The influence of UK emissions reduction targets on the emissions of the global steel industry

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Abstract

The steel industry is the world's largest industrial source of CO_2 emissions. Recent UK economic policies have led to reduced domestic steel production giving an apparent reduction in national emissions. However, demand for goods made from steel has not reduced. Emissions have thus been transferred not reduced and implementation of UK climate policies may in future expand this 'carbon leakage.' This paper explores how future UK demand for goods made from steel might be supplied while satisfying national climate policies, and how this will influence global CO_2 emissions. Current flows and stocks of steel are estimated from existing databases. Evidence from other developed economies suggests that per capita stocks are tending towards a saturation level so future demand is forecast from population growth and the expected rate of replacement of a stable stock. The carbon intensities of five different steel-making routes are used to predict the allowed scale of future domestic steel production within the industrial emissions allowances set in four energy pathways defined by the UK Government. The remaining requirement for steel must be sourced offshore and the associated emissions are predicted, to give an estimate of the global emissions arising from final demand in the UK. The results show that current UK climate strategy may have a limited effect in reducing the CO_2 emissions of the global steel industry, unless the UK shifts towards producing more of its own steel products with domestic secondary steel-making. This option would also increase the security of UK supply and support an expansion of UK manufacturing.

Keywords: steel; emissions; climate targets; United Kingdom.

1 Introduction

Despite decades of effort to reach world-leading levels of energy-efficiency, the steel industry is still the world's largest industrial source of carbon dioxide emissions, mainly due to the requirement for coal to convert ore into molten iron (Allwood *et al.*, 2012). According to the World Steel Association (2014), global crude steel production has soared over the last decade from 904 Mt in 2002 to 1559 Mt in 2012, despite the 2008 financial crisis. Global average steel consumption per capita is therefore rising at 3.6% per year (Gutowski *et al.*, 2013a). The carbon emissions of the steel industry have accordingly grown over the same period, from around 1.6 to 2.8 Gt CO_2, amounting to around 25% of industrial emissions.

Napp *et al.* (2014) identify two conventional strategies for reducing CO_2 emissions in the steel industry: (i) switching to more efficient production routes; (ii) increasing the efficiency of current routes, e.g. via fuel switching or widespread adoption of best available technologies. However, Allwood *et al.* (2010) estimate that a worldwide implementation of efficiency improvements cannot deliver the energy and emissions savings needed to meet emerging emissions reduction targets, so material efficiency and demand reduction strategies will also be required. This has been confirmed by Gutwoski *et al.* (2013a,b).

The stock of steel embedded in end-use products grows with the net accumulation of inflows of new goods less the outflows of goods scrapped at end-of-life. Pauliuk *et al.* (2014) link steel stocks to the provision of services, thus giving better insights into opportunities for material efficiency. This is particularly important for steel-intensive goods which have a long life, but when recycled offer significant energy and carbon savings compared with primary production. Hu *et al.* (2006) identify the importance of increased steel recycling to reducing carbon emissions, while noting that limited scrap availability and quality may constrain the use of secondary steel.

The UK Government has committed to a target of reducing its territorial greenhouse gas (GHG) emissions to 80% of 1990 levels, by 2050. This commitment has important implications for UK industries, since in 2007 the industrial sector was responsible for 25% of UK direct emissions and 27% of final energy uses (HM Government, 2013a, b). The UK steel industry emitted 16% of all direct industrial GHG emissions in 2007, not counting the emissions associated with the use of electricity.

Previous analyses predict that climate policies may lead to a significant relocation of energy-intensive industries (such as steel making) away from OECD countries, but this may result in higher global emissions (Babiker, 2005). For the UK, further dependence on imported steel (carbon leakage) could lead to increased imports from countries with less stringent climate policies. Current evidence on direct steel trade suggests that carbon leakage in the EU steel sector is already occurring, but recognises the lack of data on steel contained in imported and exported end-use products (ECORYS, 2013).

Several estimates have been made of the potential for energy and emissions reduction in the steel industry in various countries, for example by Gielen *et al.* (2002) for Japan and Chen *et al.* (2014) for China. Pardo *et al.* (2013) have forecast the energy requirements and emissions of the European steel industry until 2030, incorporating the implementation of breakthrough steel-making technologies. These analyses provide compelling examples of the effect of changes in the energy system and the technology of steel-making on emissions. However only one of them considers the impacts on global emissions, and none examines the consequences of climate policies with a focus on the demand for steel goods.

This paper develops an estimate of the global emissions associated with future demand for steel in the UK, subject to four possible pathways for the development of the UK energy system. The focus of this analysis is the demand for goods that contain steel ("steel goods" such as buildings, vehicles and equipment) but, as steel is widely traded, the performance of steel producers both in the UK and elsewhere must be considered.

2 Current and future supply of steel to the UK

This section begins with an examination of the flows of steel required to supply steel goods to the UK today followed by a prediction of future demand, based on stock dynamics. The emissions intensities of five technology options for future steel production are defined, and emissions allowances for steel production calculated according to four pathways for the energy system.

2.1 Current flows and stocks of steel

Previous analyses of the flow of steel through the UK have estimated the production required to deliver final demand, and accounted for trade flows. Michaelis *et al.* (2000) examined material flows within the steel sector from 1954 to 1994, estimating energy requirements for the conversion of raw materials to final goods. Geyer *et al.* (2007) and Davis *et al.* (2007) examined both the production flows of steel and the end-of-life scrap generated from 1970 to 2000. These analyses also provide an estimate of the annual additions to the stock of steel. Dahlström *et al.* (2006) updated this analysis for 2001. Wang *et al.* (2007) presented a database of steel flows in 2000 comprising the production, fabrication, manufacturing, use, waste management, and recycling stages for 68 countries, including the UK.

These analyses provide context for this paper, but do not account for activity in other countries required to satisfy domestic demand for steel goods, and do not integrate material flows with stocks of steel. An estimate of the global flow of steel required to meet demand for steel goods in the UK is therefore developed. Accounting for additions to stock by new purchasing and removals from stock at end-of-life for recycling allows an estimate of the total stock. The reference year is 2007, chosen as the most recent year with available data and without global economic recession.

2.1.1 Methodology and data

The UK has a rich history of detailed steel statistics at different stages of the supply chain. Our estimate of UK steel flows has been developed as follows:

- The flow of steel through different production routes was obtained from the 2007 assessment by Griffin *et al.* (2013).
- ISSB (2008) provided 2007 data for production and trade of steel goods, direct sales of steel to manufacturing industries by product and industrial sector, and steel contained in imported goods.
- Steel contained in exported goods was estimated from HMRC (2014) data by product type for 2007, with the steel content by product category taken from Dahlström *et al.* (2004).

The allocation of steel to final product categories requires many data sources. ISSB (2008) provides detail for UK manufacturers purchasing steel through direct purchases from domestic steel producers, but does not provide equivalent detail for purchases from stockists or imports. However, Moyniham *et al.* (2012) provide an estimate of the use of steel in UK construction in 2006 , so the same allocation was assumed for 2007. For the remaining product categories, the composition of end-use products estimated by Dahlström *et al.* (2004) was used.

Unlike those for steel production and trade, statistics on scrap arisings are scarce. However, Dahlström *et al.* (2004) have estimated recycling rates by product category. In addition, ISSB (2008) provides statistics on UK scrap exports, stock changes, and scrap consumption by the UK steel industry. Therefore, total scrap arisings have been estimated by summing the net exports and consumption in the steel industry and dividing by the recycling rate estimated by Dahlström *et al.* (2004). Pre-existing UK steel stock was estimated from the per capita stock figures of Pauliuk *et al.* (2013b). The activity of steel producers and industrial manufacturers in other countries required to supply imports of finished steel products and imports of steel contained in manufactured goods was assumed to be proportional to the global flows provided by Cullen *et al.* (2012) for 2008.

2.1.2 Results

In 2007, UK industry produced 15 Mt of steel and UK consumers purchased 20 Mt of steel goods, 13 Mt of which were imported (Figure 1). These intense trade flows reflect business options across different stages of the supply chain. In the UK, the automotive industry exemplifies the discrepancy between trade and domestic end-use consumption: around 80% of the vehicles assembled in the UK are exported, most of them manufactured with imported steel (SMMT, 2014). Such trade flows justify the need to look at both UK and the rest of the world steel activity, since the performance of both influences the overall impact of demand for steel goods.

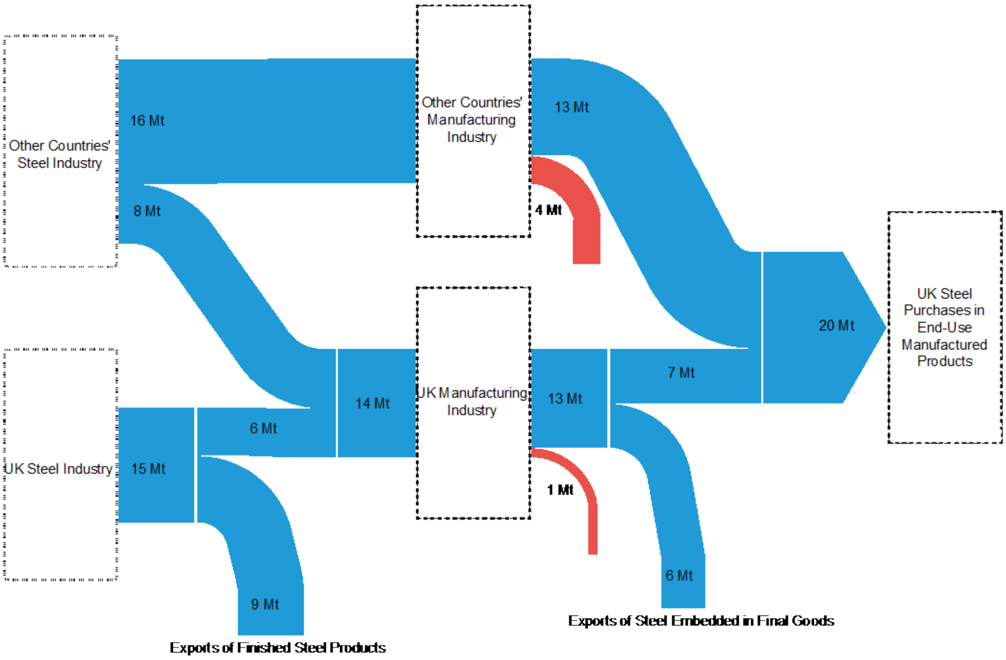

Figure 1. UK and rest of the world activity to supply steel goods to the UK in 2007. Red flows represent fabrication scrap. Due to rounding errors inflows and outflows may not appear equal.

Figure 2 shows the global material flows required to deliver steel goods to the UK in 2007. The right side of Figure 2 shows that 20 Mt of steel was added to stock. Grey lines represent the flows of steel produced by the UK steel industry. Delivering this 20 Mt of steel goods required production of 28 Mt of liquid steel in the UK or elsewhere. Only 17% of this (3.3 Mt) was produced in the UK, of which 79% came from primary production in basic oxygen furnaces (BOF) (using 84% hot metal from blast furnaces (BF) and 16% scrap), and 21% from secondary production in electric arc furnaces (EAF) (using 5% hot metal from BF and 95% scrap).

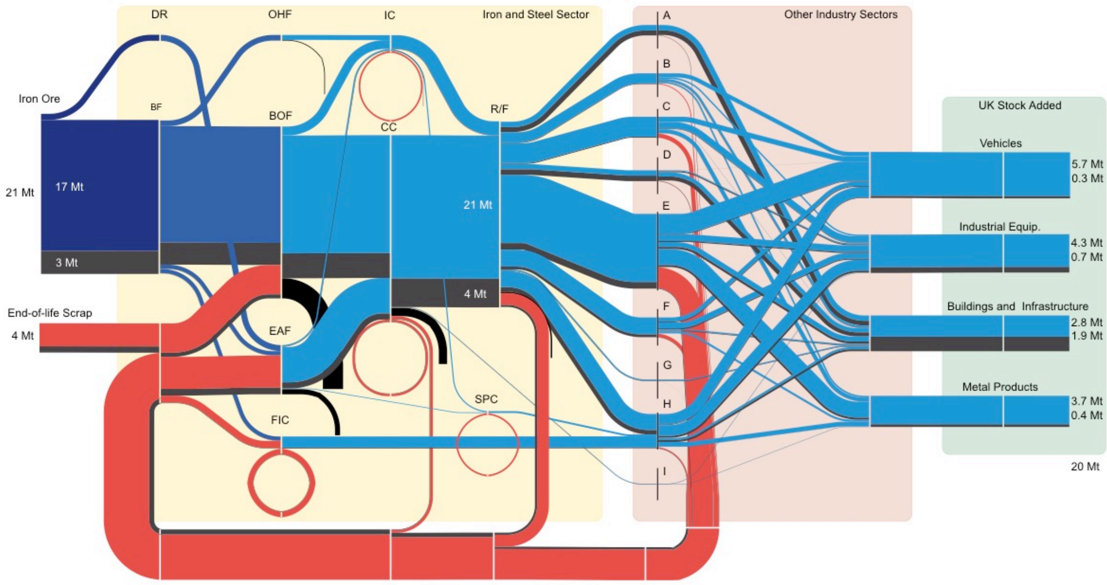

Figure 2. Iron and steel flows required to supply steel goods to the UK in 2007. The width of each flow is proportional to the mass flow. Grey areas represent the mass flows produced by the UK steel industry. Blue / red areas represent the iron and steel / scrap mass flows in the rest of the world required to supply UK demand. Production processes: DR: direct reduction; BF: blast furnace; OHF: open-hearth furnace; BOF: basic oxygen furnace; EAF: electric arc furnace; FIC: foundry iron casting; IC: ingot casting; CC: continuous casting; SPC: steel product casting: R/F: rolling / forming. Finished and semi-finished steel products: A: Rods and bars for reinforcement; B: Rods in coil; C: Hot rolled bars and lengths; D: Heavy sections, sheet piling, rails, and rolled accessories; E: Sheets; F: Plates in coil and in lengths; G: Light sections; H: Tubes, pipes, and others; I: Ingots, blooms, billets, and slabs.

In total, 24% (6 Mt) of the liquid steel produced to supply UK demand is scrapped during process and fabrication stages and internally recycled. This yield loss is higher (around 30%) for sheet steel, which is rolled into constant width coils and then cut to shape during fabrication. At present, process and fabrication scrap (6 Mt) exceeds net end-of-life scrap (4 Mt).

Figure 3 shows the flow of steel into stocks of four categories of steel goods. Steel flows in the green box are the gross additions to stock from Figure 2. The net additions to stock were estimated by subtracting the removals in the red box in Figure 3 from the inflow of new goods. Net additions were around 7 Mt of steel in 2007, mainly buildings and infrastructure (3 Mt) and vehicles and metal goods (around 2 Mt each). Industrial equipment seems to exhibit a steady state with new steel added at the same rate it is retired. These estimates indicate that 9 Mt of end-of-life scrap were collected in the UK, around two thirds of which was exported.

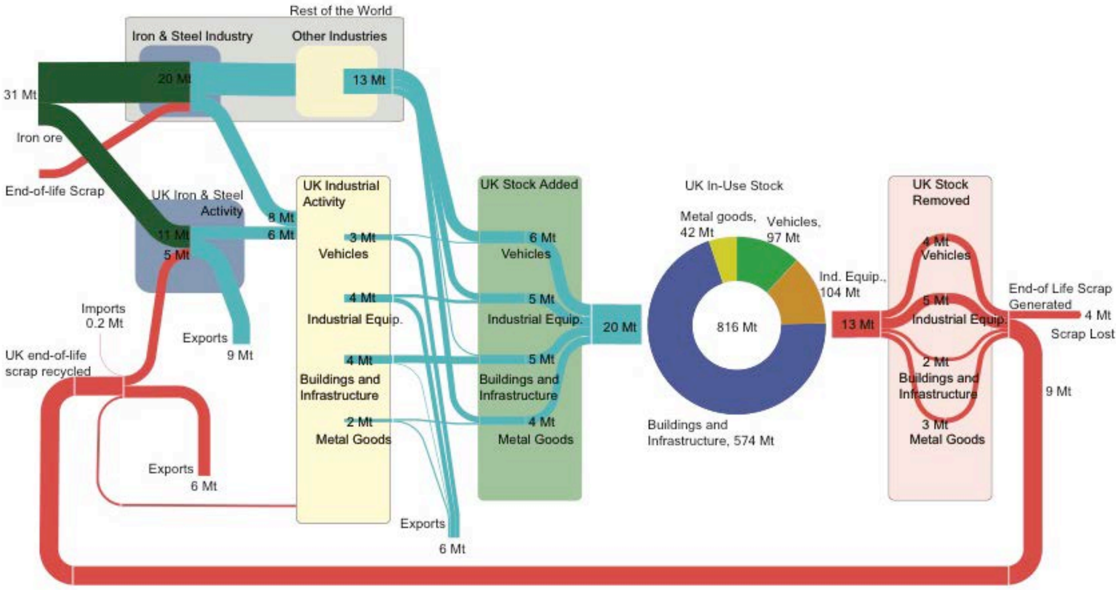

Figure 3. Summary of additions and withdrawals to the stock of steel goods in the UK by product category in 2007. Blue / red arrows represent the steel / scrap mass flows, respectively. Green arrows represent iron in iron ore flows.

Figure 3 shows that most UK steel production is exported, as is most of the scrap collected in the UK, and that most of the steel contained in products purchased in the UK was made elsewhere. Consequently, changes in the emissions intensity of UK steel production have relatively little impact on the total emissions caused by UK purchasing (calculation details can be found in the supplementary information file - Table 5). The scope for reducing dependence on steel imports and for increasing the use of domestic scrap, whilst reducing global CO_2 emissions, depends on the future configuration of the steel industry and energy sector. Some options to explore this scope are examined in the next sections and their consequences for global CO_2 emissions are assessed.

2.2 Estimating steel demand in 2050

Pauliuk *et al.* (2013a) developed a dynamic in-use stock model to estimate future demand for steel and available scrap arisings, predicting that the stock of steel in Western Europe should reach a saturation level by 2030 at around 13 tonnes per capita. If this is the case, steel demand in 2050 would comprise that required to replace end-of-life disposals plus that required by population growth. The rates of steel goods replacement and population growth therefore determine the demand for new steel products.

The Office for National Statistics (ONS, 2013) projects a growth in the UK population from 61.4 million in 2007 to 77 million in 2050, when the growth rate is expected to be around 300 thousand inhabitants per year. Thus, per capita saturation stocks $\left(\frac{S_i}{P}\right)$ and product average lifetimes (L_i), estimated by Pauliuk *et al.* (2013a), along with annual population growth rates (ΔP) allow an estimate of the demand for new steel added to stock $(S_{+,i})$ for each product category i, according to Eq. (1). Assuming that the yields (η_i) of production for each product category remain constant (at the rates shown in Figure 2), the corresponding demand for crude steel in 2050 can be predicted for each product category $(D_{CS,i})$, by eq. (2), as shown in Table 1.

$$S_{+,i} = \frac{S_i}{L_i} + \frac{S_i}{P}\Delta P \qquad (1)$$

$$D_{CS,i} = \frac{S_{+,i}}{\eta_i} \qquad (2)$$

Table 1. Estimate of UK demand for crude steel in 2050.

Product categories	Saturation stock [tonnes per capita] (Pauliuk *et al.*, 2013a)	Average lifetime [years] (Pauliuk *et al.*, 2013a)	Demand for new steel additions to stock [Mt]	Demand for crude steel [Mt]
Vehicles	1.3	20	5.4	7.4
Industrial equipment	0.9	30	2.6	3.4
Buildings and infrastructure	10.0	75	13.3	16.4
Metal goods	0.6	15	3.3	4.6
Total	12.8		24.5	31.7

2.3 Steel production technology options

Iron ore reduction in blast furnaces is the process most responsible for energy use in steel making, so efficiency improvements are strongly dependent on this process (Gutowski *et al.*, 2013b). From the flow analysis presented in subsection 2.1, 81% of the iron used to deliver steel goods to the UK is produced in blast furnaces from iron ore, 3% is direct reduced iron, and only 16% is recycled from scrap. In contrast, for steel produced in the UK, two thirds comes from blast furnaces, with one third from scrap.

New technologies such as direct reduction of iron can reduce CO_2 emissions, because coke is substituted with natural gas. This technology is not currently deployed in the UK, but is already used elsewhere. The International Energy Agency (IEA, 2009) identifies further options for iron-making including smelt reduction processes and the use of alternative energy resources, but most of these are still in an early stage of development. Amongst the most promising alternatives are FINEX, HIsmelt, and HISarna, which may improve carbon and energy intensities, although they still require further development before widespread deployment (IEA, 2009, 2010; Fischedick *et al.*, 2014; IEA, 2014). However, these options depend also on the development of CO_2 capture and storage (CCS). It is unclear to what extent CCS can be deployed in the near future, given the risks and deployment barriers diagnosed by Bruckner *et al.* (2014) and the absence of commercial large-scale experience.

Recycling steel scrap in electric arc furnaces, has much lower carbon intensity than primary steel making, and is already practised in the UK. However, the potential deployment of this secondary production route is constrained by the availability of scrap (Oda *et al.*, 2013). Recycling at present is also inhibited by problems with end-of-life scrap quality and contamination. Reck *et al.* (2012) claim that despite significant potential for improvements in recycling efficiency, practical recycling rates of metals will be constrained by these problems and consequently a truly closed-loop system for metal will remain infeasible for several decades.

Only three technologies for steel making are likely in the near future: blast furnaces, direct reduction and scrap recycling. The balance of future deployment of these three technologies in UK steel making will evolve in response to global competition, investment decisions, environmental policies, the evolution of the energy sector, and many other economic variables. Given uncertainty about these drivers, five scenarios for the future mix of production technologies used in the UK steel industry in 2050 are proposed in Table 2. Scenario A assumes the same mix of production routes used in 2007. Scenario B uses only primary production, with the current shares of iron sources for BOFs. In scenario C steel is only produced in electric arc furnaces fed with the current shares of scrap and pig iron. Scenario D, with half the crude steel produced by the scrap/DRI-EAF route, requires 75% of the feedstock as scrap. Scenario E using only the Scrap/DRI-EAF route alone, requires that the EAF is fed by equal amounts of DRI and scrap.

Table 2. Definition of scenarios of UK crude steel production in 2050 by share of iron sources. BF: blast furnace; BOF: basic oxygen furnace; EAF: electric arc furnace; DRI: direct reduced iron.

UK crude steel production scenarios		**A**	**B**	**C**	**D**	**E**
Iron sources	Steel-making routes	BOF;EAF	BOF	EAF	EAF	EAF
Hot metal from BF	BOF	67%	84%	5%	–	–
DRI	EAF	–	–	–	25%	50%
Scrap	BOF;EAF	33%	16%	95%	75%	50%

2.4 GHG emissions allowances

To achieve its commitment to reduce emissions, to 80% of 1990 levels by 2050, the UK Government has developed a Carbon Plan, with four possible pathways for the energy system (HM Government, 2011). These pathways summarised in Table 3 all anticipate a significant reduction of final energy use by industry by 2050, but with different configurations of the energy sector. Further details can be found in the supplementary information as summarised in Table 5.

Table 3. Energy pathways defined by the Carbon Plan (HM Government, 2011).

Pathways	Description
CoreMARKAL	Central energy pathway generated by the UK MARKAL energy model (AEA, 2011). It considers a mix of technologies and resources that deliver the overall minimum system cost. Postulates the decarbonisation of the electricity generation in the UK and the use of CCS technologies.
Higher carbon capture and storage (CCS), more bioenergy	Postulates a higher deployment of CCS technologies than in the CoreMARKAL pathway. It considers higher use of bioenergy across all sectors.
Higher renewables, more energy efficiency	Postulates a higher deployment of renewable electricity generation technologies than in the CoreMARKAL pathway. It considers stricter energy efficiency targets to the UK industry, resulting in less GHG emissions allowed to industry than in the CoreMARKAL pathway.
Higher nuclear, less energy efficiency	Postulates a higher deployment of nuclear energy in the UK than in the CoreMARKAL pathway. It considers that most of the energy efficiency gains will take place in transports and buildings, resulting in a relaxation of energy use targets imposed on industries.

The Carbon Plan includes specific goals for GHG reductions in the metals industry, achieved by a combination of shifting energy demand to low carbon energy vectors and increased efficiency in energy use across the industry. Since the analysis of the feasibility of the Carbon Plan trajectories for the metals sector is out of the scope of this work, the CO_2 emissions limits are used only as targets against which the different scenarios of UK steel production outlined in Table 2 are tested.

The emissions of the UK steel industry in 2050 were predicted using the industry sector energy configurations as implemented in the Carbon Calculator developed by DECC (2014). Since industry is only disaggregated to the level of the whole metals sector, an additional assumption for the share of final energy available to the steel industry in 2050 was made at 66% of the total final energy of the metals sector (which was the share in 2007) in order to calculate the emissions allowances for the steel sector in 2050. These are shown in Table 4.

Table 4. UK electricity emissions savings, and final energy demand and CO_2 emissions allowances for the UK steel industry in 2050 for each of the Carbon Plan pathways (defined in Table 3).

	CoreMARKAL	High CCS, more bioenergy	High renewables, more energy efficiency	High nuclear, less energy efficiency
Electricity emissions savings [gCO_2/kWh]	91	138	57	17
Final energy demand allowance [TWh]	23.9	23.9	23.9	30.7
Emissions without CCS in industry [$MtCO_2$]	15.5	15.2	16.0	55.6
Emissions with CCS in industry [$MtCO_2$]	21.1	20.8	21.6	55.6

Table 4 shows that the allowances for CO_2 emissions in 2050 are similar for most of the Carbon Plan pathways. The notable exception is the "Higher nuclear, less energy efficiency" pathway that envisages more ambitious energy efficiency targets for transport and buildings, so gives a less restrictive target to industry. The combination of the emissions allowances for the pathways in Table 4 and the technology scenarios of Table 2 are examined in Section 3.

Table 5. Methodological details included in the supplementary information file.

Supplementary information file – section	Description
1. The Carbon Plan and energy pathways for the UK	This section provides detailed information on the Carbon Plan that has been developed by the UK Government to achieve a low carbon economy. This includes the four energy pathways considered in the Carbon Plan and the current and future final energy uses by energy vector for the metals industries.
2. UK steel flows	This section reports the estimate of UK steel flows in 2007. It shows all values behind the Sankey diagram of Figure 2.

3 Forecasting production, imports, and emissions associated with demand for steel goods in the UK

The previous section defined a method to estimate the scale of steel demand, the structure of the UK steel industry and its allowed carbon emissions. This section predicts the carbon emissions intensities of steel production for each combination of technology scenarios and energy pathways (section 3.1). The impacts of each of these combinations on steel trade (section 3.2) and global emissions (section 3.3) follow.

3.1 UK steel production and emissions intensity

Milford *et al.* (2013) developed a method to estimate the carbon intensity of steel production, taking into account every stage of the production process and the carbon intensity of the electricity mix used in the production process. This method was used to estimate carbon intensities by technology scenario and energy pathway, assuming widespread deployment of best available practices and taking into account the different levels of electricity decarbonisation in each pathway as shown in Table 6. Details of these calculations are provided in the supplementary information (Table 9).

Table 6. Estimate of carbon intensities for the UK steel industry in 2050 [t CO_2 / t crude steel].

Crude steel production scenarios	CoreMARKAL	High CCS, more bioenergy	High renewables, more energy efficiency	High nuclear, less energy efficiency
A: Current Scrap / BF – BOF	1.8	1.8	1.8	1.8
B: BF – BOF	2.2	2.2	2.2	2.2
C: 95% Scrap – EAF	0.1	0.1	0.2	0.2
D: 75% Scrap / 25% DRI – EAF	0.5	0.5	0.5	0.5
E: 50% Scrap / 50% DRI – EAF	0.9	0.8	0.9	0.9

Estimated carbon intensities (Table 6) and emissions limits for each energy pathway (Table 4) can now be used to estimate allowed crude steel production in the UK for each technology scenario. However, besides limits on CO_2 emissions, scrap availability may also constrain steel production. Secondary steel production routes only produce a small fraction of crude steel production, so scrap used in electric arc furnaces (EAF) is primarily well-controlled process scrap that occur inside steel plants. Alloy contamination in less controlled end-of-life scrap may be dealt with by increasing the share of process scrap in EAF. If secondary production from scrap increases, there may be insufficient process scrap for this purpose, so the potential for deploying scenarios C, D, and E may be restricted by domestic scrap availability.

Domestic scrap availability in 2050 (S_a) may be estimated by eq. (3). It is assumed that the stock of steel in the UK has saturated, so scrap arisings should equal the demand for new steel (S_+). Available scrap (S_a) comprises end-of-life steel goods collected for recycling ($\varepsilon\, S_+$) plus the process $\left(S_p\right)$ and fabrication $\left(S_f\right)$ scrap arisings from the UK steel and manufacturing industries. Table 7 shows the results.

$$S_a = \varepsilon\, S_+ + S_p + S_f \tag{3}$$

Table 7. Calculation of available scrap in the UK in 2050.

	Variable	Value
S_+:	Demand for new steel additions to stock [see Table 1 of the article]	24.5 Mt
	End-of-life scrap arisings	24.5 Mt
ε:	Recycling rate	90 %
S_p:	Process scrap arisings [see yield losses presented in the SI file]	3.3 Mt
S_f:	Fabrication scrap arisings [see yield losses presented in the SI file]	4.6 Mt
S_a:	Available scrap	29.9 Mt

The results of this section can now be used to predict the future composition and emissions of steel production in the UK. However, one further element of calculation developed in the next section is to consider the emissions of steel production outside the UK required to satisfy demand for steel goods.

3.2 Steel imports and their emissions intensity

Figure 4 shows the domestic production and required imports of crude steel for each technology scenario and energy pathway. The green bars indicate crude steel production in the UK and are obtained by dividing the UK steel industrial emissions allowances in Table 4 by the UK emissions intensities in Table 6, subject to scrap availability in the UK (Table 7). The blue bars show the import requirements estimated by subtracting the estimate of domestic production from estimated demand (31.7 Mt – Table 1) for each combination of scenario and energy pathway. Imported steel CO_2 emissions are estimated assuming the global average factor of 1.1 t CO_2 / t crude steel estimated by Allwood *et al.* (2010) for 2050. The estimate of net import requirements does not consider the intermediate steel imports and exports shown in Figure 1, but only overall import requirements, assuming that all UK produced steel is used domestically. As a consequence, the results show that making more use of UK steel reduces global emissions, as the average carbon intensity of steel-making in other countries would be higher than that in the UK.

For most energy pathways, Figure 4 shows reduced imports of crude steel if secondary steel-making expands, with a consequent reduction in emissions intensity. For the “Higher nuclear, less energy efficiency” pathway, higher emission allowances lead to increased domestic crude steel production and reduced steel imports. A transition to a production mix with 50% from direct reduced iron and 50% from scrap in EAFs (shown in scenario E) reduces the constraint of scrap availability and domestic crude steel production could exceed demand, leading to net exports from the UK.

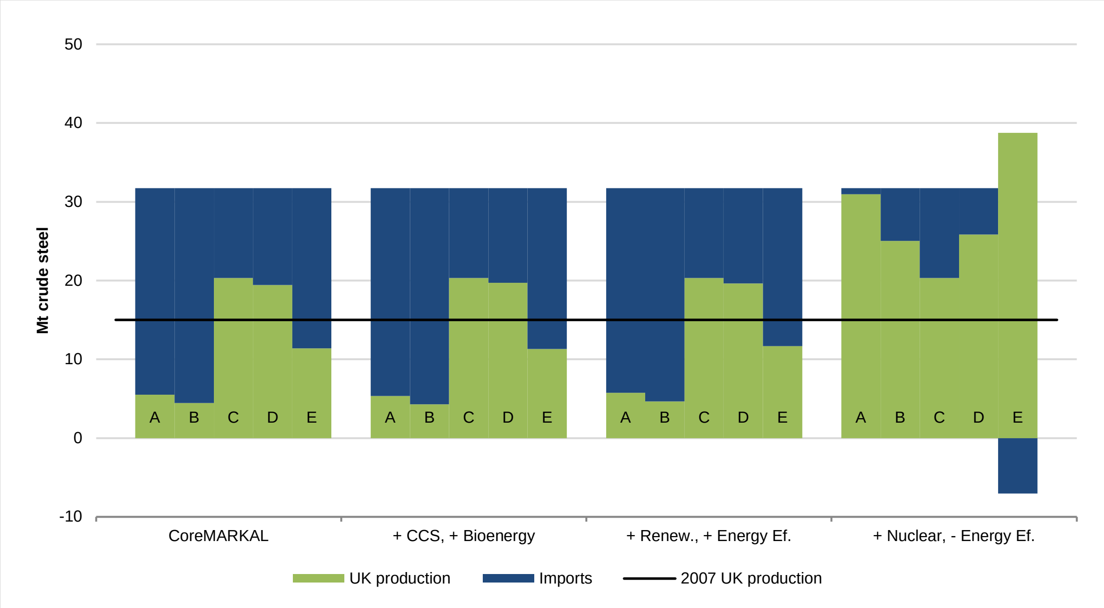

Figure 4. Estimated origin of UK crude steel supply in 2050.

3.3 Global CO_2 emissions to supply future UK demand for steel

Global emissions for meeting UK demand for steel in 2050 are estimated for each combination of energy pathway and technology scenario. A sensitivity analysis was performed to examine the effect of variations in the following four parameters:

- the use of carbon capture and storage technologies (CCS) in the UK steel industry subject to the limits estimated in the DECC Calculator for each energy pathway;
- the level of electricity decarbonisation;
- the share of available end-of-life scrap used for secondary steel-making, provided that the quality of scrap used as feedstock does not compromise the quality of crude steel produced;
- the average lifetime of steel goods.

Table 8 shows the different levels of these four parameters considered in this analysis. Figure 5 to Figure 8 show estimated global CO_2 emissions, subject to variations of these four parameters. All the values behind these figures are presented in the supplementary information file (Table 9). In Figure 6 to Figure 8 green bars represent the best-case options and blue, yellow and red represent additional emissions that would occur if the given restrictions were applied. The emissions of UK steel production are also represented in these graphs with a cross. The parameters kept constant in each graph are shown in grey in Table 8.

Table 8. Parameters examined in the sensitivity analysis.
Levels in grey were kept constant for each individual parameter variation.

CCS in the UK steel industry	Level of electricity decarbonisation	Share of end-of-life scrap used	Product lifetimes
Yes	Same level as in 2007	100%	+50%
No	Same level as predicted for 2020	75%	+20%
	Same level as predicted for 2030	50%	Baseline as in Table 2
	Same level as predicted for 2050	25%	-20%

Figure 5 to Figure 8 show that maintaining the current mix of production technologies or shifting to more primary steel-making with BF leads to higher global CO_2 emissions (scenarios A and B). These emissions are generally around 20% less than in 2007, but are 20% higher for the "Higher nuclear, less energy efficiency" pathway. Global CO_2 emissions are reduced for those scenarios that anticipate a higher share of scrap as iron source (scenarios C, D, and E).

The use of CCS in the UK steel industry would contribute to the reduction of CO_2 emissions from energy uses other than electricity. Figure 5 shows a greater potential for emissions savings due to CCS where steel production in the UK is higher and the fraction of production from scrap is reduced (scenarios D and E). The "Higher nuclear, less energy efficiency" pathway assumes that there is no use of CCS technologies in industry.

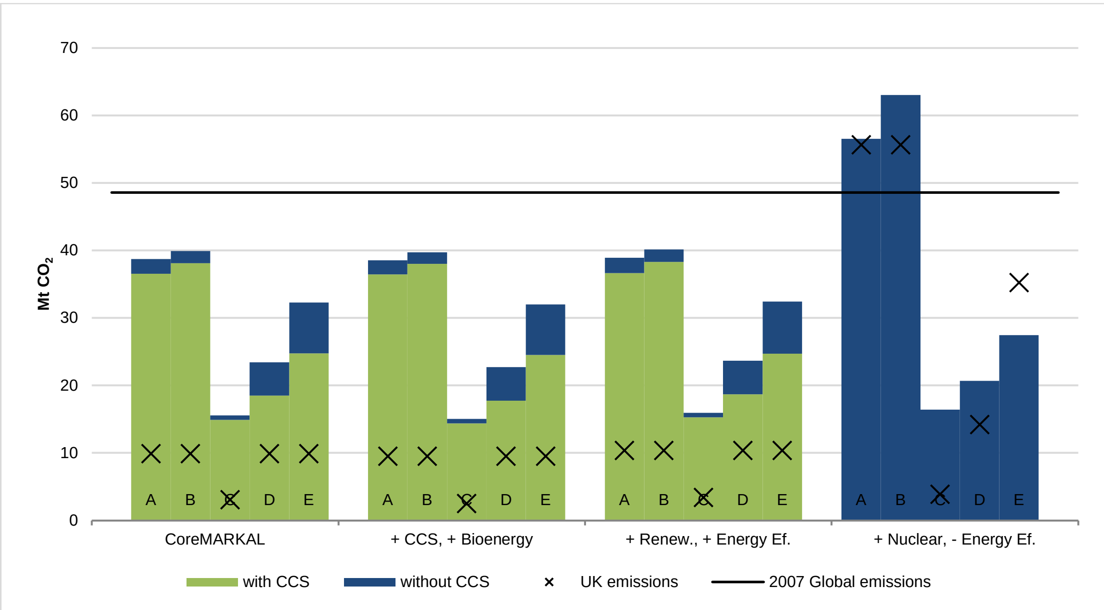

Figure 5. Total CO_2 emitted to supply the UK demand for crude steel in 2050, subject to the use of CCS technologies in the UK steel industry.

Global emissions reductions from different levels of UK electricity decarbonisation (Figure 6) arise only from electricity uses. For any energy pathway, the more electricity used in steel production, the higher the potential emission savings from electricity decarbonisation (scenarios C, D, and E).

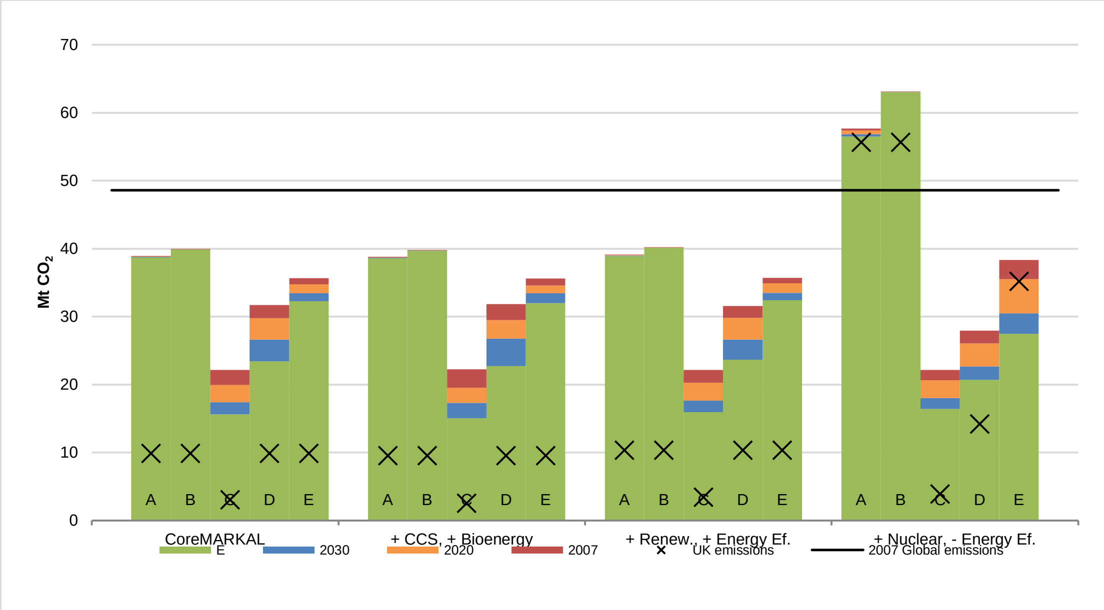

Figure 6. Total CO_2 emitted to supply the UK demand for crude steel in 2050, subject to the level of electricity decarbonisation in the UK.

For some scenarios, UK steel production is limited by the availability of domestic end-of-lfe scrap. This is the case of scenarios C and D, for which a decrease in the share of end-of-life scrap used for steel production would require more imports and hence more global emissions (Figure 7).

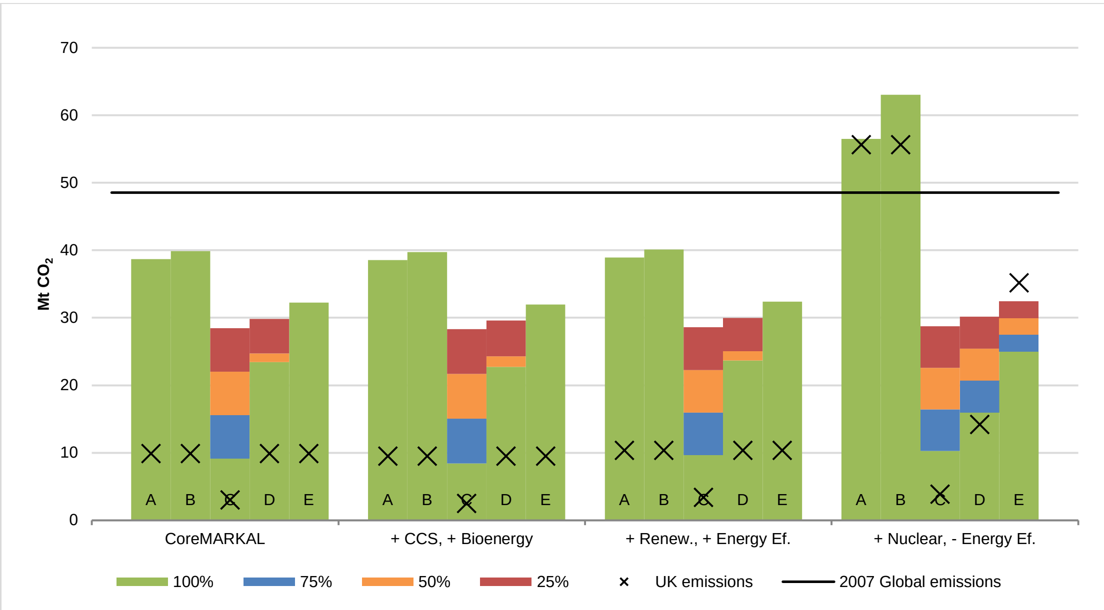

Figure 7. Total CO_2 emitted to supply the UK demand for crude steel in 2050, subject to the share of end-of-life scrap used in UK secondary steel-making routes.

Figure 8 shows emissions savings from increasing the lifetimes of steel goods. Product lifetime extension leads to reduced demand for crude steel. A decrease in product lifetimes would result in global emissions similar or above current levels, if steel production remains mainly dependent on primary steel-making using BF (scenarios A and B).

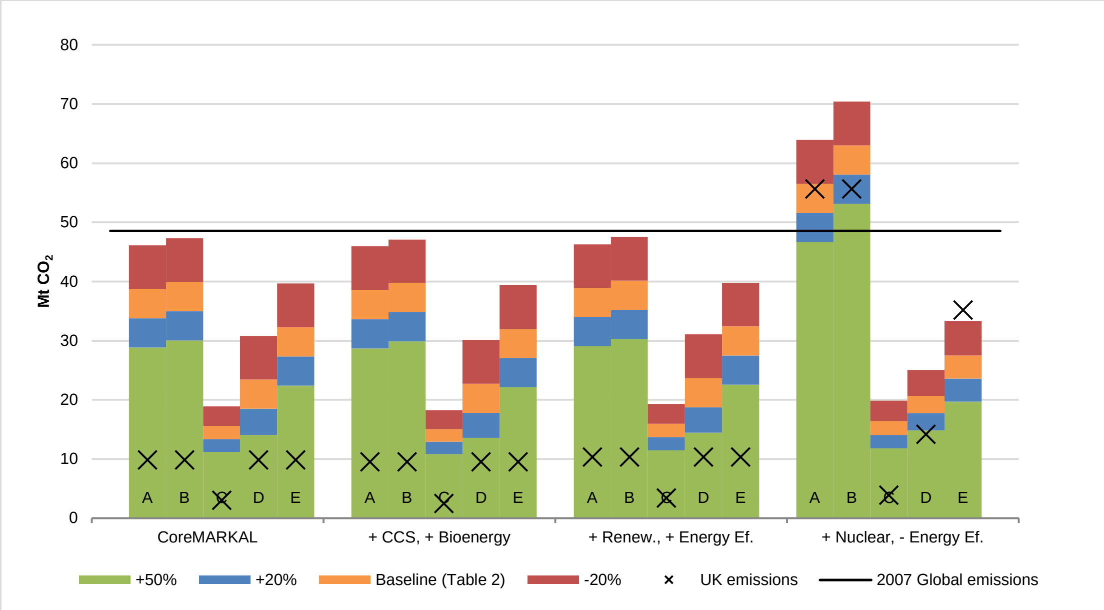

Figure 8. Total CO_2 emitted to supply the UK demand for crude steel in 2050, subject to different levels of average product lifetime.

Table 9. Detailed results included in the supplementary information file.

Supplementary information file – section	Description
3. Steel production carbon intensities	This section presents the intermediate results and calculation details of the estimated carbon intensities of steel production for each combination of steel-making route and energy pathway shown in Table 6.
4. UK steel supply: sensitivity analysis	This section presents the detailed results of the sensitivity analysis obtained for each steel-making route and energy pathway, varying the levels of electricity decarbonisation in the UK, the share of end-of-life scrap used in the secondary steel-making routes, average products' lifetime, and the use or not of CCS technologies.

4 Discussion

The results of this paper suggest the following key findings:

- The UK Carbon Plan (HM Government, 2011) will have limited or no effect in reducing global carbon dioxide emissions from the steel industry, unless UK steel production shifts towards secondary steel-making from scrap and domestic use of this steel is maximised.
- Increased use of domestic end-of-life scrap helps to limit global CO_2 emissions, reduces dependence on steel imports, and would require an expansion of UK manufacturing.
- A combination of DRI and scrap in EAFs may prove to be the most reliable low carbon steel-making production route, provided the domestic use of UK steel is maximised. This option significantly reduces the constraints related to end-of-life scrap availability in the UK, although it requires significant capital investments in new DRI assets.
- If UK production relies on the blast furnace route using current infrastructure it will lead to higher global CO_2 emissions than alternative production options. In this case, increased steel imports would be required to offset reduced UK steel production.

- Regardless of any change in the structure of the UK iron and steel industry, meeting CO_2 reduction targets without a strong dependence on net steel imports would require demand reduction. Extending the lifetime of steel goods decreases the demand for crude steel without reducing UK steel production and consequently reduces global CO_2 emissions.

If the steel industry continues with today's mix of technologies, domestic production will have to reduce significantly, or greater emissions reductions will be required in other sectors to allow for higher emissions from the UK steel industry. In this case, current emissions targets would have limited impact on global emissions. However, a widespread change to UK steel production would involve large capital investments.

Maximising the use of scrap for steel-making achieves the lowest emissions both within the UK and globally, across all energy pathways and sensitivity analyses considered in this analysis, provided the domestic use of UK steel is maximised. However, this option is limited by the availability of end-of-life scrap in the UK. The approach taken in this paper does not consider different grades and alloying elements in scrap and their different potential for recycling. This raises uncertainty about the global emissions predicted for the scenarios where the use of scrap is maximised. Due to material losses inherent in production and manufacturing it is not possible to achieve a completely closed loop system with no primary production. This is the case even when ignoring limitations with end-of-life scrap recovery and quality (as discussed in section 3.1).

The most reliable production system could involve a combination of DRI production and EAFs. Such a system maximises scrap utilisation whilst limiting emissions and minimising the UK dependence on steel imports. The use of EAFs benefits from increased electricity decarbonisation expected from current UK energy policy. However, even with the current electricity generation mix EAFs offer lower emissions intensity the BF route.

Reducing demand for steel through products' lifetime extension can be supported by other strategies including using less steel by design and more intensive use of steel products. Allwood *et al.* (2012) provide a comprehensive analysis of such opportunities. These strategies can reduce CO_2 emissions associated with steel demand but do not require a reduction in UK steel production. Instead they could avoid carbon leakage by reducing the need for steel imports, whilst supporting an expansion of UK manufacturing and protecting employment through both steel production and the growth of industries such as repair and maintenance.

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References

AEA. *Pathways to 2050 - Detailed Analyses, MARKAL Model Review and Scenarios for DECC's 4th Carbon Budget Evidence Base*. Didcot, UK: Ricardo-AEA, 2011.

ALLWOOD, J.M., CULLEN, J.M., CARRUTH, M.A., COOPER, D.R., MCBRIEN, M., MILFORD, R.L., MOYNIHAM, M.C., PATEL, A.C.H. *Sustainable Materials with Both Eyes Open*. Cambridge, UK: UIT Cambridge, 2012.

ALLWOOD, J.M., CULLEN, J.M., MILFORD, R.L. *Options for achieving a 50% cut in industrial carbon emissions by 2050*. Environmental Science and Technology, 2010, **44** (6): pp. 1888-1894.

BABIKER, M.H. *Climate change policy, market structure, and carbon leakage*. Journal of International Economics, 2005, **65** (2): pp. 421-445.

BRUCKNER, T., BASHMAKOV, I.A., MULUGETTA, Y., CHUM, H., NAVARRO, A.D.L.V., EDMONDS, J., FAAIJ, A., FUNGTAMMASAN, B., GARG, A., HERTWICH, E., HONNERY, D., INFIELD, D., KAINUMA, M., KHENNAS, S., KIM, S., NIMIR, H.B., RIAHI, K., STRACHAN, N., WISER, R., ZHANG, X. *Energy Systems*. In O. EDENHOFER, R. PICHS-MADRUGA, Y. SOKONA, E. FARAHANI, S. KANDER, K. SEYBOTH, A. ADLER, I. BAUM, S. BRUNNER, P. EICKEMEIER, B. KRIEMANN, J. SAVOLAINEN, S. SCHLÖMER, C. VON STECHOW, T. ZWICKEL AND J.C. MINX. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.

CHEN, W., YIN, X., MA, D. *A bottom-up analysis of China's iron and steel industrial energy consumption and CO2 emissions*. Applied Energy, 2014, **136**: pp. 1174-1183.

CULLEN, J.M., ALLWOOD, J.M., BAMBACH, M.D. *Mapping the global flow of steel: from steelmaking to end-use goods*. Environmental Science & Technology, 2012, **46**: pp. 13048-13055.

DAHLSTRÖM, K., EKINS, P. *Combining economic and environmental dimensions: Value chain analysis of UK iron and steel flows*. Ecological Economics, 2006, **58** (3): pp. 507-519.

DAHLSTRÖM, K., EKINS, P., HE, J., DAVIS, J., CLIFT, R. *Iron, Steel and Aluminium in the UK: Material Flows and Their Economic Dimensions*. CES Working Paper 03/04. Surrey, UK: University of Surrey, 2004.

DAVIS, J., GEYER, R., LEY, J., HE, J., CLIFT, R., KWAN, A., SANSOM, M., JACKSON, T. *Time-dependent material flow analysis of iron and steel in the UK. Part 2. Scrap generation and recycling*. Resources, Conservation and Recycling, 2007, **51** (1): pp. 118-140.

DECC. *DECC 2050 Pathways Calculator, version 3.6.1.* London, UK: Department of Energy and Climate Change, 2014.

ECORYS. *Carbon Leakage Evidence Project: Factsheets for selected sectors*. Rotterdam, The Netherlands, 2013.

FISCHEDICK, M., ROY, J., ABDEL-AZIZ, A., ACQUAYE, A., ALLWOOD, J.M., CERON, J.-P., GENG, Y., KHESHGI, H., LANZA, A., PERCZYK, D., PRICE, L., SANTALLA, E., SHEINBAUM, C., TANAKA, K. *Industry*. In O. EDENHOFER, R. PICHS-MADRUGA, Y. SOKONA, E. FARAHANI, S. KANDER, K. SEYBOTH, A. ADLER, I. BAUM, S. BRUNNER, P. EICKEMEIER, B. KRIEMANN, J. SAVOLAINEN, S. SCHLÖMER, C. VON STECHOW, T. ZWICKEL AND J.C. MINX. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.

GEYER, R., DAVIS, J., LEY, J., HE, J., CLIFT, R., KWAN, A., SANSOM, M., JACKSON, T. *Time-dependent material flow analysis of iron and steel in the UK. Part 1: Production and consumption trends 1970-2000*. Resources, Conservation and Recycling, 2007, **51** (1): pp. 101-117.

GIELEN, D., MORIGUCHI, Y. *CO2 in the iron and steel industry: An analysis of Japanese emission reduction potentials*. Energy Policy, 2002, **30** (10): pp. 849-863.

GRIFFIN, P., HAMMOND, G.P., NORMAN, J.B. *Industrial Energy Use from a Bottom-Up Perspective: Developing the Usable Energy Database (Beta version)*. UKERC, UK Energy Research Centre, 2013.

GUTOWSKI, T.G., ALLWOOD, J.M., HERRMANN, C., SAHNI, S. *A global assessment of manufacturing: Economic development, energy use, carbon emissions, and the potential for* *energy efficiency and materials recycling*. Annual Review of Environment and Resources, 2013a, **38**: pp. 81-106.

GUTOWSKI, T.G., SAHNI, S., ALLWOOD, J.M., ASHBY, M.F., WORRELL, E. *The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2013b, **371** (1986).

HM GOVERNMENT. *The Carbon Plan: Delivering our Low Carbon Future*. London, UK: HM Government, Department of Energy & Climate Change, 2011.

HM GOVERNMENT. *Digest of UK energy statistics (DUKES)*. London, UK: Department of Energy & Climate Change, 2013a.

HM GOVERNMENT. *Final UK greenhouse gas emissions national statistics: 1990-2013*. London, UK: Department of Energy & Climate Change, 2013b.

HMRC, HM Revenue & Customs [online] Trade statistics. 2014. Available from Internet: https://www.uktradeinfo.com/Pages/Home.aspx.

HU, C.Q., CHEN, L.Y., ZHANG, C.X., QI, Y.H., YIN, R.Y. *Emission Mitigation of CO2 in Steel Industry: Current Status and Future Scenarios*. Journal of Iron and Steel Research International, 2006, **13** (6): pp. 38-42,52.

IEA *Energy Technology Transitions for Industry: Strategies for the Next Industrial Revolution*. Paris, France: International Energy Agency, 2009.

IEA *Energy Technology Perspectives 2010: Scenarios & Strategies to 2050*. Paris, France: International Energy Agency, 2010.

IEA *Energy Technology Perspectives 2014: Harnessing Electricity's Potential*. Paris, France: International Energy Agency, 2014.

ISSB. *United Kingdom Iron and Steel Industry Annual Statistics, 2007*. The Iron and Steel Statistics Bureau, 2008.

MICHAELIS, P., JACKSON, T. *Material and energy flow through the UK iron and steel sector. Part 1: 1954–1994*. Resources, Conservation and Recycling, 2000, **29** (1-2): pp. 131-156.

MILFORD, R.L., PAULIUK, S., ALLWOOD, J.M., MÜLLER, D.B. *The roles of energy and material efficiency in meeting steel industry CO2 targets*. Environmental Science and Technology, 2013, **47** (7): pp. 3455-3462.

MOYNIHAM, M.C., ALLWOOD, J.M. *The flow of steel into the construction sector*. Resources, Conservation and Recycling, 2012, **68**: pp. 88-95.

NAPP, T.A., GAMBHIR, A., HILLS, T.P., FLORIN, N., FENNELL, P.S. *A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries*. Renewable and Sustainable Energy Reviews, 2014, **30**: pp. 616-640.

ODA, J., AKIMOTO, K., TOMODA, T. *Long-term global availability of steel scrap*. Resources, Conservation and Recycling, 2013, **81**: pp. 81-91.

ONS, Office for National Statistics [online] UK National Population Projections. 2013 [cited 15/1/2015]. Available from Internet: http://www.ons.gov.uk/ons/interactive/uk-national-population-projections---dvc3/index.html.

PARDO, N., MOYA, J.A. *Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry*. Energy, 2013, **54**: pp. 113-128.

PAULIUK, S., MILFORD, R.L., MÜLLER, D.B., ALLWOOD, J.M. *The steel scrap age*. Environmental Science & Technology, 2013a, **47** (7): pp. 3448-3454.

PAULIUK, S., MÜLLER, D.B. *The role of in-use stocks in the social metabolism and in climate change mitigation*. Global Environmental Change, 2014, **24** (1): pp. 132-142.

PAULIUK, S., WANG, T., MÜLLER, D.B. *Steel all over the world: Estimating in-use stocks of iron for 200 countries*. Resources, Conservation and Recycling, 2013b, **71**: pp. 22-30.

RECK, B.K., GRAEDEL, T.E. *Challenges in metal recycling*. Science, 2012, **337** (6095): pp. 690-695.

SMMT. *Motor Industry Facts, 2014*. London, UK: The Society of Motor Manufacturers and Traders, 2014.

WANG, T., MÜLLER, D.B., GRAEDEL, T.E. *Forging the Anthropogenic Iron Cycle*. Environmental Science & Technology, 2007, **41** (14): pp. 5120-5129.

WORLD STEEL ASSOCIATION. *The three Rs of sustainable steel*. Brussels, Belgium: World Steel Association, 2009.

WORLD STEEL ASSOCIATION. *Steel Statistical Yearbook*. Brussels, Belgium: World Steel Association, 2014.