Citation for published version:
Griffin, P & Hammond, G 2019, 'Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective', *Applied Energy*, vol. 249, pp. 109-125. https://doi.org/10.1016/j.apenergy.2019.04.148

DOI:
10.1016/j.apenergy.2019.04.148

Publication date:
2019

Document Version
Peer reviewed version

Industrial Energy Use and Carbon Emissions Reduction in the *Iron and Steel* Sector: A UK Perspective†

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ABSTRACT

The opportunities and challenges to reducing industrial energy demand and carbon dioxide (CO_2) emissions in the *iron & steel* sector are evaluated with a focus is on the situation in the *United Kingdom of Great Britain and Northern Ireland* (UK), although the lessons learned are applicable across much of the industrialised world. It is the largest industrial sector in the UK in terms of energy demand and '*greenhouse gas*' (GHG) emissions, and accounts for some 26% of GHG emissions from British industry. Current *Best Available Technologies* (BAT) will lead to short-term energy and CO_2 emissions savings in *iron & steel* processing, but the prospects for the commercial exploitation of innovative technologies by mid-21st century are far more speculative. The attainment of significant falls in carbon emissions over the period to 2050 will depend critically on the adoption of a small number of key technologies [e.g., energy efficiency techniques, fuel switching towards bioenergy, and *carbon capture and storage* (CCS),], alongside the decarbonisation of national electricity supply. The blast furnace is the most efficient energy conversion process in the sector, but also the largest energy user and consequently a priority target for energy demand reduction. Many existing technologies could reduce a significant proportion of process energy loss, e.g., heat recovery at the coke ovens, sinter plant, and electric arc furnace, and further heat and gas recovery from the basic oxygen furnace. The uptake of key BAT technologies for hot-rolling could reduce sector primary energy by 18% and GHG emissions by 12%. Further potential may be available for blast furnace operation by optimising chemical transfer to minimise *blast furnace gas* (BFG) production. Nevertheless, there are a number of non-technological barriers to the take-up of such technologies going forward. Other radical process technological innovations (such as the 'electrowinning' or so-called HISARNA process) are likely to be available in the longer term.

KEYWORDS: Iron & steel; Industrial energy analysis; Carbon accounting; Enabling technologies; Improvement potential; United Kingdom

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†**Full citation:** Griffin, P.W. and G.P. Hammond, 2019. 'Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective', *Applied Energy*, **249**: 109-125 [DOI: 10.1016/j.apenergy.2019.04.148].

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1. INTRODUCTION

1.1 Background

The *iron & steel* industry is the largest industrial sector in the *United Kingdom of Great Britain and Northern Ireland* (UK) in terms of both energy demand and 'greenhouse gas' (GHG) emissions, and accounts for some 26% of GHG emissions from British industry (see Fig. 1 [1-3]). There are large differences between industrial sub-sectors in the end-use applications of energy, especially in terms of products manufactured, processes undertaken, and technologies employed (see Fig. 2 [2,3]). It is clear that the *basic metals* sub-sector (see again Fig. 2), of which *iron & steel* is by far the most dominant sub-sector, gives rise to the third largest industrial energy consumption in the UK; caused principally by high temperature heating processes (85%) and, to a lesser extent, electrical motors (4%) [3]. The blast furnace is at the core of its operations, which reduces iron ore (Fe_2O_3) at high temperatures into iron (Fe) with the use of carbon as a chemical reductant. Subsequently, iron is then converted into steel, which is cast and finished to produce a number of industry outputs (including ingots, slabs, sheets, plates, bars, rods and sections) consumed by a wide range of downstream industries. These encompass, for example, construction, motor vehicles, metal fabricating industries, and consumer goods. Steel is also produced from scrap, and is arguably the most recycled and recyclable material on the planet [4]. The *iron & steel* sector overall depends on a high throughput of natural resources with energy costs making up a significant proportion of its total production cost. The sector has always been highly energy conscious, and has made significant improvements to efficiency over the years. Today the sector is also subject to a raft

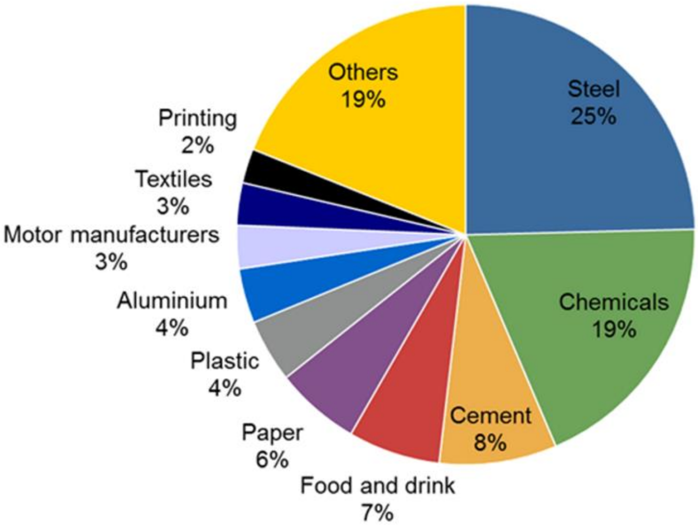

Fig. 1. *Greenhouse gas* (GHG) emissions from UK industry. *Source:* Griffin *et al.* [2,3].

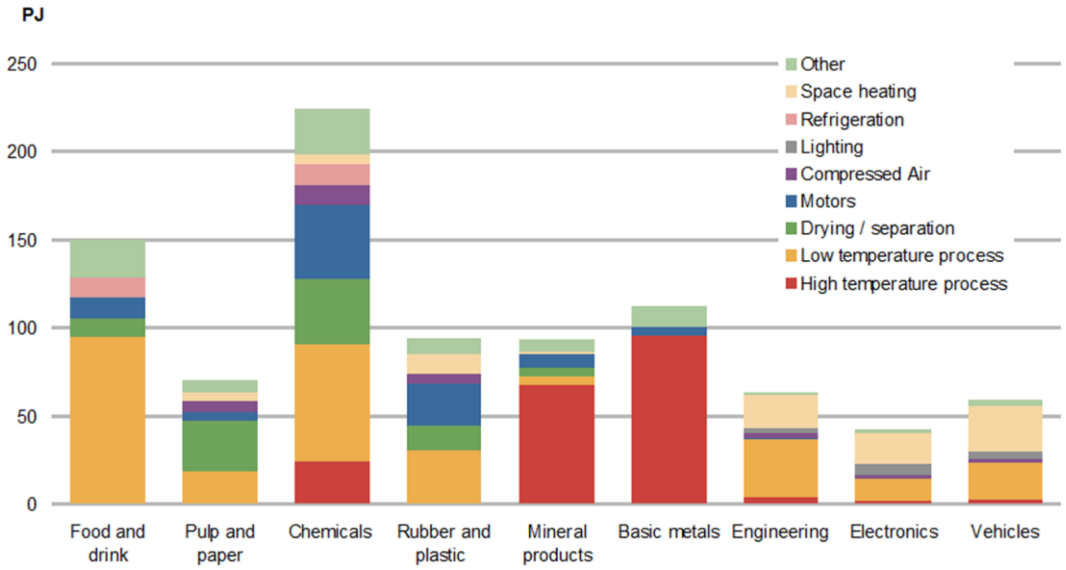

Fig. 2. Final UK energy demand by industrial sub-sector and end-use. *Source:* Griffin *et al.* [2,3].

of government regulations designed to stimulate GHG emissions reduction in order to mitigate global warming [1-3], i.e., a legally binding UK target of an 80% reduction by 2050 against a 1990 baseline (although the British Government has asked its independent advisors – known as the *Committee on Climate Change* (CCC) - to consider the implications of Britain becoming 'net-zero' on the same timeline). Industrial leaders believe that there is only limited room left for improvement based on existing technologies [5]. In addition, steel is a highly traded commodity, and the sector fears that the cost associated with unilateral GHG emissions reduction in Europe could lead to carbon leakage: the situation that will arise if European businesses were to transfer production to other countries that have laxer GHG emission constraints. A comprehensive material property database was collated by Hammond & Jones [6,7], including embodied energy and GHG emissions associated with various steel products. This *Inventory of Carbon and Energy* (ICE) contains 'cradle-to-gate' data on a range of steel alloys from both virgin and recycled (scrap) sources.

Technical opportunities for the 'deep decarbonisation' of industry have been under active development and options appraisal elsewhere in the industrialised world. These have naturally been focused on *energy-intensive* (EI) industrial sectors, including *iron & steel* [8-15]. In the latter sector there are various ways in which the process-related GHG emissions associated with the production of virgin steel can be substantially reduced 11]: process-integrated *carbon capture & storage* (CCS) plant, electrification (or 'electrowinning'), and biomethane/hydrogen *direct reduced iron* (DRI). Morfeldt *et al.* [9] used a global energy-economic systems model (ETSAP-TIAM), together with a *Scrap Availability Assessment Model*, to assess the links between steel demand, recycling rates, and the international availability of scrap. This northern European team (from Belgium, Sweden and The Netherlands) found that energy efficiency improvements would only secure *iron & steel* sector decarbonisation out to 2050 if coupled with CCS plant deployment. In contrast, these coupled models [9] indicated that H_2-based steel production could prove a major climate change option for virgin material should CCS not be feasible. In a German context, Arens *et al.* [12] suggested that efforts to reduce *carbon dioxide* (CO_2) emissions from the *iron & steel* sector should focus on incremental improvements in the medium-term, because innovative processes (such as H_2-based DRI or steel from electrolysis employing CO_2–free electricity) will take decades to develop and deploy. (CO_2 is the principal GHG [1] having an atmospheric residence time of about 100 years.) Åhman *et al.* [11], again from a northern European perspective (Belgium and Sweden), expressed the belief that the radical reductions in GHG emissions beyond 2050 will require disruptive technologies in the steel industry (e.g., electrowinning or the so-called HISARNA concept).

1.2 The Issues Considered

The present study builds on work by Dyer *et al.* [16] commissioned by the UK *Government Office for Science* (GO-Science) and on a recent 'Advanced Review' by Griffin *et al.* [1]. In each case, a variety of assessment techniques for determining potential energy use and GHG reductions were discussed. Griffin *et al*. [1] then evaluated the wider UK industrial landscape with the aid of decomposition analysis [17] in order to identify the factors that have led to energy and carbon savings over recent decades. They then assessed the improvement potential in two sectors: 'Cement' and 'Food & Drink', which represent *energy-intensive* (EI) and *non-energy-intensive* (NEI) industrial sectors respectively. Subsequently, a similar analysis was undertaken of the 'Chemicals' [2] and 'Pulp & Paper' [3] sectors of UK industry. They fall on the boundary between EI and NEI industries. In contrast, the *iron & steel* industry is clearly an EI sector that gives rise to a major share of industrial energy use and GHG emissions both in the UK and worldwide. It accounts in Britain, as noted above, for some 26% of GHG emissions from industry (see again Fig. 1 [1-3]). The historical development of the *iron & steel* industry, along with the locations of its process plants, are typically dictated by the availability of nearby resources {e.g., of iron ore and energy (hydro-power or 'water wheels', charcoal, coal, and subsequently coke)}. Thermodynamic and economics-based methods have been utilised to quantify and cost the technology improvement potential for reducing sector energy and GHG emissions in the UK *iron & steel* sector going forward, although the lessons learned are applicable across much of the industrialised world.

Baseline data employed here has been extracted from an industrial *Usable Energy Database* (UED) that was produced by Griffin *et al.* [18,19] for the *UK Energy Research Centre* (UKERC). Griffin *et al*. [1] described the basis of the appraisal methods adopted, and full details of the present study can be found in the PhD thesis of Griffin [20] (together with associated '*technology roadmaps*' illustrating a range of energy and GHG emission pathways out to 2050). *Technology roadmaps* for the UK *iron & steel* sector presented here are based on various alternative scenarios: named *Low Action* (LA), *Reasonable Action* (RA), *Reasonable Action including CCS* (RA-CCS), and *Radical Transition* (RT) respectively. They represent future projections that match short-term (say out to 2035) and long-term (2050) targets with specific technological solutions to help meet the key energy saving and decarbonisation goals. Their contents were built up on the basis of the cost-effective improvement potentials associated with various processes employed in the sector, and embedded in the UED [1,18,19]. They help identify the steps needed to be made by developers, policy makers and other stakeholders in order to ensure the decarbonisation of the *iron & steel* industry.

2. THE *IRON & STEEL* SECTOR

2.1 Historical development of the iron & steel industry

Learning to smelt iron (Fe) from its ore – principally containing the oxide Fe_2O_3 – was a major step in human development. 'Arabic science' in the ancient world from about 3500 BCE {before the 'Common Era' (CE)}, based largely in Egypt and the Near East, led to the early smelting of metals [especially copper, gold and mercury (or '*quicksilver*' - Hg), as well as alloys like bronze [2,21-24]. But it was only around 2000 BCE that iron became commonplace in Egypt. It began to replace bronze in Europe around 1000 BCE [23], but its high melting point (1,535°C for pure iron) in contrast to copper (1,083°C) made it difficult to smelt until furnace construction had developed sufficiently to reach such temperatures [21,25]. However, iron ore was one of the most abundant global elements, and henceforth became the prime material for implements in the 'Iron Age' [25] that stemmed in the British Isles from about 800 BCE to the Roman invasion of 43 CE. Iron ore arose from four mineral sources [25,27]: *magnetite* (richest of all with 65% iron, although unavailable in Britain), *haematite* that often occurred in separate bluish nodules (high-grade 'kidney' iron; ~50% concentration), *blackband* of medium quality (~30%) found in coal measures, and *Jurassic* iron discovered in a broad band across England from the North Yorkshire Moors in the North East of England to the Cotswold Hills in the South West (but of low grade; ~20% concentration). Early techniques of iron-making involved partially enclosed fires that were typically built on hill-tops or exposed positions to provide a good blast of natural wind for the draught [25]. They were known as 'bloomeries' [25-27], due to the spongy or putty-like mass (a 'bloom') of red-hot iron that would be extracted from the furnace and hammered (or 'forged') into a 'bloom' [27] to form weapons or tools [28]. Their output was very small; only a few kilograms (kg) of metal per day [25].

Molten iron (having about 4% carbon) was traditionally allowed to run off into shapes moulded in sand that resembled a sow with her sucklings; thus giving rise to the term 'pig-iron' [25]. It is now more often termed 'cast-iron' [27]. The first European such cast-iron dates from 1380 CE, when it was used in building and construction as it was found to be very strong in compression. It was initially made in tiny quantities which was subsequently reheated to reduce the surface carbon, and produced 'wrought' (or 'bar') iron, i.e., iron capable of being worked [25,26]. In 1700 CE indigenous iron production in the UK accounted for just 12,000 tonnes a year via inefficient processing, based on small, localised production facilities. This led to the growth in multiple small ironmasters that then grouped together in small iron producing areas, like South Wales. Transport routes were poor, and rudimentary furnaces were dependent upon the amount of timber in the area: everything needed to be close at hand. The industry was also labour intensive and, while the labour supply was good, this resulted in very high costs. Most iron was therefore imported into the UK during this pre-industrial era, particularly in the form of cheaper imports from Sweden [25]. Over half of the iron used in Britain came from this source.

Furnace design began to improve significantly with the application of mechanical draught by water-powered bellows, increases in size, and other refinements [25]. Such improvements constituted the 'blast furnace' [28], which is thought to have been developed in what is now Belgium before 1400 BC [27]. It produced about a tonne of metal in 24 hours [27], and had basic features that have remained essentially unchanged to the present day. The development of iron making was one of the basic elements that underpinned the industrial revolution in Britain. Initially, the only fuels available for the early blast furnaces were mainly charcoal [25] or sometimes peat [26]. In order to complete the charge, a flux (usually limestone) was added to the iron ore and charcoal to encourage the slag to separate from the molten metal during combustion [26-28]. This charge, together with the need for water power to operate bellows, meant that iron making became a backwoods process; developed in heavily wooded countryside by fast-running streams [25] and sited near sources of limestone. However, Abraham Darby the Elder (c. 1678-1717) succeeded in using coke instead of charcoal as a fuel in 1709 at his blast furnace in Coalbrookdale (Shropshire in the West Midlands of England) [25,26,28]. Fortunately, he had local coal with excellent coking properties that, together with increased blast that he adopted, overcame problems due to undesirable coal impurities. Thus, blast furnaces began to relocate from backwoods to coalfields, which gave rise, for example, to the 'Black Country' landscape of the Midlands [25]. A steam engine was first used to pump water back up to power a water wheel around 1750. This process only lasted a small time as the industry became better able to move around as coal took over. In 1767, Richard Reynolds (1735-1816) helped costs fall and raw material travel further by developing the first iron rails, although this was superseded by canals.

The rotary action steam engine devised by James Watt (1736-1819) in 1781 led to an increase the furnace size and to the use of bellows, thereby helping to boost production [25]. Henry Cort (c. 1740-1800) invented a puddling process in 1784, as a means of getting most of the impurities out of iron and enabling large-scale production [27]. Cast-iron was melted in a 'reverberating' furnace, and then stirred (or 'puddled') while molten [25]. It was subsequently extracted from the furnace and rolled into the required shapes [27]. This wrought iron was strong and adaptable; often termed 'malleable' iron because of its utility. Thus, it could be rolled into bars, sheets and strip, and split into rods for nail-making and other purposes [25]. 1825 has been called the start of what is sometimes called the 'new Iron Age', as the iron-making experienced a massive boost from the heavy demand for railways, which needed iron rails, iron in the rolling stock, bridges (the *Forth Bridge* in Scotland was completed in 1889 [24]), tunnels, and much more. In addition, civilian use increased. Britain became renowned for railway iron and, after the initial high demand dropped, the UK exported iron for railway construction abroad. Iron production in the UK rose to over two million tonnes by 1850, with the iron industry being a net exporter.

Steel has now almost entirely superseded wrought iron, although forging processes have continued with few changes into the age of steel-making [25]. The earliest method of steel-making systematically was the 'cementation' process, whereby new minerals stick the grains together; just as cement (from a bag) binds sand grains in a bricklayer's mortar. Thus, iron and charcoal (carbon) were heated together for up to 10 days in order to achieve 'carburization'. In the mid-18th Century, Benjamin Huntsman (1704-1776) developed commercially the ‘crucible’ steel-making technique, whereby measured constituents were sealed in crucibles for treatment in a coal-fired furnace [25]. He was a Doncaster clockmaker, who set up his works near Sheffield (a city in Yorkshire in the north of England) in 1751 [21]. A breakthrough in quantity production of mild steel (iron with a carbon content of 0.1-0.2%) came about in 1856 when Sir Henry Bessemer (1813-1898) [24,25,27,28] developed his ‘converter’, and instigated a new era of mass-produced, cheap steel. It consisted of a cylindrical steel pot approximately 6m high, originally lined with a siliceous refractory, into which air was blown in through openings (‘tuyeres’; pronounced ‘tweers’ [27]) near the bottom, creating oxides of silicon and manganese [28]. This becomes part of the slag, whilst the carbon was carried out in the stream of air. It can produce, within a few minutes, an ingot of steel ready for the forging hammer or rolling mill [27]. This process was followed by the Siemens-Martin *‘open hearth’ furnace* (OHF) in the 1860s that originated in Germany and France. This shallow, rectangular hearth uses the heat of combustion of gaseous or liquid fuels to convert a charge of scrap and liquid blast furnace iron to liquid steel. The Gilchrist-Thomas process was then devised in 1879, using a combination of phosphorus-rich pig-iron, ore, and scrap [25,27]. After the initial heating ‘campaign’ or operation, the metal is deoxidized and recarburized using coke, graphite, thermo-anthracite, or charcoal in paper packages. It largely supplanted wrought iron, which could not be made in bulk. Over 600 steel-making blast furnaces, sited on UK coalfields, existed in 1900 [24]. Subsequently, wrought iron production in Britain declined during the first half of the 20th Century, and ceased completely by the 1970s. Further refinements were made to the process, such as *basic oxygen steelmaking* (BOS) in which both molten pig-iron and steel scrap are converted into steel [28]. It utilises the oxidizing action of oxygen blown into the melt under a basic slag. This process has largely replaced earlier methods by further lowering the cost of production and increasing the quality of the final product.

By 1900 the electric arc furnace [28] was adapted for steelmaking and, by the 1920s, the falling cost of electricity allowed it to largely supplant the crucible process for specialty steels. Stainless steel, an alloy of iron with carbon and chromium, was invented by Harry Bearley (1871-1948) in 1913. It transformed the chemical [2] and food [1] industries, proved an attractive building material, and can be found in homes in the form of washing machines, cutlery, and Scandinavian-style dishes and plates that became fashionable from the 1960s [24]. The making of special steels of all kinds has for centuries been focused on Sheffield. UK Government prompted the building of new steelworks in the 1930s at Shotton (Deeside, North Wales), Ebbw Vale (South Wales), and Corby (Northamptonshire in the heart of England). Continuous wide-strip rolling, originally developed in the *United States of America* (USA), produced coils of thin steel [24]. It was first adopted in the UK at Ebbw Vale in 1938. These coils were employed in motorcar bodies and domestic appliances, as well as in tin plate [24]. The modern *iron & steel* industry is extremely large-scale and highly integrated: taking in iron ore and, via a series of processes, producing steel plate, rails, joists, and so on [25]. Indeed, the UK Government stimulated the construction of two new integrated works with strip mills at Llanwern (in Newport, South Wales) and Ravenscraig (near Motherwell in Scotland) in 1958 [24].

2.2 Structure of the modern *iron & steel* sector

The British steel industry went through cycles of restructuring and changes in ownership during the 20th Century. It was nationalized in 1951, denationalized in 1953, renationalized in 1967 {as the *British Steel Corporation* (BSC)}, and privatized in 1988 [24]. BSC faced serious problems at the time of its formation, including obsolescent plants, plants operating under capacity (and therefore at low efficiency), outdated technology, price controls that reduced marketing flexibility, soaring coal and oil costs, lack of capital investment funds, and increasing competition on the world market. The UK Government in the 1970s adopted a policy of keeping employment artificially high in the declining industry. This especially impacted on BSC, since it was a major employer in a number of depressed regions [24]. Under private control, the *British Steel* dramatically cut its work force and plants, and underwent a radical reorganization. Massive capital investment was also required in order to regain competitiveness in the world marketplace. Closure of the Ravenscraig works in 1993 marked the end of steelmaking in Scotland. *British Steel* merged with the Dutch steel producer *Koninklijke Hoogovens* to form *Corus Group* in October 1999. *Corus* itself was then taken over in March 2007 by the Indian steel operator *Tata Steel*, and is presently Europe's second largest steel producer (as *Tata Steel Europe Ltd.,* with headquarters in London), having steelmaking works in the UK and Netherlands, and manufacturing plants across Europe.

The conventional measure of production for the iron and steel industry is *tonnes of crude steel* (tcs). Crude steel is defined as the total of usable ingots, continuously cast semi-finished products (slabs, billets and blooms), and liquid steel for castings [30]. Its production peaked in the UK at 28 Mtcs in 1970, but declined dramatically after the ‘oil crises’ of 1973 and 1979. Processing capacity underwent significant rationalisation after the second such crisis and thereafter experienced a more gradual decline in sector output until about 2010, when it fell to around half that in 1970. Crude steel processing is based on either the primary route (which produces ‘virgin’ steel from iron ore), or the secondary route (which recycles steel by re-melting scrap). The energy intensity of virgin steel manufacture is around four times higher than that associated with recycling, and is presently restricted to the use of carbon-intensive fuels. Until recently, ore-based steelmaking was spread over three UK integrated steelworks (the Port Talbot, Scunthorpe, and Teesside works) of similar production capacity, and scrap-based steelmaking was spread over four electric arc steelworks (Rotherham, Tremorfa, and two sites in Sheffield). Five companies recently shared production from these seven sites [31]. The post-2008 economic recession in the UK (and globally elsewhere) resulted in the closure of some large industrial processing plants, including aluminium smelters and steel mills. However, the drop in production was not accompanied by a drop in production capacity (15-16 Mtcs), and output had been seen to recover up until 2014 [29,33].

The UK steel industry itself underwent a ‘crisis’ in 2015-2016, when major plants at Redcar (on Teesside), Scunthorpe (in Lincolnshire) – both in the North East of England - Scotland and South Wales were subject to closure or reduction in capacity [29]. This was caused by a ‘*perfect storm*’ of challenges [29], including a major growth of some 300% in the volume of steel produced international (principally in China) during the early 2000s, much of this surplus Chinese steel was exported {with the *European Union* (EU) experiencing a 50% increase from this source at this time}, the consequent ‘glut’ on the global market pushed steel prices down, and UK steel producers had to operate in a domestic environment in which its overhead costs (e.g., industrial electricity prices and business rates) were higher than many of their international competitors. In 2016 China produced 808 Mtcs, whilst the UK outturn was only 8 Mtcs [29]. Thus, *Sahaviriya Steel Industries* (SSI) closed its Redcar plant in September 2015 (having then had the second largest blast furnace in Europe), while other British steel manufacturers (such as *Tata Steel* and *Caparo*) reduced their capacity [29]. Nearly half the decline in industrial GHG emissions in the following year was the result of these actions [32]. It is estimated that *Tata Steel*, with its largest plant at Port Talbot in South Wales, had contributed 8% to Welsh industrial and extractives economic turnover, as well as 3% to the total Welsh economic output in 2011 [29]. This made it the biggest private sector contributor to the economy of Wales. *Tata Steel* and *thyssenkrupp AG* (the German multinational conglomerate) signed definitive agreements in June 2018 to combine their European steel businesses into a 50/50 Joint Venture as *thyssenkrupp Tata Steel B.V.* It aims to be a leading pan-European high quality flat steel producer with a strong emphasis on performance and technology leadership. The merged company, which (at the time of writing) still has to overcome *European Commission* competition concerns, would be the Europe's second-largest steelmaker after *ArcelorMittal*.

A simplified process flow diagram illustrating the production of steel through its key sub-processes, and via both process routes, is depicted in Fig. 3 [20,34]. Large amounts of coal are fed into coke ovens at the integrated steelworks, and then converted into coke. The bulk of this coke is charged into the blast furnace for three purposes: its combustion releases heat to

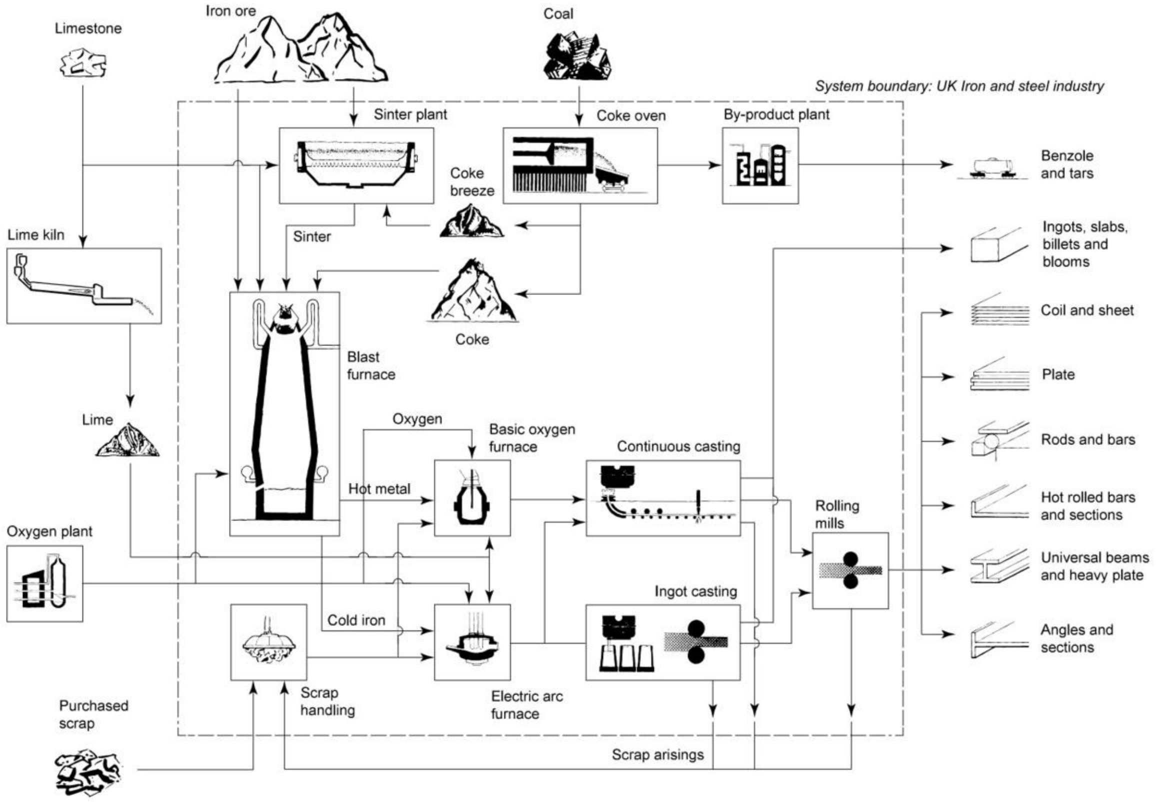

Fig. 3. Simplified process flow diagram of the UK *iron & steel* sector. *Source:* Griffin [20]; adapted from the *Energy Audit Series* [34].

raise the temperature of the furnace; its carbon content acts as a reducing agent to separate iron; and its mechanical properties give physical support to burden materials, while being porous enough for hot gasses to permeate to the furnace top [20,34]. Tar and benzole products are separated from the raw coke oven by-product gas to be sold. Iron ore, coke breeze and limestone are charged to the sinter plant where they are roasted and agglomerated to form sinter. Sinter is the main form in which iron ore enters the blast furnace. The pig iron, or 'hot metal', from the blast furnace is charged with steel scrap (15% by weight) into the *basic oxygen furnace* (BOF), where a large amount of oxygen is blown in to remove excess carbon and produce liquid steel. Waste gases from the coke oven, blast furnace and BOF are utilised as fuel elsewhere in the steelworks to heat processes directly and raise steam in boilers for process use and electricity generation.

Operating outside of integrated steelworks is the *electric arc furnace* (EAF) into which scrap is charged with <5% *cold iron*, i.e., ambient temperature or unheated iron (analogous to '*cold steel*'). The main energy input to this process is in the form of electricity, which is purchased from the UK national power grid. Other steelmaking furnace types with different iron-scrap input shares have been used over the years that are now obsolete. Most notably, the basic OHF was ultimately phased out in 1979 owing to its inefficiency and high running costs compared with the newer BOF technology. Specific scrap recycling illustrated in Fig. 3 mirrors the EAF output trend from 1980 onwards. Today most liquid steel from the BOF and EAF is continuously cast into slabs, billets and blooms. Otherwise, they are cast into ingots which may be reheated and primary rolled to form steel in a semi-finished state. The need to reheat steel ingots before rolling makes this a less efficient casting route. Over the years, the sector has phased out ingot casting, except for low volume orders and special applications. Semi-finished steel is allowed to solidify and cool before it is either reheated and fed into hot-rolling mills or exported oversees. The saleable finished steel product is a direct output of the hot-rolling mill or the output of a series of rolling, and possibly coating, operations.

A Sankey diagram of plant-level fuel, steam and electricity flows into the UK *iron & steel* sector is depicted in Fig. 4 (c. 2010) [20]. Most of the coal is converted to coke by the coke ovens for use in the blast furnace and sinter plant. The industry produces coke at a slight deficit to blast furnace requirements and so some is necessarily purchased. Other manufactured fuels include *coke oven gas* (COG), *blast furnace gas* (BFG) and *basic oxygen furnace gas* (BOFG). They are process by-products of the plant from which they are named. These gases are combusted to supply process heat or to raise steam in boilers. The steam is used at the process plant or in turbine generators for electricity production. Natural gas is employed to supplement the by-product gases at processes or as the single process fuel input, particularly for processes situated outside integrated steelworks sites. A small amount of fuel oil and gas oil is used for minor ancillary processes. In 2010 a significant amount of fuel oil was consumed as blast furnace injectant, but has since been substituted by coal. Analogous

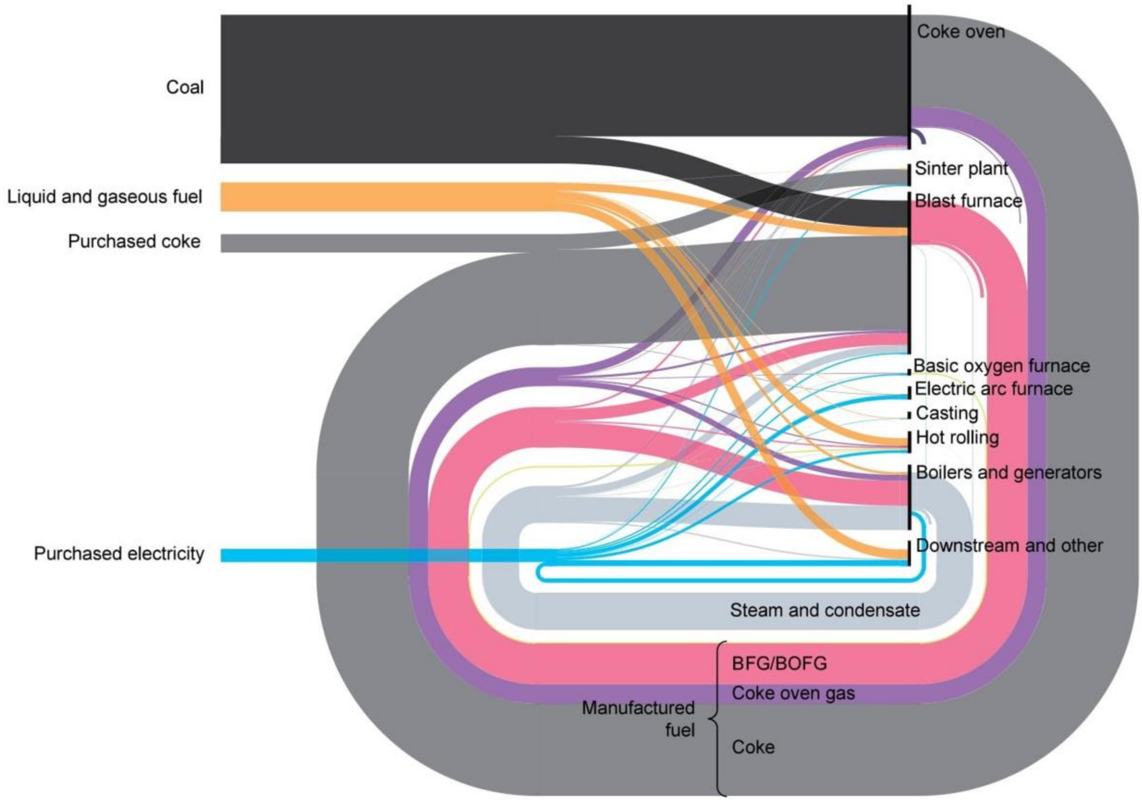

Fig. 4. Sankey diagram of plant-level fuel, steam and electricity flows in the UK *iron & steel* sector (c. 2010). *Abbreviations:* BOF - basic oxygen furnace; BOFG - basic oxygen furnace gas. *Source:* Griffin [20].

material flow diagrams have been provided by the *International Steel Statistics Bureau* [35].The industry then ran at nearly full capacity producing 14.4 Mtcs (~85% capacity utilisation), whilst about 3 Mtcs was exported, 0.1 Mtcs sold directly to indigenous consumers, and the remainder used as feedstock for hot-rolling [35]. About 10.4 Mtcs of hot-rolled steel was produced, just over a quarter of which was used as feedstock for finishing processes. After cold rolling and other downstream mill losses, production approximated to 10 Mtcs of *European Coal and Steel Community* (ECSC) finished or end products. This value was estimated using a weighted average rolling mill yield efficiency of ~92% [20], which equates to the amount of internally arisen scrap published by the *Iron and Steel Statistics Bureau* [30]. Net home and export delivery of industry products, including slab, was 14.2 Mtcs. This figure incorporates a small additional finishing yield loss due to the use of some ECSC products as feedstock to other industry products (including bright bars, cold rolled narrow strip, tubes and pipes), and would imply an import by the industry of about 1 Mtcs of steel for conversion.

3. METHODS AND MATERIALS

3.1 A hybrid top-down/bottom-up approach

There are two broad ways to modelling the industrial sector [1]: top-down and bottom-up approaches, as illustrated in Fig. 5 [3]. A top-down approach splits industry into sub-sectors,

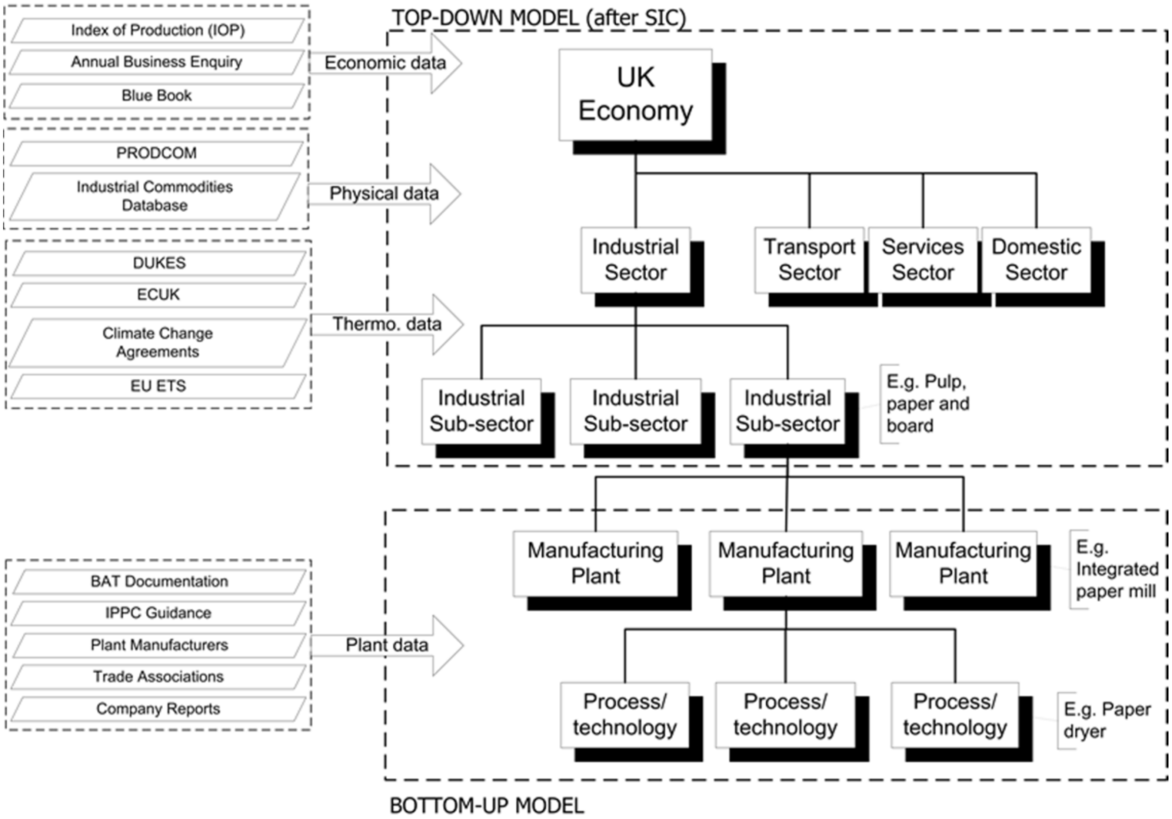

Fig. 5. Schematic representation of an integrated top-down and bottom-up modelling approach for the UK industrial sector. *Source:* Griffin *et al.* [3].

usually based on available statistical data, and employs this data to determine energy use, output, energy intensity and other measures for which data is available. This approach has the advantage of covering a large proportion of energy demand, but it is limited by the level of disaggregation available from industry-wide statistical sources. Thus, the conclusions that can be drawn from such top-down studies are often only ‘indicative’ in nature. In contrast, a bottom-up approach would typically focus on a single industrial sub-sector. Energy use can then be separated into lower order sub-sectors, processes or manufacturing plants. The data used for this type of bottom-up study will come from more specific information sources, such as trade associations, company reports, and case studies. Bottom-up studies can therefore result in more accurate findings [36], although they can be limited in the breadth of application.

A hybrid approach was employed to develop an industrial *Usable Energy Database* (UED) by Griffin *et al*. [18,19] for the UK industrial sector; as part of the research programme commissioned by the *UK Energy Research Centre* (UKERC). Aspects of both top-down and bottom-up methods were adopted, with detailed bottom-up studies set within a top-down framework. Using this approach would normally entail focusing on a number of sub-sectors for the bottom-up study [1], with the remainder of the sector being treated in a generic manner. Sub-sectors that use a large amount of energy are obviously prioritised for bottom-up studies. Clearly, those that use energy in a relatively homogeneous manner are easier to analyse. Sub-sectors that are not the subject of detailed bottom-up modelling require a focus on the potential reduction in emissions through widely-used, ‘cross-cutting’ technologies [1,18,19].

3.2 Identification of iron & steel processes

Energy demand and GHG emissions in the UK *iron & steel* sector principally result from the large consumption of coal. Remaining energy use is dominated by natural gas and electricity. Both coal and natural gas consumption has increased over time as a proportion of total fuel intake has natural gas. Petroleum has progressively been substituted, and no longer plays a significant role in the sector. Reduction in the proportion of primary electricity demand has resulted from efficiency gains at external power stations [18], and a relative decline in steel production via the EAF. About half of the energy demand at the process plant level is provided from primary fuels. Most of the coal is converted to coke via coke ovens for use in the blast furnace and sinter plant. The industry produces coke at a slight deficit to blast furnace requirements and so some has to be purchased externally. Other manufactured fuels include *coke oven gas* (COG), *blast furnace gas* (BFG) and *BOF gas* (BOFG), which are process by-products of each process. These gases are combusted to supply process heat or to raise steam in boilers. The steam is used at the process plant, or in turbine generators for electricity production. Natural gas is used to supplement the by-product gases or as a single process fuel input, particularly for processes situated outside integrated steelworks. A small amount of fuel oil and gas oil are still used for minor ancillary processes. In about 2010, a significant amount of fuel oil was consumed as blast furnace injectant, but has since been substituted by coal.

Around 80% of net *iron & steel* sector energy was required for the following processes (see again Fig. 3 [20,34]):

- Blast furnace, including stoves and blowers (53%)
- Coke oven (9%)
- Sinter plant (8%)
- Hot rolling mill, including reheat furnace (7%)
- Electric arc furnace (EAF), including secondary metallurgy (2.5%)
- Basic oxygen furnace (BOF), including secondary metallurgy (0.5%)
- Casting, including continuous casting machine and ingot casting soaking pit with primary mill (0.4%)

The remaining 20% is needed for boilers and power generation plant, and finishing processes downstream of hot-rolling (such as cold rolling and coating operations). Ironmaking - coke oven, sinter plant and blast furnace - accounts for 70% of sector energy demand.

4. TECHNOLOGICAL IMPROVEMENT POTENTIAL

4.1 Process improvement

A technology portfolio was identified consisting of measures available for retrofitting at the UK baseline *iron & steel* sites [20]. The portfolio comprised: coke dry quenching; 200 kg/*tonnes of hot metal* (thm) blast furnace coal injection; blast furnace slag heat recovery;

sinter plant main exhaust and cooler exhaust heat recovery; maximum BOFG and heat recovery; scrap preheating; and 33% thin slab casting. The *Best Available Technologies* (BAT) includes slag heat recovery, which has the same uptake of thin slab casting as in the technology portfolio itself. This portfolio of enabling technologies achieved about ¾ of the technical improvement potential at BAT sites in terms of energy demand reduction, and ⅔ of possible GHG emissions mitigation. It was found that applying the options identified in the technology portfolio at an integrated site required a slight increase in boiler capacity for electricity generation to utilise an increased surplus of by-product gases. In a BAT-integrated site it was necessary to generate nearly all electricity demand in this way. This may result in some electricity being sold to the national power grid.

4.2 Process and system replacement

In terms of disruptive technologies, the main focus has been on the potential role of industrial CCS [8-15]. Rootzén & Johnsson [10] examined the potential of industrial CCS in EI sectors within a Nordic context, and found that large-scale deployment would result in a significant 'penalty' in terms of its energy use and CO_2 emissions. A techno-economic appraisal of CCS in several EI industries by Leeson *et al.* [13] found that the main factor influencing cost reduction measures were the start date of large-scale deployment. The delay in instigating CCS demonstrations, as in the case of the UK, will prove costly in the long-term [32]. Indeed, many industrialists view CCS, or *carbon capture and utilisation* (CCU), as being costly technologies that will probably continue to be prohibitively expensive out to 2050 [41]. Possible exceptions to that are sectors with large processing facilities, such as chemicals and steel plants. The CCU community typically argues that the processing of usable products from CO_2 emissions adds economic value to offset the costs of 'carbon capture', whereas CCS (unless used in connection with enhanced oil or gas recovery) is a high cost process. The clustering of GHG networks between electricity generators and industrial process plants, together with their coupling to offshore storage facilities, is an important requirement for the practical adoption of CCS (and possibly CCU) in the UK and elsewhere [1]). It is illustrated in the map produced by Griffin *et al.* [2] of the potential CCS/CCU cluster sites around the UK: see Fig. 6. Clearly, this would require ongoing RD&D as part of a collaborative programme with the manufacturing/processing sectors and electricity and gas supply utilities.

Direct reduced iron (DRI) sites [32] import all their electricity requirements, except in the case of the MIDREX capture site [38] (a DRI process using a shaft-reactor that was developed by Midrex/Kobe Steel) and biomass ULCORED (a shaft-based DRI process with an optimised design for CO_2 recovery and higher fuel efficiency [20]) site with excess syngas. It is assumed that with the former additional capture from onsite electricity generation is a prerequisite to investing in CCS, whilst the syngas that is surplus with the latter process is utilised for auto-generation. Thus, EAF plant was evaluated on the basis of being located on a '*greenfield*' site (i.e., an area of usually agricultural or amenity land, which is being considered for commercial or industrial development) and incorporating processing equipment modelled for the *Ultra Low CO_2 Steelmaking* (ULCOS) project [39]. All other replacement sites shown were '*brownfield*' locations (i.e., disused commercial or industrial sites envisaged for redevelopment) with replacement technologies modelled against the UK

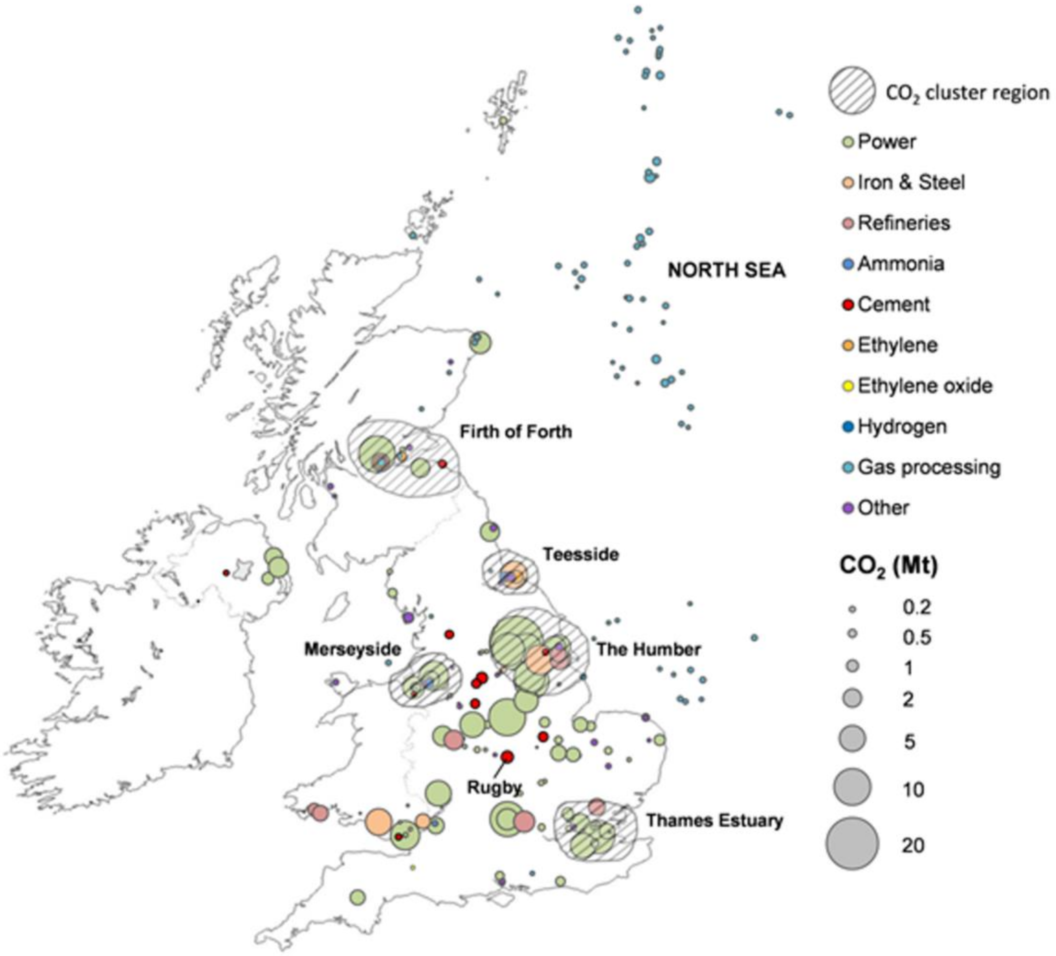

Fig. 6. Distribution of CO_2 point sources and clustering opportunities in the UK. *Source:* Griffin *et al.* [2].

baseline with the performance of all other plant unchanged. Direct GHG emissions were found to be lower for the excess bio-syngas site [40], because a higher proportion of energy demand is met by carbon-free syngas. Scope 2/3 GHG emissions are likely to be subject to significant reduction in the future. This would have the greatest effect on the ULCOWIN (‘electrowinning’ or alkaline electrolysis) site. Identified technologies and measures generally fit into three broad categories. Fuel switching was 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 burnt fuel in the sub-sector; much of it being used in *combined heat and power* (CHP) plant.The UK Government has from time-to-time aimed at developing a sustainable CCS/CCU industry that might capture emissions from clusters of industrial process plants and electricity power stations linked together by a pipeline network transporting CO_2 to suitable storage sites offshore [2,32]. These CCS clusters hold out the prospect of providing integrated CO_2 pipeline networks, which could be formed of multiple branches that link individual sources to a common hub and main pipeline; thereby sharing CCS infrastructure [32]. These integrated pipelines could considerably decrease the costs of transport, particularly from smaller CO_2 sources. In addition, CCS clusters could potentially reduce significantly the disruption and transaction costs, as well as investment risks [41], associated with permitting and installing multiple point-to-point pipeline networks [32]. Indeed, CO_2 transport and storage costs present a greater hurdle than that associated with capture costs themselves [1]. But there are major challenges in commercially financing CO_2 pipelines [41] that are likely to be over-sized in the period before CCS becomes a mature, commercial technology [32]. Cluster regions of industrial activities have been identified for storage under both the North Sea and the North East part of the Irish Sea [32]. The distribution of these CO_2 point sources and potential UK CCS cluster regions are illustrated again in Fig. 6 [2]. They are principally along the East Coast of the UK adjacent to depleted oil and gas fields in the North Sea: the Firth of Forth in Scotland, Teesside in the North East of England, and the Humber and Thames Estuaries on the East Coast of England. Cooper & Hammond [32] recently observed that the main industrial area in Wales (and one of the largest agglomerations in the UK) is on its South Coast, but doesn't have an appropriate CO_2 storage locations in its vicinity, i.e., beneath the Bristol Channel or the North Atlantic Ocean. In contrast, the more modest industrial area in the North East of Wales could make use of the adjacent Liverpool-Manchester CCS cluster with storage capacity in the Irish Sea. Nevertheless, pipeline technology for building a CO_2 transport network is ready to be rolled out, and the UK already has preliminary plans for at least two large CO_2 transport hubs (see again Fig. 6), e.g., at the *Teesside Collective CCS Project*. Indeed, the UK Government is committed to the support of ongoing CCS/CCU initiatives to test the potential for the development of industrial CO_2 pipeline clusters on Teesside, Merseyside, South Wales, and Grangemouth as set out in its 2017 *Clean Growth Strategy* (CGS) [42].

4.3 Energy and emissions from baseline integrated and replacement technology sites

The energy and GHG emission intensities (measured in GJ and tCO_{2e} per tcs) for the baseline integrated steelworks are presented in Fig. 7 and 8 respectively. The baseline site is contrasted with that of a range of other sites incorporating the identified existing and future replacement technologies. All sites were constructed for replacing the integrated site (along with casting, hot-rolling, downstream and other activities) being unaffected, except for process fuel mix which will inevitably be subject to change. The EAF site is *greenfield* and incorporates process plant modelled for the ULCOS project [20,39], whilst all other replacement sites shown in Fig. 7 and 8 are *brownfield*. The GHG emissions resulting from *carbon fixation from biomass growth* (C-fix) lead to some sites becoming 'carbon negative', as more CO_2 is taken from the atmosphere and stored than that which is emitted. Direct emissions are lower for the excess bio-syngas site, because a higher proportion of energy demand is met by carbon free syngas. It should be noted that Scope 2/3 GHG emissions will be subject to significant reduction in the future. This would have the greatest effect on the ULCOWIN site and, consequently, favours that technology. It is also apparent that a minimum purchase of grid electricity remains after auto-generation. This reflects the UK practice in which some downstream finishing activities occur off-site, and so they have been modelled without the use electricity from centralised generating plant.

4.4 Abatement cost curves

The *Marginal Abatement Cost Curve* (MACC) was developed by the Stockholm office of the management consultancy McKinsey & Company [20,43]. It represents a graph of the last

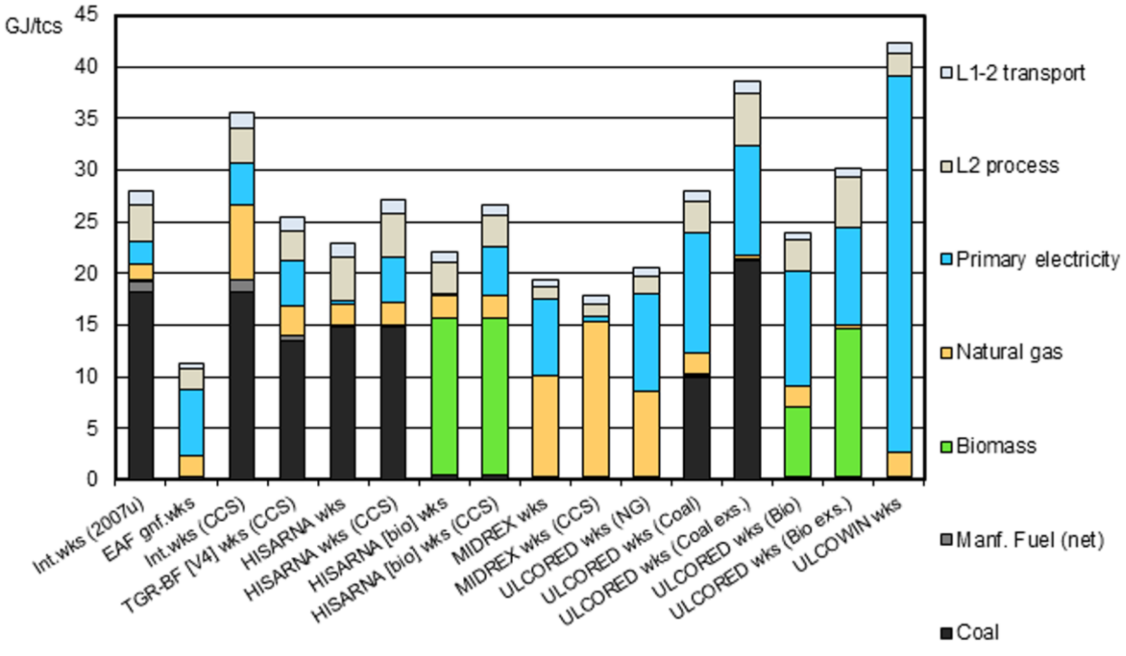

Fig. 7. Baseline integrated site and replacement technology site *Net Energy Requirements* (NER). [L1-2 - GHG Scope 1 and 2 emissions; L2 – GHG Scope 2 emissions; wks - works; Int. – integrated; TGR-BF - top-gas recovery blast furnace; HISARNA - an amalgam of the ancient Celtic word for iron ('Isarna') and the name of the melting vessel ('Hismelt').] *Source:* Griffin [20].

(marginal) unit or cost for GHG emissions abatement, and enables the presentation of low carbon options as alternatives to *business as usual* (BAU) industrial activity. Different measures or technologies for reducing GHG emissions across an economy or within a specific sector can therefore be assessed in terms of the associated extra (or marginal) costs and abatement compared with a specified baseline. The baseline is the BAU part of the sector or economy that the option replaces. The cost associated with this technological option is the annualised cost over the lifetime of the technology and is calculated using a discounted cash flow analysis.

Abatement economics are presented under ‘dynamic future’ regimes [20], which presumes that production begins in 2030 with changes in resource prices and grid emissions factor being incorporated. The electricity supply decarbonises, and changes in BOF scrap and process efficiency towards BAT levels are included. Specifically, this is a 67% move towards the BAT level and a 40% move towards maximising BOF scrap input (i.e., from 15% to 23% of metallic charge). Grid, BOF scrap, and efficiency changes are averaged over the production life, thereby yielding the average annual specific abatement for each technology. The abatement option under the future dynamic regime and a 2050 emissions trading price of 100£/tCO_2 is illustrated in Fig. 9. (Other regime possibilities can be found in the PhD thesis of Griffin [20].) Such MACC graphs have been employed here as a means for evaluating the cost-effectiveness (ranking) of the various decarbonisation options that were then incorporated into the UK *technology roadmaps* (presented in Section 5 below).

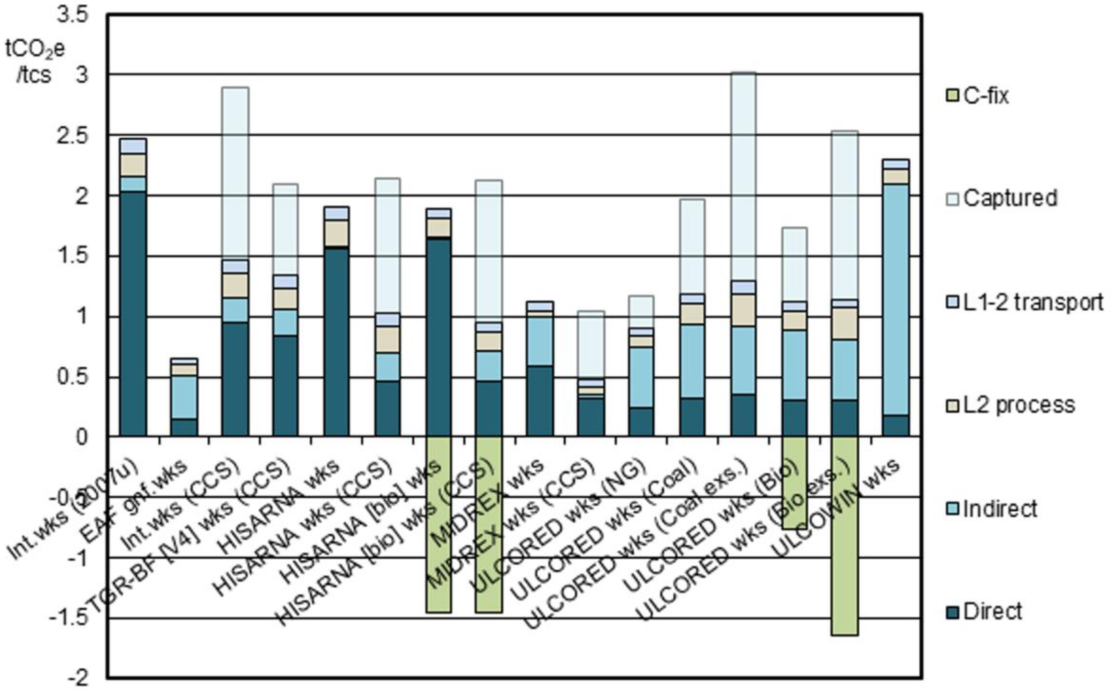

Fig. 8. Baseline integrated site and replacement technology site *'Greenhouse Gas' (GHG) Emissions*. [L1-2 – GHG Scope 1 and 2 emissions; L2 – GHG Scope 2 emissions; wks - works; Int. – integrated; TGR-BF - top-gas recovery blast furnace; HISARNA - an amalgam of the ancient Celtic word for iron ('Isarna') and the name of the melting vessel ('Hismelt').] *Source:* Griffin [20].

In reality, only one or a few replacement technologies could be anticipated in the future. This is why a comparison between alternatives, as opposed to the cumulative effect of a portfolio of additive options (i.e., true MACC graph) is presented here (e.g., in Fig. 9). All key options and the base integrated site have an equal share (6%) of original crude steel production from the base integrated site. The baseline sites are the integrated steelworks and the EAF steelworks. No replacement sites have been identified for the EAF steelworks have the integrated steelworks as their baseline. The EAF works is, however, is subject to process improvements towards the BAT level. The error-bars on Fig. 9 are based on production cost uncertainty, and represent a proportion of the abatement cost. Thus, the approximate error in the calculation of these production costs is based on the uncertainty in all key capital and variable costs (excluding carbon trading price). The price increases were modelled from 50 to 100£/tCO$_2$ over the 2030-2050 period with the trend continuing beyond 2050 [20]. This follows the lower boundary of price range suggested by the UK Government [44] for use in futures modelling, which is 100-300£/tCO$_2$ in 2050. C-fix is assumed here; as it is incorporated in UK Government guidelines for emissions accounting [20].

It may be observed (see again Fig. 9) that future abatement cost is subject to the opposing effects of an improving baseline and increasing fuel prices. The former is improvement relative to the integrated site, because HISARNA and *top gas recycle blast furnace* (TGR-BF)

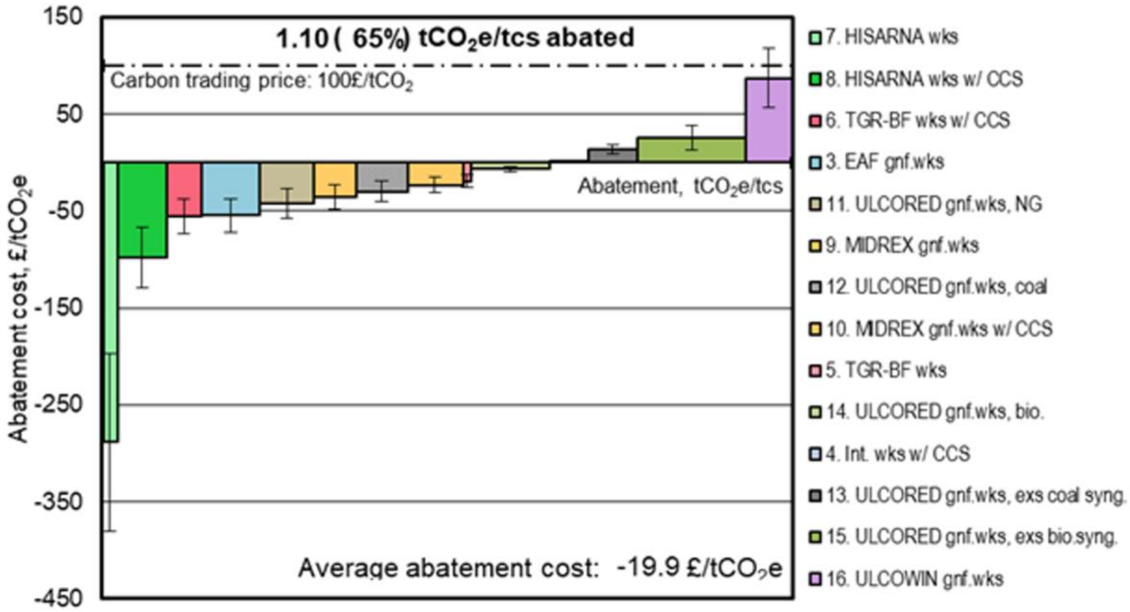

Fig. 9. Illustrative comparative abatement cost ‘curve’ for technologies applicable to the *iron & steel* sector. (Example under the 2030 future dynamic regime and a carbon trading price reaching 100£/tCO_2 in 2050.) *Source:* Griffin [20].

sites provide less opportunities for process efficiency gain. Moreover, BOF scrap increase at the baseline site is more effective in that it substitutes conventional blast furnace iron [20]. Increasing fuel prices favour processes with lower energy intensity, but not those using more natural gas and electricity, for which prices are projected to increase at a steeper rate than coal [20,44]. In particular, MIDREX sites and the natural gas-based ULCORED system becomes more expensive in terms of abating emissions. Conversely, the coal-based HISARNA site reduces in abatement cost significantly as its energy input is dominated by coal, and most of its electricity demand is met via a waste heat recovery system. However, the largest reduction in abatement cost occurs for the ULCOWIN site despite its high electricity intensity. This is because the decarbonised electricity price is likely to increase faster than the price of most fuels. ULCOWIN and biomass ULCORED systems with excess syngas, become economic only at the higher carbon trading prices [20]. The coal-based ULCORED with excess syngas would also require the higher price, because it employs gasification at particularly low efficiency. Hence, the coal ULCORED site without excess syngas is preferable.

5. UK *IRON & STEEL* ‘TECHNOLOGY ROADMAPS’ TO A LOW-CARBON FUTURE BY 2050

5.1 Background

A set of *technology roadmaps* have been developed in order to evaluate for the potential deployment of the identified *iron & steel* technologies out to 2050. The extent of resource demand and GHG emissions reduction was therefore estimated and projected forward. Such roadmaps represent future projections that match short-term (say out to 2035) and long-term (2050) targets with specific technological solutions to help meet key energy saving and decarbonisation goals. A bottom-up *technology roadmap* approach has been adopted, based on that previously used by Griffin *et al.* [1-3,45] to examine the impact of UK industrial decarbonisation in the cement, chemicals, food & drink, and pulp & paper sub-sectors respectively (for further details see also Griffin [20]). Thus, their contents were built up on the basis of the improvement potentials associated with various technological processes employed in the *iron & steel* sector and that were embedded in the UED [1,18,19]. These decarbonisation options were ranked in terms of their cost-effectiveness with the aid of the MACC graphs (such as that depicted in Fig. 9).

5.2 Baseline UK *iron & steel* technology projections

The baseline projections are adjusted for future years based on forecasts of steel production, scrap availability, and grid related energy and emissions intensity. The status of plant and equipment efficiency is separate from the action of replacing processes, and these were also taken into consideration. It is assumed that the grid will decarbonise by 85% over the period 2010-2050. For simplification, it is assumed that the UK is effectively 'self-sufficient' consumer of finished steel. The projected apparent steel use is calculated by multiplying the extrapolated steel intensity with the forecasted growth in *Gross Domestic Product* (GDP) [20]. Production trends include a dip due to the 2008 global economic recession. However, because the fall in output was mostly unaccompanied by a reduction in plant capacity, future crude steel production for the *technology roadmaps* is assumed to be stationary. The trend was presumed to develop from a base of 12Mtcs (which roughly equates to 75% of capacity), although UK steel capacity was reduced by about 3Mt following the closure of the Redcar plant in September 2015. This trend may be deemed conservative, but takes into consideration the sensitivity of production to resource price shocks and wider economic factors [20].

It is widely viewed that availability of scrap for steelmaking in Europe and globally is likely to increase over the period between 2030 and 2050 [46,47]. Scrap derives from three sources: obsolete scrap (largely emanating from infrastructure and product turnover); prompt scrap (raised from steel consuming manufacturing industries, e.g., automotive cut-offs); and home scrap (arising from within the UK *iron & stee*l sector itself). The main increase in scrap availability would come from obsolete scrap, which the *Boston Consulting Grou*p [46] expect to continue at least until 2020. This would be additional to the EU's 2.5 Gt scrap stockpile, which is increasing at a rate of some 20 Mt per year [20]. While Europe appears in no shortage of scrap, the global scrap market has been predicted to grow considerably in the next 30 to 40 years driven by obsolescence in China, and later India, possibly reducing global BOF/EAF share from 70/30 to 50/50 [47]. A key issue is how this would affect the balance of scrap trade in the UK. Scrap produced in Europe divides into three regions: Northern Europe, Southern Europe, and Central Europe. Northern and Southern Europe account for 85% of European crude steel production [20]. Northern Europe is a net scrap exporter and produces steel with a BOF/EAF share of 70/30 while Southern Europe, which grew its industry later than Northern Europe, has a share of 30/70 and is a net scrap importer. The UK is consistently the largest single net exporter of scrap in Europe, and in 2016 had a BOF/EAF share of 84/16. The UK's net export of scrap is typically around 60-70%, as a proportion of crude steel production, compared with just 15% for Northern Europe as a whole. Thus, it was assumed here that scrap consumption in the UK will increase annually by an average of 0.44-2.2%

(mean 1.3%) over the period to 2050, and that this increase will become steeper after 2030. The lower boundary is equivalent to increasing scrap consumption by 10% of the amount exported in the baseline year of 2016.

All sites are assumed to progress towards an uptake of improved ancillary plant and equipment. This is defined here as the level needed to achieve BAT. A baseline efficiency is defined in respect to the potential of disruptive replacement technologies. The potential of a new HISARNA smelting furnace, for example, is lowered if it displaces state-of-art coke-dry-quenching batteries, heat recovery equipped sinter plant, or a well-run blast furnace with high coal injection rate. Similar arguments apply when substituting iron with scrap at the BOF, or regarding the effect of grid decarbonisation (which is curbed by the use of scrap preheating at the EAF) [20].

5.3 Scenario definition

The identified improvement technologies for the UK were incorporated into the *iron & steel* industry *technology roadmap* framework through a series of scenarios. The baseline year for the framework was taken as 2010. Full details of the both the 2010 baseline and the BAT/BPT improvements can be found in the UKERC industrial UED [18,19]. Four future scenarios were devised in order to demonstrate this approach. Ideas from the authors' earlier roadmaps were drawn on in constructing some of the core scenarios for the *iron & steel* sector, such as those indicated below [1-3,20,43]:-

- ***Reasonable Action*** **(RA).** All identified efficient technologies are installed by 2025, and retired plants are replaced with best practice ones by 2030.
- ***Reasonable Action including CCS*** **(RA-CCS).** This scenario is based on RA, but includes CCS. Biomass co-firing with CCS may, of course, mitigate upstream emissions on a full life-cycle basis, due to potential 'negative emissions' [2,3]; something that will need careful study in future research.
- ***Radical Transition*** **(RT).** This scenario explores a boosted or radical version of the reasonable action (without CCS) scenario.

5.4 Alternative UK *iron & steel* sector technology roadmaps

Changes relating to baseline efficiency, BOF scrap and the grid may be described collectively as 'cross-cutting measures' insofar as their effects are not confined to a single site option. However, the effect does vary between sites. The influence of cross-cutting measures may be attributed in a number of ways. This is depicted in Fig. 10, which gives three perspectives (A, B and C) on attributed energy and emissions intensity reductions for an illustrative roadmap: *Reasonable action with CCS* (RA-CCS). In this example, CCS equipped TGR-BF and HISARNA technologies are applied equally to two thirds of existing integrated site capacity. The remaining third is half replaced by *greenfield* EAF capacity. Projected grid decarbonisation is met and sector scrap level reaches the mean (45%) of the projected range (supplying a 23% BOF scrap input and 30% EAF production). Baseline efficiency achieves two thirds of the BAT standard, which includes slag heat recovery and 33% thin slab casting, by 2030 and thereafter remains stable. Perspective A (see again Fig. 10) separates the effect of

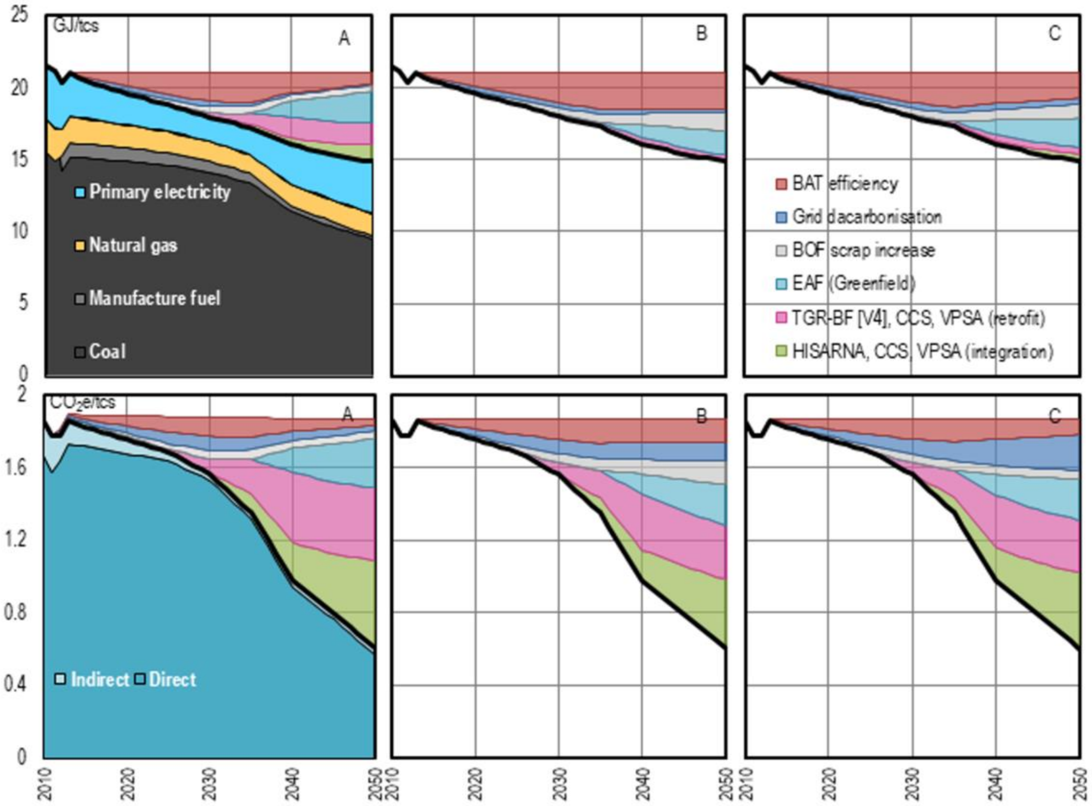

Fig. 10. Multi-perspective decomposition of future energy and GHG emissions intensity for the *reasonable action with CCS* (RA-CCS) 2050 roadmap of the UK *iron & steel* sector. *Source:* Griffin [20].

cross-cutting measures from technologies that are incumbent in 2016. Perspective B shows the effect of applying the replacement technologies to the otherwise improved baseline structure (also Fig. 10). The cross-cutting effects shown are as they would be to the baseline structure in the absence of any replacement technology deployment. Thus, the technology effects represent the true impact of their application as an alternative to how the sector would otherwise progress, i.e., the counterfactual effect. As can be observed, the influence of EAF, TGR-BF and HISARNA has been reduced. Perspective C (again Fig. 10) shows the true effect of the cross-cutting measures on the sector restructured by the replacement technologies. The remainder represents the effect of the technologies as separated from all cross-cutting measures. As can be observed, the effect of grid decarbonisation increases to a larger extent as the new structure demands an increasing proportion of purchased electricity. Conversely, the effect of BOF scrap increase is lowered as there becomes less BOF capacity to replace and processes upstream of the BOF have significantly reduced emissions intensity. HISARNA has a greater conflict with baseline efficiency because it replaces more of these upstream processes than would TGR-BF; the former replaces coke oven capacity and sinter plant, while the latter only partly replaces coke oven capacity and maintains the sinter plant. This is evidenced by a larger impact of TGR-BF from perspective A, but a slightly larger increase in the impact of the HISARNA process from perspective B to perspective C.

A biomass counterpart roadmap, designated RA-CCS [bio], or BECCS, incorporates the charcoal-based HISARNA (see Fig. 11) instead of the coal-based HISARNA. Here the dashed

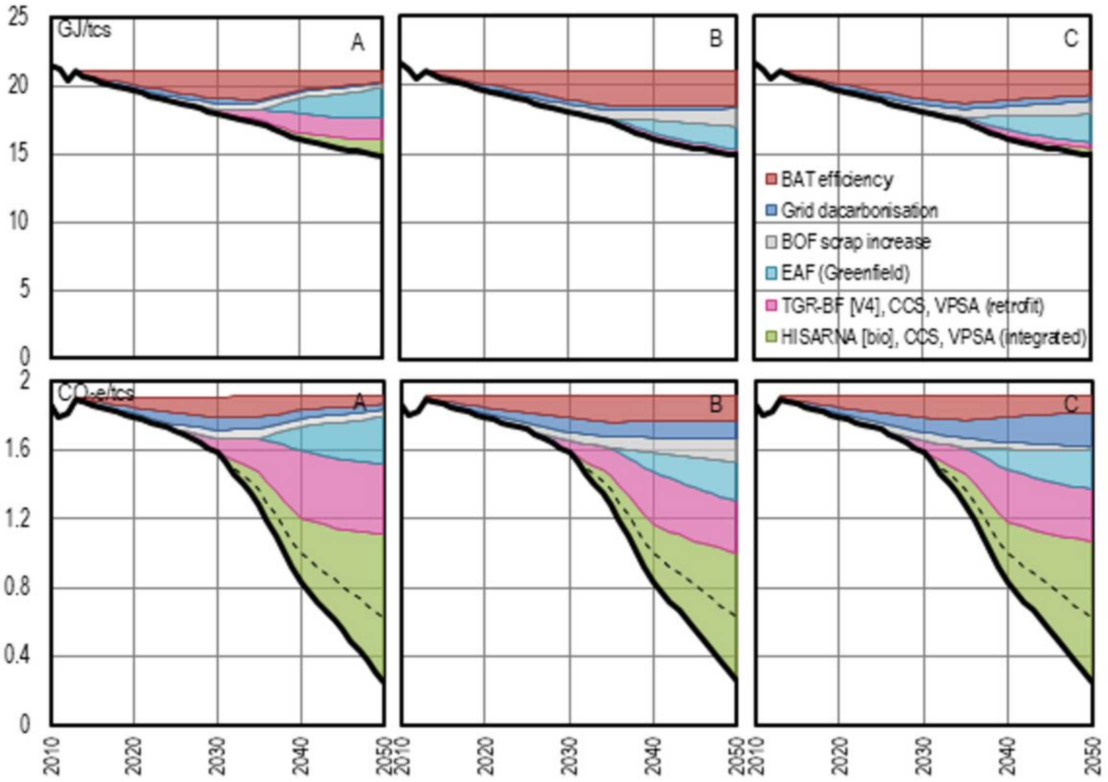

Fig. 11. Multi-perspective decomposition of future energy and GHG emissions intensity for the *reasonable action with biomass CCS* (RA-CCS [bio]) 2050 roadmap of the UK *iron & steel* sector. *Source:* Griffin [20].

line represents the emissions profile for which carbon fixation is unaccounted. The '*Radical process transition*' (RT) roadmap then represents an ambitious structural shift culminating in the ultimate cessation of blast furnace ironmaking in the UK (see Fig. 12). There is also no dependence in this case on CCS. All steel conversion takes place in EAFs with an average 45% iron input for the sector, i.e., having the upper boundary (55%) of projected sector scrap share. The iron is supplied five eighths from MIDREX and three eighths from ULCOWIN, equating to a 70/30 share in 2050 production from these sites respectively. The ULCOWIN process demands more energy, and therefore virtually all of its abatement relies on grid decarbonisation. BAT improvement measures reduce more significantly in perspective C, as more capacity is replaced by *greenfield* sites. Other options are described and illustrated in the PhD thesis of Griffin [20].

A comparison of the dynamic sector production costs associated with the roadmaps is shown in Fig. 13. These are relative to the projected baseline under increasing steps of emissions trading price. For simplicity, this trading price is incorporated in each case as rising linearly from 0£/tCO_2 in 2010. The sector would profit from the absence of emissions trading in some of the *Reasonable Action* (RA) roadmaps. Over the middle steps of trading price, RA roadmaps generally display the most attractive economics. RA roadmaps without CCUS fade in their appeal relative to *Radical Transition* **(**RT) and *Biomass Process Transition* (BT) roadmaps [20], and RA-CCS [bio] (or BECCS) become more economically attractive than

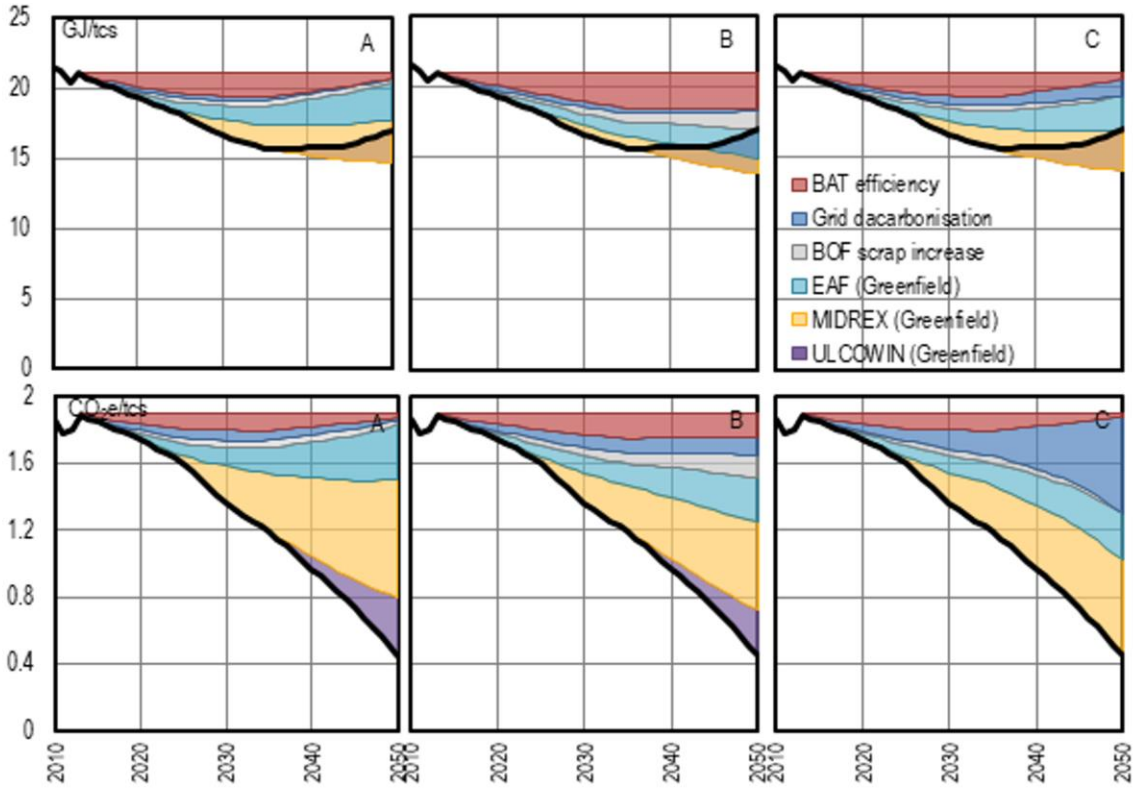

Fig. 12. Multi-perspective decomposition of future energy and GHG emissions intensity for the *radical process transition* (RT) 2050 roadmap of the UK *iron & steel* sector. *Source:* Griffin [20].

RA-CCS. Considerable savings in future production cost may be available according to the *technology roadmaps* represented in Fig. 13. However, these savings exist in the context of absolute increases in production cost, which should not be allowed to become uncompetitive.

6. COMPARISON WITH THE UK GOVERNMENT'S *IRON & STEEL* TECHNOLOGY ROADMAPS

The UK *Department of Energy and Climate Change* (DECC) and *Department for Business, Innovation & Skills* (BIS) contracted a consortium of consultants from *WSP/Parsons Brinckerhoff* (PB) and *DNV.GL* to undertake the development of a set of '*Industrial Roadmaps for Carbon Reduction and Energy Efficiency to 2050*' (see, for example, the *iron & steel* report [48]). The robustness of the WSP/PB and DNV.GL approach mirrors the wide-scale industrial stakeholder engagement in this project. Consequently, their sector roadmaps largely reflect back the views of the industry representatives that participated in the sector workshops, face-to-face interviews, site visits, and a cross-sector conference. In order to evaluate the pathways out to 2050 the consultants developed a simplified modelling framework, which realistically yielded a wide range of uncertainties in terms of the delivery of a decarbonised UK industrial sector. In common with earlier studies (like that of Griffin *et al.* [45]; already published at that time) the pathways indicate a broad range of possible UK industrial carbon reductions or uncertainties by 2050.

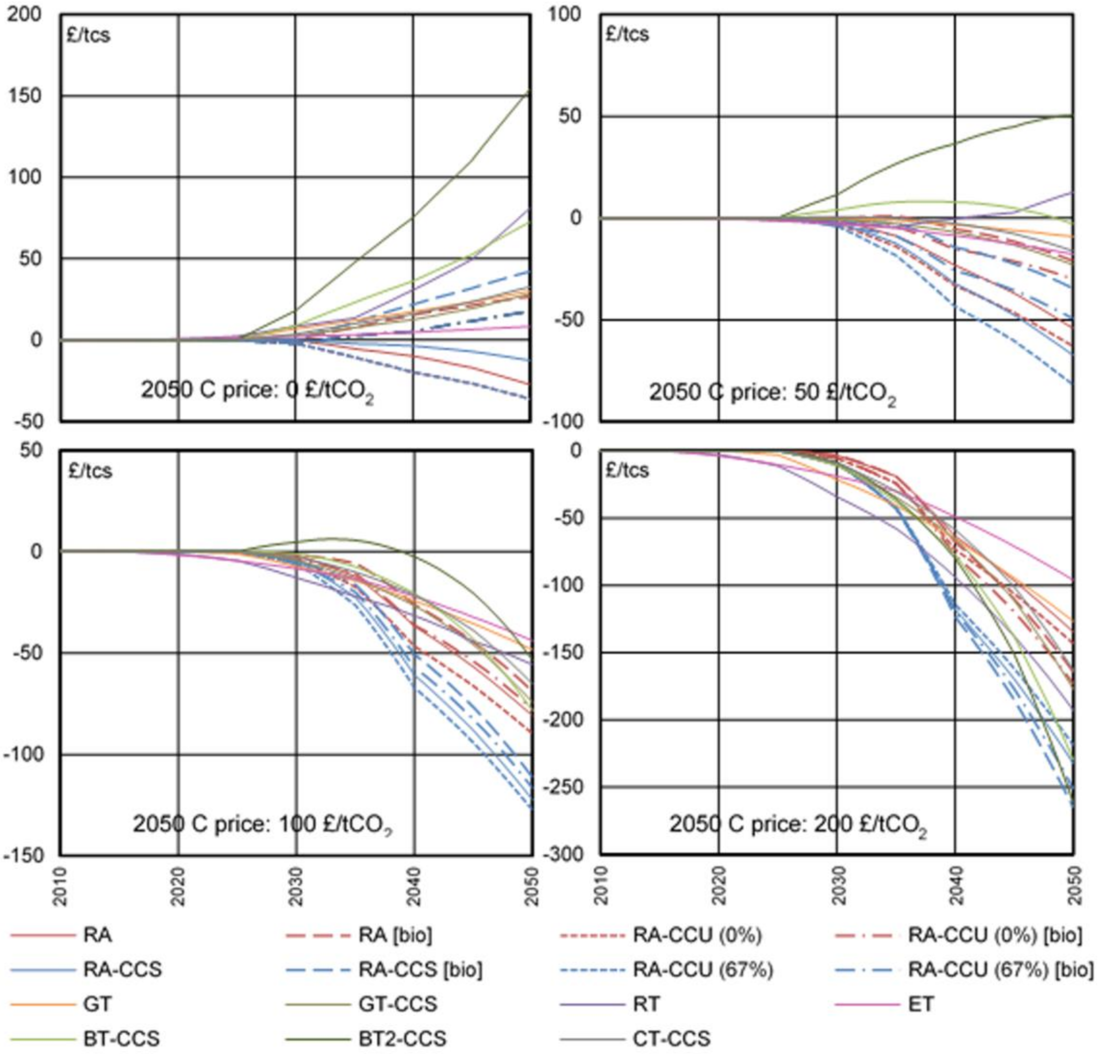

Fig. 13. Relative production cost pathways of illustrative technology roadmaps of the UK *iron & steel* sector. *Source:* Griffin [20].

The PB/DNV.GL models[1] do not directly link the reported emissions reductions under a given pathway to the demand for different fuels, electricity and process emissions (which are often coupled to a sector's material inputs). This is evident when comparing the emissions savings by electricity decarbonisation between pathways. These savings appear the same regardless of pathway, which seems an unlikely outcome as the combinations of different options under these pathways will have different electricity demands. So the effect of electricity decarbonisation will not be equal between the pathways. There is also concern over whether the energy demand and emissions data are consistent in the *Iron & Steel* [48] and *Chemicals*

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[1] The present authors (along with their former colleague Dr Jonathan B. Norman, now at the University of Leeds) were commissioned by DECC in 2015 to provide them with a technical peer review of these roadmaps covering the general methodology, as well as the specific reports for the *Chemicals*, *Iron & Steel*, and *Pulp & Paper* sectors. They were evaluated in order to provide an overall assessment of the rigour of the approach taken by the consultants across the whole of UK industry, and to identify its strengths and weaknesses.

sectors (i.e., calculating emissions data from the reported energy demand does not concur with reported emissions in the model). It could be argued that a more detailed ‘bottom-up’ approach structuring the sector models from the process plant level up, with all significant fuel and material inputs and outputs included (e.g., Griffin *et al.* [1,18,19]) would give a more accurate assessment of the improvement offered through the various technologies. The omission of material flows from the model, and how these would change with the adoption of different technologies, also limits the detail on cost changes. In some cases this could cause large errors.

The lack of ‘bottom-up’ modelling in the PB/DNV.GL pathways limits the representation of technology interactions. Synergistic and conflictive effects arise from the combination of efficiency and fuel switching, process and structural change, electrification and grid decarbonisation, biomass and CCS, and virtually any other measure available. For example, a blast furnace may be retrofitted with a top-gas recovery system. This would reduce coke rate and, in turn, coke oven output. Efficiency improvements to the coke oven would then be more limited in the emissions savings offered and the effect of charging more scrap to the *basic oxygen furnace* (BOF) steelmaking [28] would be reduced as its effect is to displace a lower emitting iron-making process. Meanwhile, surplus production of by-product fuels would be reduced significantly resulting in a switch to more natural gas. In addition, the higher demand for oxygen by the recovery system is likely to require an on-site *air separation unit* (ASU) demanding electricity, and thereby increasing the effect on the sector of grid decarbonisation. And so on.

Representatives from five *iron & steel* manufacturers were interviewed by the consultants in connection with their study [48]. A crucial factor for energy demand and emissions in this sector is the proportion of ore-based to scrap-based steel production. The ‘electric arc furnace’ (EAF) share was not modelled as an option, nor was the balance of production route considered in the PB/DNV.GL pathways. Abatement options were heavily weighted towards incremental technologies, while important medium-to-long-term options over the period to 2050 are omitted or only superficially covered: key capture technologies are grouped together despite significant differences in cost, emissions reduction, fuel requirements, etc. The reason given for grouping the technologies was “participants felt unable to identify specific technologies that are expected to play a significant role in different Pathways”. However, this would suggest that this is a cause for, not against, the modelling of specific technologies, especially if they are to play a ‘significant role’ (in contrast to the more incremental technologies, which are of lower consequence). This case exemplifies the high dependency of the consultants on the input of stakeholders or workshop participants. In addition, *Direct Reduced Iron* (DRI) and electrolysis options are not included in the PB/DNV.GL pathways.

Comparisons between the GHG emissions pathways associated with the present *technology roadmaps* and the ‘pathways’ produced by the DECC-BIS consultants (PB/DNV.GL) [48] are shown in Table 1. The emissions trajectories derived from the present work reflect the more dramatic routes in terms of the degree of decarbonisation by 2050. Falls in emissions are clearly more rapid following the deployment of commercial-scale CCS or BECCS from 2030 onwards. However, *Biomass Process Transition with CCS* (BT-CCS) relies on biomass

Table 1 – UK Industrial Decarbonisation Technology Roadmaps to 2050: *Iron & Steel* Sector

ASP/PB and DNC.GL Emissions Pathways* (% of 2012 Gross Sector GHG[†] Emissions)						Present Technology Roadmaps (% of 2012 Gross Sector GHG[†] Emissions)					
Pathways	**2012**	**2020**	**2030**	**2040**	**2050**	**Roadmaps[‡]**	**2012**	**2020**	**2030**	**2040**	**2050**
Reference	100	95	93	91	91	**RA-CCS**	100	99	88	54	34
Business as Usual	100	91	89	85	85	**A-CCS [bio]**	100	99	88	44	13
20-40%	100	91	85	79	71	**GT**	100	99	87	44	14
40-60%	100	91	85	60	54	**BT-CCS**	100	97	84	53	11
Max Technical	100	91	72	58	39	**RT**	100	97	75	54	25

* Commissioned by the UK *Department of Energy and Climate Change* (DECC) and *Department for Business, Innovation & Skills* (BIS) in 2015; published as a Government report [48].

[†] GHG = Greenhouse Gas

[‡] Description of the present 2050 technology roadmaps: RA-CCS – *Reasonable Action Including CCS* (see Fig. 10); RA-CCS [bio] - *Reasonable Action Including BECCS* (see Fig.11); GT – *Gas Process Transition* [20]; BT-CCS – *Biomass Process Transition With CCS* [20]; and RT – *Radical Transition* (see Fig. 12).

gasification that yields a means for obtaining more diverse forms of energy from the thermochemical conversion of biomass than is the case with conventional combustion. It involves the burning of biomass in a limited supply of air to yield a combustible gas in three stages: devolatization, combustion and reduction. Methane and other hydrocarbons are produced from the biomass during devolatization by the action of heat that leaves a reactive char. In the combustion stage, the volatiles and char are partially burned in air or oxygen to generate heat and CO_2. Finally, during the reduction phase, CO_2 absorbs heat and reacts with the remaining char to produce carbon monoxide (CO; a combustible or producer gas). The presence of water vapour (H_2O) in a fixed bed or fluidized bed gasifier results in the production of hydrogen (H_2) as a secondary fuel component. But the downside of biomass gasification is its high costs [20].

Overall, the present *technology roadmaps* of the UK *iron & steel* sector lead to greater decarbonisation by 2050 than the ‘official’ estimates of DECC-BIS and their consultants (*WSP/Parsons Brinckerhoff* and *DNV.GL*). Both the RA-CCS [bio] and BT-CCS roadmaps with their negative GHG emissions result in a fall from 2012 (the DECC-BIS baseline) to between just 13 and 11%. That would be a significant achievement, albeit one that relies on bringing CCS to a commercial-scale realisation – a daunting, although not impossible task. A contrast is the possibility of a *Radical Transition* **(**RT), see again Table 1, that might lead to a decarbonisation of 25% compared to the lowest official forecast of under the '*Max Technical*' (or *Max Tech*) pathway of a fall in emissions to 39% of the 2012 DECC-BIS baseline. This would require a combination of carbon abatement options that are both highly ambitious, but that the consultants viewed as being "reasonably foreseeable" when non-technical barriers are set to one side. Clearly, none of the present, or indeed the official government [48], roadmaps/pathways achieve zero emissions by 2050 (as indicated in Table 1). The UK Government's independent *Committee on Climate Change* (CCC) [49] recognises that some sectors of the British economy will be more difficult to decarbonise than others. Industry in general is seen as being one of these challenging sectors, along with transport. On the other hand, electricity generation might well be cost-effectively decarbonised prior to 2050. The use of *negative emissions* technologies (such as BECCS) is likely to provide 'head room' for other sectors. So the present aim of the CCC (and, by extension, the UK Government) is to see the whole of the British economy reach the 80% GHG reduction target by 2050 against the 1990 baseline, rather than all the individual sectors.

Carbon, capture and storage/utilisation (CCS/CCU), the use of biomass, and decarbonised electricity are all key options in both the present and UK Government *technology roadmaps*/emissions pathways for the *iron & steel* sector. However, each of these options is the source of considerable uncertainty in terms of their availability to industry. Although it is recognised there has been some attempt to understand the sensitivities in the use of CCS and biomass within the DECC-BIS pathways, a fuller discussion of these key technologies, and the uncertainties involved across all sectors would be a valuable addition to that work. This could include, among other things, a 'no CCS' pathway for all sectors. Obviously, innovations in capture technologies are likely to occur over the timespan out to 2050 [1,2,13-15,20]. The development of CO_2 transport hubs will require an interlinking of industrial and power station networks for onward storage in the North Sea (as discussed in Section 4.2 above; see also Fig. 6). UK produced biomass is severely resource constrained, whilst imported feedstocks will be limited by sustainability considerations [2,3,49].

7. CONCLUDING REMARKS

A bottom-up energy and material database (the industrial UED [18,19]) has been extended and exploited to examine past, present and future resource demands and GHG emissions associated with the UK *iron & steel* sector. Information at the process plant level was sought from primary and secondary sources to characterise in detail the technological structure and status of the sector. They were built to analyse the resource use, emissions abatement, and economics of future technologies. Systems were distinguished and defined in terms of site activity and steelmaking process routes. A number of thermodynamic and economics-based methods were utilised to quantify and cost the potential for reducing sector energy and emissions. Information at the process plant level was sought from primary and secondary sources to characterise in detail the technological structure and status of the sector. Systems employed by the UK *iron & steel* sector were identified and defined in terms of site activity and steelmaking process routes. Process energy analyses and carbon accounting methods were then used to evaluate the wider energy and GHG emissions impact of the industry. Thermodynamic improvement potential of baseline processes was determined and Sankey flow diagrams were constructed to map material [35], energy (see Fig. 4) and exergy losses (presented in the PhD thesis of Griffin [20]). The relative economic viability of the abatement technologies is highly dependent on variable operating costs, which are in-turn subject to fuel and material price fluctuations. The emissions trading price is also influential, though some technological configurations, such as the HISARNA and TGR-BF processes, could provide economic saving without an emissions trading price.

The historical development of the *iron & steel* industry, along with the locations of its process plants, are typically dictated by the availability of nearby resources [e.g., of iron ore and energy (water, charcoal, coal, and subsequently coke)]. Its principal processing sites within the UK have remained in place from the time of the *Industrial Revolution* until well into the present century (see again Fig. 6). Blast furnaces are the most efficient energy conversion process in the sector, but also the largest energy user and a priority target for reducing energy use. Many efficient techniques have not yet been taken up by the sector. These include, among others, heat recovery at the coke ovens, sinter plant, and electric arc furnace, and further heat and gas recovery from the basic oxygen furnace. It was found that the uptake of key BAT for hot-rolling could reduce sector primary energy by 18% and GHG emissions by 12%. Further improvement potential may be available for blast furnace operation by optimising chemical transfer to minimise BFG production. Likewise, improved efficiencies of heat and power facilities could be enhanced via the use of by-product gas. However, the maximum improvement potential of existing technologies falls well short of national and European emission reduction targets.

The sector was modelled for technological change over the period 2010-2050. A range of existing and future technological options from incremental retrofit equipment to radically different process routes were identified and represented at the site level. The use of ‘negative emissions technologies’, such as combining biomass with CCS (i.e., BECCS facilities) [32], could overcome the technical limit on GHG emissions reduction from primary production. Cluster regions of industrial activities have been identified for CO_2 storage under both the North Sea and the Irish Sea are shown in Fig. 6 [2]. Alternatively, net zero carbon could be achieved in the future by combining novel electrolysis methods with a decarbonised electricity supply. Strategic investment in sustainable charcoal and CCU applications would also serve to alleviate the risk of CO_2 emissions from processing, transport and storage technologies. In the absence of charcoal or CCUS, a radical process transition leading to higher scrap use would be required.

Wider resource use efficiency options [13] leading to reduced sector output could play a part in reducing the risk against, and cost of, emissions abatement. This would involve a broad structural shift from energy-intensive manufacturing to energy-frugal services [16]. Decisions made by the final consumer (whether industry, households or government) affect the amount of energy embodied in products and have the potential to influence energy demand [50,51].

Such resource use efficiency improvements are often terms '*circular economy*' (CE) measures, and seek to reorganise products and services by designing out waste, recycling and reusing materials, and thereby minimising their negative side effects [32]. Improvements in resource efficiency has been stimulated in the UK by Allwood *et al.* [50]; albeit with a focus on material use. Cooper *et al.* [51] recently examined the potential for '*putting less in*' {e.g., reducing the content of products (via the use of stronger steels) or reducing losses of material throughout the supply chain (via better yields due to lowering the proportion of steel supplied as steel products to the total amount of steel produced)} and '*getting more out*' (e.g., life extension through the reuse of components, such as steel beams). They collated evidence on specific quantifiable approaches, calculated their combined overall supply chain impacts by way of input–output analysis, and then used thermodynamic analysis to investigate the aggregate effects [32,50]. Several potential CE interventions were examined in a global context, across the *European Union* (EU-27), and in the UK. They found that using CE approaches could significantly improve steel material efficiency, e.g., by reducing yield losses in forming. Such measures resulted in a boost of some 0.6-1.5% for intermediate to maximum technical improvements in UK material efficiency; equivalent to 225 PJ to 290 PJ per annum [51] used directly in the British steel sector. Cooper *et al.* [51] found that generally techniques for '*getting more out*' had greater potential in a UK context than those associated with '*putting less in*'.

In common with earlier studies, the pathways indicate a broad range of possible UK industrial carbon reductions or uncertainties by 2050. In the shorter term, in the period up to around 2020-2030, these will rely on the adoption of existing or currently available technologies. Dyer *et al.* [16] observed that the pathway and priorities over this period are relatively clear. But the prospects for the commercial exploitation of innovative technologies by the middle of the 21st Century are highly speculative. The attainment of the estimated falls in carbon emissions depends critically on the adoption of a limited number of key technologies, e.g., carbon capture & storage (CCS)/carbon capture & utilisation (CCU), energy efficiency techniques, and biomass CHP. Clustering to utilise industrial surplus or 'waste' heat will depend on the possibilities for the co-location of process plant and adjacent 'good quality' end-use opportunities for the recovered heat [1-3,32,45] (see again Fig. 6). The vision of the main UK manufacturer (*Tata Steel*) is most reflected in the RA roadmaps. They were one of the founder signatories of the ULCOS programme, and is co-developing the HISARNA concept at its Ijmuiden site in the Netherlands [47]. It has also signalled interest in *top gas recycle blast furnace* (TGR-BF) technology. However, the likelihood of CCS being deployed at scale and in time for the UK sector is uncertain. This is not least because *Tata's* Port Talbot site is not located within the priority industrial cluster areas so far identified for CO_2 transport infrastructure (see Section 4.2 and Fig. 6). Several European steelmakers have recently initiated projects on fossil-free production {e.g., based on hydrogen via renewable electrolysis (such as H_2-based DRI) [52]} A range of policy and financial instruments are clearly going to be required in order to implement these decarbonisation strategies.

There is a growing body of international guidance on the type of policy instruments needed to encourage the take-up of industrial decarbonisation measures [32]. Policy approaches will be required to support research, development, demonstration and deployment in order to stimulate near-zero-CO_2 basic materials (such as *iron & steel*) and novel, pre-commercial mitigation technologies in the future, although they may need international agreements, particularly on climate change, to offset the constraints of global, price-competitive markets [11,14,15]. Decarbonisation options for basic materials processing offer little by way of 'co-benefits' [11], and these technologies often give rise to significant additional costs. Napp *et al.* [14] therefore advocated 'carbon pricing', subsidies and other economic instruments to incentivise fuel-switching and low-cost efficiency measures. They also foresaw the need for energy and GHG emissions monitoring systems; something that has been taken up as part of the BEIS *Streamlined Energy and Carbon Reporting* (SECR) proposals [42]. Åhman *et al.* [53] also argued in favour of the use of public funds to finance the up-scaling and demonstration of new low-carbon dioxide technologies in order to share the risks. That is perhaps something that is more acceptable in a northern European context than in Britain [32]. In any event, much still needs to be done on both the technology and policy development fronts in order to reduce significantly the CO_2 emissions of UK industry by 2050.

ACKNOWLEDGEMENTS

This is an extended and updated version of a paper originally presented at the *10th International Conference on Applied Energy* (ICAE2018) held in Hong Kong over the period 22-25 October 2018 (denoted then as paper ICAE2018-560). The work reported forms part of a programme of research at the University of Bath on industrial decarbonisation that has been supported by a series of UK research grants and contracts awarded by various bodies associated with the *UK Research and Innovation* (UKRI) *Energy Programme* for which the second author (GPH) was the holder. Research reported here originally formed a part of the 'core' research programme of the *UK Energy Research Centre* (UKERC); Phase 2 [under Grant NE/G007748/1]. The first author (PWG) undertook his contribution to the present work as part of a UKERC flexible funding project entitled '*Industrial Energy Use from a Bottom-up Perspective*' [for which the second author (GPH) was the *Principal Investigator*]. The second (GPH) author continues to work in the field of industrial energy use and carbon emissions reduction supported by the UK *Engineering and Physical Sciences Research Council* (EPSRC) 'End Use Energy Demand' (EUED) Programme, as part of the *Centre for Industrial Energy, Materials and Products* (CIE-MAP) [under Grant EP/N022645/1], as one of its Co-Directors.

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