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Title: "Carbon intensive materials in a deeply decarbonised world: can country-based budgeting work?"

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Abstract:

International climate negotiations are now moving towards country-based action driven by national pledges, and comprehensive global emissions trading appears a remote prospect. This article examines the impact this could have on emissions and production of carbon intensive traded products. It compares estimated production and emissions from iron and steel and cement from global analyses with country-based modelling results from the Deep Decarbonization Pathways Project. The analysis shows that the aggregation of country-level modelling tends to underestimate global emissions from Iron and steel and cement, when these products could account for up to a fifth of a +2°C compatible carbon budget to 2050. Second, the analysis shows that country-based action benchmarks such as equal per capita emissions are not suitable to cover traded emissions intensive materials. For some exporting nations, by 2050 steel production alone could amount to the total national emissions allowance on an equal per capita basis. There is a risk that resource intensive countries opt out of the common per capita benchmark, and of inefficient carbon leakage. One solution in the absence of comprehensive global emissions trading would be to create a global emissions budget for the production of GHG intense products based on best practices. This would be incorporated in the global GHG budget and national GHG per capita budgets. The analysis suggests that a global iron and steel allocation would be between 0.4 and 2.0 $GtCO_2$ in 2050. Emissions allocations to all other sectors combined would then be about 1.3 to 1.45 tCO_2 per capita, compared to 1.5 tCO_2 with steel included in the national average. Finally, the analysis highlights the critical importance of global efforts to improve technologies and material efficiency in emissions intensive commodities manufacturing and use.

Policy relevance statement:

This article presents new empirical findings on global iron and steel and cement production in a low-carbon world economy, demonstrates the incompatibility of equal national per capita emissions allocations with efficient global production of emissions intensive products, and offers policy relevant insights and suggestions on how these issues could be resolved in practice, given the policy framework likely to emerge under the Paris agreement.

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1. Introduction

The theoretically optimal approach to reconciling the production and consumption of emission intensive commodities in different countries is international trading in emissions allowances at a common global price. Emissions intensive industries would be located wherever they can produce most cheaply after accounting for the cost of emissions, and trade flows in emissions intensive goods would be matched by trade in emissions permits (as per Coase, 1960).

In practice, however, there is no imminent prospect of full global emissions trading. A bottom-up approach of nationally determined contributions is now the key determinant of international climate change negotiations, and prevailing experience is that effective carbon prices vary greatly between countries (OECD, 2013). This article examines whether country-based planning without global coordination is appropriate for highly emissions intensive traded products. It focuses on CO_2 emissions from the manufacturing of iron and steel[1] and cement, which are likely to be critical in future decarbonisation efforts.

It also considers whether benchmarks typically used to compare country-based action in the context of a near complete decarbonisation are suitable to cover the production of carbon intensive products. This is illustrated with national per capita emissions benchmarks which were used in the DDPP (SDSN, 2014).

It does so by comparing country-based modelling results from the Deep Decarbonization Pathways Project (DDPP, 2014; DDPP, 2015) to benchmarks from global models. DDPP is a collaborative initiative to understand how the world's largest emitters can transition to a low-carbon economy in line with limiting the increase in global mean surface temperature to less than two degrees. DDPP modelling results indicate national emissions trajectories in a world where countries are aiming for similar domestic per capita carbon dioxide (CO_2) emissions by 2050. The benchmarks, however, represent a globally coordinated approach to reducing emissions from those sectors. The paper analyses the differences between those two datasets and investigates some of the potential implications for global policy and accounting frameworks.

IEA's 2DS (2015) scenario, consistent with the IPCC RCP 2.6 scenario (2014) indicates 2050 global emissions of about 14.4 $GtCO_2$ for a 50% chance of keeping global warming below 2 degrees (IEA, 2015), with a total budget up to 2050 of 1055 Gt CO_2. This is equivalent to 1.5 t CO_2 per year per capita assuming the world's population will reach 9.5 billion by 2050, in line with the medium fertility projection of the UN Population Division (DDPP, 2014). 1.5 t CO_2 emissions per capita in 2050 is used as a benchmark by the DDPP project (DDPP, 2014).

[1] In this article, 'iron and steel' refers to the integrated manufacturing of iron and steel, which produces crude steel from iron ore. It corresponds to ISIC 241 in the International Standard Industrial Classification of All Economic Activities (UNSD, 2008)

According to the production and technology assumptions in the IEA's 2DS scenarios, iron and steel and cement will result in cumulative emissions of 201 Gt CO_2 between 2011 and 2050 (IEA, 2014; CDP, WRI & WWF, 2015). This represents 19% of the available CO_2e budget (IPCC, 2014). As we show in this paper, properly accounting for and managing those emissions will be critical to help the world stay within the CO_2 budget.

This article uses results from 12 country studies under the DDPP: Australia, Brazil, Canada, China, Indonesia, Italy, Japan, Mexico, South Africa, South Korea, Russia and the United States. Together, they represented 74% of global steel production (Worldsteel, 2015) and 68% of global cement production in 2010 (USGS, 2015).

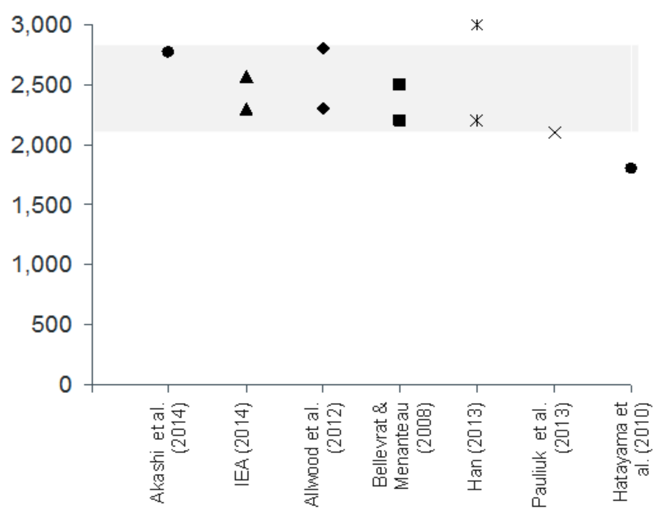
2. Iron and steel

Production projections

Estimates of global requirements

Demand for steel is mostly driven by construction of buildings and infrastructure (56% of all demand today), followed by production of metal goods and various equipment (Allwood, Cullen, & Milford, 2012). As a consequence, demand is particularly high in developing countries during periods of infrastructure and equipment investment growth. Economic growth eventually leads to a saturation of per capita stock (Hatayama, Daigo, Matsuno, & Adachi, 2010). When looking at steel annual demand to 2050, most projections suggest that it will reach between 2,100 Mt and 2,800 Mt, corresponding to about 35% to 80% growth from 2012 levels (Akashi, Hanaoka, Masui, & Kainuma, 2014; Allwood et al., 2012, Bellevrat & Menanteau, 2008; Han, 2013; IEA, 2014; Pauliuk, Milford, Müller, D. B., & Allwood, 2013). Hatayama et al. (2010) estimates future production to be lower, but the analysis discounts the contribution from recycled scrap, which can explain the difference. Figure 1 below summarises the sources considered in this article.

Figure 1 - Estimated annual demand for steel in 2050, Mt[2]



[2] Two data points for one source represent a range.

Significant literature exists on the opportunity to improve material efficiency, but it seems to be seldom accounted for in materials demand projections. For example, IEA (2014) estimates that demand for materials will be the same in its 2DS and 6DS scenarios. Most other analyses reviewed for this article do not mention material efficiency, or consider it in separate scenarios.

Table 2 summarises the theoretical technical opportunities for material efficiency in the five major categories of improvements (Fischedick et al., 2014). In this section, we only consider opportunities which reduce the overall demand for materials, and will review opportunities which can reduce the share of primary materials in total production in the next section focused on emissions intensity of production. Opportunities to substitute steel for other materials, such as engineered timber in construction (Lehman, 2013) or aluminium in car manufacturing (Roth, Clark, & Kelkar, 2001) could substitute or supplement material efficiency improvements.

Adding up all those opportunities suggests that total steel demand could be reduced by up to 75%. Opportunities which rely on increasing product lifespan could be having negative impacts on other decarbonisation activities, such as improvement in the energy efficiency of the building and vehicle stock. Ignoring those opportunities, the opportunities to reduce steel demand still add up to about a 58% reduction potential. This is broadly consistent with estimates by Higashi (2012) which found that reductions of about 40 percent could be achieved. Applying 40 to 58 percent reduction to the demand range established in the previous section, this suggests that total steel demand by 2050 could range between 43 percent reduction and 8 percent increase on 2012 levels should all opportunities be implemented.

Table 1- Estimated opportunities to reduce materials demand from material efficiency

End use sector	Use today (A)	Reducing yield losses in production (B)	Re-using old material (C)	Designing products using less materials (D)	Using products for longer (E)	Reducing overall demand for services (F)	Total potential reduction in demand (G*)
Construction	51%	0%	15%	19%	47%	40%	**78%**
Mechanical machinery	14.5%	6%		33%	9%	7%	**55%**
Metal products	12.5%	9%		27%	75%	0%	**86%**
Automotive	12%	10%		45%	13%	39%	**78%**
Other transport	4.8%	10%		45%	13%	39%	**78%**
Electrical equipment	3%	6%		33%	9%	7%	**55%**
Domestic appliances	2%	9%		27%	75%	0%	**86%**
Total	**100%**	**4%**	**15%**	**27%**	**39%**	**28%**	**75%**

*G = 1 - (1 - B) × (1 - C) × (1 - D) × (1 - E) × (1 - F)
Source: Cooper & Allwood, 2012; Milford et al., 2011; Milford et al., 2013; Worldsteel, 2015

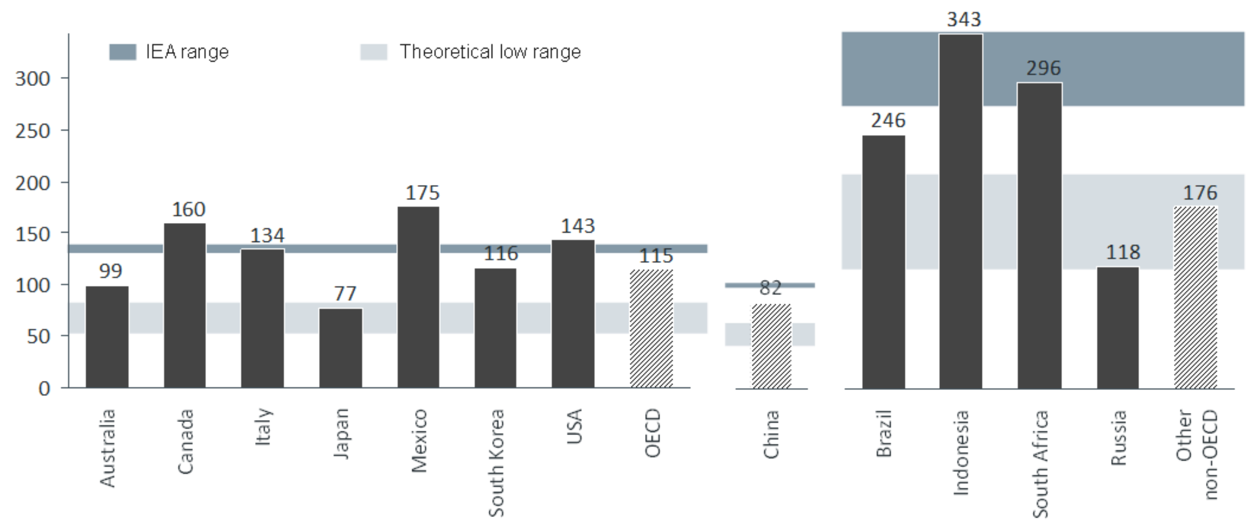
Results from country-level modelling

In this section, DDPP country modelling results (2015) regarding iron and steel production to 2050 are compared to two benchmarks to assess how realistically they represent global production and emissions requirements from iron and steel production to 2050: IEA (2014,

2015) estimates which are aligned with most of the literature, and a theoretical low range which corresponds to the 40 to 58 percent reduction from the IEA (2014) estimates.

When looking at results by DDPP country, it appears that growth broadly stays within the range of the lowest and highest benchmark levels for each country (see Figure 3). Production growth in non-OECD countries appears to be further below baseline estimates than in OECD countries, which could also be due to higher growth expectations in non-OECD countries not included in the DDPP project. China's DDPP production projections are also at the lower end of the literature estimates, which range from 430 Mt to 850 Mt by 2050, or -33% to +33% on 2010 levels (Chen, 2014; Gambhir, 2013; IEA, 2015; Zhou, 2014).

Figure 2 - Steel production growth by country in DDPP modelling, compared with demand level estimates, index (2010 = 100)



Source: Cooper & Allwood, 2012; Higashi, 2012; IEA, 2014, 2015; Milford et al., 2011; Milford et al., 2013; SDSN & IDDRI, 2014; Worldsteel, 2015

Emissions intensity projections

Summary of literature

According to most estimates, the current emissions intensity of the iron and steel making process is about 1.8 tCO_2/t steel (Allwood et al., 2012; Birat, 2010; Carbon Trust, 2011; IEA, 2009b, 2014, 2015; WorldSteel Association, 2015c). Based on this estimate, the iron and steel sector is estimated to have created about 2.8 Gt of CO_2 emissions in 2012, which represents 8% of CO_2 emissions in that year (Oliver, Janssens-Maenhout, Muntean, & Peters, 2013). One key parameter that drives emissions intensity of production is the relative share of primary (from iron ore) and secondary (from recycled steel crap) production, given that secondary steel production is much less emissions intensive than primary production (Morfeldt et al., 2015), for reasons explained below.

In primary production there are several possible processes with different energy and emissions requirements. The most common route is BF-BOF (blast furnace, basic-oxygen furnace), which has largely replaced open hearth furnaces (OHF). . The key energy input and emissions source is the coking coal, used as reductant and fuel; natural gas and oil can also be used (WSA, 2014b). The main alternative modern method for primary steel production is the DRI-EAF

(Direct reduced iron electric arc furnace) route. The DRI process uses natural gas (90% globally) or coal (10%, mainly in India) for energy and a syngas of hydrogen and carbon monoxide as the reductant (IEA 2007). Natural gas reduces the direct GHG intensity of reduction compared to coal. After reduction, the metallic iron is then melted in an Electric Arc Furnace (EAF) (Fischedick et al., 2014). The remainder of global steel production comes from secondary production via EAF. The table below summarises estimates of current average and best performance (BP) by route, as well as what best available technologies (BAT) and technologies under development could deliver. In the table, casting and rolling was separated from steelmaking and should be added to each of the routes' results to obtain overall energy and emissions estimates.

Table 2 – Overview of iron and steel technologies performance per ton crude steel

Technology	Energy use, GJ			Emissions intensity,		Emissions w/o CCS, tCO2			Emissions w CCS,		Comments and sources
	Direct fuel	Electricity	Total	Direct fuel	Electricity *	Direct	Indirect	Total	% Direct captured	Total, tCO2	
BF-BOF											
2012	20.2	0.8	21.0	0.099	0.147	2.0	0.1	2.1	0%	2.1	Birat, 2010; Carbon Trust, 2011; 2013; Morfeldt et al., 2015
BP	14.4	0.6	15.0	0.099	0.147	1.4	0.1	1.5	0%	1.5	Birat, 2010; Carbon Trust, 2011; Fischedick et al., 2014; Milford et al., 2013; Morfeldt et al., 2015; Worrell, Price, Neelis, Galitsky, & Zhou, 2007
BAT	11.5	0.6	12.1	0.099	0.006	1.1	0.0	1.1	0%	1.1	IEA, 2009, 2014; Carbon Trust, 2011; Milford et al., 2013
New technologies											
Bio-coke	11.5	0.6	12.1	0.020-0.042	0.006	0.2-0.5	0.0	0.2-0.5	0%	0.2-0.5	CSIRO, 2013; Carbon Trust, 2011; Fischedick et al., 2014; IEA, 2009
CCS	15.0	0.8	15.8	0.099	0.006	1.5	0.0	1.5	90%	0.2	EPA, 2012; Fischedick et al., 2014; IEA, 2009
Electrolysis	*No detail provided*									0.2	Carbon Trust, 2011; Fischedick et al., 2014; IEA, 2009; Milford, 2013
DRI-EAF											
2012	15.9	3.8	19.7	0.090	0.147	1.4	0.6	2.0	0%	2.0	Birat, 2010; Oda, Akimoto, Sano, & Homma, 2009;
BP	12.1	1.9	14.0	0.056	0.147	0.7	0.3	1.0	0%	1.0	Oda et al., 2009; Worrell et al., 2007
BAT	12.1	1.9	14.0	0.056	0.006	0.7	0.0	0.7	0%	0.7	Oda et al., 2009; Morfeldt et al., 2015
New technologies											
CCS	15.7	2.5	18.2	0.056	0.006	0.9	0.0	0.9	90%	0.1	EPA, 2012; Fischedick et al., 2014
Hydrogen	12.1	1.9	14.0	0.008	0.006	0.1	0.0	0.1	0%	0.1	Fischedick et al., 2014; IEA, 2014; Kavanagh, 2008; Oda et al., 2009
EAF (scrap)											
2012		3.2	3.2		0.147	0.0	0.5	0.5	0%	0.5	Birat, 2010; Worrell et al., 2007
BP		1.6	1.6		0.147	0.0	0.2	0.2	0%	0.2	Birat, 2010; Worrell et al., 2007
BAT		1.6	1.6		0.006	0.0	0.0	0.0	0%	0.0	IEA, 2009, 2014; Milford et al., 2013
Casting and rolling											
2012	2.2	0.4	2.7	0.056	0.147	0.1	0.1	0.2	0%	0.2	Birat, 2010; Worrell et al., 2007
BP	1.6	0.3	1.9	0.056	0.147	0.1	0.0	0.1	0%	0.1	Birat, 2010; Worrell et al., 2007(8?)
BAT	0.2		0.2	0.056	0.006	0.0	0.0	0.0	0%	0.0	Worrell et al., 2007
Total (excluding BF-OHF)											
2012	17.1	2.0	19.1	0.1	0.3	1.6	0.3	1.9	0%	1.9	WSA, 2015a, 2015b

* BAT electricity emissions intensity taken from SDSN & IDDRI, 2014. 2012 average emissions intensity set as global average for this analysis (CCA, 2014).

One of the options to reduce emissions is to increase the share of production from scrap. This is usually constrained by the volume of steel scrap available compared to the total steel demand and the requirements of the end use. EAF steel products depend on the quality of the scrap steel fed in and may have residual impurities that make them unsuited for purposes where cold rolling and malleability are required (Denis, 2014). Estimates on the share that could be achieved by 2050 vary between about 50% and 75% (Allwood et al., 2012; IEA, 2009b; Milford et al., 2013; Morfeldt, 2015; Pauliuk et al., 2013). Given that there is a limited amount of scrap available, increasing the share of recycled steel beyond 50% would require significant improvements in material efficiency so as to reduce the overall demand in final steel (Allwood et al., 2012; Milford et al., 2013).

As shown from the table, several technologies are under development (e.g. DRI-EAF using hydrogen as a reductant) which could deliver emissions intensities of primary production as low as 0.2 tCO_2/t steel (Carbon Trust, 2011; Fischedick et al., 2014; Milford, 2013). Combining the use of charcoal for coking and CCS could even achieve negative emissions (Carbon Trust, 2011). There are many challenges, however, to making these technologies commercial at a large scale, and some recent research efforts have slowed down due to reduced funding and a lack of long-term business case in the current policy context (Neuhoff et. al, 2014; WSA, 2014a).

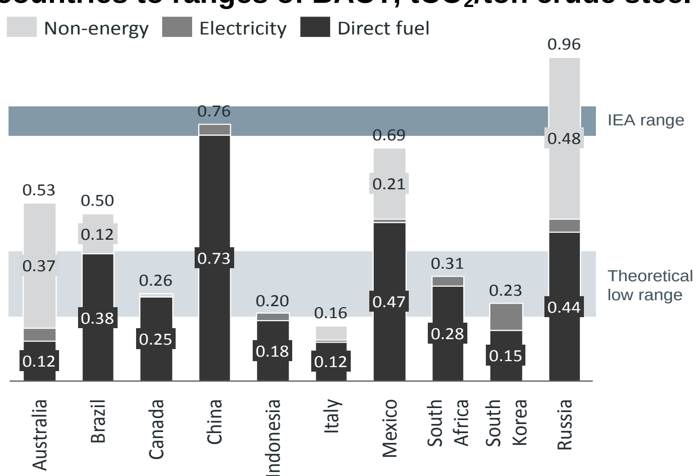
Based on these estimates, barring the widespread use of charcoal and CCS, it seems that the lowest emissions intensity of steel production which could be achieved by 2050 is about 0.2 tCO_2/t steel to 0.4 tCO_2/t steel. Recent modelling exercises result in average emissions intensities in 2050 of about 0.7 tCO_2/t steel to 0.9 tCO_2/t steel (IEA, 2014; Milford et al., 2013). This corresponds to the upper end of the range of benchmarks of 0.47 to 0.84 tCO_2/t steel adopted by the DDPP in line with the IPCC 2 degrees scenarios (DDPP, 2014).

Results from DDPP country-level modelling

Estimates of the emissions intensity of steel production vary by country, with most countries having emissions intensities around the theoretical minimum range and even one below it. Low emissions intensity estimates in countries such as Indonesia and Canada reflect local circumstances, such as all production already coming from EAF in Indonesia, and a high potential for low cost CCS in Canada. Other countries are mostly around the IEA (2014, 2015) range.

It is worth noting that most countries modelling results only include energy emissions, and so their emissions intensity estimates are likely to be below the estimates provided above. IEA (2009b) estimated that industrial processes emissions contributed about 5% of direct emissions in 2006, however it appears that different countries split direct emissions differently between processes and direct fuel combustion, with the Australian national greenhouse gas inventory for example attributing about three quarters of direct emissions from iron and steel production to industrial processes (DOE, 2015).

Figure 3 - Comparison of iron and steel emissions intensity in 2050 for various DDPP countries to ranges of BACT, tCO_2/ton crude steel[3]



Source: Carbon Trust, 2011; Fischedick et al., 2014; IEA, 2014; Milford, 2013; SDSN & IDDRI, 2014

[3] Note: non-energy emissions and analysis are only included for Australia, Canada, Italy, Mexico and Russia.

3. Cement

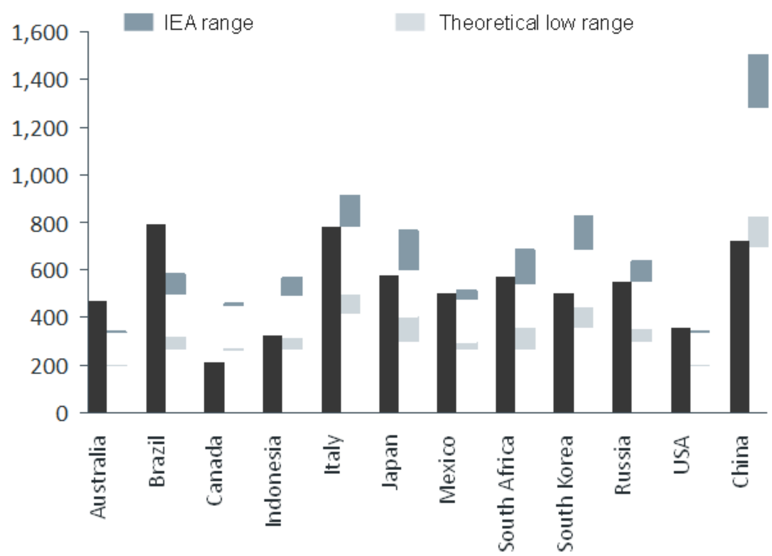
Production projections

Projections estimate that demand for cement in 2050 is likely to be between about 4.5 and 5.7 Gt (Akashi et al., 2014; Allwood et al., 2012; IEA, 2014; Müller, N., 2007), corresponding to a 18% to 50% growth compared to 2012 production levels. We estimated that material efficiency improvements could deliver about 40 percent reduction in demand, e.g. by using curved fabric moulds which allow a more targeted application of concrete (Orr, Darby, Ibell, Evernden, & Otlet, 2011), optimising the amount of cement when mixing concrete, extending construction's lifespan, and increasing the re-use of concrete elements by standardising their shape (Allwood et al., 2012; Fischedick et al., 2014).

Cement production has a very low exposure to trade, with only about 3.5% of global production estimated to be internationally traded in 2013 (Cemnet, 2015). As a result, it is possible to use future demand estimates as a proxy for future production levels. IEA (2009b) provides detailed projections for future cement demand per capita. Significant differences between IEA's 2009 and 2015 projections can be nearly fully attributed to Chinese demand, which changed from about 850 Mt in 2050 in the 2009 projections to 1,750 Mt in the 2015 projections (IEA, 2009b; IEA, 2015). As a result, we assume that the demand projections for other countries have mostly remained unchanged, and for China we present the most recent projections results (IEA, 2015).

Most DDPP country modelling results for cement production per capita are levels lower than the IEA estimates. In the case of Canada for example, production levels are even below the low range estimates in the DDPP scenario. This comes from an increase in material efficiency as well as trade in response to an increased price of production.

Figure 4 - Cement production by country in DDPP modelling, compared with IEA demand level estimates, kg per capita



* Australia's benchmark was modelled on similar countries and Indonesia on "other developing Asia".

Source: Allwood et al., 2012; Fischedick et al., 2014 ;IEA, 2009, 2014, 2015; Orr et al., 2011; SDSN & IDDRI, 2014

Emissions intensity projections

Greenhouse gas emissions associated with cement production come from both energy and non-energy sources. Process emissions, about 50% of total emissions, are created during the production of clinker, a key component of cement, in which limestone (CaCO3) is converted to lime (CaO) through a calcination reaction (CIF, 2015; Fischedick et al., 2014). The remainder of the emissions comes from energy use, with about 40% coming from fuel combustion for thermal processes and 10% from electricity consumption primarily used for cement grinding and also transport (CIF, 2015; CSI, 2015; Fischedick et al., 2014).

Overall, cement production was estimated to create 2.3 $GtCO_2$ of direct emissions in 2012 (IEA, 2015). In addition, it consumed about 370 TWh of electricity (IEA, 2015), which is likely to have created about 200 $MtCO_2$ of indirect emissions (CCA, 2014), bringing total emissions to about 2.5 $GtCO_2$. This represents about 7% of CO_2 emissions in that year (Oliver et al., 2013). Opportunities to reduce cement emissions can be categorised in four main categories: energy efficiency, shift to alternative fuels, reduce the clinker/cement ratio, and capture and store CO_2 emissions (Ali, Saidur, & Hossain, 2011; Fischedick et al., 2014; IEA, 2009a).

Table 3 below summarises the key drivers of emissions creation in the production of cement. The first column summarises the average performance of cement production in 2012, while the middle column represents what could be achieved based on some of IEA's published assumptions (2009a, 2009b, 2014, 2015). This scenario leads to a direct emissions intensity of about 0.31 tCO_2e/t cement by 2050, between the low and high emissions intensity from IEA's 2DS scenario of 0.30 and 0.38tCO_2e/t cement respectively (IEA, 2014). The rightmost column corresponds to the top end of possible values for the various factors considered based on the literature, resulting in emissions intensity of about 0.24 tCO_2/t cement.

This range is in line with the benchmarks of 0.24 to 0.39 tCO_2/t cement adopted by the DDPP project based on IPCC 2 degrees scenarios (DDPP, 2014). This is also in line with modelling results for China's cement production which resulted in emissions intensities of about 0.4 tCO_2/t cement in best available technology (BAT) scenarios and of about 0.22 tCO_2/t cement in extreme scenarios (Xu, Fleiter, Fan, & Eichhammer, 2014).

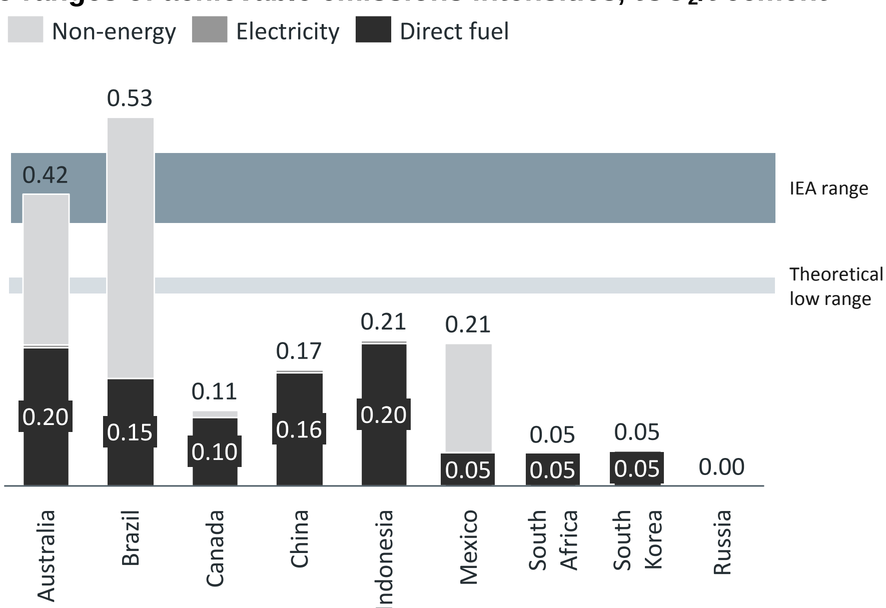
Fischedick et al. (2014) suggest even lower emissions intensities around 0.1 tCO_2/t cement could be achieved through the use of CCS, bioenergy and low carbon electricity, but more research is required. Several companies are looking at developing low or even negative carbon cements, or processes that allow direct separation and capture of CO_2 (IEA, 2009b). However, progress in these technologies is slow due to cost and reliability challenges (Osowiecki, 2015). It could also be possible to increase carbonation –or reabsorption of CO_2 by concrete and cement via post-use crushing and exposure to atmosphere (PCA, 2015).

Table 3 - Summary of options to reduce cement emissions and resulting emissions intensity

Metric	Unit	2012 average	IEA	Low range	Sources
Clinker emissions					
Direct emissions intensity	tCO2/t clinker	0.88	0.46	0.38	
Direct energy emissions intensity	tCO2/t clinker	0.34	0.16	0.15	
Thermal energy consumption	GJ/t clinker	3.7	3.1	3.1	Ali at al., 2011; Barcelo et al., 2013; Fischedick et al., 2014; IEA, 2009; IEA, 2015
Average emissions intensity of fuels	tCO2/GJ	0.09	0.05	0.05	
Use of alternative fuels	%	2%	37%	60%	CIF, 2005; IEA, 2009; IEA 2015; Orr et al., 2011
Average emissions intensity of fossil fuels	tCO2/GJ	0.092	0.056	0.056	IEA, 2015; WRI, & WBCSD, 2010
Average emissions intensity of alternative fuels	tCO2/GJ	0.044	0.044	0.044	Benhelal et al., 2013; IEA, 2009
Process emissions intensity	tCO2/t clinker	0.54	0.54	0.54	EPA, 2002; IEA, 2009
CCS capture	%	0%	34%	45%	IEA, 2009; IEA 2014
Cement emissions					
Total emissions intensity	tCO2/t cement	0.66	0.33	0.24	
Direct emissions intensity	tCO2/t cement	0.61	0.31	0.23	IEA, 2014; IEA, 2015
Clinker to cement ratio	%	69%	68%	60%	CIF, 2005; IEA, 2015
Direct emissions intensity of clinker substitutes (waste products)	tCO2/t substitute	0	0	0	Benhelal et al., 2013; Fischedick et al., 2014; IEA, 2009b
Indirect emissions intensity	tCO2/t cement	0.05	0.02	0.02	
Electricity use	MWh/t cement	0.096	0.80	0.80	IEA, 2015; Fischedick et al., 2014
Average emissions intensity of electricity	tCO2/MWh	0.55	0.02	0.02	CCA, 2014; SDSN & IDDRI, 2014
Energy emissions intensity	*tCO2/t cement*	*0.29*	*0.09*	*0.07*	

In the figure below, the emissions intensities of cement production from DDPP modelling are compared to the range of emissions intensities from the IEA roadmaps (2009a, 2014), and the *low range* value presented in the previous section.

Figure 5 - Comparison of cement emissions intensity in 2050 for various DDPP countries to ranges of achievable emissions intensities, tCO_2/t cement[2]



Source: Fischedick et al., 2014; IEA, 2014; Xu et al., 2014; SDSN & IDDRI, 2014

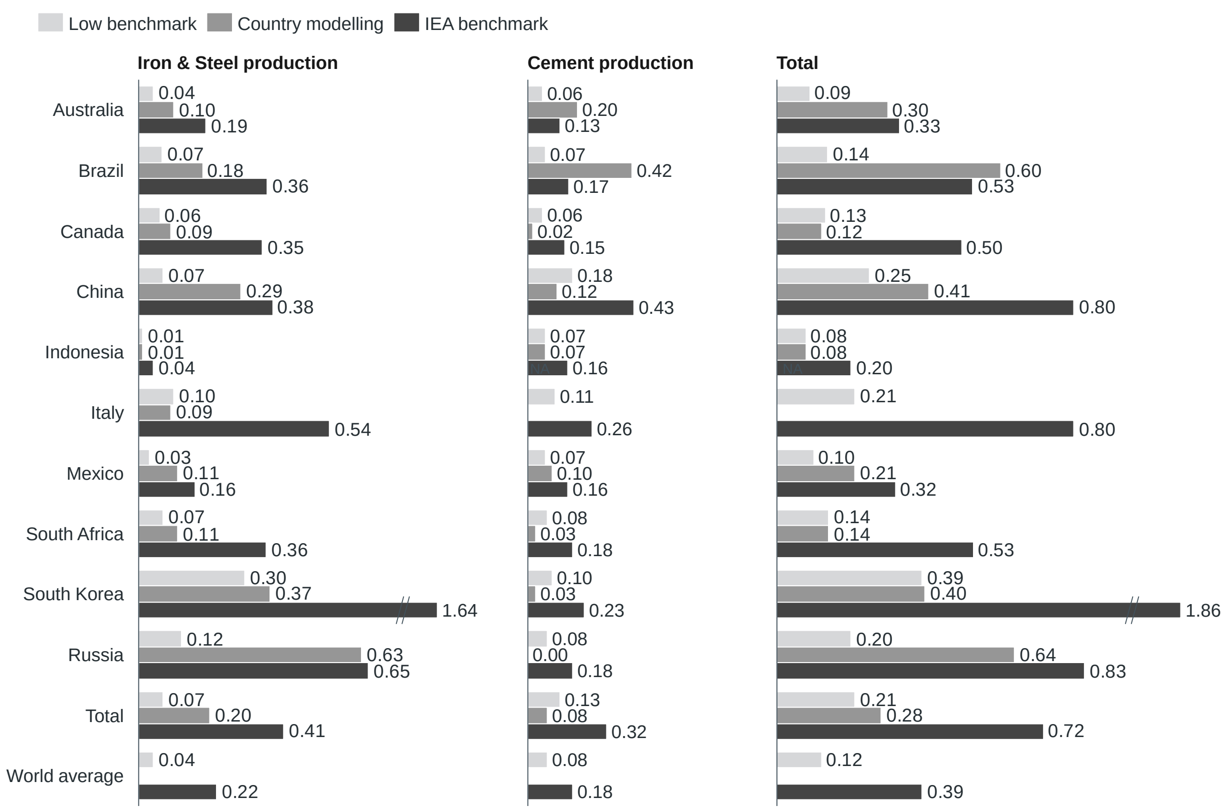
Energy emissions from cement production in most DDPP countries modelling fall well below the benchmark range. This is mostly due to very low non-energy emissions. Only four countries include non-energy emissions estimates in their analysis; two have non-energy emissions in line with the benchmark (Australia, Mexico) while two have near zero non-energy emissions (Canada, Russia).This results in average non-energy emissions significantly below the benchmark values. These results suggest that further work is needed to standardise accounting of emissions from cement production in modelling exercises, and to better understand what best practice technologies could be implemented under what policy assumptions.

4. Impact on countries' carbon emissions pathways

Per capita impact of iron and steel and cement production

This section discusses the impact that iron and steel and cement production might have on national emissions budgets if they were based on per capita allocations. In line with the preceding sections, we present here the DDPP country modelling results compared with two benchmarks based on the literature, namely the midpoint of the IEA range (2014, 2015), and a low benchmark corresponding to the midpoint of the low range for production volumes and emissions intensity estimates. For steel, benchmark production volumes were calculated based on the DDPP production estimates, scaled by country categories (OECD, China, other-non OECD).

Figure 6 - Iron and steel and cement production emissions in 2050, tCO_2 per capita



Source: Carbon Trust, 2011; Cooper & Allwood, 2012; Fischedick et al., 2014; Higashi, 2012; IEA, 2009, 2014, 2015; Milford et al., 2011; Milford et al., 2013; SDSN & IDDRI, 2014; Worldsteel, 2015

In total, residual emissions from iron and steel production and cement production represent on average 0.28 tCO_2 per capita amongst DDPP countries in current modelling results. If the IEA benchmark was used, then those residual emissions would add up to about 0.72 tCO_2 per capita, over 2.5 times more than current results. Should that benchmark be applied, South Korea would be particularly impacted with 1.86tCO_2 per capita, followed by Russia, Italy and China with around 0.80 tCO_2 per capita. The minimum impact on DDPP countries should material efficiency improvements and very ambitious technology strategies be implemented would be 0.21 tCO_2 per capita, about 25% below current results.

Implications for global accounting and management of emissions

These results highlight several issues with country-based management of emissions intensive products.

Risk of overshooting a global emissions target

Consistently for both materials, country models tend to underestimate future production volumes and emissions intensities compared to widely accepted benchmarks, which implies that bottom up emissions projections based on individual countries' modelling may underestimate future global emissions.

This is in particular true for countries which did not model non-energy emissions, as CO_2-process emissions from iron and steel and cement production are likely to be material by 2050. For cement, unless CCS is employed, process emissions could represent about two third of emissions in 2050 (IEA, 2009) equivalent to about 0.12 tCO_2/capita in the IEA benchmark (2014).

Inadequacy of equal per capita emissions benchmarks to cover traded emissions intensive materials, endangering risks of carbon leakage

The analysis suggests that equal per capita benchmarks are not adequate for emissions intensive materials, especially when highly traded like iron and steel. Based on the IEA benchmark, iron and steel emissions would represent over a quarter of the 1.5 t CO_2 per capita benchmark in the DDPP countries, and countries like South Korea which are very large exporters of steel could see emissions from steel production exceed their total carbon allocation.

Steel is a highly traded product, with about one third of global emissions associated with steel production embodied in international trade (Carbon Trust, 2011). In particular, primary production, the most emissions intensive form of production, is highly concentrated with about 90% of primary production located in DDPP countries in 2013 (WSA, 2015b). Geographic reallocation of production, for example more in line with consumption, or towards countries which could produce low emissions steel at the lowest cost, could reduce the range of country impact as observed in the DDPP modelling results. A full coverage international emissions trading system could for example accomplish this.

The issue is less pronounced for cement where trade is currently limited so that country consumption in most cases is very similar to production (Cemnet, 2015). However, it is possible that given its high emissions intensity, trade of clinker could increase in the future as transport cost reduces compared to carbon or production cost, with cement production staying localised.

Leakage protection mechanisms could be introduced to reduce the risk of carbon leakage, for example consumption-based taxes per ton of steel or cement consumed (Neuhoff et al., 2014). Other potential impacts include reduced ambition of national reduction targets in steel producing countries, which could result in decreased ambition globally.

5. Conclusion

We have analysed a new set of country-based modelling of deep emissions reductions trajectories and compared it with global modelling in the literature. Our goal was to shed light on the implications for decarbonisation of GHG intense materials production and the global carbon budget if average per capita emissions benchmarks were adopted.

The analysis shows that purely nation-based management of emissions intensive products runs the risk of overshooting a global emissions target. According to the IEA benchmark, iron and steel and cement could make up a quarter of two-degree compatible global CO_2 emissions by 2050, and for some exporting countries account for the total national equal per capita allocation. Second, the analysis shows that equal per capita emissions benchmarks are not suitable to cover traded emissions intensive materials. They could induce carbon leakage or result in resource intensive countries opting out of the common per capita benchmark, and consequent overshooting of global carbon budgets.

Comprehensive international emission trading in the context of national emissions allocations that add up to a total budget would solve these issues. However this seems a remote prospect in the nationally based pledge-and-review framework that is expected under the Paris climate agreement. Instead, the issue of emissions intensity products will likely need to be dealt with separately.

An approach which could ensure appropriate allocation of global emissions would be to create a global budget for emissions from traded GHG intense materials, based on best practice, with the remaining global CO_2 emissions budget allocated according to per capita benchmarks. This could prevent inefficient carbon leakage and facilitate alignment between international efforts and the allocated budget. While not first-best, such a ‘two budget’ approach could effectively address the risk of emissions intensive production blowing out national carbon budgets of resource rich countries.

The analysis suggests that a global iron and steel allocation compatible with limiting the increase in global mean surface temperature to less than two degrees would be between 0.4 and 2.0 $GtCO_2$ in 2050. The higher value, corresponding to the IEA technology roadmaps as opposed to the theoretical minimum, would represent 13.5% of the total cumulative CO_2 emissions budget between 2011 and 2050. This corresponding to 0.04 to 0.22 tCO_2 per capita in 2050 on average, with much higher allocations in some countries. The allocation for all other emissions sources would be about 1.3 to 1.45 tCO_2 per capita, compared to 1.5 tCO_2 per capita with steel included at the national level.

A similar approach could be taken for production of clinker. In this case, a budget of about 0.7 to 1.7 $GtCO_2$ would be allocated to cement production, which would correspond to 0.08 to 0.18 tCO_2 per capita.

Finally, the analysis highlights the critical importance of global efforts to improve technologies and material efficiency in emissions intensive commodities manufacturing and use. Based on recent analyses, residual emissions from iron and steel and cement could be reduced by up to 70 percent. Strong international action is needed to incentivise research, development and prototyping of low GHG intensity steel and cement technologies as well as improvements in material efficiency.

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