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published in Environmental Science and Technology.

The published version of the article including its correct citation can be found under

**http://dx.doi.org/10.1021/es3031424**

# The roles of energy and material efficiency in meeting steel industry $CO_2$ targets

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ABSTRACT

Identifying strategies for reducing greenhouse gas emissions from steel production requires a comprehensive model of the sector but previous work has either failed to consider the whole supply chain or considered only a subset of possible abatement options. In this work a global mass flow analysis is combined with process emissions intensities to allow forecasts of future steel sector emissions under all abatement options. Scenario analysis shows that global capacity for primary steel production is already near to a peak and that if sectoral emissions are to be reduced by 50% by 2050, the last required blast furnace will be built by 2020. Emissions reduction targets cannot be met by energy and emissions efficiency alone, but deploying material efficiency provides sufficient extra abatement potential.

INTRODUCTION

The steel industry is responsible for nearly 9% of anthropogenic energy and process $CO_2$ emissions.[1] Targets set by the IPCC and now translated into law in many countries, require that global emissions are cut to less than 50% of 2000 levels by 2050,[2] so if applied uniformly, the steel sector must emit less than 1 Gt $CO_2$/year by 2050. However, by 2050 population growth and economic development are likely to increase steel demand.[3]

Anticipating future steel sector emissions requires projection of both demand and process emissions intensities. Several groups, including the International Energy Agency (IEA),[3,4] make these projections typically with economic analysis to project demand, and industry surveys to project process intensities. However, all projections to date consider only part of the challenge. For example, the economic model used by Hidalgo et al.[5] considers only emissions arising from fuel use: emissions from electricity use and chemical reactions are excluded. Yellishetty et al.[6] consider only the production of crude steel and anticipate emissions factors using regression analysis without reference to technical limits. The IEA[3,4] similarly ignores the downstream process of rolling and manufacturing. Oda et al.[7,8] assume energy efficiency improvements can be achieved only up to current Japanese levels, while also considering carbon capture and storage (CCS) but no other process innovations. Neelis and Patel[9] construct scenarios for production, energy use and $CO_2$ emissions to 2100, but do not consider novel steelmaking technologies, nor changes to energy supply. Work by CIRED, Enerdata and LEPII to project global $CO_2$ emissions from the steel sector starts with a reference scenario, shows a peak in $CO_2$ emissions in 2030 at over 1.8 Gt $CO_2$/year and then a reduction to 1.6 Gt $CO_2$/year[10] attributed to an increase in Electric Arc Furnace (EAF) production. The Research Institute of Innovative Technology for the Earth (RITE)[11] anticipate emissions savings of 2 Gt $CO_2$/year arising as a consequence of technology innovation in response to a high carbon price, but fail to specify these innovations. Unsurprisingly this approach seems unrealistic within the industry, as demonstrated by Birat et al.[12]

A key determinant of future emissions is the ratio between primary (from ore) and secondary (from scrap) steel production. Hidalgo et al.[5] determine this ratio based on cost estimates, with no limits to scrap availability. In practice, scrap collection for recycling has become increasingly effective (the World Steel Association[13] estimate that recovery rates for steel were 83% in 2007), so it is more likely that the ratio of primary to secondary production will in the foreseeable future be determined by scrap availability. Efforts to project future scrap supply, such as those by Hatayama et al.,[14] have largely used Material Flow Analysis (MFA) combined with models of in-use stocks and product life-times, and this approach can also be used to forecast future steel demand. Müller[15] and Müller et al.[16] show that per capita steel stocks saturate in developed economies, so future demand depends on the rate at which current stocks are replaced, and demand in developing economies can be forecast assuming similar saturation. Pauliuk et al.[17] use this approach to project future steel stocks and consumption in China.

Only Oda et al.,[7,8] Neelis and Patel[9] and the IEA[3,4] project global emissions to 2050. In all three analyses, growth in steel demand outweighs gains from process efficiency, so their proposals to reduce emissions require extensive deployment of CCS, although this has yet to be implemented anywhere. However, Allwood et al.[1] raise a different possibility: even if demand for the services provided by steel grows as forecast, it might be met with less production of liquid steel, by pursuing material efficiency. Allwood et al.[18] identify a range of material efficiency options:

- replacement demand can be reduced by increasing product lifespans;
- the saturation level for stocks of existing goods and the demand for new goods could be reduced by using goods more intensely;
- lightweight product design could reduce the average mass of material per product, for example, Carruth et al.[19] find that about 30% of the mass of a standard I-beam could be saved through designing an optimised, variable-section beam;
- better manufacturing processes could reduce yield losses;
- fabrication scrap could be diverted to other uses rather than melted, for example, ;

- components from unwanted products and buildings could be re-used without melting, for example, Gorgolewski et al.[20] examine the re-use of structural steel and Tilwankar et al.[21] observe re-use of up to 95% of the steel recovered by India's ship breaking industry.

All of these material efficiency options provide the same level of technical service while using less liquid steel. Evidence about the potential of each strategy is given by Allwood et al[22], however the impact of trade-offs between the different material efficiency options was not explored.

The ambition of this paper is thus twofold: to provide a comprehensive forecast of future emissions in the steel industry, using a stock-based MFA approach and spanning the whole supply chain from ore or scrap to final products; and, to identify physically credible pathways by which the steel sector can achieve emissions reduction targets including material efficiency options.

## METHODS

The basis of the analysis developed in this paper is summarised in equation (1):

$$\text{Total emissions} = \sum_{i \text{ processes}} \left( \text{Emissions intensity}_i \times \text{Massflow}_i \right) \tag{1}$$

A global model of steel flows and emissions factors in 2008 is first developed and used to predict 2008 sectoral emissions, which can be validated against reported data. Future emissions are forecast from mass flows, accounting for demand growth and material efficiency, and process emissions intensities accounting for efficiency gains, technology innovations and changes to the energy supply mix.

The present-day global flow of steel is reported in Cullen et al.'s[23] Sankey diagram of iron and steel flows for 2008. The only non-iron/steel material flow considered in the model is coke as coking operations are driven by steel production and emissions intensive. Historic and future mass-flows into and out of in-use stocks are determined by the multi-regional four-product stock model described in the accompanying paper by Pauliuk et al.[24] This model forecasts a 'business as usual' increase of just 60% in global steel final product demand by 2050, which is significantly lower than the doubling assumed by the IEA.[3,4] The difference arises from using a stock-based, rather than a production-based model, and from using lower population estimates.

Steel industry emissions may arise directly from fossil fuel combustion, indirectly from electricity use or from chemical reactions. For comparability with other estimates of sectoral emissions, we include emissions only up to the production of semi-finished products, e.g. cold rolled coil, sections or wire rod. The emissions impact of non-iron/steel material flows, such as the production of zinc for galvanizing, is excluded, as are the (relatively small) downstream emissions of manufacturing and construction. Estimating global average values for the emissions intensities in equation (1) is difficult:

- the steel industry prefers to report emissions for specific products rather than process intensities due to commercial sensitivity and the incomparability of processes which may be more or less coupled;
- where process emissions data have been published, they are often inconsistent. For example data may or may not include indirect and process emissions, and data may be averaged over a region or business, or reported as global best practice.

Therefore the global average emissions intensities of upstream processes reported in Table 1, have been derived from 15 sources as described in detail in Section 1.3 of the Supplementary Information, along with the emissions intensities of 14 downstream processes used in the analysis.

| Process | Total emissions factor (t $CO_2$/t output) |
|---|---|
| Sintering | 0.22 |
| Coking | 0.43 |
| Ironmaking - blast furnace (BF) | 1.48 |
| Ironmaking - direct reduction (DR) | 1.28 |
| Steelmaking - basic oxygen furnace (BOF) | 0.12 |
| Steelmaking - EAF with scrap and DRI input | 0.36 |
| Steelmaking - EAF with 100% scrap input | 0.33 |
| Continuous casting | 0.007 |

**Table 1:** Global average total $CO_2$ intensity values (including direct, indirect and process emissions) for upstream processes for 2008.

The model assumes that steel production from end-of-life scrap can be a perfect substitute to steel produced from ore, which is not currently true. The implications of this assumption for the development of scrap separation and recycling technologies, as well as the collection and recycling rates used in the model, are discussed in the accompanying paper by Pauliuk et al.[24]

The mass-flow data[23] and emissions intensity factors of Table 1 can now be used in equation (1) to predict 2008 steel industry emissions. In the first column of Table 2 these are compared with global steel emissions reported by Birat.[12] (The most recent IEA report is 2.6 Gt $CO_2$ for 2006.[4])

| | Recent global sector emissions (Gt $CO_2$) | Sections (t $CO_2$/t section) | Hot rolled coil (t $CO_2$/t HRC) | Cold rolled coil (t $CO_2$/t CRC) |
|---|---|---|---|---|
| Model value | 2.8 (2008 value) | 1.38 | 2.02 | 2.27 |
| Reported value | 2.8 (2009 value)<br>3.1 (2007 value)<br>quoted uncertainty: ±25%[12] | 1.56[25] | 2.01[25] | 2.19[25] |

**Table 2:** Validation of proposed $CO_2$ intensity dataset by comparison with reported values

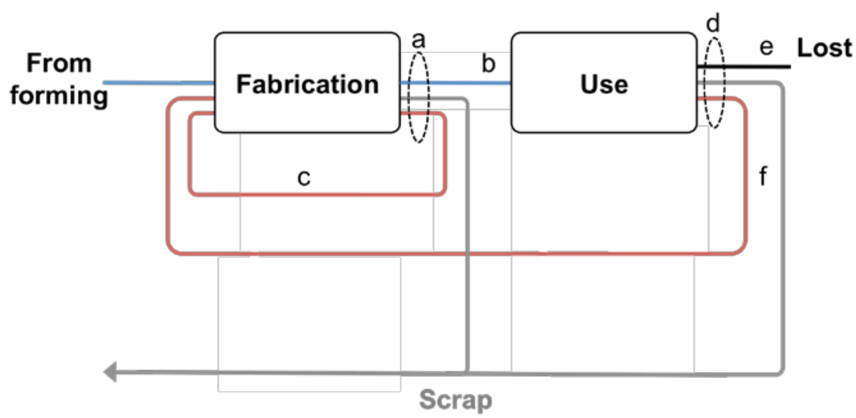
The last three columns of Table 2 also compare $CO_2$ emissions for three semi-finished products predicted with the model against Life Cycle Inventory data from the World Steel Association.[25] The model results were calculated using the Sankey diagram of global steel flows by Cullen et al.[23] to identify the process route and the share of EAF and BOF steel that goes into each product. The model's emissions factors were used to calculate global emissions arising from the production of each semi-finished product, which were normalised per tonne of product, to allow comparison with the World Steel Association data. The reported values in Table 2 are in fact the results of models: as Birat notes, no comprehensive registry of steel sector $CO_2$ emissions exists, so reported values are themselves estimates based on a set of assumptions.[12] The predictions of the model developed above therefore appear to be in sufficient agreement with other reported values to give confidence in using the model for scenario development.

Emissions scenarios are now constructed by anticipating changes in future mass-flows and emissions intensities. Future demand for steel services is forecast in the accompanying paper[24] by projections of regional population, product lifetimes for four product categories and evolution of per capita stocks. It is assumed that with economic development, these per-capita stocks evolve towards some predictable saturation level at a future time, estimated based on current stock-growth trajectories. For each future year, the flow of products leaving in-use stocks at the end of their useful life is determined by using a model of product lifetime, which assumes a normal distribution. The annual volume of steel products required to meet both new and replacement demand can then be calculated. By scaling present day metal flows along the supply chain (using data from Cullen et al.[23] as the baseline) by future steel demand, we can evaluate the annual production volume for the different forming and fabrication activities and the scrap generated. The model assumes that all available scrap is recycled in the EAF or in the BOF, with iron production used to top-up the level of steel production required to meet demand. However, in future, steel services may be delivered with less liquid steel by using the material efficiency options described in the introduction.

The six material efficiency strategies are defined by the indices below and can vary from 0 (no material efficiency) to 1 (maximum material efficiency):

- Less metal, same service: $M_L$ = 1 – (New product mass/Original product mass) (2)
- More intense use: $M_I$ = 1 – (New number of products required to provide service/Original number of products required to provide service) (3)
- Life extension: $M_X$ = 1 – (Original mean product life (years)/New mean product life (years)) (4)
- Fabrication scrap diversion: $M_D$ = Mass of scrap diverted for re-fabrication/Original mass of fabrication scrap sent for recycling (5)
- Re-use: $M_R$ = Mass of scrap diverted for re-use/Original mass of end-of-life scrap sent for recycling (6)
- Fabrication yield improvement: $M_Y$ = 1 – (Original fabrication yield/New fabrication yield) (7)

The effects of six material efficiency indices on reference material flows are shown in Figure 1. Individual indices are defined for each product category.




Less metal, same service: $b_{new} = b_{original} \times (1 - M_L)$
More intense use: $b_{new} = b_{original} \times (1 - M_I)$
Life extension: $d_{new} = f((\tau_{original} \div (1 - M_X),\sigma)$
Fabrication scrap diversion: $c = (a\text{-}b) \times M_D$
Re-use of end-of-life scrap: $f = (d\text{-}e) \times M_R$
Fabrication yield improvement: $a_{new} = a_{original} \times (1 - M_Y)$

**Figure 1:** Impact of material efficiency indices on reference material flows ($\tau$ = mean product life, $\sigma$ = standard deviation of product life)

Because the strategies of material efficiency have had relatively little attention, limiting values of the implementation factors of Figure 1 have been estimated. Carruth et al.[19] provided such an estimate for lightweight design applied to several case studies. Cooper and Allwood[26] provide an estimate of the potential for re-use of steel components across four product categories. Analysis in pages 22 to 29 of the Supporting Information, based on case studies and interviews, of the potential for the remaining material efficiency strategies, leads to the estimates in Table 3. These estimates are based on theoretical technical feasibility and provide an upper bound to the impact of material efficiency strategies.

| Strategy | Transport | Industrial equipment | Construction | Products |
|---|---|---|---|---|
| Less metal, same service ($M_L$) | 0.45 | 0.33 | 0.19 | 0.27 |
| More intense use ($M_I$) | 0.39 | 0.07 | 0.40 | 0.00 |
| Life extension ($M_X$) | 0.13* | 0.09 | 0.47 | 0.75 |
| Fabrication scrap diversion ($M_D$) | 0.72* | 0.64* | 0.00 | 0.68* |
| Re-use of end-of-life scrap ($M_R$) | 0.30* | 0.17 | 0.15* | 0.11* |
| Fabrication yield improvements ($M_Y$) | 0.10 | 0.06 | 0.00 | 0.09 |

**Table 3:** Theoretical limits to material efficiency strategies for different product categories. Strategies marked with an asterisk (*) would be affected by trade-offs with other material efficiency strategies, so their estimated potential has been reduced.

Future values of the emissions intensities in equation (1) depend on three features of technology evolution: the rate at which average technology is raised to the standard of current best available technology (BAT); the development of future technologies beyond current best practice; the future average emissions intensity of electricity generation. Due to the high costs of energy to the steel industry, it is likely that over time, the average emissions intensity of production technology will converge to that of current BAT. The IEA reported that in 2006, global implementation of current BAT had the potential to reduce the steel industry's $CO_2$ emissions by 390Mt, which was approximately 14% of the steel sector's 2006 emissions.[4] Based on this observation, we assume that best practice emissions factors are on average 14% lower than the global average emissions factors reported in Table 1 and the Supporting Information. This model assumes that global average emissions factors converge on best practice emissions factors by 2020, with the transition modelled by an S-curve. Beyond current BAT, novel ironmaking routes could be less emissions-intensive than conventional routes, however, as these technologies are still in development, all the emissions savings quoted in the literature are estimates. (The calculations used to estimate novel process emissions factors based on the emissions savings found in literature are detailed in the Supporting Information. We assume that CCS is applied in conjunction with electricity production but is not used directly to sequester $CO_2$ emissions from ironmaking.)

- Top-gas recycling and fuel substitution (50% reduction in coke inputs required for the blast furnace): by using pure oxygen rather than air and re-circulating the gas produced during ironmaking in the blast furnace to utilise un-reacted carbon monoxide, carbon inputs to the blast furnace could be reduced by 30%.[27] In addition, some coke inputs may be displaced by alternative fuels, such as oil, gas, or plastics. The total reduction in coke input to the blast furnace due to the combination of top-gas recycling and fuel substitution is estimated to be 50%.
- smelt reduction (1.6 t $CO_2$/t iron): the two-stage smelt reduction process, whereby iron ore is first partially reduced in a solid state, before final reduction and melting in a pool of molten iron, could eliminate coking and sintering, so while the smelt reduction process may be more energy intensive than the blast furnace, the smelt reduction process route may deliver an emissions intensity of 80% of the blast furnace route;[28]
- advanced direct reduction (1.0 t $CO_2$/t DRI): the reduction of iron ore in a solid state (rather than in a liquid state, as in the blast furnace) could eliminate coking and perhaps sintering, and the direct reduction-EAF route could have an emissions intensity half that of the BF-BOF route due to the use of gas rather than coal as a reducing agent.[29] However, the requirement for low cost natural gas, low carbon electricity and high quality ore will limit the uptake of and emissions savings from this technology;

- electrolysis, the deposition of iron when an electrical current is passed through a suitable liquid, could eliminate coking and sintering, and if coupled to a low carbon electricity source (e.g. nuclear) could lead to emissions intensity as low as 0.24 t $CO_2$/t iron[30] (16% of the emissions from the blast furnace). However this technology is in the early stages of development and commercial application may be years away; the technology faces the same challenge as the aluminium industry – the need to develop and commercialise an anode that is inert towards the metal oxide.
- the emissions intensity of electricity may in future decrease if the grid is decarbonised through implementation of CCS, nuclear power or increased renewable capacity. This analysis will explore scenarios with electricity decarbonisation ranging from 25 to 75% by 2050, which is in line with the IEA's scenarios (16 to 78%).[3]

All five of these technologies could be applied to any extent in future, constrained largely by investment decisions, so their impact on emissions is investigated through scenario analysis. Seven scenarios are investigated:

- business-as-usual (BAU) in which it is assumed that recovery rates increase to 90% and scrap input to the BOF increases from 10% to 20% by 2050, and that BAT is reached by 2020;
- three "energy efficiency" scenarios with, in addition to the BAU improvements, low, medium or high deployment of novel technologies and electricity decarbonisation;
- three "energy & material efficiency" scenarios, with a medium level of energy efficiency, and the full technical potential of material efficiency from Table 3 attained at slow, moderate and fast rates.

The transition from current levels to any of the seven scenarios is assumed to follow an S-curve.

Table 4 summarizes the key variables used in each of the scenarios and pages 29 to 30 of the Supporting Information describes the additional assumptions and parameters used to define the scenarios.

| Scenarios / Parameters | BAU | Energy efficiency | | | Energy & material efficiency | | |
|---|---|---|---|---|---|---|---|
| Year in which maximum material efficiency is reached | N/A | | | | 2050 | 2100 | 2150 |
| Top gas recycling and fuel substitution by 2050[1] | 0% | 80% | 90% | 100% | 90% | | |
| DR share by 2100[2] | 5% | 10% | 20% | 30% | 20% | | |
| Smelt reduction share by 2100[3] | 0% | 30% | 40% | 50% | 40% | | |
| Electrolysis share by 2100[3] | 0% | 10% | 20% | 30% | 20% | | |
| Electricity decarbonisation by 2050 | 0% | 25% | 50% | 75% | 50% | | |

[1] Top gas recycling and fuel substitution is defined relative to blast furnace iron production [2] DR share is defined relative to total crude steel production; [3] Smelt reduction and electrolysis share is defined relative to the massflow entering the BOF.

**Table 4:** Summary of variables for seven emissions scenarios.

## RESULTS

Figure 2 shows the time series of annual and cumulative $CO_2$ emissions predicted by the model for the seven emissions scenarios of Table 4.

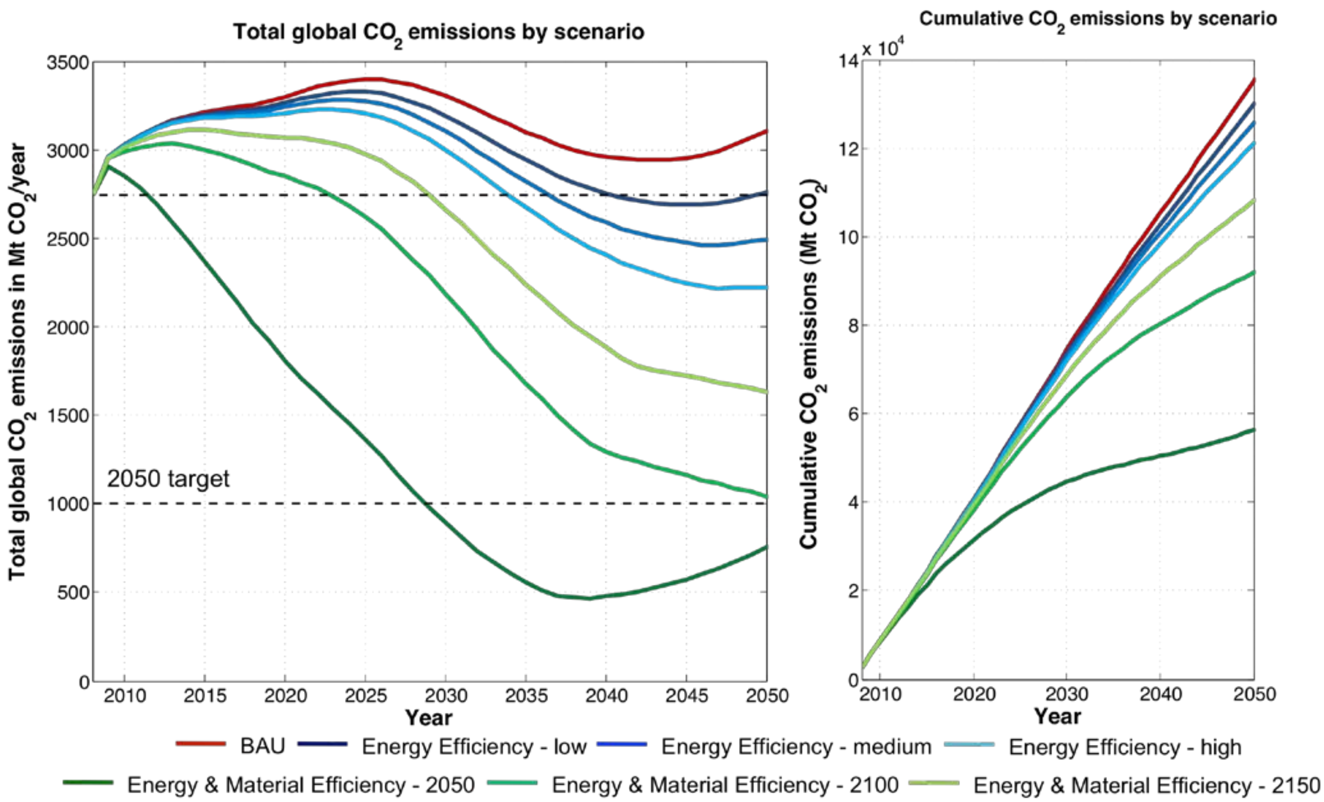



**Figure 2:** Annual and cumulative $CO_2$ emissions for seven emissions scenarios

In the first 'Business as Usual' (BAU) scenario, annual emissions peak in 2025 at levels almost 25% higher than 2008 emissions. After 2025, despite increasing final steel demand, emissions reduce to less than 3 Gt $CO_2$/year; this is due to increased EAF production, which reduces the average emissions intensity. However, by 2045, annual emissions start to increase again as the gains in the average emissions intensity are not enough to compensate for the increase in final steel demand. The "energy efficiency" scenarios show emissions reductions of around up to about 20% compared with BAU, but even with the most aggressive implementation, emissions remain over 120% higher than the 2050 target. In contrast, the emissions projection of ~~two~~ the most aggressive of the "energy & material efficiency" scenarios meets the emissions targets; the second most aggressive "energy & material efficiency" scenario very nearly meets the target. The scenario with the fastest uptake of material efficiency options (Energy & Material Efficiency-2050) shows a rebound after 2040 as the rapid implementation of lightweight design and life extension restricts subsequent scrap availability, however, the cumulative emissions for this strategy are still the lowest. Cumulative emissions could become an important indicator if emissions targets become linked to the concept of a "carbon budget", as proposed by WBGU.[31]

The cumulative emissions for the three "energy efficiency" scenarios are similar to that of the BAU scenario, while the cumulative emissions for the three "energy and material efficiency" scenarios are significantly lower. This difference is due partly to the large impact material efficiency strategies have on reducing the steel flows along the supply chain and the emissions arising from each process, and partly due to the diminishing impact of primary steel production as steel recycling meets a greater proportion of steel demand.

Figure 3 shows steel sector emissions broken down by process for the BAU scenario and the mid-range "energy efficiency" and "energy & material efficiency" scenarios.

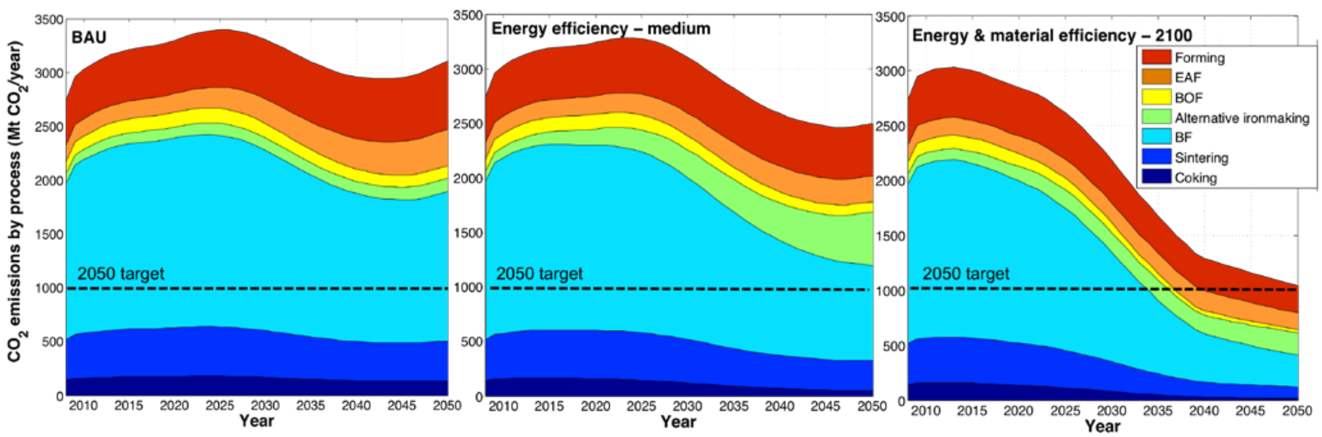



**Figure 3:** $CO_2$ emissions by process for BAU, Energy Efficiency-medium and Energy & Material Efficiency-2100 scenarios

In the BAU scenario, the emissions breakdown remains approximately constant, with the majority of emissions arising from the blast furnace. In the other two scenarios, blast furnace emissions are significantly reduced; in the "energy efficiency" scenario, emissions from alternative ironmaking technologies increase while in the "energy & material efficiency" scenario, the reduction in liquid metal production results in lower emissions for all processes.

Each of the future steel scenarios has different requirements for production capacity. Figure 4 shows the evolution of primary (BOF) and secondary (EAF) steelmaking output in the "energy & material efficiency" scenario, compared to the BAU outputs determined in the accompanying paper by Pauliuk et al.[21]

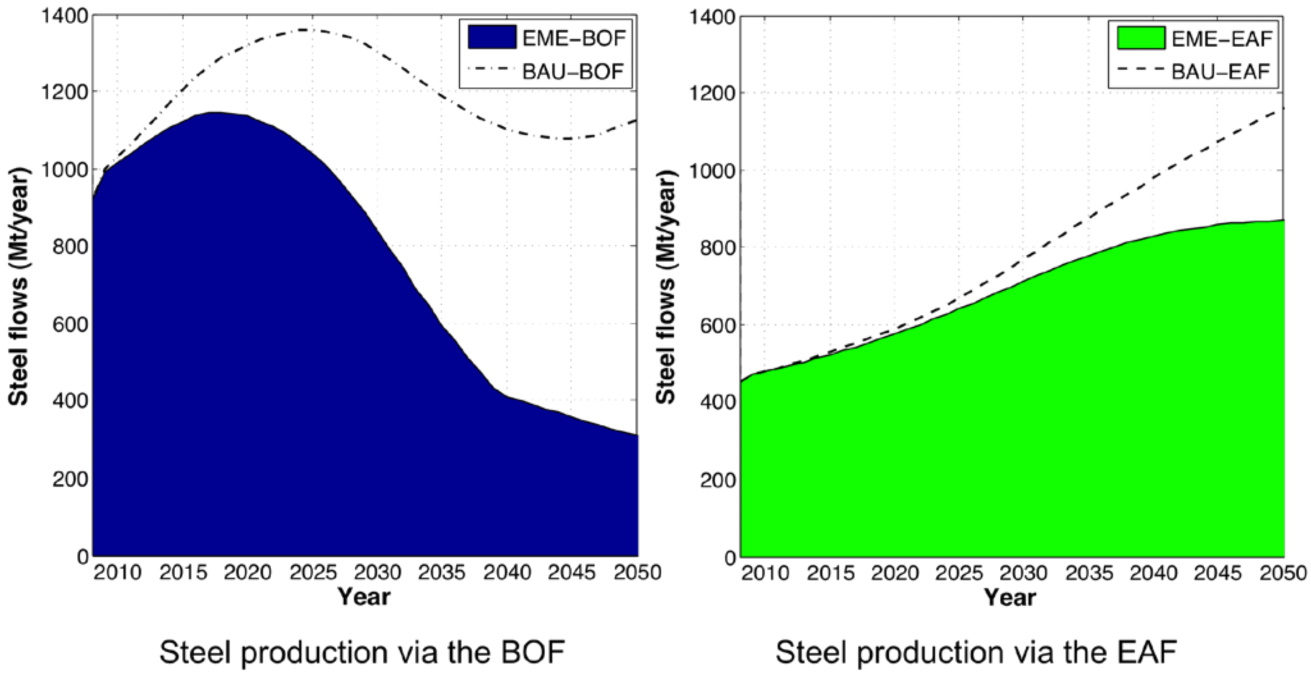



**Figure 4:** Global primary and secondary steel outputs for the "energy & material efficiency" (EME) and BAU scenarios

In both scenarios, EAF output is forecast to increase from current levels, however, the increase is less marked in the "energy & material efficiency" scenario due to a more limited supply of scrap. The stronger contrast is between projections of BOF output: in the BAU scenario, BOF output peaks around 2025 before reducing to a local minimum around 2045 and increasing thereafter. In the "energy & material efficiency" scenario, BOF output peaks in 2018 before reducing steadily to about 35% of current output. This suggests that without other actions to constrain emissions, global blast furnace capacity will increase by about 50% to 2025. However, if the target to halve global emissions by 2050 is to be met, we are within a decade of building our last blast furnace: any further increase in global blast furnace capacity beyond this level will prevent achievement of the targets.

The results of Figures 2-4 depend on both data and model uncertainties, so the sensitivity of predicted global 2050 $CO_2$ emissions to key model parameters and scenario variables has been tested and is reported in detail in the SI. This analysis demonstrates that emissions are most sensitive to predicted population. As the population projections used in the analysis of this paper are lower than those used in previous analysis,[3,4] the global emissions predicted here may be under-estimated, which would further underline the value of material efficiency options.

A further sensitivity analysis is used to investigate which of the scenario variables should be prioritised for emissions reduction. In this sensitivity analysis, we use the emissions forecast for the "Energy & Material Efficiency – 2100" scenario as the reference scenario. From the reference scenario, we explore the effect of eight small changes to the model on the emissions forecast. The eight changes explored are:

- A 10-year delay to the introduction of additional energy efficiency technologies.
- A 20-year delay to the introduction of additional energy efficiency technologies.
- A 10-year delay to the introduction of material efficiency strategies.
- A 20-year delay to the introduction of material efficiency strategies.
- A 20-year advance to implementing energy efficiency technologies, i.e. the maximum implementation level is reached 20 years before the time in the reference model.
- A 20-year delay to implementing energy efficiency technologies, i.e. the maximum implementation level is reached 20 years after the time in the reference model.
- A 10% reduction in the saturation level for material efficiency strategies.
- A 10% increase in the saturation level for material efficiency strategies.

Figure 5 shows the results of the sensitivity analysis:

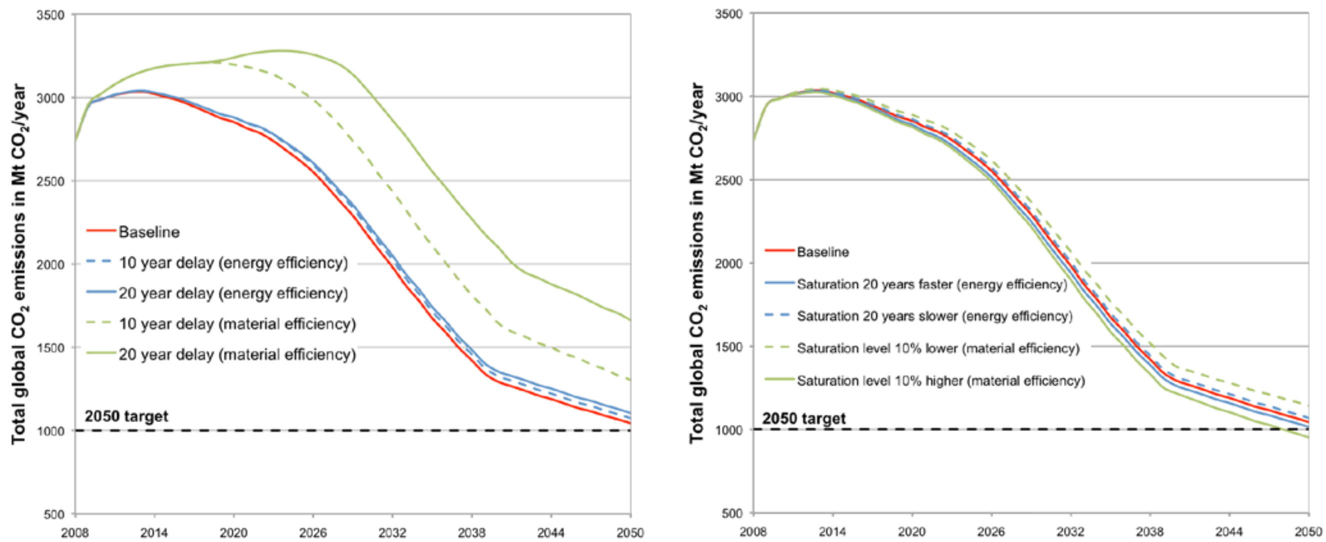



**Figure 5:** Sensitivity analysis showing the impact of changes to scenario variables on the emissions forecast based on the "Energy & Material Efficiency – 2100" scenario

The change that has the biggest impact on the emissions forecast is a delay to the introduction of material efficiency strategies. A 10 or 20-year delay results in 2050 emissions 25% or 60% higher than the reference case. In contrast, delays to introducing energy efficiency measures, delayed saturation of energy efficiency measures, and a 10% increase or reduction in material efficiency levels, have only a small impact on the emissions forecast, within ±10% of the reference case emissions.

DISCUSSION

*Can the emissions targets be met?* Figure 3 shows that in the BAU scenario, total emissions increase by 13% from 2008 to 2050, due to the switch from BF to the less emissions intensive EAF route alleviating the 60% increase in final product demand. However, even if the most aggressive energy efficiency strategies are employed, the targets for significant emissions reductions cannot be met. Only by employing material efficiency measures on top of energy efficiency measures can such targets be achieved. Motivating and coordinating the uptake of strategies along the whole supply chain and across the whole range of products is likely to require significant changes in government support and policy. Implementing material efficiency strategies has a large impact on the cumulative emissions released over the period from 2008 to 2050. While the less aggressive material efficiency strategies may not meet the emissions targets on the basis of yearly emissions, these scenarios are more likely to achieve prospective cumulative emissions targets compared to business-as-usual and energy efficiency only scenarios. The sensitivity analysis has shown that a delay in the introduction of material efficiency strategies has the biggest impact upon future annual emissions; a 10-year delay in starting to apply material efficiency strategies will cause 2050 emissions to be 25% higher than if implementation begins immediately. Therefore, the priority should be the introduction of material efficiency measures as soon as possible into the supply chain. While further work is required to establish the limits to material efficiency, this should not become a barrier to applying material efficiency strategies that have already been identified.

*How much more blast furnace capacity do we need?* Global blast furnace capacity is approaching its maximum required level: current output is below current capacity, and if the projections of future demand and scrap supply are correct, less than 450 Mt of additional blast furnace capacity is required by 2025. This is a stark contrast to the recent expansion in China, where pig iron production nearly quadrupled from 1998 to 2008.[29,31] Furthermore, if global emissions from the steel sector are to be reduced by 2050, almost no further increases in blast furnace capacity can be tolerated. EAF capacity, however, must increase rapidly: even in the "energy & material efficiency" scenario, EAF capacity must increase by over 90% from 2008 levels. The results show a clear a transition from primary to secondary production, which relies on the development of end-of-life sorting and refining technologies such that recycled steel can substitute for primary steel for all products.

The high investment costs associated with steelworks is likely to create resistance to capacity reductions as investors prefer to "milk" existing assets. However, steel industry executives should be aware that any new investment in primary capacity creates a significant risk of over-supply and hence low prices.

*What options do policy-makers have to pursue emissions reductions?* Material efficiency would lead to reduced steel production and policy-makers could support this transition through promoting opportunities for new businesses, for example through deconstruction and reuse, maintenance over longer product lives, and diverting scrap into other uses. Policy-makers could also challenge existing consumer behaviour, for example promoting product life extension over disposal, or promoting shared ownership over single-ownership. The pursuit of material efficiency also has a potential policy benefit through reducing national dependency on imports, and avoiding overcapacity.

*Opportunities for further work:* Future extensions to this work could consider substitution effects between products or materials, and the economic implications of technology and capacity decisions. As work on material efficiency progresses, data on limits and trade-offs for the six material efficiency strategies could be refined.

## ACKNOWLEDGMENTS

The authors thank Daniel Cooper for information on material efficiency limits, and Professor John Barrett and colleagues for providing data on the origin of domestic steel consumption. The Cambridge authors are supported by an EPSRC Leadership Fellowship, reference EP/G007217/1.

SUPPORTING INFORMATION AVAILABLE The Supporting Information includes: emissions factor calculations; material efficiency limits; rationale for emissions scenario variables; methodologies for evaluating future regional production capacity and regional emissions footprints. This information is available free of charge via the Internet at http://pubs.acs.org/.

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