Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050

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Carbon emissions from industry are dominated by production of goods in steel, cement, plastic, paper, and aluminum. Demand for these materials is anticipated to double at least by 2050, by which time global carbon emissions must be reduced by at least 50%. To evaluate the challenge of meeting this target, the global flows of these materials and their associated emissions are projected to 2050 under five technical scenarios. A reference scenario includes all existing and emerging efficiency measures but cannot provide sufficient reduction. The application of carbon sequestration to primary production proves to be sufficient only for cement. The emissions target can always be met by reducing demand, for instance through product life extension, material substitution, or "light-weighting". Reusing components shows significant potential particularly within construction. Radical process innovation may also be possible. The results show that the first two strategies, based on increasing primary production, cannot achieve the required emissions reductions, so should be balanced by the vigorous pursuit of material efficiency to allow provision of increased material services with reduced primary production.

Introduction

Over two-thirds of anthropogenic carbon dioxide (CO_2) emissions arise from the use of energy and process emissions, totalling 28 giga-tonnes of CO_2 ($GtCO_2$) in 2006 ((*1*), p 51). These emissions are broken down in Figure 1 showing that 36% arise in industry, 56% of which are driven by production of five key material groups—steel, cement, plastic, paper, and aluminum.

Figure 2 shows that steady growth in demand for these materials has accelerated since 2000, driven by growth in Asian construction.

The analysis of emissions and demand leading to these figures based mainly on refs *1 and 2* is in the Supporting Information. This includes analysis of demand forecasts for these materials, showing that demand is likely to double by 2050.

The IPCC report (ref *3* Table 3.10, p 229) recommends a minimum cut in total annual global emissions of 50%–85% from 2000 levels by 2050 to stabilize the global mean temperature rise between 2.0 and 2.4 °C above preindustrial levels. In response, internationally, leaders at the recent G8 summit agreed that global emissions should be reduced by 50% before 2050 (*4*). Nationally, targets are entering policy
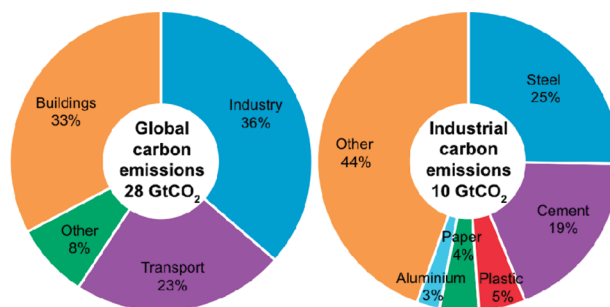
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FIGURE 1. Global anthropogenic CO_2 emissions related to energy and industrial processes (a) for all sectors and (b) for industry.
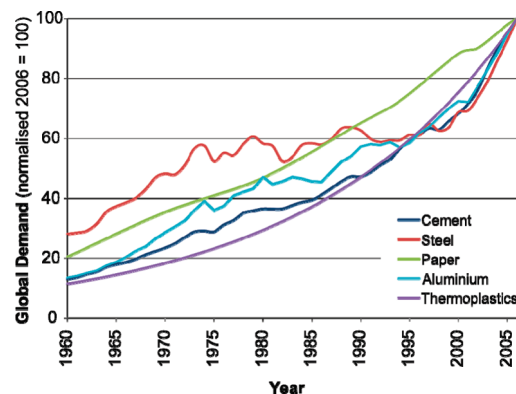

FIGURE 2. Normalized global demand for the five key materials since 1960.

as law, for example the UK Climate Change Act 2008 commits to an 80% cut in emissions by 2050 (*5*).

The energy intensive industries are currently lobbying to be allowed reduced target reductions compared to the transport and buildings sectors. Table 1 shows how setting a less ambitious target for industry leads to the need for more severe targets for other sectors. Each row shows how a reduced cut for the industry sector leads to a greater target cut for all other sectors.

Table 1 shows that if demand doubles, and industry negotiates a less aggressive target, the target for all other sectors is probably infeasible. As a result, while planning emissions reduction strategies at present, it is essential to identify a physical basis for the industrial sector to achieve at least a 50% cut in total emissions by 2050 even as demand for industrial products grows.

Can emissions be halved while demand for these five materials doubles? The simplest approach to meeting this target would be to take action within the incumbent primary materials industry. However, as these materials are energy intensive, they have already been subject to significant efficiency improvements. Table 2, based on recent sector surveys described in detail in the Supporting Information (section 2) predicts a *technical reduction potential* for the five materials.

The calculation of Table 2 has assumed the following: all technology emission reductions are additive; all technology can be implemented worldwide by 2050; where a mitigation range is given, the maximum reduction is achieved. The table shows that efficiency gains could give emissions reductions in the range 21–40%. This would require significant world-wide effort but is not enough to counter forecast demand growth.

TABLE 1. Options to Share a Global Emissions Reduction Target between Sectors

global emissions reduction target	options for target reduction per unit output for major sectors if demand remains constant		options for target reduction per unit output for major sectors if demand doubles	
	industry	all other sectors	industry	all other sectors
50%	50%	50%	75%	75%
	40%	56%	50%	89%
	30%	61%	31%	100%
80%	80%	80%	90%	90%
	60%	91%	80%	96%
	44%	100%	72%	100%

TABLE 2. Technical Reduction Potential for Carbon Emissions in 2050 for the Five Materials[a]

material	PD 2050	CI 2005	PE 2050	CS best practice	CS beyond best practice	PE reduction potential	CI 2050 limit
steel	2370	1.7	4030	710	650	1360 (34%)	1.1
cement	4250	0.8	3530	770	650	1420 (40%)	0.5
plastic	470	2.4	1130	110	130	240 (21%)	1.9
paper	950	1.2	1130	200	250	450 (40%)	0.7
aluminum	120	8.8	1070	50	200	250 (23%)	6.8

[a] PD: Projected Demand (Mt); CI: global average Carbon Intensity (kg CO_2/kg); PE: Projected global Emissions (Mt CO_2); CS: global Carbon Savings (Mt CO_2).

TABLE 3. Current and Projected Recycling Rates

description	steel	cement	plastic	paper	aluminum
postconsumer discards (Mt)	265	231	110	299	16.1
postconsumer recovered scrap (Mt)	173	0	5	129	6.3
current recycling rate	65%	0%	5%	43%	39%
projected maximum recycling rate	90%	0%	30%	81%	90%

As production from scrap requires less energy than from primary material, can emissions be reduced by increased recycling? If the recycling rate is defined as the percentage of postconsumer discards returned to be made into new products, it can be calculated from global material mass balances. Based on data given in the Supporting Information (section 3), current and projected recycling rates are shown in Table 3.

For metals, recycling rates can be increased. Paper recycling can also be increased but has a low yield due to fiber damage in pulping and can be more carbon intensive than primary production which is largely fueled by waste products from tree pulping. Recycling of plastics is inhibited by the wide variety of compositions in use, and there is no route to recycle cement. Recycling of metals, paper, and plastic remains energy intensive.

The managers of incumbent primary materials industries must aim to increase output. Given limited scope for further process efficiencies, their options within this constraint are
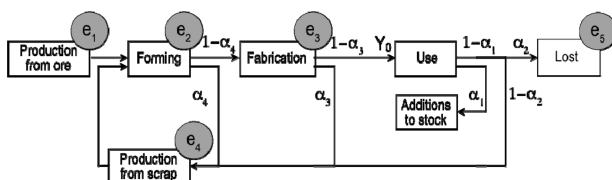

FIGURE 3. Definition of coefficients required for analysis of flows and emissions.

either to convert all processes to electricity, and find a supply of carbon-free electricity, or to adopt carbon capture and storage (CCS). All other sectors will also be competing for carbon-free electricity, and there are technical difficulties in achieving electrically powered concrete and steel production, so this option is difficult. Hence current industry lobbying is strongly focused on CCS: according to the IEA (1), without widespread deployment of CCS, energy related industrial emissions in 2050 are expected to be 63% higher than today. The aggressive implementation of CCS proposed in ref 1 attributes a 17% (ACT scenario) and 37% (BLUE scenario) reduction of industrial CO_2 emissions by 2050 through CCS ((1), p 109). However, the first industrial scale power generation with CCS opened in Schwarze in Germany in September 2008, so the true costs of CCS remain unknown but are predicted to be in the range 200−500 USD/tCO_2 and require an estimated USD2.5 trillion to upgrade all industrial plants ((1), pp 43−45). Furthermore, the availability of suitable storage sites is uncertain and the risks of an accidental release of sequestered CO_2 are unknown.

In contrast to the quest for CCS, Smil (6) suggests that the three major strategies for energy efficiency in industry are maximizing production efficiencies (as shown in Table 2), reducing use of energy intensive products through design and recycling, and "doing without".

Three possible strategies for emissions reduction in industry, in addition to process efficiency, increased recycling, and CCS, emerge from this suggestion: (1) reducing demand for materials through light-weighting, life-extension, or substitution of other materials; (2) nondestructive recycling in which components are reused with some processing, but without being reduced to liquid form; and (3) radical process innovations which allow shorter, less energy intensive process routes from liquid material to completed component.

The objective of this paper is to examine whether these approaches should form part of a low carbon industrial strategy, even though it is unlikely that they will be pursued by existing raw material producers.

TABLE 4. Flow Ratios and Emissions Rates Used in the Analysis

	steel		cement		plastic		paper		aluminum	
	2006	2050	2006	2050	2006	2050	2006	2050	2006	2050
Y_0	1100	2400	2400	4300	230	470	380	1000	40	120
α_1	0.64	0.20	0.90	0.20	0.50	0.20	0.11	0.20	0.60	0.20
α_2	0.35	0.10	1.00	1.00	0.95	0.70	0.57	0.19	0.61	0.10
α_3	0.11	0.09			0.02	0.02	0.06	0.05	0.20	0.16
α_4	0.14	0.11							0.27	0.22
e_1	1.80	0.95	0.83	0.45	1.99	1.26	0.90	0.43	8.82	5.43
e_2	0.28	0.18					0.65	0.42	0.75	0.48
e_3	0.17	0.11			0.42	0.27	0.10	0.06	0.38	0.24
e_4	0.36	0.25			0.43	0.35	0.99	0.79	0.46	0.37
e_5					2.88	1.86				

Analysis of Current and Future Material Flows and Emissions

Our analysis of present and future materials flows and emissions is developed through a series of Sankey diagrams in which the global flow of a material is shown through various process stages, with the magnitude of the flow indicated by the width of the corresponding flow line. A detailed history and survey of the use of Sankey Diagrams is given by Schmidt (7, 8) and our diagrams are constructed using the schematic model of Figure 3.

The lines in the figure represent the flow of material and the gray circles indicate CO_2 emissions. The flows and emissions are calculated from demand Y_0, coefficients α which are ratios showing how the flow divides, and coefficients e which are unit emissions in kgCO_2/kg material processed. Emissions e_5 arise only from plastics incineration. No emissions are attributed to the use-phase of the materials, as these will be reported by other sectors and any credit given to materials producers leads to double-counting. Figure 3 shows that a fraction α_1 of the material entering use in a given year is not discarded during that year, so is "added to stock". Globally, in construction for instance, that ratio is currently high as the number of buildings in use is increasing. Future emissions forecasts are sensitive to this ratio, as net additions to stock require additional primary materials production, which is often the most energy intensive process. α_2 is the fraction of discarded material that is lost and hence not recycled; α_3 and α_4 are rates of yield loss in manufacturing, due to skimming, edging, cropping, blanking, machining, and scrap.

The data for our analysis in both 2006 and our reference case for 2050 are given in Table 4 based on sources discussed in the Supporting Information.

The analysis for 2050 flows and emissions is based on five possible scenarios. The first, 2050CEE, is intended as a highly optimistic projection of "business as usual" based on actions taken by the incumbent primary materials industry. This scenario, using the coefficients for 2050 in Table 4, assumes all efficiencies in Table 2 (reducing e_1), the maximum recycling rates of Table 3 (reducing α_2), 20% of all energy supplies are "de-carbonized" (reducing $e_1 - e_4$), and the energy intensity and yield of all downstream processes are also improved by 20% (further reducing $e_2 - e_4$ and also reducing α_3 and α_4). In addition, for plastics, emissions e_5 are reduced in 2050 by the assumed offsetting benefits of heat recovery from plastics incineration.

The other four scenarios adopt 2050CEE as a baseline and make further changes. 2050CCS applies increasing levels of CCS to all emissions (i.e., both process emissions from combustion and reactions and those associated with electricity generation) associated with primary production, thus reducing e_1. 2050NDR explores "non-destructive recycling" in which a fraction of the end-of-life waste stream is diverted from "production from scrap" into "product fabrication". An example of 2050NDR is the reuse of steel from old buildings, with a fabrication step, but without melting and recasting. 2050RED predicts the reduction in 2050 demand for materials (Y_0) required to meet the emissions target. 2050EFF explores the development of radical new processes for forming, fabrication and production from scrap with lower energy use and improved yield—thus reducing e_2, e_3, e_4, α_3, and α_4.

Results

Based on the data for 2006 in Table 4, and the schematic diagram of Figure 3, Figure 4 shows the global flows and emissions of the five key materials in 2006.

For steel, cement, aluminum, and plastic, Figure 4 shows that primary production is the dominant source of emissions. For paper, primary emissions are lower than for papermaking, as most pulping factories use waste biomass in their fuel mix. For cement there is no recycling, and plastics recycling is currently negligible due to the large range of polymer formulations, fillers, and additives in use. Both steel and aluminum diagrams show large return flows of process scrap. The figures for all materials except paper show that a substantial fraction of current production is added to stock, due to growth in global demand.

Figure 5 shows the Sankey diagram for steel in 2006 and under the five 2050 scenarios defined above, with the assumption that 20% of annual demand in 2050 is added to stock. Figure 5a is the same as Figure 4a, but rescaled. Figure 5b shows the 2050CEE scenario for steel with carbon and efficiency improvements giving an emissions decrease of 14% compared to 2006 despite increased demand. 2050CCS gives only a 40% reduction despite zero emissions from primary production, as emissions from the energy for forming, fabrication, and recycling exceed the 2050 target. 2050NDR shows that if 92% of material sent for recycling were diverted via a fabrication stage, the target could be met. In 2050RED, if demand were reduced by 43% compared to 2050CEE, the target would be achieved. In 2050EFF the emissions and scrap rates have been reduced by 51% to meet the target.

The results for the five 2050 strategies can be summarized by a single ratio. If the strategy is successful, the ratio is the rate of implementation required to meet the target. If 100% implementation fails to meet the target, the ratio is of the emissions in excess of the 2050 target divided by the target emissions. In effect this second number is also the excess of production over that which would be possible if the emissions target were imposed so indicates the need for demand reduction. However, this summary ratio is dependent on the accuracy of the 2050 demand forecast. Two uncertainties are therefore considered: the absolute level of demand in 2050, and the fraction of 2050 demand which is added to stock. Figure 6 illustrates for 2050NDR applied to steel, the
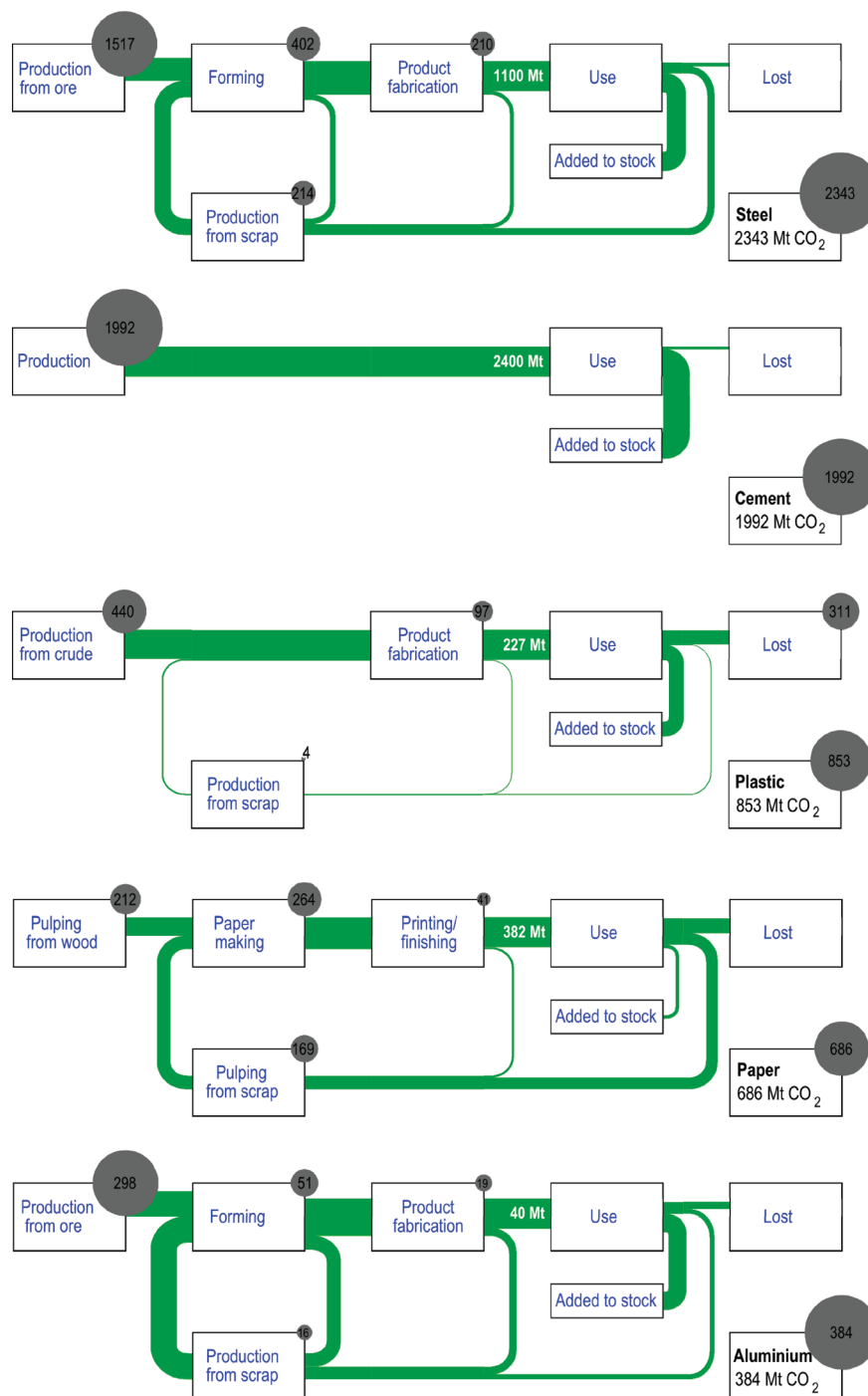
FIGURE 4. Sankey diagrams for flows and emissions of the five key materials in 2006.

sensitivity of the implementation ratio to these two forecasting uncertainties.

The 25 nodes on the "flag" of Figure 6 show the summary ratio varying as the forecast level and growth rate of 2050 demand vary. The left most red dot shows that if 2050 demand reaches exactly the IEA forecast level, and if in 2050 demand has saturated so no new material is added to stock, the emissions target can be met if 47% of all material being sent for recycling is instead reused without melting via a fabrication step. However, the right most red dot shows that if in 2050, demand is at the IEA forecast, but 40% of that year's demand is added to stock (so discards from use are only 60% of new demand) then even if all material sent to recycling were reused without melting, the emissions target could not be met and would be exceeded by 34%. As the forecast level of demand increases (nodes moving vertically upward), the required rate of implementation increases. As the forecast demand growth rate increases (nodes to the right along a line) the required rate also increases, indicated by the upward slope. In general, a *large* flag indicates high sensitivity to the absolute demand forecast for 2050, and an *angled* flag indicates high sensitivity to the rate of demand growth in 2050.

Based on repeated analyses of the type of Figure 5, Figure 7 recreates the sensitivity results of Figure 6 for all five materials under the five 2050 scenarios.

Figure 7 shows that the emissions target is not met by 2050CEE for any material under any forecast demand level or growth rate. 2050CCS is only fully successful for cement. For aluminum, with lower demand, CCS is effective because the energy of primary production dominates total requirements. For the other three materials, even with full imple-
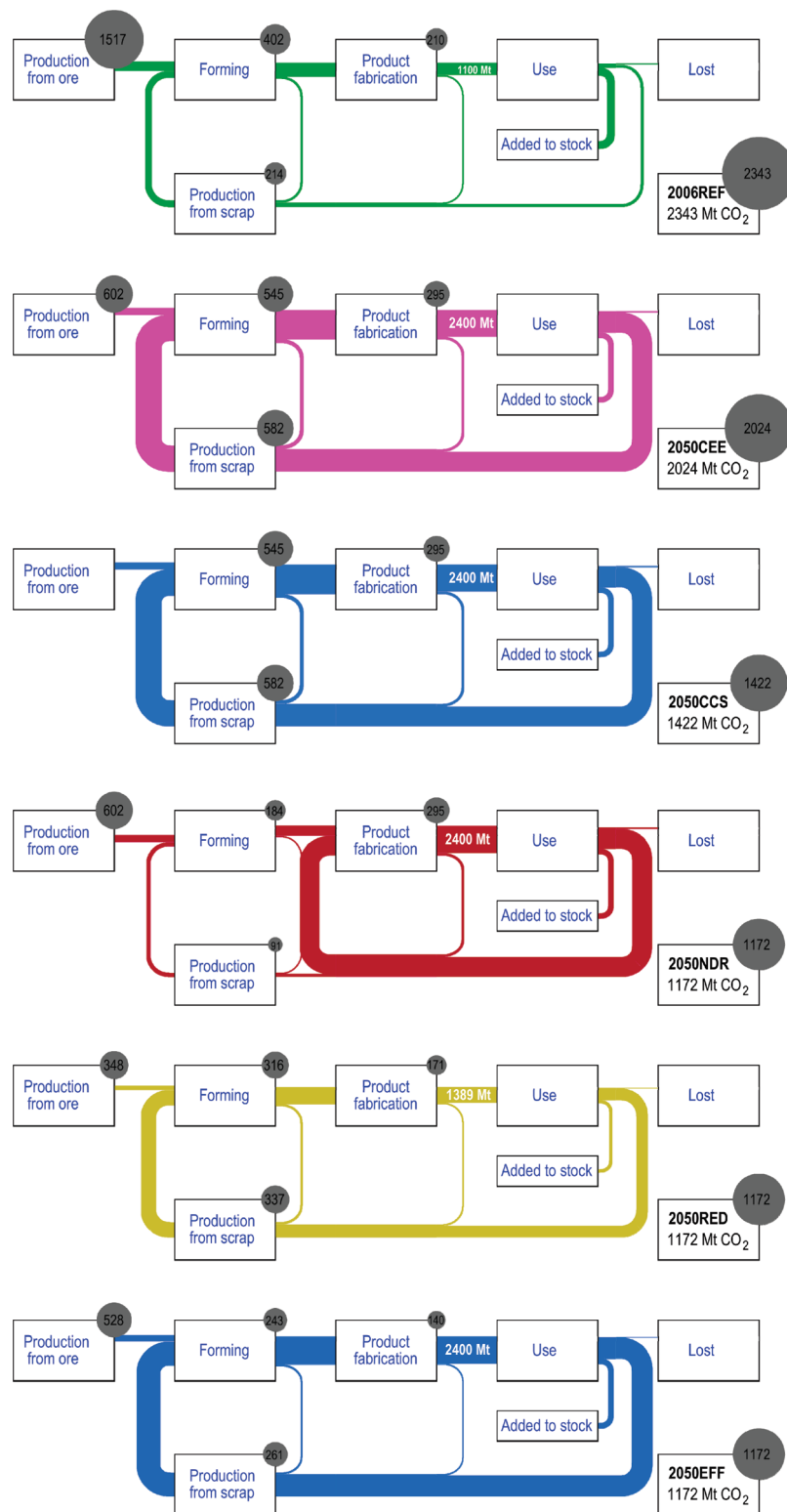
FIGURE 5. Sankey diagrams representing global steel production and associated CO$_2$ emissions for (a) 2006, (b) 2050CEE, (c) 2050CCS, (d) 2050NDR, (e) 2050RED, and (f) 2050EFF scenarios.

mentation of 2050CEE and perfect implementation of CCS to all primary processes, the 2050 target is not met.

2050EFF could reach the target for all materials except cement if new processing routes can be found with ∼50% less energy for converting liquid material to finished products and ∼50% reduction in scrap rates. This may be possible for the two metals if the current number of thermal cycles can be reduced along with scrap and trim losses.

2050RED is successful for all five materials if 2050 demand is reduced by ∼50%. This could occur through substitution of other less energy intensive materials (for example in the proposal (*9*) to build high-rise buildings from wood), "light-weighting" through intelligent design and new manufacturing routes (the aluminum beverage can has become 20% lighter in the past 20 years), or service-life extension (for instance by designing flexible buildings that can be modified rather
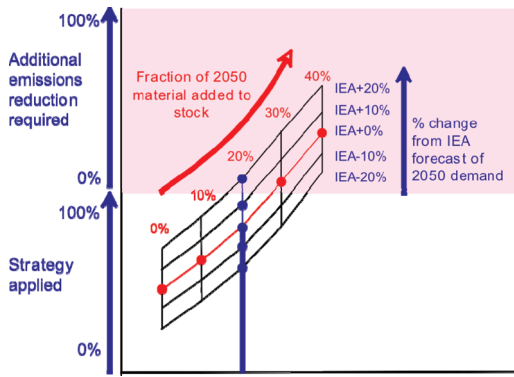
FIGURE 6. Key results for the 2050NDR scenario for steel showing sensitivity to forecast demand and additions to stock.

than demolished, designing modular vehicles and appliances in which separate components can be upgraded individually, or using refillable rather than disposable beverage cans).

2050NDR shows mixed success. For cement, only, it would be sufficient and some evidence exists of a developing market for reuse. Addis (*10*) presents design guidance for reuse in construction reporting that prefabricated components, such as precast concrete floor panels, may be separated from the structural frame and reused. Based on two case studies of buildings designed and constructed with reused components, Gorgolewski (*11*) reports challenges due to the need for certification, the lack of an established supply chain, increased labor costs in deconstruction, refabrication, and

design, and emphasizes the need for reversible joining techniques. Office paper could be reused if early results on novel unphotocopying techniques can be further developed (*12*), and aluminum can be recycled at room temperature by cold-bonding, with 5% of the energy of conventional recycling by melting (*13*). Remanufacturing of components is already practiced by Caterpillar (*14*).

In most cases, the flags of Figure 7 show that as additions to stock increase, the required rate of implementation of a strategy (or failure to reach the target) increases. However, cement shows no sensitivity to additions to stock (as all energy is associated with primary production) except an inverse sensitivity in 2050NDR as increasing additions to stock reduces the availability of material for reuse. Plastic also shows a reversed sensitivity to additions to stock in several cases, due to emissions during incineration.

Discussion

All scenarios in this analysis assumed 2050CEE, including global implementation of all known technology improvements in primary production, some energy decarbonization, improved recycling rates, and a 20% efficiency gain in all other processes. The analysis has shown that if global demand for these materials doubles as expected, emissions can only be reduced by 50% with an increase in primary output if at least 50% of all industrial emissions are avoided or captured. Radical process efficiencies explored in 2050EFF may be discovered, but are difficult to anticipate and hence cannot be easily included in policy.
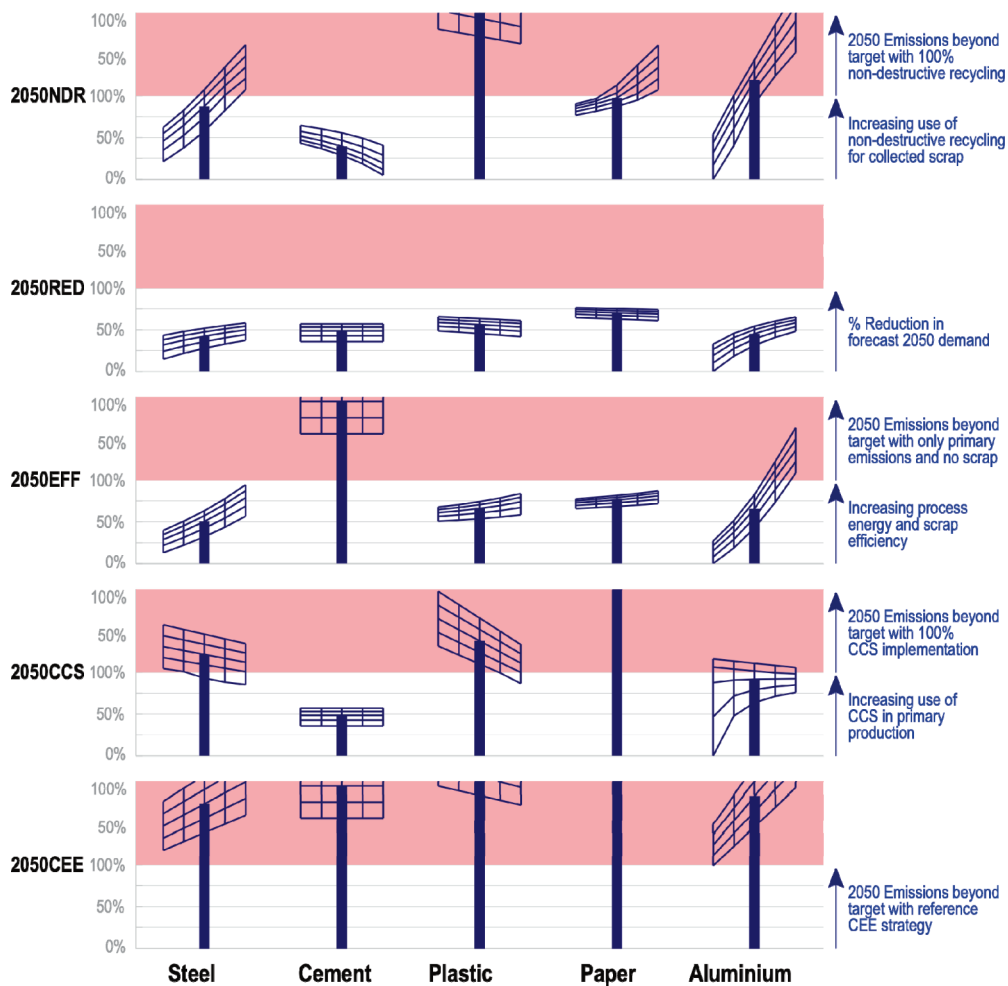

FIGURE 7. Forecast implementation rates required to reach the 2050 emissions reduction target (or excess emissions with full implementation) for the five key materials under five scenarios.

However, an alternative strategy for emissions reduction in industry is to *reduce primary materials output*. This could be achieved through increasing product lifespan, reducing material requirements through efficient design, nondestructive reuse of components or materials, or material substitution. These strategies cannot be easily pursued by incumbent primary materials industries, but are physically possible and could have a significant impact.

Are these scenarios also economically credible? CCS is anticipated to cost US$200–500 per tonne of CO_2 sequestered. For steel, structural sections are currently priced around $1000 per tonne which would be increased by $700 with midpriced CCS. In comparison, used girders sold to scrap are worth ~$300 per tonne—so the economic case for 2050NDR is already strong when compared with 2050CCS, provided the additional costs of deconstruction and logistics can be managed. 2050RED requires less material than 2050CEE, although total costs will depend on the additional processing costs of creating optimized products. Potential lost revenue from reduced material sales could be offset by servicing materials over a longer life.

The intention of this paper has not been to predict exact flows and emissions in 2050. Instead, the paper has asked whether the strategies of incumbent players can meet emissions reduction targets and the results show that this is unlikely. Strategies for providing increased service from existing materials may be able to contribute significant emissions reductions at relatively low cost. However, their development is unlikely to be immediately profitable, so they will not be developed by existing primary material producers whose shareholder value depends on output growth—unless those companies are sufficiently vertically integrated to replace income from materials output with income from other material processing and servicing. The key questions arising from our analysis that we plan to address in future work are as follows:

- How much of the projected emissions and primary material savings can be achieved in practice for each of the scenarios aiming at reduced primary material consumption? What are the technical limits for each strategy?
- What infrastructure, systems, services, regulation, or standards would be required to promote and support the scenarios?
- How do the additional costs of processing associated with reduced primary materials consumption compare to the saving in materials purchasing? Assuming that in many cases the scenarios will lead to increased cost, what new business models are possible, and what interventions from government might be required? Will demand for each material be strongly influenced by future energy/carbon prices?
- Can total demand for material goods be significantly manipulated or constrained? Does a reduction in

materials input to each unit of service lead to some form of rebound effect, with an overall increase in demand for the service?
- To what extent do the strategies evaluated for the five materials considered in this paper apply to the remaining 44% of industrial carbon emissions?

Supporting Information Available
Breakdown of CO_2 emissions, survey of known energy efficiency technologies, current and maximum projected global recycling rates, material demand forecasts, constructing the 2006 Sankey diagrams, estimating the carbon emission factors for 2050CEE, and SI references. This material is available free of charge via the Internet at http://pubs.acs.org.

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