied.

- Nature of relationship with baseline: Technologies are defined as additional or replacement to the applicable baseline. This is important in defining the costs of the technology, and in a technology's relationship with other technologies that affect the same baseline. This is further discussed below. Some technologies may actually be a replacement for existing technology but are modelled as additional here, comments in the database indicate where this is the case.
- Applicability of technology to baseline (maximum technical potential): If this is 100% the technology could feasibly by deployed throughout the defined baseline. If this is less than 100% there is some technical restriction that prevents the technology being utilised throughout the baseline. As an example some efficiency options for blast furnaces are only applicable to a certain design of furnace. This is then represented by a value of less than 100% here.
- Current level of technology adoption, in reference to the maximum technical potential: the technology may already be employed in some baseline production. This is represented by a non-zero value here. This is given in reference to the maximum technical potential defined above.
- Maximum further technical adoption: Given the previous two constraints what amount of production can the technology be applied to. This is calculated by: Baseline output x Applicability of technology to baseline x (1-Current level of technology adoption).

It was not always possible to separate the applicability of technology, from the current level of adoption. For some technologies a value simply of further potential was available. These cases are identified in the database with a comment.

Cost information

Costs information is provided on three areas:

- Baseline costs: the cost of replacing the existing baseline technology at the end of its life.
- Technology costs: the costs of implementing the technology
- Costs increase: the difference between the technology cost and baseline cost.

For technologies defined as “Additional” baseline costs were not given. Only the technology costs are important and these are equal to the costs increase. Where a technology is defined as “Replacement” baseline costs were given in addition to technology cost, as it is the difference in costs that will often be considered for economic decision making. If a technology is invested in before the end of the existing equipment’s life however different criteria may be used, potentially taking into account the remaining lifetime of the baseline equipment. For some replacement technologies cost information was not available as a separate baseline and technology cost and so only the costs increase is given. This cost information can be used with information on the costs of fuel use (and other parameters) to calculate the economic viability of the technology.

All costs are given in £2010. In converting to £2010 the Chemical Engineering Plant Cost Index (CEPCI) was used to convert non-2010 data to 2010. Currency conversion values for 2010 were then used if required to get GBP.

Over time, and with successful adoption, the costs of some technologies may be expected to reduce. This was not modelled in the database, but information on the technologies such as current adoption and the stage of development may be used to make assumptions about changing costs.

The following information was given for costs:

- Lifetime: the years that the technology would be expected to be in service. This was an area where information was often lacking and assumptions had to be made. These are detailed in comments within the database.
- Comments on cost information: Any relevant information regarding the cost information is shown here, including important assumptions or limitations.
- Reference: this relates to the technology costs information. Some processing and calculating was usually undertaken in getting from the published values to the value given in the database.

- Capital costs (including minimum and maximum): The cost of installing the technology, given per unit of baseline output (as defined above) per year. This should include all costs of equipment and installation. It is not always easy to ensure these costs are fully included, when taken from literature, although efforts were made to do so. Considerable uncertainty surrounds many costs. Some of the information sources used indicated a range of costs, for some technologies the range was based on the costs reported in different sources, for others assumptions were made. A standard variation was adopted for many of the technologies where information on the range of costs was not available. This was based on the Technological Maturity Level (see below). For Commercial technologies a range of ±20% was used, for technologies at the demonstration stage ±30%, and for technologies at the Research and Development stage ±50%. The assumptions used for the costs range may vary from these standards based on the author's knowledge of the technology and baseline. These assumptions are indicated in the comments related to costs information.
- O&M costs (including minimum and maximum): These involve maintenance and other cost changes, such as increased productivity offered by a measure. These are given per unit of baseline output per year. Where information is not available a standard value of 5% of capital costs was often assumed. These O&M costs do not included the effect of changes of inputs or outputs to the process (mostly energy related) as detailed later in the worksheet.

Modelling constraints

This section covers important information regarding the technology that is not captured in the cost information or technical constraints. Primarily this refers to interactions between technologies. As a technology is adopted and the baseline changes the effect of subsequently adopted technologies may be altered.

- Technology interaction. This defines how the technology interacts with other technologies that effect the same baseline and can be utilised together (i.e. they do not conflict, see below). This is a difficult area to represent as there can be considerable uncertainty or a lack of information on this area. Additionally the technology may interact differently dependent on which other technology it is utilised with. However an attempt has been made to generally characterise this parameter as it can have an important effect on the results of employing multiple technologies. Three technology interactions are characterised:

- Additive: the savings from the technology are independent of the baseline. If multiple additive technologies are applied the total saving is the same as the sum of the savings when applying technologies separately.
- Proportional: the savings are best represented as a percentage of the baseline. Therefore if the baseline energy use reduces due to the adoption of other technologies the savings offered through a proportional technology would reduce.
- Absolute: the technology performance remains the same regardless of the baseline. This is typical of replacement technologies.

The classification of a technology can be defined by the source of information as well as the characteristics of the technology. For example the improvement potentials listed for some technologies are given in literature as the improvement offered when they are applied together. Additionally for measures that involve fuel switching the effect of subsequently applied technologies will have to account for this as the baseline energy use may have changed considerably.

- Comments: Any additional information not covered elsewhere that is important in how the technology is modelled.
- Synergies: When the adoption of two or more technologies together provides synergistic benefits it is detailed here.
- Conflicts: Certain technologies cannot be employed together. Details are provided here. Technologies that conflict could both be employed in the subsector, but could not be applied in producing the same output. Eg. two conflicting technologies could each be employed to 50% of the baseline output (assuming there are no other constraints on their adoption).

Market limitations on adoption

This section details constraints on technology adoption beyond those previously discussed.

- Expected commercialisation year: Not all technologies are currently available. The expected year of commercialisation is given here.
- Technological maturity level: For those technologies that are not yet commercial they may currently be in the demonstration stage, or may not have progressed beyond research and development.
- Degree of technological change: This categorisation is based on work by (De Beer 2000), where further details can be found. Briefly an evolutionary change is one that follows the general trend of increasing efficiency and can be retrofit to existing plant. It may involve an addition to the existing equipment or a purchase of new equipment that only affects a small part of the overall plant. A major change requires a factory refit, and large scale purchase of new equipment but would usually produce the same output as the baseline technology. A radical change would require a factory refit and could involve a change in the product output, whilst performing the same service.
- Significant factory refit required: Some equipment cannot be installed without significant disruption to the baseline process. Due to the costs associated with such a disruption it is unlikely such installation would take place without a factory refit occurring.
- Expected adoption in 2020-2050, in reference to maximum (further) technical potential: even where a measure is economic it will not see complete adoption immediately. The expected adoption is given in reference to the maximum (further) technical potential (as defined above). The expected take-up at intervals is given where available. For many technologies this is unknown and left blank. Uptake could be modelled based on parameters such as the degree of technological change and the technological maturity level.

Baseline/ Technology/ Reduction of energy and materials data

Each of the headings of Baseline, Technology and Reduction includes the same parameters, these are given per unit of output. The baseline measure gives the current parameters for the technology baseline identified. The technology information refers to expected performance of the implemented technology. The reduction information is the difference between the baseline and technology values, hence identifying the improvement potential offered by the technology, in regard to the 2010 baseline. As the baseline changes with the adoption of technologies the Technology Interaction parameter (discussed above) provides information on how the improvement potential offered by subsequent technologies would be expected to change. The information given for the baseline, technology and reduction is:

- Energy inputs: the fuels listed will be common for the subsector that is the subject of the table. Some inputs may be outputs from other parts of the subsector. This is primarily the case for iron and steel where sites are highly integrated, but may also apply for electricity and steam inputs in other subsectors. Referring to the baseline sheet should inform about how these inputs are produced.
- Energy outputs: some of the investigated areas output energy flows. Where a technology change increases the output of an energy source it is not always clear how best to account for these, this mainly applies to the Iron and steel sector. For example an output of steam arising from heat recovery is only a saving when used to offset conventional energy use. It may be used to generate electricity, or offset boiler fuel input. Similarly an increase in production of a manufactured fuel such as coke oven gas (COG) or blast furnace gas (BFG) can be used to generate electricity, or offset a conventional fuel. The most likely use of these outputs will be indicated where applicable.
- Non-energy inputs/ outputs: energy focussed technology changes can also affect non-energy inputs and outputs. These are detailed as required. Not all non-energy inputs and outputs are covered, the focus of the work is direct energy use and related emissions rather than indirect, or embodied energy (with the exception of the emissions arising from grid electricity demand). The non-energy inputs and outputs therefore only include those that are significantly affected by the application of technology options.
- Direct fuel related emissions: are calculated with relevant emissions factors, as given in the global parameters worksheet. These may be changed when input into TIMES. For some energy inputs, such as steam, no direct emissions occur from its use. A representative emissions factor is used to indicate the emissions from the production of the steam. Similarly savings in some manufactured fuels, such as coke oven gas, reduce emissions by offsetting purchased energy. A representative emissions factor for manufactured fuels may also be used in these cases.
- Indirect fuel related emissions (grid electricity only): this has the potential to change under future generation scenarios. Again this may vary when input into TIMES.

- Process related emissions: non-energy related emissions of GHGs.
- Captured emissions: for CCS options these become important.
- SEC (final energy basis): the specific energy consumption, the net energy requirement of the process per unit of output.
- Specific emissions: net of direct, indirect, process-related and captured emissions per unit of output.

Further technical information

This gives details on the technical performance of the technology.

- Comment on technical performance information
- Improvement potential error margin. The technical performance of a technology obviously has some uncertainty attached.
- Comment: Details if the error margin is estimated or based on a range of performance values from the literature.
- References related to technology data: these cover literature used in constructing information related to the technology. In most cases some further processing/ assumptions were required to obtain the technology parameters, rather than being taken directly from the references given here.

Iron and steel sector

Iron and steel is the largest single user of energy in the UK industrial sector as well as being highly energy intensive. Basic production of iron and steel is considered fairly homogenous. It consists of several sub-processes, producing various intermediate products which are used as part of an integrated system. The sector is very energy conscious and so data availability is good. The International Steel Statistics Bureau (ISSB) manages the data on UK Iron and steel energy and material production and use and was consulted for this assessment (ISSB 2012). The information used covers SIC (2007) 24.1-3.

Baseline

It was decided that the baseline of the Iron and Steel subsector should use data from 2007, as opposed to 2010, as this was the most recent year for which data was available that all UK blast furnaces were operational. In 2010 a significant proportion of the sector's capacity was mothballed. These mothballed blast furnaces have since been relit and so representing the baseline with all blast furnaces operational was felt to be the most accurate depiction of the sector.

Energy and material flows were mainly sourced from ISSB (2012) and the Digest of UK Energy Statistics (DECC 2013a), with further detail on fuel demands at the plant level provided by IISI (1996). This enabled the average flow of energy and materials through each major process plant in the subsector to be modelled. Figure 1 illustrates this flow and the integration of secondary fuels, such as coke and blast furnace gas, throughout the system.

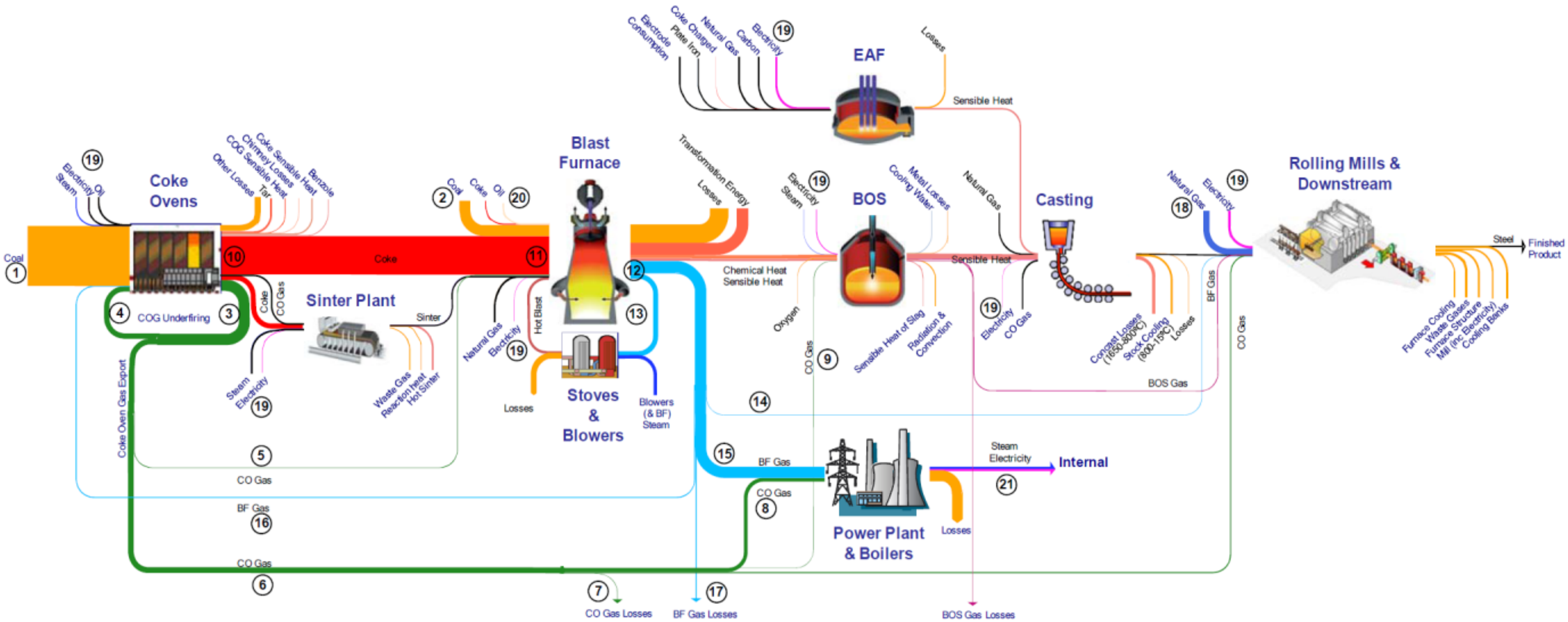

Figure 1: Simplified Sankey diagram of the UK iron and steel subsector (DECC 2011) (This diagram was not produced from the analysis in this project and is based on the year 2009.)

The subsector baseline was modelled with the following sub-processes. Each of these sub-processes has its own physical output which was used for defining specific measures of input and output. These specific measures were also given per tonne of crude steel (the sector level output) in the baseline:

- **Coke oven**: Processes coal into coke for use in the blast furnace. Due to the various functions of coke in the blast furnace, not just as a fuel but also as a reductant and for its mechanical properties, it is not possible to switch away from coal in the Iron and steel subsector. Other outputs from the coke ovens include coke breeze, which is used at the sinter plant, and coke oven gas (COG), which is recycled back into the process and used elsewhere in the works as a fuel.
- **Sinter plant:** Prepares iron ore for the blast furnace.
- **Blast furnace**: Consisting of a blast furnace, stoves and blowers. Smelts iron ore to produce hot metal (pig iron) and produces the by-product blast furnace gas BFG), which is recycled back into the process and utilised elsewhere in the works as fuel.
- **Basic oxygen furnace:** Is fed with hot metal from the blast furnace, supplemented with metal scrap (about 10%), and oxygen to produce liquid steel.
- **Electric arc furnace.** Fed with over 90% scrap and small amounts of cold iron to produce liquid steel.
- **Continuous casting.** Casting liquid steel into crude steel slabs, blooms and billets.
- **Ingot casting.** Casting liquid steel into crude steel ingots.
- **Hot rolling plant.** Covers all hot rolling mills, such as hot-strip, rod and bar and section.
- **Power plant and boilers.** Utilises most of the surplus coke oven and blast furnace gas. The UK configuration is modelled as boilers, which raise steam, some of which is used for processes, some for condensing turbines (producing electricity) and some for back-pressure steam turbines (producing electricity and outputting the steam at a slightly lower pressure). The system taken together can be thought of as a CHP plant.
- **Downstream and other.** Covers secondary finishing operations not already modelled as hot-rolling, and other miscellaneous activities. This is made up by the remaining fuels after all the above processes and gas losses are a taken from the subsector total.

The subsector was split into two site types: Integrated works and electric arc steelmaking. The former includes all iron-making plant (coke oven, sinter plant and blast furnace). It includes all power plant (condensing turbine and back-pressure steam turbine CHP) and most boiler capacity (generating steam for auto-generation and processes). The electric arc steel making site includes the electric arc furnace and all ingot casting. Remaining primary finishing (Continuous casting) and secondary finishing (hot rolling and other downstream processes) were split between the sites. A separate assessment was undertaken based on steel product yields to determine approximate production of secondary finishing mills before attributing them to each site based on the typical products they produce (Environment Agency 2004).

Figure 2 shows the flow of energy through the iron and steel subsector as modelled. The sector transforms most of its primary input into its own manufactured fuels such as coke, coke oven gas and blast furnace gas.

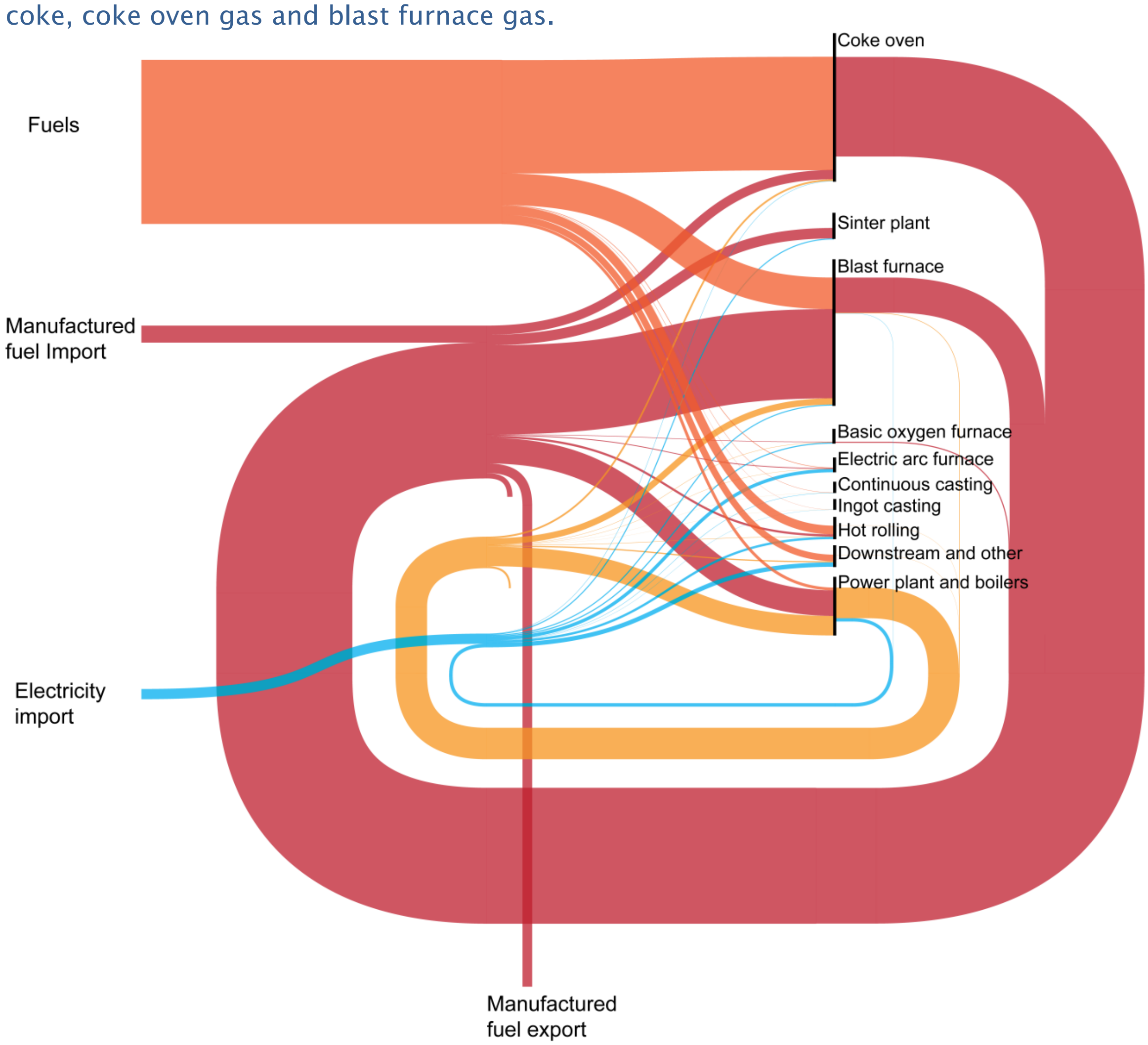

Figure 2 Sankey energy flow diagram of the UK Iron and Steel subsector, as modelled

Improvement potential

Identified technologies and measures are broadly grouped into two categories:

- **Process level.** These mainly include retrofit technologies for process plant including heat and fuel recovery in various forms. Also considered are fuel switching options in terms of replacing coke use in blast furnaces with alternatives. A number of reports are used to inform these choices (Department of Energy 1984, European Commission 2012a, Institute for Industrial Productivity 2012, International Iron and Steel Institute 1998, NEDO 2008, US Environmental Protection Agency 2010, Worrell et al. 2010, Worrell et al. 1999), along with information on the UK baseline. Where a manufactured fuel (such as coke oven gas, blast furnace gas or basic oxygen furnace gas) is saved or the yield increased its effect on a sector level, in terms of energy demand and emissions, will usually be to offset a purchased fuel (often natural gas in the case of gaseous fuels).
- **System level.** This includes the incorporation of technologies at the system, or site, level. Two areas are distinguished: rebalancing of existing structure and the introduction of alternative systems new to the UK subsector.
    - Existing system change: This is the shifting of production from the Blast furnace (BF-BOF, or integrated) route, to the Electric (EAF) route. The BF-BOF route was measured as being around four times more energy[2] and CO_2 intensive. Increasing the proportion of EAF steelmaking would therefore reduce sector energy demand and emissions.
    - Alternative systems: A number of emerging new technologies have been modelled. These include the four major future steelmaking options identified by the ULCOS project (Birat 2012): Top-gas recovery, HISARNA, ULCORED[3] and ULCOWIN[4]. The MIDREX direct reduced iron route was also included as commercially available option. Other schemes to ULCORED such as Japan's COURSE50 programme were not assessed as they are less relevant to the UK case. For example hydrogen flash smelting, in which hydrogen is extracted from coke oven gas and injected into the blast

[2] Energy intensity is 2.5 times greater in primary energy terms as the EAF route purchases large amounts of electricity.

[3] Advanced direct reduced iron process with CCS.

[4] Alkaline electrolysis.

furnace, is less appropriate for the scale of the UK industry (IEA GHG 2013b).

The key alternative system options to BF-BOF are summarised in Figure 3 and Figure 4. In the case of Top-gas recovery and HISARNA, these are modelled as being incorporated into existing UK integrated works. Direct reduced iron options and Electrolysis are modelled as Greenfield sites. It should be noted that the technologies that offer potential for substantial CO_2 emissions reduction, apart from ULCOWIN, are CCS options. Moreover, ULCOWIN can only assure lower emissions if it is supplied with low or zero carbon electricity.

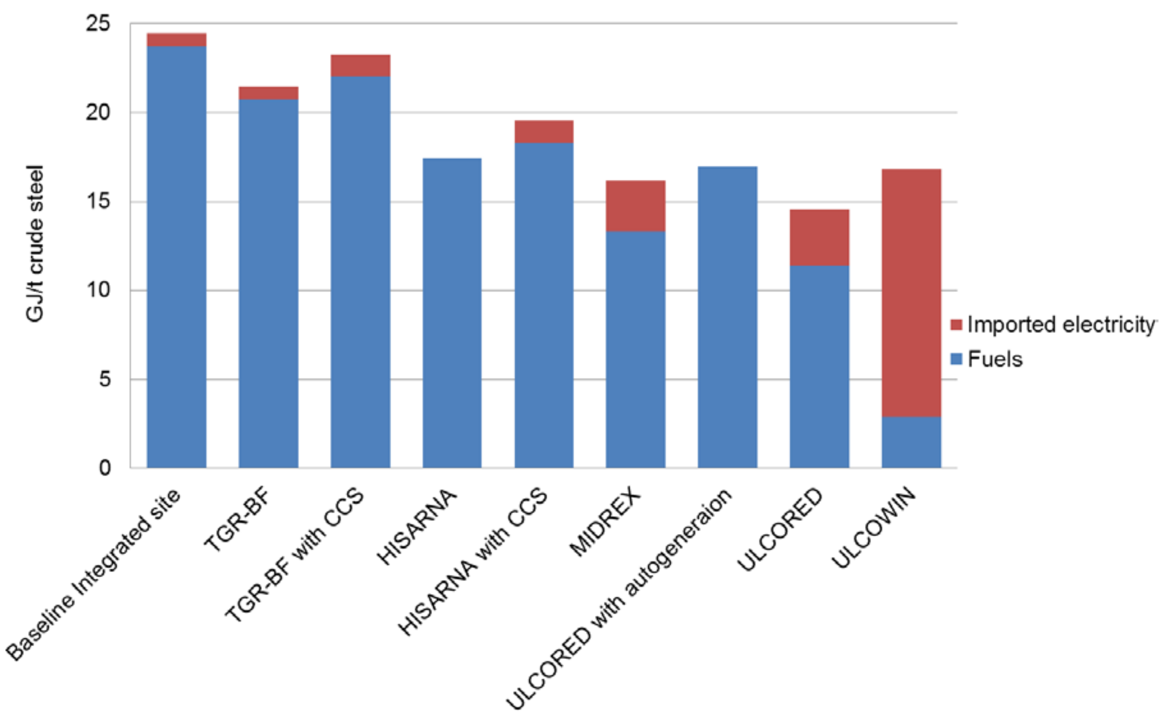

Figure 3 Summary energy intensities of alternative steelmaking systems in the UK (Birat 2012, Birat et al. 2008, IEA GHG 2013a, International Iron and Steel Institute 1998, Link 2008). (Note that TGR-BF, HISARNA and ULCORED consume significantly more oxygen than the base case which would show slightly higher imported electricity if incorporated).

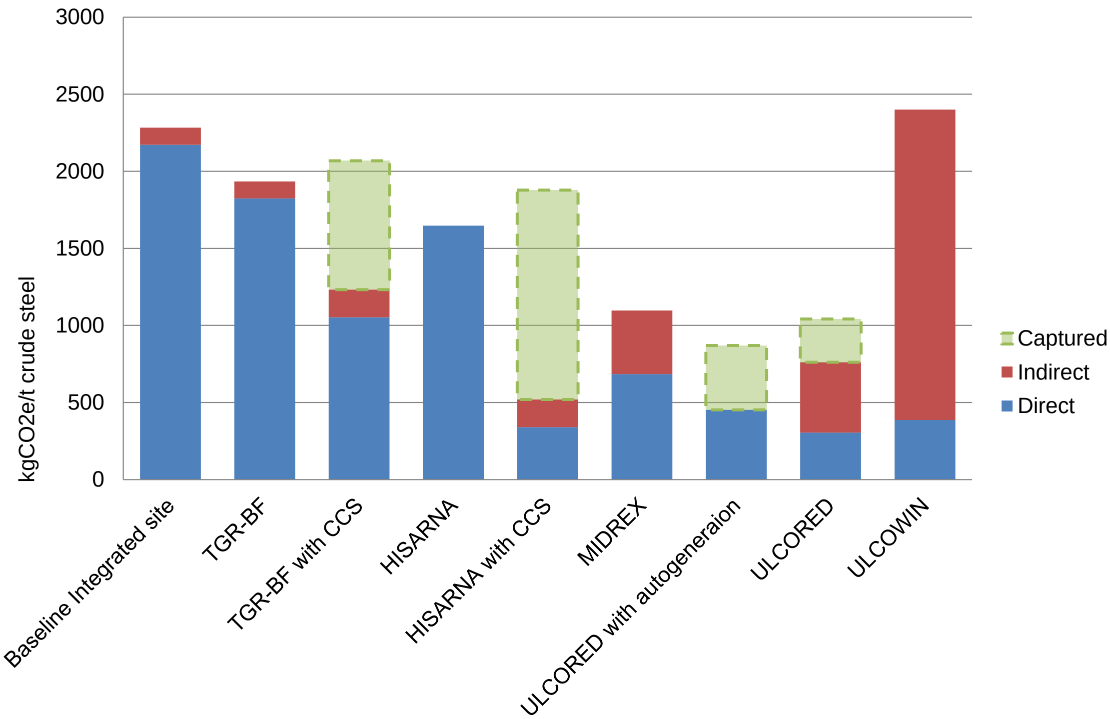

Figure 4 Summary CO_2 emissions intensities of alternative steelmaking systems in the UK (Birat 2012, Birat et al. 2008, IEA GHG 2013a, International Iron and Steel Institute 1998, Link 2008) (Note that TGR-BF, HISARNA and ULCORED consume significantly more oxygen than the base case which would show slightly high indirect emissions if incorporated).

Chemicals sector

Chemicals is a complex collection of many diverse and interacting subsectors covering a wide range of feedstocks, processes and products. Physical outputs are moved around on an international scale within or between companies. The industry is also highly focused on private R&D and protective of information, meaning that data availability is particularly poor. As such the assessment here is less representative of the UK case than for other sectors. Baseline process efficiencies and plant load factors are largely based on information covering the region of Western Europe. The information used covers SIC (2007) 20-21.

Baseline

The baseline was modelled as twenty seven different subsector processes, each with its own physical output. However, due to data restrictions, only a few of the sub-processes identified were analysed for improvement potential[5]:

- Steam cracking (Olefins): This process is at the heart of the UK petrochemicals subsector and produces olefins which form the base of many other chemicals including plastics. Olefins such as ethylene, propylene and butadiene are derived from gas and petroleum feedstock such as ethane, propane, butane, naphtha and gas oil. It is by far the largest energy demanding subsector, in terms of both fuel and feedstock, of the chemicals industry.
- Reformate fractionation (Aromatics): This refers to the extraction of benzene and toluene, known as aromatics, some of which may be extracted from pyrolysis gasoline, a by-product of steam cracking, and some from reformate, which is a product of the catalytic reforming of naphtha at refineries.
- Steam reforming (Hydrogen and Ammonia): Steam reforming is a method of producing hydrogen from natural gas (methane) feedstock, releasing CO_2 as a by-product. It is primarily undertaken in the UK for the production of ammonia though a hydrogen focused facility was also accounted for.
- Ostwald process (Nitric acid): This is the process by which nitric acid is produced from ammonia, resulting in emissions of nitrogen dioxide (N_2O), which is a potent greenhouse gas.
- Mercury cell process (Chlor-alkali): This is a process of producing chlorine by electrolysis of a salt solution, a co-product of which is hydrogen.

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[5] Despite this the baseline represents a good split of the UK chemicals industry structure that may be utilised in future assessment.

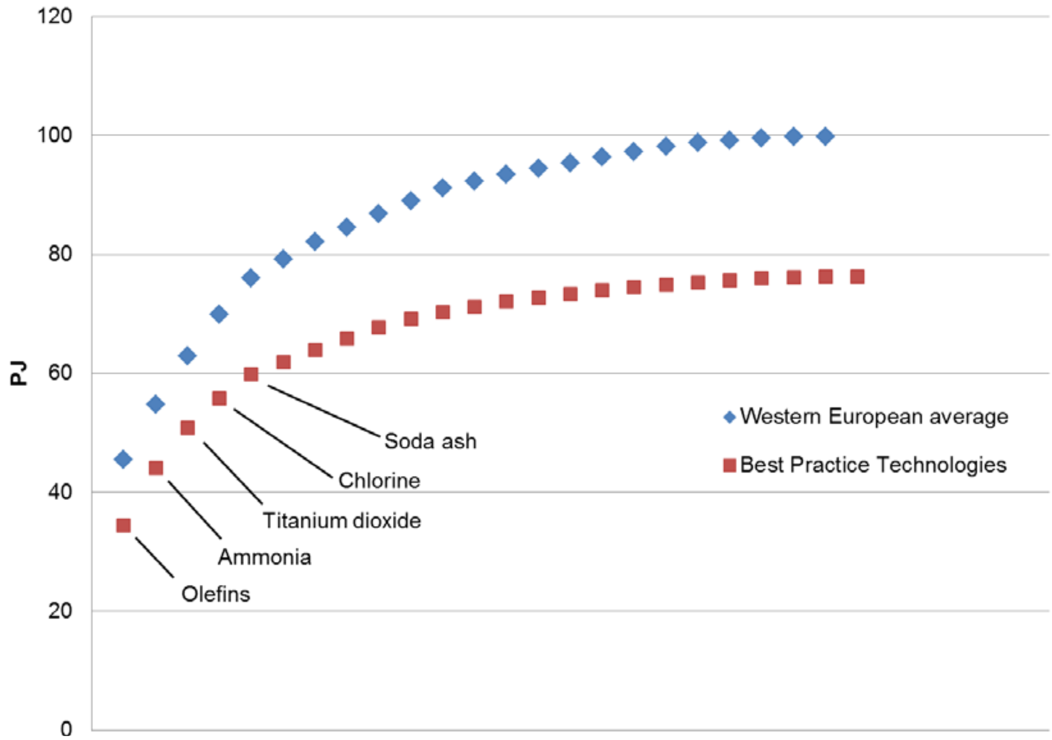

Figure 5 Final energy demand (Fuel, electricity and steam) from modelled processes applying average Western European and best practice technology efficiencies to estimated UK production (APPE 2013, DECC 2013a, ICIS 2013, IEA 2009b).

Figure 5 illustrates the processes modelled and their contribution to the subsector's overall energy demand. The method and assumptions for building the baseline structure are described here:

- Chemical process plant capacity data was sourced from chemical profile articles of the industry intelligence provider (ICIS 2013).
- Plant production levels were calculated by applying estimated load factors. For the petrochemical industry, load factors were calculated from APPE (2013) which publishes production and capacity figures of key products and derivatives in Western Europe. The average capacity of the products listed was used for other organic chemicals. Inorganic chemical plant load factors were informed in part by further articles sourced from (ICIS 2013). Where information was not available, a default value of 70% was incorporated. The exceptions to these methods are:
    - Olefins, calculated by analysing petrochemical feedstocks (DECC 2013a) with literature on their typical product yields in steam cracking (Meyers 2004);
    - Ammonia, using an estimate by USGS (2012).

- Baseline process efficiencies were taken from a report by the IEA (2009a), on production in Western Europe. The exception to this was Ammonia, for which the data for combustion and feedstock use of natural gas was sourced from ONS (2013), Oxygen from IISI (1998), and Hydrogen from the European Commission (2012b).
- The subsector final demand fuel split (DECC 2013a), which is primarily natural gas, was applied to the processes as an average. Regarding steam and electricity demand, the subsector split between self-produced and imported was also applied across the processes. This was to ensure that an average emissions factor would be applied at the process level.

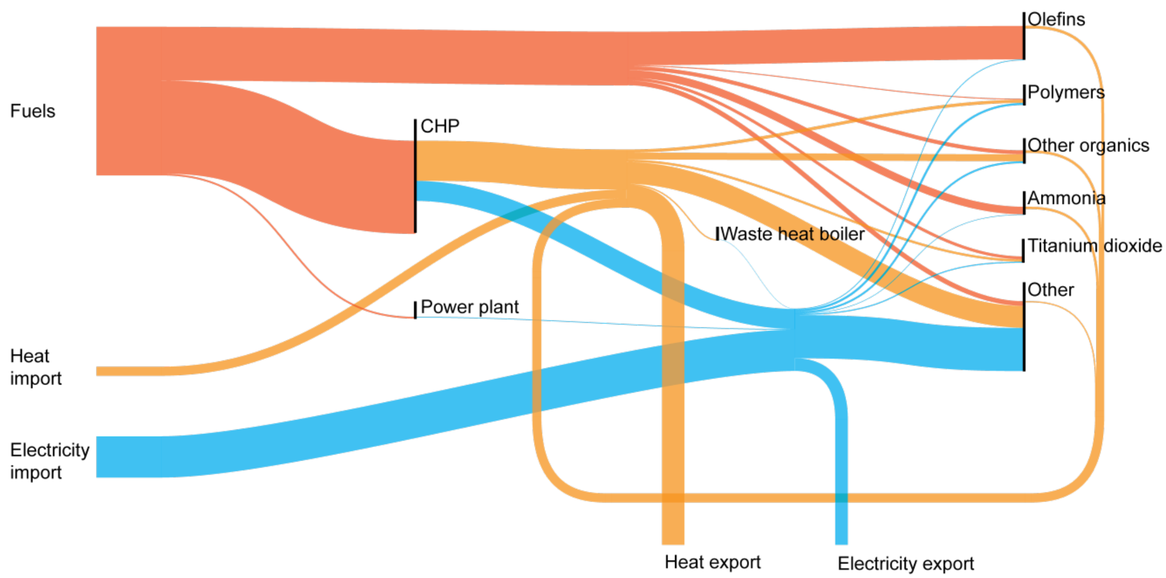

Figure 6 Sankey energy flow diagram of the UK Chemicals subsector as modelled.

Figure 6 shows the flow of energy through the subsector as modelled. The method and assumptions for building this baseline structure are described here:

- The data underlying the subsector model is based on DUKES (DECC 2013a).
- Special attention was given to CHP within the Chemicals subsector. Some CHP plants within the Chemicals subsector are classified as major power producers (MPP) and so are outside the scope of the final energy demand given in DUKES, (DECC 2013a) but are included in the representation of the Chemicals subsector here. Using a number of the tables from DUKES and personal correspondence with the analysts at DECC (Judd 2013) fuel use within CHP and autogeneration was specified.
- Electricity demand was split between grid and autogenerated electricity.

- Imported heat, exported heat and exported electricity were accounted for. Approximately 60% of the electricity produced by CHP in the Chemicals subsector is exported (50% to the grid and 10% to other industrial subsectors) (Judd 2013).
- The remaining fuel demand not used in CHP or autogeneration is used by processes, in addition to auxiliary boilers and other miscellaneous equipment.
- The processes modelled in a bottom-up manner account for 92% of the non-CHP fuel demand.
- The steam and electricity demand represented by a summation of the bottom-up modelled processes account for 50% and 25% of the total demand respectively. These may appear low as these energy carriers have higher demand for energy overheads such as the lighting and heating of buildings, and auxiliary processes associated with, but not included in, the chemical process demands listed by the IEA (2009).

Improvement potential

Identified technologies and measures generally fit into three broad categories. Fuel switching is not identified separately but occurs via many of the process substitution options. Natural gas, the least CO_2 intensive fossil fuel, is by far the most widely combusted fuel in the subsector, much of it is used in CHP plant.

- **Process improvement**. These include retrofit technologies such as dividing wall columns and membranes for chemical separation.
- **Process substitution**. These include all options assessed by Ren (2009) in his thorough account of long-term opportunities for the petrochemicals sector. They range from the replacement of steam cracker plants with the existing state-of-the-art, to radically different biotechnologies presently in the R&D stage, such as bio-ethanol-to-ethylene. Many of the technologies would entail a large structural shift in the way petrochemicals are produced in the UK. Most of the replacements entail a substitution in feedstock as well as fuel, and therefore have significant energy and emissions ramifications for upstream fuel processing industries. These processes were also analysed by Ren (2009), but were not included in this assessment as they belong outside the scope of the Chemicals baseline. Improvement potential of these replacements should not be considered in isolation and to properly understand their potential would require an extension of the definition of industry to include the refineries sector.

- **Carbon sequestration.** Opportunities for retrofitting post-combustion CCS onto existing steam crackers were assessed (Johansson et al. 2012). There is also significant opportunity to apply CCS to steam reformers (Collodi and Wheeler 2010, Element Energy 2010). This option is relatively cheap as the process already produces a pure stream of CO_2.

Food and drink sector

The Food and drink (FD) subsector was challenging to model due to its heterogeneous nature. The approach taken was to model subsectors of FD that were large users of energy and to represent the improvement potential in the remainder of the subsector through cross cutting technologies. The three subsectors focussed on were:

- The manufacture of Dairy products
- The manufacture of Meat products
- The manufacture of Bakery products

Even within these subsectors the operations were heterogeneous and it was not possible to model all energy use within each subsector in detail. Lack of information on both the baseline and improvement potential options was encountered. The modelling of the three subsectors is detailed below. The discussion also covers the remainder of the FD subsector's energy use.

The improvement potential options assessed tend to focus on energy efficiency. Less information is available on radial process change than in other subsectors. Although the FD subsector comprises a significant proportion of industrial energy demand its non-energy-intensive nature means longer-term emissions reductions have not received the same attention as in other subsectors.

Figure 7 shows the representation of the three subsectors within the FD subsector. The database details the end use in these three subsectors and also how they fit within the wider FD subsector.

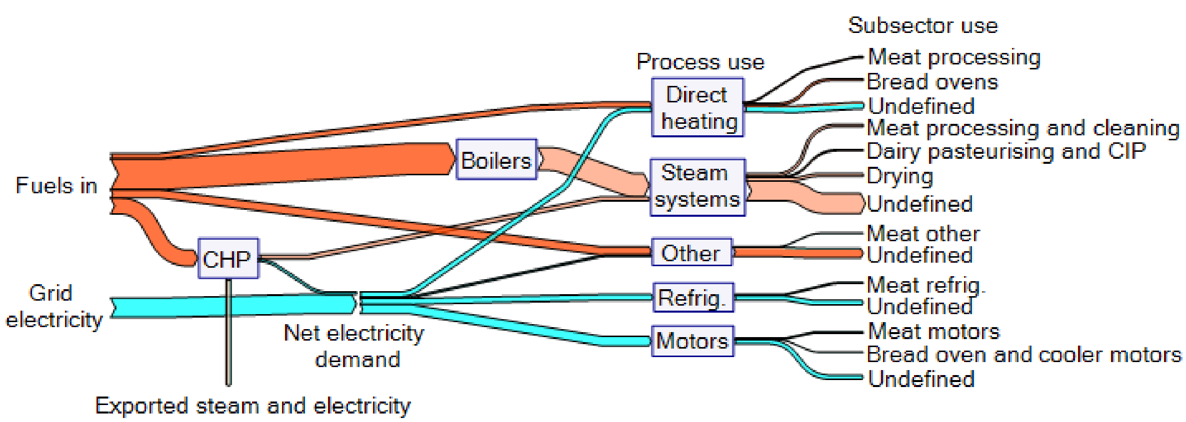

Figure 7: Sankey diagram of Food and drink subsector.

Dairy sector

Baseline energy use

It was found that the SEC of various processes within the subsector (pasteurisation, homogenisation, separation, storage etc) varied greatly by type of product produced (liquid milk, cheese, milk powders etc). The SEC even for a relatively well defined output was also found to show considerable variation within literature (Brush et al. 2011, Carbon Trust 2010b, Cox 1986, Food and Agriculture Organization of the United Nations: Animal Production and Health Division 2010, Natural Resources Canada 2001, Ramirez et al. 2006a, Xu and Flapper 2009, Xu and Flapper 2011). These variations were thought to be due to large variations in energy efficiency seen throughout the subsector and also as varying product types (eg. different types of cheese) significantly affected energy demands. Two processes that are utilised in the manufacture of all products in Dairy manufacture: pasteurisation and cleaning in place (CIP) were focussed on here. This was due to the information available on improvement potential, as well as difficulty in representing the baseline energy use.

Output of the sector was represented by raw milk input, rather than the output of products. This was due to the mixed nature of outputs and as the common processes in processing raw milk were the focus of the subsector representation. Information from (DEFRA 2011) was used to represent raw milk input. Other datasets (AEA 2011a, ONS 2012b) either had questions over coverage (eg. the separation of farm and manufacturing operations), concerns about accuracy (such as double counting of outputs from one part of the industry, that are inputs to another) or information that was not compatible with information on SECs.

SEC data was taken from a number of sources:

- The overall SEC for the sector was based on a study specific to the UK (Carbon Trust 2010b) in which there was reasonable confidence. This also showed good agreement with the CCA (AEA 2011a), with discrepancies thought to be due to the CCA also covering some farm operations. The SECs of the individual processes were compared to this overall value when assessing their accuracy.
- The baseline SEC for pasteurisation was based on the reported outputs of products from the subsector (DEFRA 2011), and the expected SEC of pasteurisation of each of these (Brush et al. 2011)[6]. In comparison to the overall subsector SEC this measure was found to given reasonable agreement with other sources (Ramirez et al. 2006a) in relative terms (i.e. the proportion of total energy use represented by pasteurisation).

[6] Other studies were discounted due to the sites studied showing considerably better or worse SEC at a site level than the UK average.

- The baseline SEC for CIP was based on the proportion of total site energy use thought to be represented by CIP (Ramirez et al. 2006a) and the broad agreement of this value with other sources (Carbon Trust 2010b, Natural Resources Canada 2001).
- Other energy using processes were not detailed, pasteurisation and CIP as represented here comprise 50% of the overall subsector SEC. The fuel split used was based on information from ECUK (DECC 2012d).

There was limited data on the subsector's energy demand to compare to the modelling of the subsector here. Information on energy demand was not available from statistical sources at the required level of disaggregation since 2007 (DECC 2012d). The energy use represented here by the site level SEC and product output covers 60% of that reported for SIC 10.51 in 2007 (15.51 under SIC2003). There is a high level on uncertainty with the information at high levels of disaggregation from publically available datasets (DECC 2012d) and the SIC classification may include some operations further down the supply chain. A comparison of these sources is therefore difficult. As the SEC utilised in the modelling is based on sites included in the CCA it may also be based on larger and more efficient sites. Within these CCA sites there is substantial variation in site SEC, even where similar product is manufactured (Carbon Trust 2010b). This could be taken as an indication for the high improvement potential offered from switching to best practice, but also of the uncertainty of baseline information.

The economic output of the sector is estimated as £1159m GVA based on that for SIC 10.51 (ONS 2012a). Although as discussed above all energy use may not be covered within this SIC classification, all raw milk production is and so the GVA is taken as that for the entire subsector.

Improvement potential

The technological improvement within the dairy sector was heavily based on a study by the (Carbon Trust 2010b). The UK specific nature of the study made it more valuable than other sources in estimating the potential improvement in the sector. Various assumptions had to be taken to calculate the parameters required within the database from those given in the source. The improvement potential focussed on pasteurisation and CIP, for the reasons given above. Improvements at the site level were also assessed in terms of general good practice. Although information on technologies was available from other sources (Brush et al. 2011, European Commission 2006) it tended to not include the required information on technological performance and costs to allow inclusion in the database.

Bakery sector

Baseline

The assessment of the bakery sector focuses on baked products (mainly bread) produced at the industrial scale (rather than small craft bakeries). Output is based on that reported for 2008 at sites included in the CCA (Carbon Trust 2010a), scaled to 2010 based on information from PRODCOM (ONS 2012b). This covers the majority of bread production, it does not include the production of cakes and other products included within SIC 10.71. Overall 70% of physical output from SIC 10.71 is covered. There may be similar savings available in the non-modelled subsector as many of the same processes are used, although this was not examined here.

The processes within the bakery sector that are the focus of the modelling are ovens and coolers. This was as these processes are common to all bakeries, represent the majority of energy use at the sites, and required information on technological improvement potential was available.

There is considerable variation recorded between different bakeries in terms of SEC (Le-bail et al. 2010). The information utilised is therefore taken from UK specific sources where possible.

- The SECs of direct fired and indirect fired ovens were based on information from the (Carbon Trust 2010a). The SEC for direct fired ovens was found to agree well with other sources (Khatir et al. 2012a).
- The split of production between the two types of ovens, which show large differences in efficiency, was calculated given the proportion of site emissions that ovens are responsible for (Carbon Trust 2010a), the SECs of the different types of oven and appropriate emissions factors. This was found to agree reasonably with the expected split of ovens reported in the UK bakery sector (Carbon Trust 2010a, Khatir et al. 2012a).
- The Cooler SEC was based on information reported by the (Carbon Trust 2010a).
- Overall subsector SEC was based on that reported by the (Carbon Trust 2010a). The end uses other than ovens and coolers were not detailed, but some site level improvement technologies were considered. The oven and cooler energy use accounts for approximately 60% of energy demand on a final energy basis.

The lack of energy use data at disaggregated SIC codes for 2010 prevents a full comparison of the energy use represented here with all that classified within SIC 10.71, however comparing to 2007 values (DECC 2012d) approximately 65% of energy use within the SIC code is represented by subsector as modelled here.

The economic output included within the bakery sector as modelled is calculated based on the proportion of PRODCOM sales, in value terms for SIC 10.71, that are represented by the physical output modelled. This proportion is applied to the GVA for SIC 10.71 (ONS 2012a) to estimate the GVA of the bakery sector as modelled. As other outputs of the sector (such as cakes) have higher value per tonne than bread (ONS 2012b) a high proportion of physical output is covered (70%), but it is lower in economic terms (48% of GVA).

Improvement potential

Similarly to the Dairy sector the technological improvement within the bakery sector was heavily based on a study by the (Carbon Trust 2010a), due to its UK specific nature. Various assumptions had to be taken to calculate the parameters required within the database from those given in the source. The improvement potential focussed on bakeries and coolers. Other sources (Khatir et al. 2012a, Khatir et al. 2012b) were used to complement the Carbon Trust work.

Meat sector

Baseline

Output information was based on physical output reported by PRODCOM (ONS 2012b). This data broadly agrees with that available from other sources (DEFRA 2012a, 2012b), PRODCOM was preferred due to the availability of more disaggregate information. The SECs for various outputs were based on those reported by (Ramirez et al. 2006b), with some calculation and assumptions where incomplete. The end use of energy information was consolidated to give the values in the database. There was considerable uncertainty surrounding some detailed energy uses, this consolidated end use information was therefore preferred to more detailed, but uncertain data. Fuel split was based on information from ECUK (DECC 2012d).

The subsector as modelled here included the production and processing of beef, sheep, pork, poultry and processed products. Farm operations were not included. Rendering operations were not included, this is due to uncertainty surrounding both the classification of outputs and the SEC of these operations. The lack of energy use data at disaggregated SIC codes for 2010 prevents a full comparison of the energy use represented here with all that classified within SIC 10.1, however comparing to 2007 values (DECC 2012d) approximately 75% of energy use within the SIC code is represented by the output level and overall SEC used here. The difference could be accounted for by the rendering operations.

The economic output included within the meat subsector as modelled is calculated based on the proportion of PRODCOM sales, in value terms for SIC 10.1, that are represented by the physical output modelled. This proportion is applied to the GVA for

SIC 10.1 (ONS 2012a) to estimate the GVA of the meat subsector as modelled. The vast majority of economic output is represented here (93%). This would be expected as the output not included (mainly rendering) is of low value.

Improvement potential

Due to the uncertainties surrounding detailed end use information and the variety of end uses throughout the meat sector technology of a more cross-cutting nature was the focus of improvement potential, although with an application more specific to the meat sector. The potential for better heat integration on a meat producing site, including the use of heat pumps, and the recovery of heat from refrigeration equipment was estimated based on a number of sources (AEA 2000, Dalsgard et al. 2000, Fritzson and Berntsson 2006a, Fritzson and Berntsson 2006b, Heat Pump & Thermal Storage Technology Centre of Japan 2010, Martin et al. 2000b) and own calculations.

Other subsectors

Baseline

The SIC 2007 codes covered by the modelling here were 10 and 11. Overall output was measured by GVA (ONS 2012a), a physical measure was not appropriate given the mixed nature of outputs from the sector. The overall energy use of the sector and split into end uses was based on information from national statistics (DECC 2012a, 2012f) with calculations and processing of the data as appropriate.

Although DECC statistics split heating use in the Food sector between low temperature processes and drying (DECC 2012f) there is not detailed information on more precise temperature requirements or on the use of steam systems. The use of steam systems was estimated at 50% of final energy demand based on previous studies (FDF 2008, US DOE 2004).

Fuel split of different processes was based on information reported by (DECC 2012e), taking into consideration the fuel splits of the subsectors modelled above (Meat, Dairy and Bakery products). It was also assumed that no electricity was used for steam systems, and the coal assigned to heating processes was all utilised by steam systems rather than direct heating. The level of electricity assigned to heating processes in the source data appears high (DECC 2012e), whilst that going to motor systems seems comparatively low in comparison with other sources (Market Transformation Programme 2003). This may be as electricity that is used for motor systems within heating systems, for example pumps and fans in steam systems and drying systems, is classified within heating processes. Therefore motor system use is adjusted to agree with the proportion of electricity demand accounted for by motor systems in a survey of UK energy use in motors (Market Transformation Programme 2003). This electricity demand is then removed from the totals going towards heating. This still results in a large proportion of direct heating being supplied by electricity however. Overall boiler efficiency is assumed to be 74%, in line with the industrial sector as a whole (see the cross-cutting sector information). Details of CHP use were taken from DUKES (DECC 2012b, 2012c), with the fuel use for exported electricity and heat specified. The fuel demand for drying was assumed to be filled by steam systems.

Improvement potential

At the level of the subsector technologies that offer improvement potential were considered.

- **Heat pumps**: Analysis work undertaken for the UK Food and Drink sector (Norman 2013), which drew on previous work in the area (Heat Pump & Thermal Storage Technology Centre of Japan 2010, Hita et al. 2011) identified a potential to replace 10-50% of final energy demand currently supplied by steam systems with heat pumps. The maximum technical potential of this measure was set at 50% of the current demand for steam in the undefined subsectors (within the Dairy and Meat subsector similar measures are already applied). The uptake of this technology is set so the lower end of the estimation is immediately available, and this increases to the maximum uptake as heat pump technology is expected to develop, higher temperatures are reachable and efficiency improves. In estimating the technical performance of heat pumps conventions were adopted as detailed in (Norman 2013). This performance could vary considerably dependent on the temperature of supply and demand. It was assumed that low temperature surplus heat from compressed air systems, refrigeration equipment and heating systems was utilised in the majority of cases. Cost information was based on information from a previous study (Fritzson and Berntsson 2006b). There was considerable uncertainty here due to the large variability in the heat pump installations possible.
- **Energy management**: (AEA 2000) found 40% of UK Food and drink companies did not employ energy management and there was potential for a 9% saving at these sites. It was assumed that this measure was applicable to 30% of energy input not covered by subsector studies. This reduction was due to the expected take up of this opportunity since the study in 2000. Costs were also taken from a case study reported by (AEA 2000).
- **Heat recovery**: Heat recovery measures in the Food sector were applied to drying systems. Technical and economic information was calculated from (Martin et al. 2000b).
- **Cross-cutting technologies**: Opportunities for motor and boiler systems in addition to those given here are covered in the cross-cutting work sector.

Paper sector

Baseline

Energy inputs were based on information from the trade association, the Confederation of Paper Industries (Morgan 2013). This covers all paper mills (fifty one sites) in the UK but not the manufacture of "finished paper products" that use energy in a different manner. The information here covers SIC (2007) 17.12. This energy use covers around 50% of energy demand at the 3 digit SIC level, SIC 17.1 (DECC 2012d). Output from these mills is taken from the CCAs (AEA 2011a) and confirmed by the CPI (Morgan 2013), the energy demand differs slightly from that reported in the CCA due to the use of renewable energy sources that were not reported under the CCA. Economic output is taken from the ABS (ONS 2012a).

- Fuel use in CHP is based on reported autogenerated electricity (Morgan 2013) and sector H:P ratio calculated from (DECC 2012b). Overall efficiency of CHP is also taken from (DECC 2012b). Information on exported electricity from CHP was given by the trade association (Morgan 2013). The fuel used in producing this exported electricity was calculated based on information from DUKES (DECC 2013c).
- Non-CHP fuel input is assumed to be used in steam systems, based on a report by the (Carbon Trust 2011).
- The SEC of processes was based on information from the (Carbon Trust 2011). This was scaled to match the total electricity demand reported by the CPI (Morgan 2013). Using the same scaling factor for steam use this defined the efficiency of the boilers. This gave an efficiency of 82%, which was high in comparison to the average for the industrial sector but not unreasonably so. As the paper sector is energy-intensive it could be expected to have a higher boiler efficiency than the industrial sector average.

The baseline energy use of the subsector is represented in Figure 8 below.

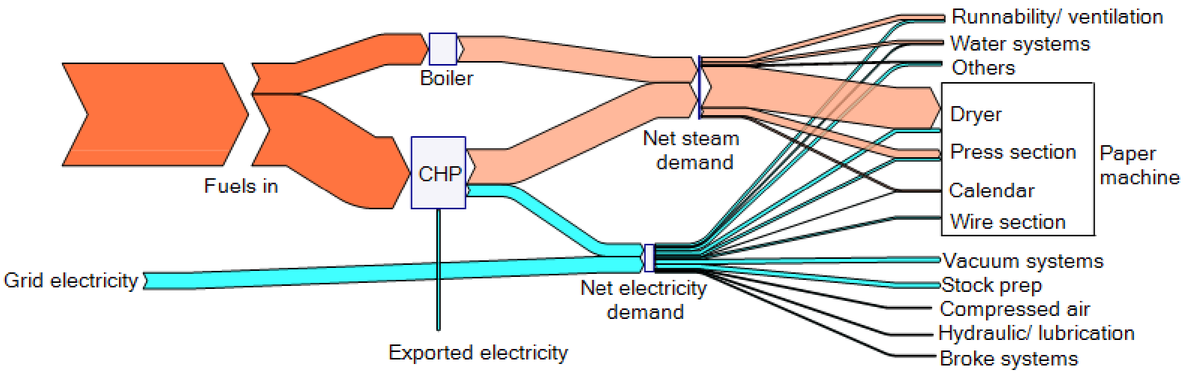

Figure 8: Sankey diagram of Paper subsector.

Improvement potential

Improvement potentials have been extracted from a report by the (Carbon Trust 2011) which particularly focuses on the UK Paper Industry. This mainly covers short-term opportunities and so was supplemented with information from other sources that cover opportunities that involve more major changes to the production process (De Beer et al. 1998, Martin et al. 2000a, Martin et al. 2000b).

There may be some potential for greater use of the wastes from Paper production as fuels. This was considered in the database in terms of CHP gasification. However there was not sufficient information available to further consider this opportunity.

Pulp production is comparatively small in the UK. The sector both uses a substantial quantity of recycling and also imports pulp. Domestic pulp represents only 6% of the sector input (Carbon Trust 2011). There are only two integrated mills in the UK that use mechanical pulping. They could technically convert to chemical pulping and use the products produced (black liquor) to become net zero emitters. With CCS they could even become carbon sinks. However given the output produced and the size of sites this is considered unlikely to be realised (Centre for Low Carbon Futures 2011). Pulp production was not considered in the database.

Cement sector

Cement is a simple homogeneous subsector of industry with a single sequential process and one end product. Though it is small in terms of economic output, it is highly energy and carbon intensive. Data availability is very good and much of it was sourced from the Mineral Products Association (MPA 2011) and covers SIC (2007) 23.51. The vast majority of cement manufacture in the UK is of the form 'calcium silicate', more commonly referred to as ordinary Portland cement (OPC).

Baseline

The subsector baseline was modelled as two sub-processes, each with its own type of output:

- **Clinker production.** The physical output of this sub-process is clinker. Clinker is the single intermediate product modelled and is produced from limestone in a kiln at high temperatures. Kiln energy demand equates to the total direct fuel consumption in the subsector and all onsite CO_2 emissions derive from the kiln system. About a third of these emissions derive from the combustion of fuel and two thirds as a by-product from the decomposition of limestone. It is important to note, therefore, that most emissions cannot be affected by fuel switching or efficiency measures.
- **Grinding and mixing activities.** The physical output of this sub-process is cement. As part of the cement making process raw materials are ground before being fed into the kiln which is followed by the grinding of clinker and mixing of clinker with other materials to form cement. Grinding and mixing activities account for 85% of electricity demand, all of which is purchased from the grid.

The part of the baseline represented by kilns was split into the three types of kiln operating in the UK: semi-wet (13%), semi-dry (11%) and dry (76%) (MPA 2011). This was necessary as the scope for applying additional equipment technologies, as well as the improvement potential available through kiln replacement, is dependent on type of kiln. For example, new precalciner technology is only available to dry kilns. About 73% of dry kilns already adopt precalciners, meaning that it is technically possible for a about a further 20% of kilns (clinker production) to adopt the technology. Grinding and mixing activities were split into two: that occurring at the cement plant, and that occurring off-site.

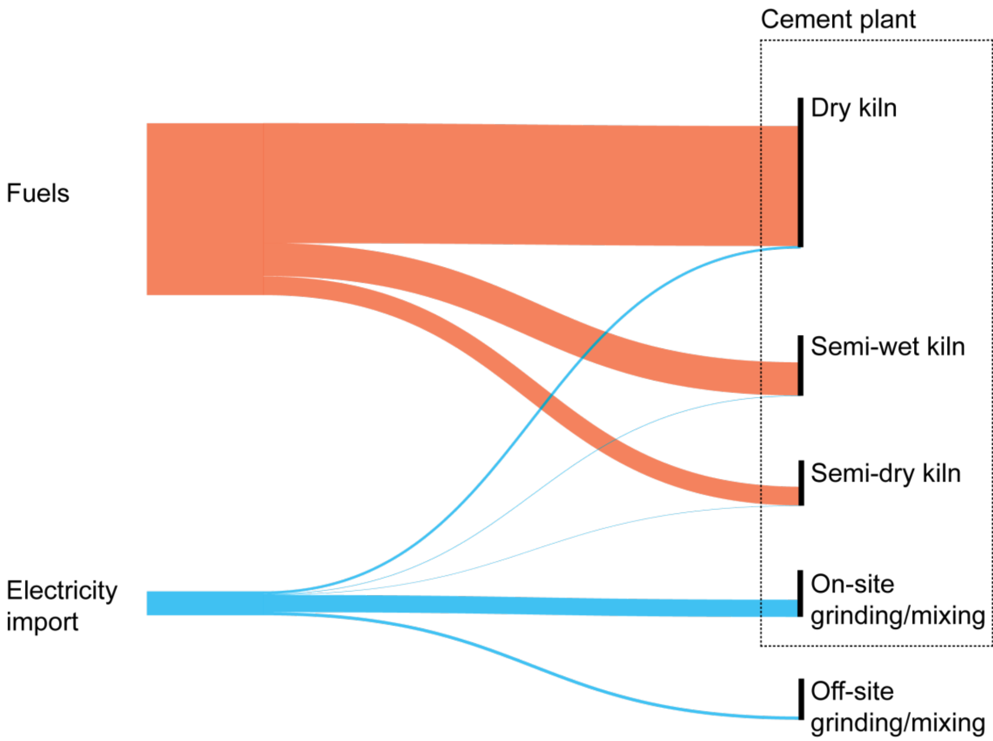

Figure 9 Sankey energy flow diagram for the UK Cement subsector as modelled (CSI 2013, MPA 2011).

Energy flows are illustrated in Figure 9. One point to note is the absence of any self-produced steam or electricity. Low temperature demand in the subsector is met by the recovery of heat from higher temperature processes.

Improvement potential

Identified technologies and measures fit into five categories:

- **Energy efficiency.** Including retrofit kiln technologies (process improvement) and kiln replacement (process substitution). Grinding improvement technologies were not included as it was not possible to determine what baseline technologies were in place.
- **Fuel switching.** The displacement of coal demand in clinker production with waste and biomass.
- **Clinker substitution.** Involving the reduction of clinker production per unit of cement by substituting for other materials: pulverised fly ash and ground granulated blast furnace slag. As this measure reduces the modelled intermediary product, clinker, it may diminish the influence of any technology applied to that part of the baseline.
- **Carbon sequestration.** This incorporates the possible future application of post-combustion carbon capture and storage technologies: post-combustion and

oxyfuel combustion. These are end-of-pipe technologies that don't conflict with the baseline output. However, they reduce CO_2 at the cost of increasing energy demand.

- **Cement substitution.** The future replacement of OPC by any of a group of identified emerging 'low-CO_2' cements. These include Novacem™, E-Crete™, Celitement™ and Aether™ (Net Balance Foundation 2007, Stemmermann et al. 2010, Velandia et al. 2011, Walenta 2011). Any of the above measures apply to OPC manufacture. This measure may also be seen as a type of process substitution.

The top-down view and cross-cutting technologies

This section places the bottom-up studies of specific subsectors within the wider perspective of energy use within the industrial sector. It also highlights opportunities for improvement potential through cross-cutting technology, which can be applied across multiple subsectors of industry. The representation of the subsectors studied in a bottom-up manner is necessarily simplified in this section and the relevant sections of this document should be referred to for full information.

Baseline

For each subsector modelled in detail the energy demand going towards CHP and autogeneration wer detailed separately to other energy uses. The remaining energy use in industry, not modelled in detail here was also given.

The definition of total industry was based on SIC 2007 10-32 not including 19. This differs from the definition of industry used by DUKES (DECC 2013a), which includes subsectors such as construction and mining. The energy use in these subsectors is quite different to the manufacturing activities that were the focus of the current work. Final energy consumption data was taken from ECUK (DECC 2013d), in preference to DUKES (DECC 2013b), due to the higher level of subsector disaggregation, therefore allowing the preferred definition of industry to be used. Industry energy use listed as “Unclassified” was not included in the totals here. The fuels that are included within the unclassified subsector are primarily those that are not included elsewhere within the DUKES/ECUK subsector split: LPG, burning oil and Bioenergy and waste. Within the detailed subsector studies bioenergy and waste were identified as inputs to the Cement, Paper, Chemicals and Food and drink subsectors. Including unclassified energy use could therefore cause a double counting of these energy inputs.

The representation of each detailed subsector within this top-down representation is detail below:

- Iron & steel. As detailed in the relevant documentation the representation of this subsector in DUKES was not used here. Firstly as due to the mothballing of major plant 2010 data was not a good representation of overall sector use. Secondly as the energy use of coke ovens and blast furnaces are not felt to be well represented in DUKES. The detailed modelling covers SIC 2007 24.1-3. Iron and Steel as represented in DUKES also includes SIC 2007 24.51,52. The energy use in these subsectors (which was small) was estimated based on ECUK (DECC

2012d). This energy use was added to the non-modelled energy use. All CHP use within Iron & steel was covered in the subsector modelling.

- Chemicals. The sector as represented in DUKES is covered in the detailed modelling (including all CHP).
- Food & drink. The sector as represented in DUKES is covered in the detailed modelling (including all CHP).
- Paper manufacture. The energy use modelled does not cover all that classified as the Manufacture of paper and paper products in DUKES. The difference in energy use is included in the non-modelled total. All CHP use within the Paper subsector is included in the detailed modelling.
- Cement manufacture. Is included within the Manufacture of other non-metallic minerals subsector in DUKES. Although the Cement subsector was not felt to be well represented due to substantial amounts of energy supplied by Bioenergy and waste not included in the DUKES totals. The Cement sector energy use as represented here was deducted from the total industrial energy use in calculating the non-modelled total.
- Non-modelled subsector. Was calculated based on the total energy use in industry (as defined above) deducting the totals of the modelled subsectors (as detailed). The majority of CHP use within industry was covered by the modelled subsectors. The totals given for CHP in the non-modelled subsectors may be a overestimate as it was not possible to separate out the subsectors classified as "Industry" by DUKES, but not included in the definition adopted for the current work. CHP used in producing exported heat and electricity was specified. No non-CHP autogeneration was included within the non-modelled subsectors as there were concerns about the accuracy of data available.

Figure 10 below shows the energy flows to each of the modelled subsectors and the non-modelled sector from a top-down perspective.

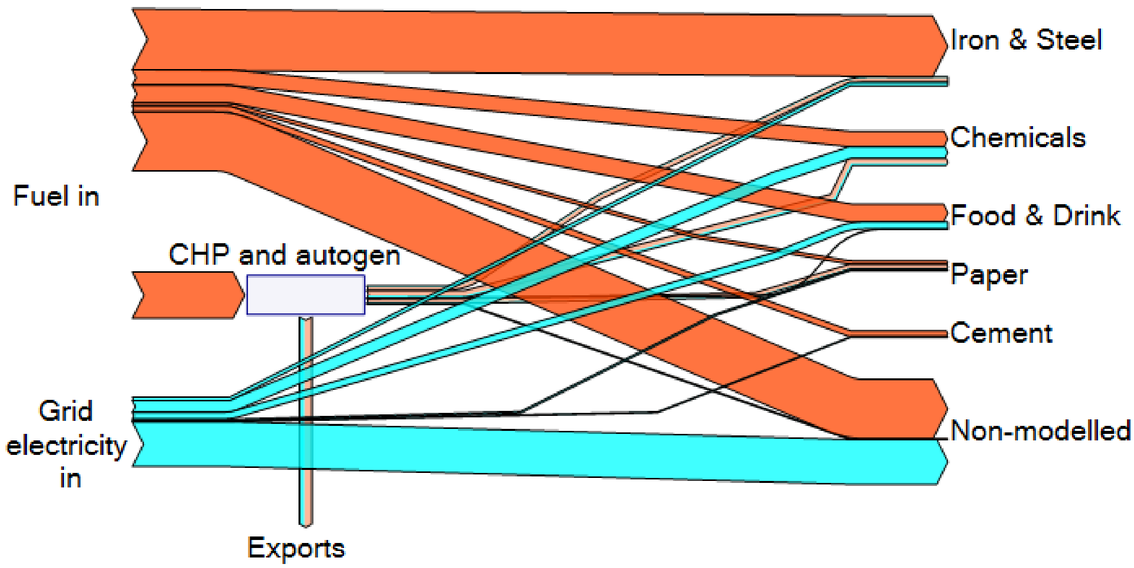

Figure 10: Sankey diagram of modelled and non-modelled subsectors of industry.

Improvement potential

There are a number of cross-cutting technologies that can be used across industrial sectors. These were applied, both to represent improvement within the modelled sectors that was not covered in the bottom-up studies, and to represent improvement potential within the non-modelled subsector.

Steam systems

Baseline

Steam systems represent a large proportion of energy use in the industrial sector, here it was estimated that 35% of final energy demand was for steam systems (IEA 2007). Cross-cutting opportunities apply to both the steam generation and steam distribution part of the system. The baseline efficiencies of 74% efficiency for generation and 82% efficiency of distribution were based on a survey of over 100 sites performed by the (Carbon Trust 2004). There was a wide range in the measured efficiencies in the study, the values used were based on the mean. The baseline efficiencies are represented in Figure 11.

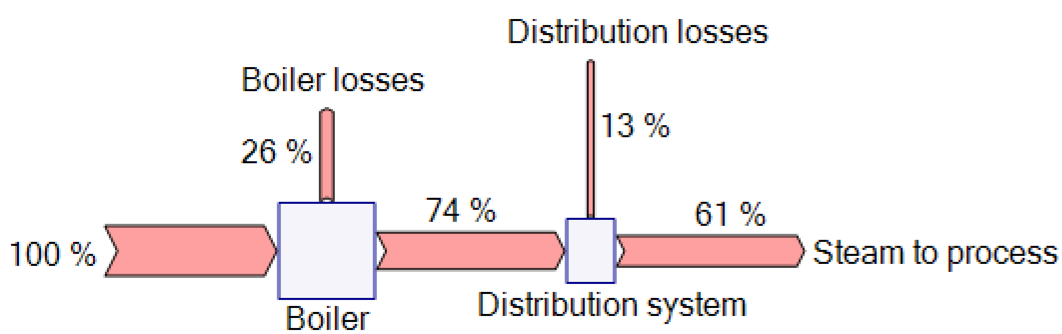

Figure 11: Sankey diagram of steam systems baseline.

The fuel split for steam systems was estimated at 90% natural gas, 5% coal, 2.5% fuel oil and 2.5% gas oil. This was based on the splits calculated for the Food and drink and Paper subsectors use of boiler systems. Information on fuel split at the sector level was not available.

Improvement potential

Improvement potential to both the steam generation (boiler) and steam distribution systems was examined. Parameters for the technologies were given in terms of per unit of steam generated for the generation system, and per unit of steam delivered for the distribution system. In assessing opportunities to improve the current baseline there are a number of technological options (for example better maintaining the boiler, recovering heat from flue gases, improving insulation of the distribution system) but in assessing the potential for each of these options the applicability to the current baseline would need to be assessed, which was not possible. Therefore the approach taken was to estimate the overall improvement offered on the baseline steam generation and steam distribution system and to estimate the overall costs of such improvement without being specific as to which technologies would be applied. Opportunities for fuel switching were also assessed.

It was assumed that all boilers could reach 80% efficiency, and half of boilers could reach an 85% efficiency. It was assumed that the steam distribution efficiency could reach 90% efficiency. These assumptions were based on existing surveys and assessments of UK industry (Carbon Trust 2004, 2007). The costs for these improvement options was based on the average cost of improvement technologies, weighted by the potential in improving efficiency at the sector level, taken from a study of US industrial steam systems (Einstein et al. 2001).

Fuel switching from oil or coal to natural gas was not considered. Coal and oil comprise a small proportion of the overall fuel demand for steam systems and it is not known what proportion of steam systems would be prevented from switching to natural gas due to being off the gas grid. The potential for switching to biomass was assessed. The efficiencies and costs of the system are based on a number of sources, supplemented with calculations to apply these to the systems under consideration (AEA 2011b, IEA 2012, NERA and AEA 2009, Saygin et al. 2012). The biomass fuel assumed was wood chips. It was estimated 75% of steam generation could technically be converted to biomass fuelled. Technically all steam production could be fuelled by biomass (Saygin et al. 2012), although storage of fuel could prevent the adoption at some sites. The limitations to biomass use will likely come from the supply of suitable fuel, and its price in comparison to fossil fuels. There is competition for biomass from other subsectors of the economy, and as feedstocks for the industrial sector (Taibi et al. 2012).

What cannot be assessed in this cross-cutting manner are improvements to the end using processes of steam systems, which reduce demand for steam. Such options are considered in the bottom-up studies for the modelled subsectors. Note that improvements in steam systems have knock on effects in the sectors that use steam in terms of the fuel saving represented by saving steam through efficiency measures.

Motor systems

Baseline

In defining the baseline for motor use both the total use of motor systems and the proportion of each end use (pumps, fans etc) within this were estimated. There were a number of sources assessed when forming the baseline of motor systems use (de Almeida et al. 2003, DECC 2012e, Market Transformation Programme 2003, McKane and Hasanbeigi 2010). Each of these was based on survey data of some kind and covered different time periods, sectors and geographical areas [(de Almeida et al. 2003) and (McKane and Hasanbeigi 2010) presented information for the EU, rather than the UK]. There were considerable differences between the information from these sources, especially if examining the results at a subsector level. The assessment of motor systems was undertaken at the level of the industrial sector here. Given the availability of data, and the considerable assumptions and uncertainties in the assessment this was felt more appropriate than a subsector level assessment.

The total use of motor systems was set at 60% of electricity demand for the industrial sector (both grid electricity and autogenerated electricity used within the sector), this is broadly in line with the sources utilised, and is often given as the estimated worldwide figure (IEA 2007, McKane and Hasanbeigi 2010). Removed from this figure were motor use within bottom-up subsectors for which improvement potential was already considered within the subsector study. This was to avoid double counting of improvement potential. All motor use within the Paper sector [estimated at 65% of electricity demand (Market Transformation Programme 2003)] and motor use within ovens and coolers in the Bakery subsector of Food and drink were removed from the total motor systems use considered for improvement.

In estimating the split between types of motor systems the (Market Transformation Programme 2003) study was used. This study was UK specific and also gave the most appropriate split of end uses for the purposes of the current work. Baseline efficiency was based on values reported for the EU (McKane and Hasanbeigi 2010). The proportion of motor use in each size range was based on that reported by (de Almeida et al. 2003) for the EU. This size range was assumed common across end uses. The size range was chosen to correspond with that related to cost information from (McKane and Hasanbeigi 2010).

Improvement potential

Information on technological improvement options was taken from (McKane and Hasanbeigi 2010), which represents the collation of information from a number of other studies, supplemented with expert opinion. This covered the end uses of pumps, fans and compressed air systems; which together account for half of motor electricity demand here. Technological improvement was estimated based on the baseline efficiency detailed above. In contrast to subsector studies where output in measured in physical or economic terms the unit of output used in motor systems is the useful energy out. In converting costs information into the format utilised here the cost per motor from the published data (McKane and Hasanbeigi 2010) was converted to a cost per unit of useful output. Costs were given for each size of motor (specified in the baseline). This utilised the efficiencies reported for Fan, Pump and Compressed Air systems by (McKane and Hasanbeigi 2010) and the mean energy use per motor in each size range from (de Almeida et al. 2003). The efficiencies were not varied by motor size, information was available to account for this (de Almeida et al. 2003), but such considerations have only a small effect and were not significant given the other uncertainties involved in the analysis.

The costs of the different technology options was not expected to change with the application of other technologies, as they are generally priced based on the size of the system, which will not change in the majority of cases. However the improvement potential offered by each technology is not additive and so a proportional improvement from the changing baseline should be adopted in calculating the overall potential offered by applying a number of technologies to the same system.

Other uses of motor systems (including refrigeration) were not included here in the assessment of improvement potential as they show much more variability in improvement options, or comprise a smaller proportion of energy demand and are focussed on a small number of subsectors. No radical technologies were examined in improving motor systems. Larger improvements could be realised by the redesign of systems, one example being the redesigning of pipe systems to minimise friction by reducing bends and maximising diameter. In such approaches considerable savings can be realised (Von Weizacker et al. 1997). Another opportunity not assessed is the recovery of heat from compressed air systems. This requires an assessment of suitable sinks for the waste heat and offers improvement on a broader system boundary than a motor system.

Other cross-cutting measures

There are a number of other cross-cutting opportunities that were not included here, due to lack of suitable information preventing inclusion within the timeframe of the project. Such opportunities are included here for further information

CHP

Undertaking an assessment of CHP potential for the sector requires data on energy demand at the site level, especially in terms of the magnitude and temperature of heat. Information on site level heat demands was not available for the current work and so the further potential for CHP technology in the industrial sector was not assessed. This is potentially an important area for improvement potential offering savings over heat generation and grid electricity, as well as offering opportunity to use bioenergy and waste fuelled CHP systems (for example see the opportunity identified within the Paper subsector). There are existing detailed assessments of CHP potential in the UK (Ricardo-AEA 2013b) but the results are not available in the required detail to allow their application within the current work. A full assessment of the opportunity for CHP could also include CCS at large sites.

Heat recovery

The opportunities to improve heat recovery have been assessed within the bottom-up subsector studies here. Such opportunities also exist throughout the remainder of the industrial sector. However they are difficult to assess on broad scale with the identification of both a heat source and a sink required. Although some assessment of technical potential for waste heat recovery within UK industry has been made (Hammond and Norman 2012, McKenna and Norman 2010) such assessments have partly relied on a bottom-up approach. Economic information is also lacking form such previous studies and so prevent inclusion in the current work.

Heat pumps

The opportunities for heat pump use were assessed within the Food and drink sector. Opportunity is also thought to exist throughout the sector in replacing low temperature heat demands. The majority of potential is thought to lie within the Food and drink subsector (Taibi et al. 2012).

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