Steel in a circular economy: global implications of a green shift in China

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Abstract

China is increasingly known for its ambitions towards an 'ecological civilisation' and a circular economy. Our article assesses the implications of an accelerated shift towards steel recycling in China. Given the relevance of steel for development worldwide as well as its environmental intensity, any such shift is likely to have implications for competitiveness in China and beyond. Recent findings suggest that China could take advantage of an increasing availability of obsolete steel scrap in the coming decades, moving towards more circular, and potentially greener, steel production. We assess such industrial restructuring from an economic perspective and address the competitiveness of China relative to other developing and industrialised regions. The analysis uses a novel global economy-wide modelling framework (ENGAGE-materials) to assess the aggregate and sector-level impacts of different scrap use options in China in the 2019-2030 time frame. The results show moderate GDP gains for China of cumulated USD 589 billion in GDP gains by 2030 despite a replacement of primary steel capacity. A more comprehensive industrial policy mix aimed at improved recycling practices and more adaptive downstream sectors could increase gains to USD 819 billion. The international implications are mixed, with losses for iron ore producers (Australia, Brazil and India) and gains for most developing countries benefiting from lower steel prices. Another result is an increasing demand for coal in electricity production if such a shift wouldn't be aligned with an accelerated energy transition towards low carbon pathways. We discuss policy implications of such alignment, potential co-benefits, and a need for green international partnerships.

Highlights

- The role of steel scrap for China's industrial competitiveness is assessed using a global economy-wide framework

- Significant GDP gains are obtained with a structural change in the steel industry towards a higher share of secondary production

- Fully benefiting from increases in secondary production requires downstream adaptability and reform of recycling practices in China

- Unwanted increases in CO_2 emissions from electricity demand in secondary production in China require a rapid shift towards more renewables

- Outside China, the most negatively affected regions are the iron exporters, but lower world steel prices can boost competitiveness downstream

Acknowledgements

This paper acknowledges funding through the ESRC funded SINCERE project (ES/L015838/1), the Natural Science Foundation of China (71704104) and the Fundamental Research Funds for the China Postdoctoral Science Foundation. We would like to thank our two anonymous reviewers for their constructive comments which have helped increase the clarity of our arguments.

1. Introduction

China has been the major emerging economy since the 2000s. As one particular feature, China dominated the global growth in iron ore and steel demand for the past two decades, currently producing one in every two tons of world's steel (WSA, 2018). The unparalleled expansion in the production of steel experienced since the early 2000s has mainly been fuelled by the internal demand for steel-intensive products and domestic infrastructure projects. Therefore, steel has been an essential material for economic development but also a major concern for CO_2 emissions and local pollution (Xu et al., 2016). With steel being a highly recyclable material (Allwood, 2013; Graedel et al., 2011), one of the most important technological options for the steel industry to reduce the negative environmental impacts and to contribute to the transition to a circular economy is the adoption of steel scrap as feed. Assessing the impacts of a potential Chinese transition to secondary steel is therefore of utmost relevance for 'latecomer' development in a greener world.

Currently, steel scrap is employed to a limited extent in steel production in China. Given the investment focus on basic oxygen furnace (BOF) capacity, the electric arc furnace (EAF) route which can run entirely on scrap has steadily fallen in importance in the past years, representing only 10% of production in 2018 compared to 39% in the European Union and 67% in the USA (WSA, 2018). Nevertheless, there has been little scope so far for more scrap-based steel production in China. Given the long lifetime of steel-based products, much of the past steel consumption is still stored as in-use stocks, whilst most of the scrap used in steel production by the current capacity mix is obtained from *pre-consumer* (prompt and home) scrap sources (McKinsey, 2017). However, the availability of *post-consumer* (obsolete) scrap is projected to increase significantly in the following decades as much of the stocks in capital goods and existing infrastructure in China start to depreciate (McKinsey, 2017; Pauliuk et al., 2013; Wang et al., 2014).

The case for an accelerated adoption of scrap-based steel production is supported at multiple levels. First, an increased demand for scrap would stimulate economic activity in the recycling sector and could lead to job creation. Second, the steel industry could reduce its environmental impacts through scrap use. For every ton of steel made from scrap through the EAF route, the use of 1,400 kg of iron ore, 740 kg of coking coal, and 120 kg of limestone are avoided (WSA, 2014) determining a 40% reduction in energy requirements and 60% less CO_2 emissions compared to iron ore-based production. Third, as China imports 80% of its iron ore requirements, the replacement of seaborne iron ore with domestic scrap could lead to gains for China's terms of trade but also to higher competitiveness for the downstream sectors. An abundant supply of scrap yielding significant price differentials between iron ore and scrap could reduce the price of secondary steel and could thus give a cost advantage to the downstream steel-intensive sectors (Wübbeke & Heroth, 2014).

If China were to develop a more circular strategy for steel, the implications would call for an integrated assessment along the following issues: 1) Potential advantages for China, related to a general move to a circular economy; 2) Potential disadvantages for current exporters of iron ore and for other suppliers (e.g. for Australia and Brazil); 3) Other impacts on international markets for steel and steel scrap, with potential advantages for scrap exporters and for those currently suffering from competition with Chinese steel; and 4) Potential environmental implications for China making the transition towards the production and use of secondary steel.

A current structural issue for the steel sector is the existing excess capacity which has built up over time due to subsidies for the maintenance of inefficient plants and for investment in new capacity (OECD, 2015). Of the 700 million tons of the global estimated excess capacity in 2015, 425 million tons were in China and mostly based on BOF (Willey Rein, 2016). Therefore, in the context of a growing availability of steel scrap, China may deal with the excess capacity issue in a reactive manner through a gradual reduction of the current predominantly BOF-based steel capacity to respond to a declining demand[1]. Alternatively, China can act through a directed policy to convert and replace part of the retiring BOF plants with new EAF plants in order to fully take advantage of the economic opportunities of an abundant scrap availability and also to promote environmental sustainability.

The topic of a growing availability of obsolete scrap in China has been addressed in a number of studies. Pauliuk, Wang and Müller, 2012; Oda, Akimoto and Tomoda, 2013; Wang *et al.*, 2014 used the Material Flows Accounting (MFA) framework to assess the past and future role of scrap in Chinese steel production. Xuan and Yue (2016) employed an IPAT model (Impacts = Production x Affluence x Technology) to forecast Chinese steel demand and production patterns given an increase in obsolete scrap supply and changes to scrap use ratios. While these analyses are grounded in flow and stock accounting principles and allow for the exploration of material demand and supply balances, they do not take into account the costs and the wider economic implications of a marked increase in scrap-based steel production.

The inclusion of economic considerations and market interactions is done in just a few cases. Wang, Li and Kara (2017) used a 'cradle-to-cradle' approach by incorporating the price interactions of iron ore and scrap in the steel production decisions in China up to 2100. Xylia *et al.* (2018) used a technology-rich cost optimisation model in combination with an MFA scrap availability model to determine the future global steel production patterns by considering CO_2 pricing scenarios in combination with emerging technologies enhancing production efficiency. By only considering elements of market dynamics within the steel sector (implying exogenous assumptions on down-stream demand and on prices for energy and labour) and hence lacking an economy-wide view on investment and production, none of these studies can capture the domestic and international competitiveness effects of the structural changes in the Chinese steel industry and implications for other regions.

The purpose of our paper is to assess the potential impact of a shift towards an accelerated adoption of secondary steel production in China in a time frame to 2030. We employ a global dynamic computable general equilibrium (CGE) model (ENGAGE-materials) which comprises an advanced level of detail regarding mining, steel production and downstream industries. At their core, CGE models capture the trade and sectoral interlinkages through general price effects stemming from policy-induced technological changes. The use of a global model in this study enables the measurement of impacts across world regions, emphasising on China, but also on other emerging economies and other important regions for the global steel markets (iron ore exporting and steel producing regions). As novel elements, ENGAGE-materials distinguishes between primary and secondary steel production technologies which take into account the possible pathways for steel production capacities across the

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[1] Indeed, China has reduced capacity in 2016 and 2017 by 120 million tons through government intervention https://www.reuters.com/article/china-steel/china-steel-capacity-to-be-brought-below-1-bln-t-by-2025-assn-idUSL3N1SQ03O

EAF and BOF routes. Furthermore, the model represents the scrap treatment and recycling sector as a standalone economic activity producing treated scrap which can be used domestically or traded internationally. The scientific and practical contribution of this study is, therefore, the formulation and development of an economy-wide framework for the analysis of circular economy policies in the global steel sector, with an application focused on the potential medium-term transitions in China.

The article is structured as follows. After this introduction section, Section 2 describes the methods together with the three scrap adoption scenarios considered for China in the 2019-2030 time frame. Section 3 presents the main results, followed by a discussion of the main results, risks and uncertainties in Section 4. Section 5 draws the conclusions.

2. Methods

2.1. Economic modelling of steel production

The analysis is conducted using the UCL Environmental Global Applied General Equilibrium model (ENGAGE-materials) which comprises an advanced level of detail regarding the steel production cycle. The current version of the model is calibrated using a modified version of the GTAP9-Power database (Peters, 2016) with the base year of 2011. The data and model evolution from Winning *et al.*, (2017) includes a further disaggregation of the mining and iron&steel sectors, as well as an explicit representation of the steel recycling and scrap treatment activities. These unique features of the model allow for a comprehensive analysis of the supply chain of steel-based commodities. The global economic activity is captured by structuring the world economy into 18 regions with the important iron ore exporters (Australia, Brazil) and steel producing countries (China, India, Japan, South Korea, USA) represented individually (see Supplementary Information). The multi-regional nature of the model allows for a full bilateral specification of international trade using the Armington approach (Armington, 1969) through which domestic and imported varieties of commodities are introduced as imperfect substitutes.

As a CGE model, ENGAGE-materials enables the consideration of demand and supply interactions across all factors of production (capital, labour, land) and commodity markets through price and quantity changes induced by different policy interventions. Therefore, the model is able to explore competitiveness changes of different pathways for the adoption of scrap and secondary steel with a high level of detail at a sectoral level (mining, steel production, downstream sectors) but also at a macro-economic level (GDP, terms of trade, exports) across all regions considered.

ENGAGE-materials adopts the standard CGE principles of market clearance, zero-economic profit, utility maximisation of households and cost minimisation of firms[2]. The model comprises 25 commodity classes, with the specification of a region-specific production function for each. Production technologies are introduced as nested CES (constant elasticity of substitution) functions which enable multiple-level substitutability of production inputs. To allow for a distinction in the use of different steel grades in the downstream sectors (e.g. construction, manufacturing), primary and secondary steel production are specified as separate commodities with distinct production technologies (Figure 1). Both primary (ISP) and secondary steel (ISS) production levels are constrained by the operating capacity specified exogenously at each yearly time step. The top-level elasticity σ allows for changes in the production capacity utilisation rates based on market conditions.

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[2] While the economics literature also discusses market imperfections and ways of modelling them (e.g. Meyer and Ahlert, 2019), the advantage of CGE principles is a consistent representation of actors and markets with useful insights into interactions and impacts.

Primary steel (ISP) is produced exclusively with iron ore through either the BOF route or the EAF route with direct reduction. The share of each technological route in total production is region-specific based on data from World Steel Association (WSA, 2018) and EXIOBASE3 (Stadler et al., 2018) and is represented by the ratio of coking coal (BOF) to electricity (EAF) in the *Tech* bundle for ISP. In addition to iron ore, ISP also uses home scrap (pre-consumer scrap) assumed to be of the same grade. Likewise, secondary steel (ISS) can be produced through both BOF and EAF routes through a blending to different degrees of treated scrap and iron ore. The extent to which ISS uses BOF and EAF is specific to each region and is reflected, as for primary steel, by the ratio of inputs into the *Feed* and *Tech* bundles. For the scenario analysis, the technical coefficients φ of these inputs are modified in the 2019-2030 time frame to reflect changes in the BOF/EAF operating capacities and in the scrap use ratios across the two technological routes (see Section 2.2).

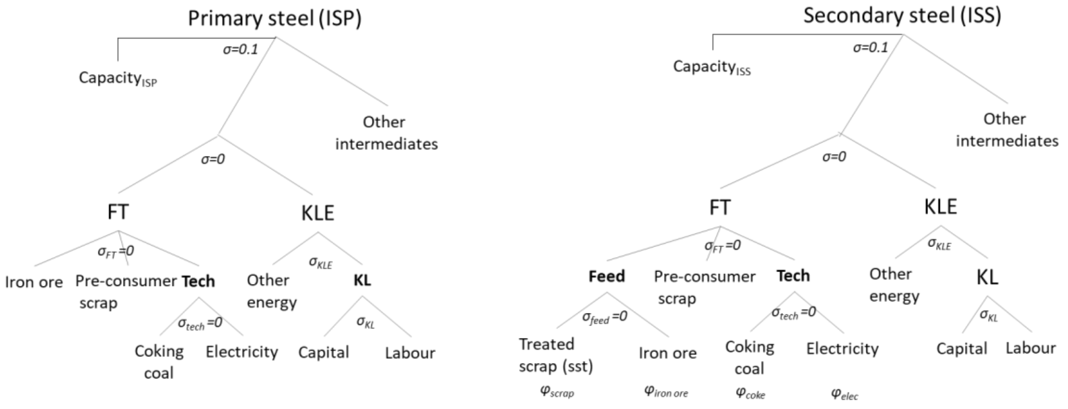

Figure 1 - Primary and secondary steel production in ENGAGE-materials. σ parameters represent the elasticity of substitution between inputs. A zero value implies no substitutability (perfect complements) given relative price changes.

The steel scrap (obsolete scrap) entering secondary steel production (ISS) is supplied by a distinct steel scrap treatment (SST) activity (Figure 2). The regional output of SST is dependent on obsolete scrap availability which is collected by the recycling sector. Specified as a distinct market commodity, steel scrap is supplied to both the domestic secondary steel sector and to the international scrap markets for use in secondary steel production by other regions.

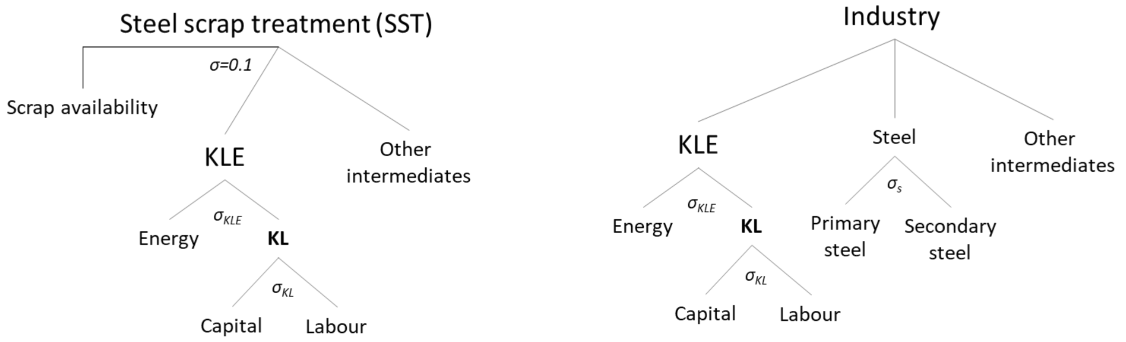

Figure 2 - Steel scrap treatment (SST) and other downstream industrial sectors in ENGAGE-materials

The production technologies of downstream steel-intensive industries in ENGAGE-materials enable a direct substitution between primary and secondary steel inputs. The substitutability of the two varieties determined by the σ_s elasticity is sector-specific and considers the differences between economic activities in their ability to adopt secondary steel. Therefore, in the base specification of the model, the construction sector has considerably higher adaptability given its lower requirements for steel alloy purity compared to other sectors such as electric equipment or car manufacturing which are more sensitive to a reduced secondary steel quality through contamination.

The model inter-temporal dynamics are introduced by accounting for GDP and population growth in the 2011-2030 time frame. GDP across all represented regions increases in line with the SSP2 socioeconomic development narrative (van Vuuren et al., 2014) and is driven by investment, changes in labour supply and total factor productivity (TFP) gains. The sector-specific changes in TFP together with changes in final demand patterns across time introduce a differentiated expansion of economic sectors with GDP growth. In addition, for steel production, changes in output are conditioned by the evolution of production capacity which is exogenously specified through the model scenarios. The expansion of the steel scrap treatment (SST) sector in terms of production and international trade is determined by the region-specific evolution of obsolete scrap availability.

2.2. Scrap steel scenarios for China

An increase in the use of obsolete scrap in China could be done on both the intensive (increasing the scrap inputs in the existing production plants) and extensive margins (extending the EAF capacity). The intensive margin through higher use of scrap in existing steel plants would imply little transformation of the current technological mix but could absorb a share of the available scrap in the short-run. Currently, EAF in China only employs 550-600kg of scrap per ton of steel produced, the rest being iron obtained through direct reduction. In the BOF route, the scrap rate is estimated at 100-150kg per ton of steel (McKinsey, 2017). These values are lower than those typically found in other large steel producing regions where scrap rates are at 900-1100kg and 180-220kg per ton of steel produced in the EAF and the BOF technologies respectively. Indeed, the scrap per steel output ratio in China was 10% in 2015 compared to 54% and 72% in the EU-28 and USA respectively (BIR, 2017).

In the long-run, the use of obsolete scrap in China could be increased on the extensive margin through new EAF capacity, similarly to other industrialised regions such as EU-28 and USA where EAF production represents 39% and 67% of total steel output respectively (WSA, 2018). However, this capacity shift would face significant challenges given the current trends in the steel industry in China which are characterised by a flattening steel demand and excess capacity (Willey Rein, 2016). Drawing on the evolution of steel demand experienced in the past by industrialised countries, this structural change in market dynamics has been anticipated (Bleischwitz et al., 2018; Oda et al., 2013; Pauliuk et al., 2013; Wang et al., 2014) and could have important economy-wide implications given that the steel industry represents a significant share of GDP and employs millions of people[3].

The results of our analysis are reported as deviations from a 2019-2030 baseline ("business-as-usual") which is the continuation of current production patterns across world regions in terms of production shares of primary and secondary steel. In our baseline, scrap use ratios in EAF and BOF are also kept constant. The steel capacity evolution for primary and secondary steel is presented in Figure 3 A) and B) respectively. The values for 2011-2018 reflect historical production values from WSA (2018), while figures for 2019-2030 are capacity projections where total steel production decreases in some industrialised regions (Japan and Western Europe), flattens in China after 2018 and increases in developing and emerging economies (Africa, Middle East, India and Latin America). The obsolete scrap availability follows the depreciation of steel-based products and capital goods in every region and was taken from MFA-based analyses in Pauliuk *et al.*, (2013) and Xylia *et al.*, (2018) - Figure 3 C). The availability of scrap grows five-fold in China (from 26 million tons in 2011 to 53 million tons in 2018 and 138 million tons in 2030) with other marked increases in India, Brazil and Mexico. In the baseline,

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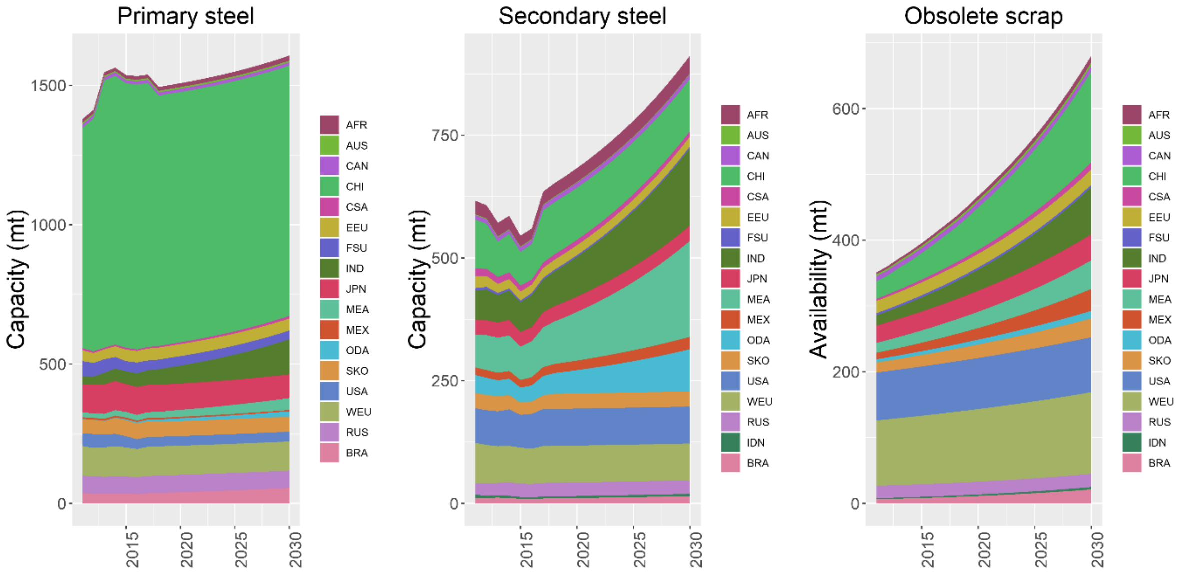
[3] http://blogs.platts.com/2016/08/05/china-steel-industry-human-cost/

the unmet supply of treated scrap in China by the domestic secondary steel production is exported to other regions. The assumptions and baseline results for the steel sector across the regions represented in the ENGAGE-materials model are outlined in Table 1 with further details in the Supplementary Information file.



A) B) C)

Figure 3 – Baseline primary steel capacity (A), secondary steel capacity (B) and obsolete scrap availability (C) for 2011-2030. Source: own projections based on OECD (2018) and WSA (2018) for capacity and on Pauliuk et al.*, (2013) and Xylia* et al.*, (2018) for obsolete scrap availability.*

The analysis of a higher scrap adoption in China is structured around three scenarios:

- INT (intensive margin only) – this scenario follows the same total steel production and primary and secondary steel shares as in the baseline but increases the scrap use ratios in EAF and BOF in China from 2019 onwards such that EAF-based steel is produced entirely with scrap by 2030. The rest of the regions continue their production practices as in the baseline. The steel scrap adoption in this scenario is an extension to 2030 of the current government policy to increase scrap use by 20% between 2016-2020 (Ministry of Natural Resources, 2016).
- EXT (both intensive and extensive margins) – this scenario uses the evolution of scrap use ratio in China from the INT scenario but also increases the share of secondary capacity in China from 13.5% in 2018 to 36% in 2030, allowing secondary steel production to grow at a rate close to that of obsolete scrap availability. EXT could also be seen as a 'green transition' scenario with a focus on the steel production sector as it triggers a move to a more circular economy in China. The plausibility of this scenario is given by the government's current policy regarding BOF plant retirement favoring a replacement with the EAF route in many Chinese provinces (OECD, 2019).
- PLUS - this more ambitious scenario has the same steel production structure in China as in EXT but also considers policies to increase the capacity of downstream sectors to adopt secondary steel. This could be achieved through improvements in recycling practices (e.g. producer responsibility and closed-loop recycling in the automotive industry) and policies encouraging eco-design of steel-based products with a focus on end-of-life disassembly possibilities. In the model, this is achieved through a higher substitutability of primary and secondary steel for the Chinese downstream sectors other than construction by changing the elasticity σ_s values

in the industrial production functions (see values in Supplementary Information). We consider PLUS as a circular economy scenario for a range of industrial activities around steel.

Given that obsolete scrap availability is driven by past demand for products and capital goods with an extended lifetime (10-50 years), its evolution across the three scenarios for the 2019-2030 period is invariant and is identical to the one in the baseline. Also, as that other low-carbon technologies for steel production (e.g. hydrogen direct reduction and CCS) may not become technically and economically viable at scale until after 2030 (Fischedick et al., 2014), these are not included in our modelling framework.

Table 1 - Baseline steel sector projections 2018-2030

Region	Total steel capacity			BASELINE Primary steel capacity			BASELINE Secondary steel capacity			Obsolete scrap availability			BASELINE Secondary production share	
	2018	2030	CAGR	2018	2030	CAGR	2018	2030	CAGR	2018	2030	CAGR	2018	2030
China	1004.6 mt	1004.6 mt	*0.0%*	898.2 mt	898.2 mt	*0.0%*	106.4 mt	106.4 mt	*0.0%*	53.3 mt	138.4 mt	*8.3%*	13.5%	13.4%
India	126.8 mt	283.9 mt	*6.9%*	56.1 mt	126.1 mt	*7.0%*	70.8 mt	157.8 mt	*6.9%*	27.2 mt	71.9 mt	*8.4%*	21.0%	19.0%
Indonesia	7.5 mt	14.8 mt	*5.8%*	3.3 mt	10.6 mt	*10.2%*	4.2 mt	4.2 mt	*0.0%*	2.1 mt	3.7 mt	*4.6%*	48.7%	21.8%
Oth Developing Asia	49.7 mt	105.4 mt	*6.5%*	7.7 mt	19.4 mt	*8.1%*	42 mt	85.9 mt	*6.1%*	6.7 mt	11.6 mt	*4.6%*	25.1%	5.6%
Japan	127.8 mt	116 mt	*-0.8%*	96.6 mt	84.9 mt	*-1.1%*	31.2 mt	31.2 mt	*0.0%*	30.6 mt	39.6 mt	*2.2%*	28.1%	30.8%
South Korea	84.9 mt	84.9 mt	*0.0%*	53.9 mt	53.9 mt	*0.0%*	31 mt	31 mt	*0.0%*	19.2 mt	28.6 mt	*3.4%*	26.7%	26.8%
Middle East	108.6 mt	238.4 mt	*6.8%*	22 mt	42.9 mt	*5.7%*	86.6 mt	195.6 mt	*7.0%*	22.2 mt	43.4 mt	*5.8%*	45.6%	49.2%
Africa	40.3 mt	54.1 mt	*2.5%*	13.3 mt	18.3 mt	*2.7%*	27 mt	35.8 mt	*2.4%*	5 mt	10.2 mt	*6.0%*	72.3%	70.5%
Brazil	47.9 mt	70.7 mt	*3.3%*	37.7 mt	55.7 mt	*3.3%*	10.2 mt	15.1 mt	*3.3%*	9.9 mt	21.2 mt	*6.6%*	21.8%	22.1%
C&S America	16.6 mt	20.3 mt	*1.7%*	5.8 mt	9.5 mt	*4.2%*	10.8 mt	10.8 mt	*0.0%*	5 mt	10.7 mt	*6.6%*	47.6%	35.7%
Mexico	24.1 mt	29.7 mt	*1.8%*	5.6 mt	4.6 mt	*-1.6%*	18.5 mt	25.2 mt	*2.6%*	15.5 mt	33.3 mt	*6.6%*	43.7%	57.1%
USA	110 mt	110 mt	*0.0%*	34.8 mt	34.8 mt	*0.0%*	75.3 mt	75.3 mt	*0.0%*	76.5 mt	83.4 mt	*0.7%*	48.4%	53.6%
Canada	21.6 mt	21.6 mt	*0.0%*	11.6 mt	11.6 mt	*0.0%*	10.1 mt	10.1 mt	*0.0%*	7.9 mt	8.7 mt	*0.7%*	32.8%	34.9%
W Europe	179.9 mt	179.9 mt	*0.0%*	104.8 mt	104.8 mt	*0.0%*	75.2 mt	75.2 mt	*0.0%*	107.9 mt	124.2 mt	*1.2%*	40.5%	40.2%
E Europe	63.5 mt	63.5 mt	*0.0%*	43.2 mt	43.2 mt	*0.0%*	20.3 mt	20.3 mt	*0.0%*	20.3 mt	23.4 mt	*1.2%*	35.8%	34.5%
Australia&NZ	7.5 mt	7.5 mt	*0.0%*	6 mt	6 mt	*0.0%*	1.5 mt	1.5 mt	*0.0%*	3.4 mt	4.8 mt	*2.9%*	19.1%	19.5%
Russia	89.6 mt	89.6 mt	*0.0%*	62 mt	62 mt	*0.0%*	27.6 mt	27.6 mt	*0.0%*	19.3 mt	20 mt	*0.3%*	36.6%	40.4%
Former Soviet Union	38.3 mt	34.7 mt	*-0.8%*	34.8 mt	31.2 mt	*-0.9%*	3.5 mt	3.5 mt	*0.0%*	3.4 mt	3.5 mt	*0.3%*	43.1%	46.3%

3. Results

3.1. Regional economy-wide impacts

At an aggregate level, there are significant differences between the three scrap use scenarios in terms of GDP impacts (Figure 4). The INT scenario, implying just higher scrap use ratios in secondary steel in China, leads to modest increases in GDP for China (+0.02% in 2030) and some negative impacts for Australia, Brazil and Russia due to a slightly lower iron ore export to China. For the other two scenarios (EXT and PLUS), the positive impacts for China are much amplified while the largest negative impacts continue to be found for some of the major iron ore producers (Australia, Brazil and India). Green transitions in the Chinese steel sector have also important positive impacts outside China that are driven by two major factors – a decrease in global steel prices which stimulate the steel-intensive activities in other regions and an increase in demand for coal given higher electricity demand in secondary steel production in China (see section 3.3). Therefore, the net regional GDP changes are determined by the relative size of losses for the iron mining sectors and the gains in coal production and steel-intensive industries. This is evident for Russia where the initial GDP losses due to lower iron ore exports (INT) turn to GDP gains as a result of higher production for coal and steel-intensive products (EXT and PLUS).

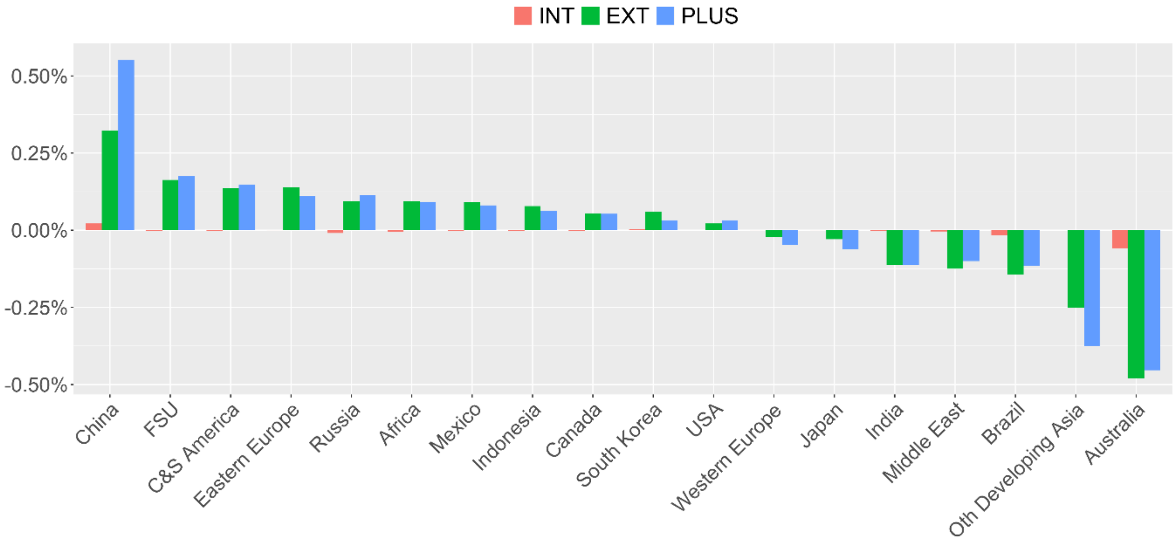


Figure 4 –Regional GDP changes in 2030. Impacts are determined as deviations from the multi-annual baseline

The increased ability of downstream sectors in China to adopt secondary steel (PLUS) enhances the positive economy-wide impacts from 0.33% to 0.55% of GDP in 2030. The cumulated GDP gains in China in the 2019-2030 period, thus, increase from USD 589 billion for EXT to USD 819 billion for PLUS. At the same time, this translates into further GDP trade-offs with the other regions as the total cumulated GDP losses for the rest of the world increase from USD 94 billion for EXT to USD 128 billion for PLUS (see Supplementary Information for regional GDP gains and losses). The higher adaptability of Chinese industrial sectors under the PLUS scenario enables them to lower their production costs by increasing the share of secondary steel inputs. This leads to gains in competitiveness for Chinese industrial commodities and, therefore, to a higher production of Chinese steel-intensive industries and consequently to a decrease in industrial output in the other regions.

From a steel price perspective, the increase in scrap use ratios without an increase in secondary steel capacity in China (INT) has only a marginal effect on steel prices (Figure 5) since Chinese steel continues to be dominated by primary production and the cost effects of a higher adoption of scrap are limited. The reduction in primary steel capacity and production in China compensated by a proportional increase in secondary steel capacity and production (EXT) translates to an increase in the price of primary steel in this country (+3.0% in 2030) and a decrease in the price of secondary steel (-20.2%). The effects of this shift in other regions is a general reduction in steel prices (a reduction in the range of 1.2-2.3% for primary steel and 0.5-2.3% for secondary steel by 2030) largely explained by lower steel imports by China[4] but also by a reduction in the price of iron ore. With the advanced adaptation of Chinese downstream sectors (PLUS), regional prices for primary steel are further reduced while secondary steel prices increase relative to the EXT scenario. These price changes are driven by a lower demand for primary steel both in China and other regions and a higher demand for secondary steel in China.

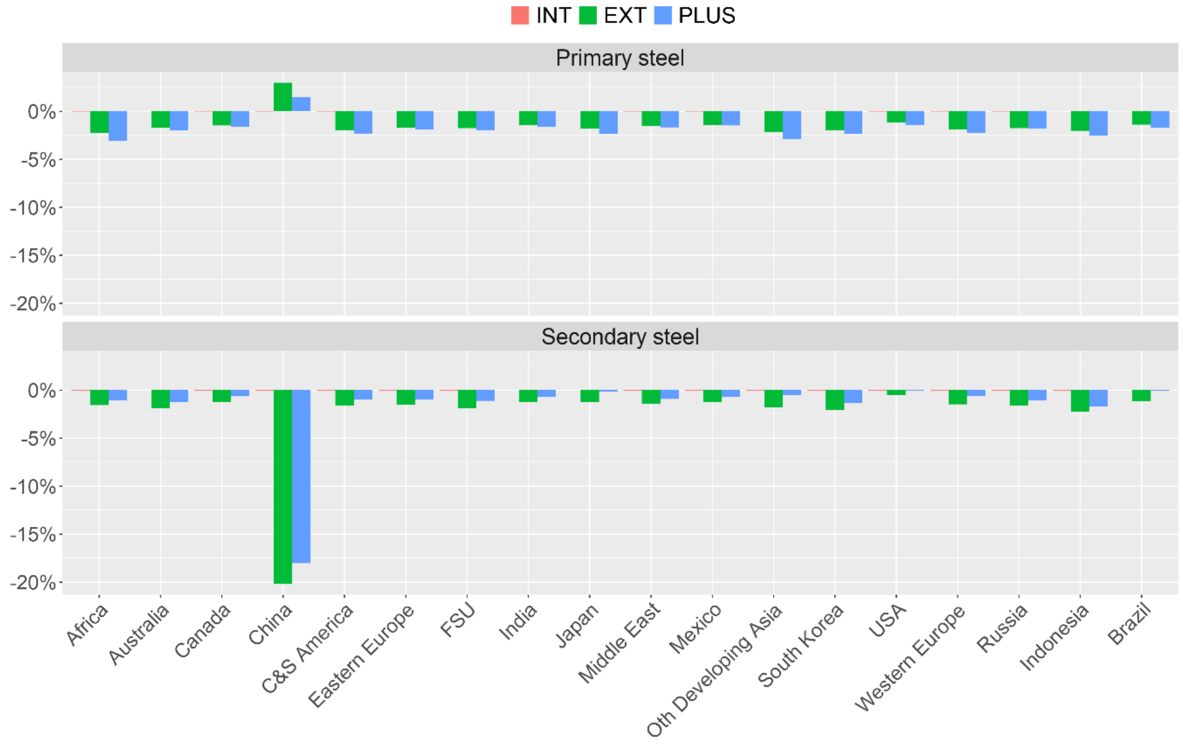


Figure 5 – Changes in regional steel prices in 2030. Changes are determined as deviations from the multi-annual baseline

3.2. Sectoral and trade impacts in China

The extent to which scrap steel and secondary steel are adopted into production activities in China determines the overall net impact on GDP but also leads to differentiated competitiveness implications for the Chinese industrial commodities. The positive impacts in INT are derived from higher activity in steel scrap treatment (+13% in 2030) and recycling (+8% in 2030) accompanied by a lower iron ore demand (-2% in 2030) (Figure 6 A). However, this scenario leads to overall negligible economy-wide impacts. In fact, changes in production are marginal on downstream activities (Figure 6 B) as the steel production mix does not change and the changes in steel price have a marginal impact over the other steel-using sectors.

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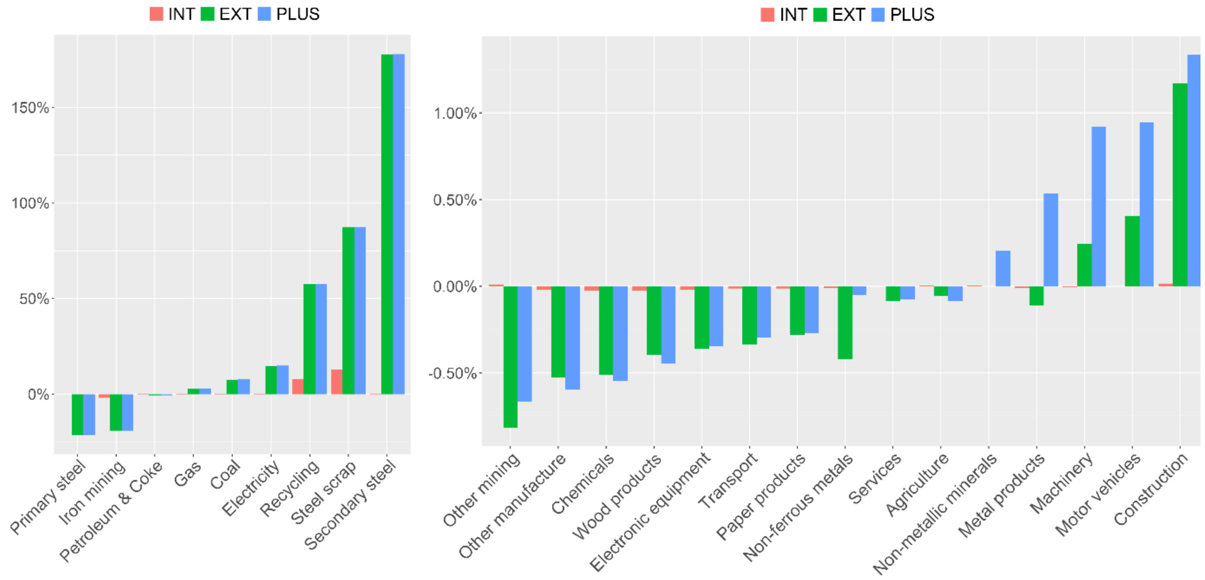
[4] The reduction in primary steel imports is determined by the Armington assumption for international trade through which domestic and imported varieties are imperfect substitutes (Armington, 1969). Thus, the significant decrease in primary steel outputs can only be marginally compensated through imports. In this case, imports increase their weight in total demand of primary steel in China, however, the total supply- and, consequently, total primary steel imports decrease.

With an increased production capacity for secondary steel in the EXT scenario, the sectoral impacts are more visible but mostly occur upstream in the steel production sectors. Primary steel production decreases by 21%, while secondary steel production increases by 178% in 2030 (Figure 7 A) to reach 35% of total steel output. Their supply chains are also affected, iron ore decreases by 19% and steel scrap treatment increases by 87% in 2030. Treated steel scrap in China could thus grow from 86 million tons (INT) to 142 million tons (EXT), while total steel scrap demand in secondary steel production in 2030 would reach 154 million tons.

The increase by 14.7% in total electricity production by 2030, largely due to a higher secondary steel production, leads to an indirect effect of a higher demand for coal and gas as China's power generation is mostly based on fossil-fuel combustion[5]. Coal domestic production and imports in China, therefore, increase by 7.6% and 7.0% respectively. Therefore, a higher use of fossil fuels to generate the additional power required for secondary steel production could potentially adversely affect the environmental gains of circular economy policies in the steel sector.



A) Steel supply chain sectors B) Downstream sectors

Figure 6 – Sectoral output changes in China in 2030. Changes are determined as deviations from the multi-annual baseline

For downstream sectors, there is a positive impact on the output of some steel-intensive sectors (production of machinery and motor vehicles increases in 2030 by 0.24% and 0.41% respectively) but notably, the largest impact is in construction (a 1.2% output increase) which is inherently more adaptable to the use of secondary steel. The other downstream sectors deal with negative outcomes as they are less able to absorb higher input shares of secondary steel in their production processes. Thus, their production costs increase directly (these sectors will still require primary steel for which the price is increasing) or indirectly through price changes across their supply chains and for factors of production (labour and capital).

With an advanced adaptation to secondary steel by the downstream sectors (PLUS), the output of all steel-intensive industries is boosted from EXT levels – metal products (+0.53%), machinery (+0.92%),

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[5] Coal and gas account for about 70% of the current power generation in China (EBEPY, 2017), while the iron and steel sector represented 13.5% of total electricity demand in China in 2011 (IEA, 2018b), the model base year, a share reflected in the model database. In the model simulations, we do not introduce any constraints to the use of coal in electricity generation as a measure coming from climate change policy.

motor vehicles (+0.95%). At the same time, while the size of the steel supply chain does not change significantly. The level of activity in other downstream sectors depends on the relative importance of the general price changes in their total costs as well as the size of the economy. Construction and the associated non-ferrous materials sectors increase their output given higher investment levels under a larger GDP. At the same time, the increase in labour and capital costs due to crowding out effects from steel-intensive sectors force the other sectors to slightly reduce their output compared to EXT.

In terms of the steel demand composition in the downstream sectors, three drivers influence the penetration of secondary steel in these sectors – the price of secondary steel relative to primary steel, the availability of secondary steel and the adaptability of downstream sectors in absorbing the increased supply of secondary steel. First, the baseline price effect of a higher scrap availability and higher scrap use rates in secondary steel production in the INT scenario enables some substitution between primary and secondary steel. For INT, the share of secondary steel for metal products, motor vehicles and machinery increases between 2018 and 2030 only by 1-2% (Figure 7). A larger increase, around 8.9%, is expected in the construction sector. Second, the substantial increase in secondary steel production without downstream adaptation modelled in EXT (35% of total steel production in China by 2030) is mostly absorbed by the construction sector where the share of secondary steel increases to 68% in 2030 from 15% in 2018, while the share of secondary steel in the other three sectors reaches only 21%. Third, the set of policies to enhance the absorption of secondary steel (PLUS) would lead to a redistribution of secondary steel demand from construction to the other sectors of the economy without net output losses for the construction sector. In this scenario, the share of secondary steel in the steel demand by metal products, motor vehicles and machinery would reach 25%, a share that is considerably higher than in the baseline year.

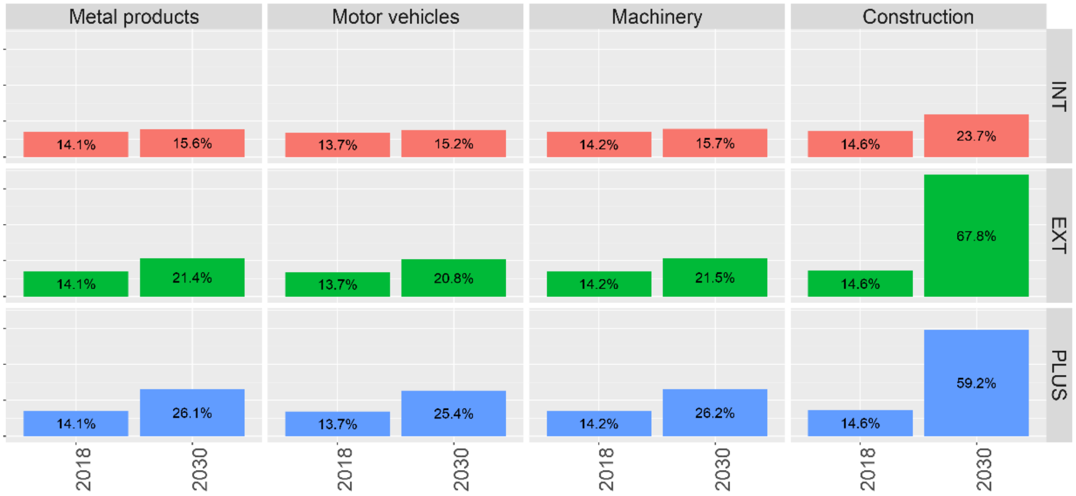


Figure 7 – Share of secondary steel demand in downstream sectors in China (% of total sectoral steel demand) in 2018 and 2030

3.3. Impacts outside China

The other regions are affected by the structural changes in the Chinese steel industry in three distinct economic areas – mining, steel production and downstream sectors. At the mining sector level, a direct impact of higher scrap use in China is the reduction of iron ore exports to China. Indeed, iron ore production shrinks across all regions especially in the EXT and PLUS scenarios (Figure 8A). In 2030, the highest output reductions occur in Africa (-14.6%), Former Soviet Union (-13.5%), Russia (-13.2%), Other Developing Asia (-12%) and Australia (-10.3%). Other important reductions relative to the absolute size of the domestic iron ore sector take place in Brazil and India.

With the increase in steel scrap demand in China, the scrap treatment across all regions increases (Figure 8B). In the EXT and PLUS scenarios, China generally decreases its scrap exports and determines higher steel recycling rates in other regions with a marked increase of 30% in Brazil and 10% in Japan and the USA. Therefore, a higher secondary steel production will lead to a change in scrap trade flows between China and the other regions. In the INT scenario, China exports about 24 million tons of scrap in 2030 with trade mainly to the USA, Western Europe, Middle East, South Korea and Other Developing Asia (Figure 9). In the EXT and PLUS scenarios, China would turn into a net importer to meet its domestic demand for scrap, with imports of 12.9 million tons in 2030 with Japan as its main partner. Brazil would replace some of the reduction in scrap export from China, with a significant increase in traded volumes to Western Europe. Nevertheless, all these changes in trade patterns remain small in comparison to the total traded volumes by the USA, Western Europe and the Middle East that do not change significantly between scenarios.

For iron ore trade, most of the changes would come from the reduction in ore demand in China which translates into 172 million tons lower imports (Figure 10). The largest decreases in trade with China occur for Australia (-75 million tons), India (-27 million tons), Russia (-27 million tons) and Brazil (-21 million tons).

At the same time, at the mining level, the increase in electricity production due to higher EAF-based output in China leads to an increased demand for coal (Figure 8C). This expansion takes place under the assumption that in the time horizon to 2030 China will not add significant constraints to the use of coal as a fuel for electricity generation. The coal sector in the EXT and PLUS scenarios, therefore, grows by 2.4% in Australia, 2.0% in Russia, and 1.1% in Indonesia and 1% Other Developing Asia in 2030 relative to the baseline.

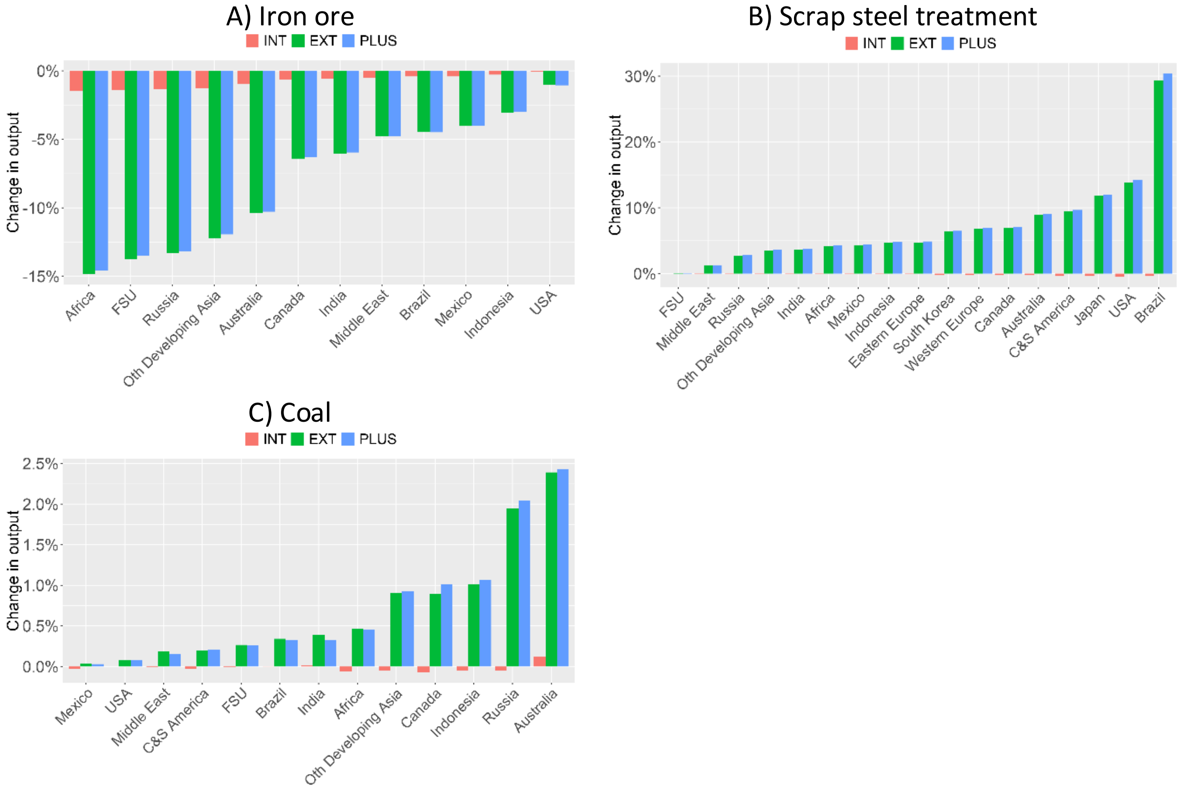
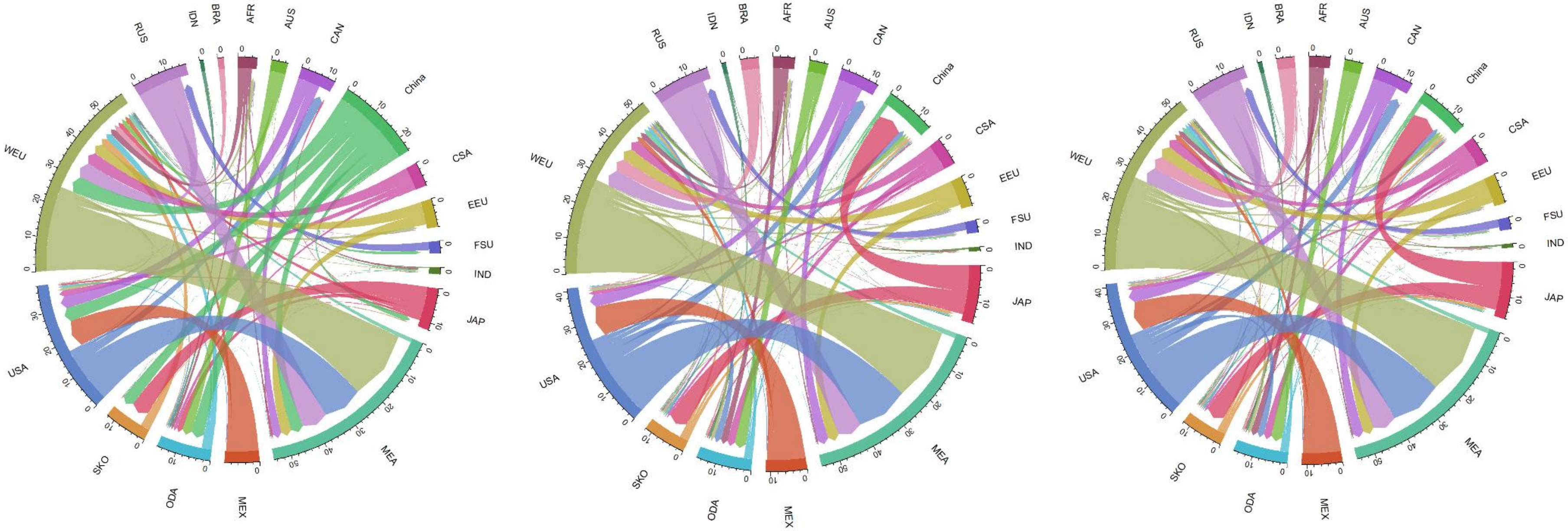


Figure 8 – Output changes in mining and scrap treatment outside China in 2030. Changes are determined as deviations from the multi-annual baseline

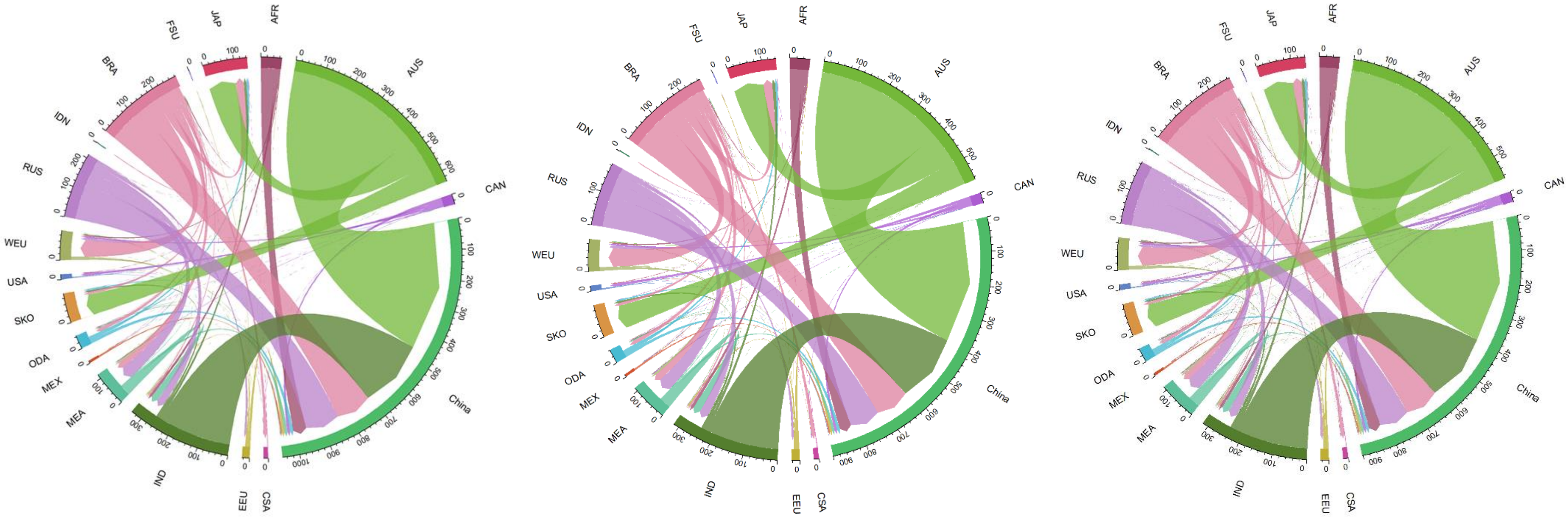


A) INT

B) EXT

C) PLUS

Figure 9 – Obsolete scrap trade between macro-regions in 2030 - in million metric tons



A) INT B) EXT C) PLUS

Figure 10 – Iron ore trade between macro-regions in 2030 - in million metric tons

Given the dominant role of China in global steel production and demand, the structural changes in EXT determine a global decrease in primary steel output. The influences outside China are small, however, negative as demand for primary steel in China is reduced enabling more exports. The most affected region is Other Developing Asia with a reduction of 0.65% in EXT by 2030, while the other major producing regions decrease their output by 0.2-0.3% (Figure 11A). The higher impact for Other Developing Asia is given by the closer trade links with China leading to a replacement of domestic production with lower-cost imports.

If the dynamics of primary steel outside China are demand-driven, those for secondary steel are supply-driven – China increases production and crowds-out secondary output in the other regions (Figure 11B). Production of secondary steel declines most in the USA (-1.6%), the Middle East (-0.8%), Mexico (-0.8%), Other Developing Asia (-0.8%), South Korea (-0.8%) and WEU (-0.7%).

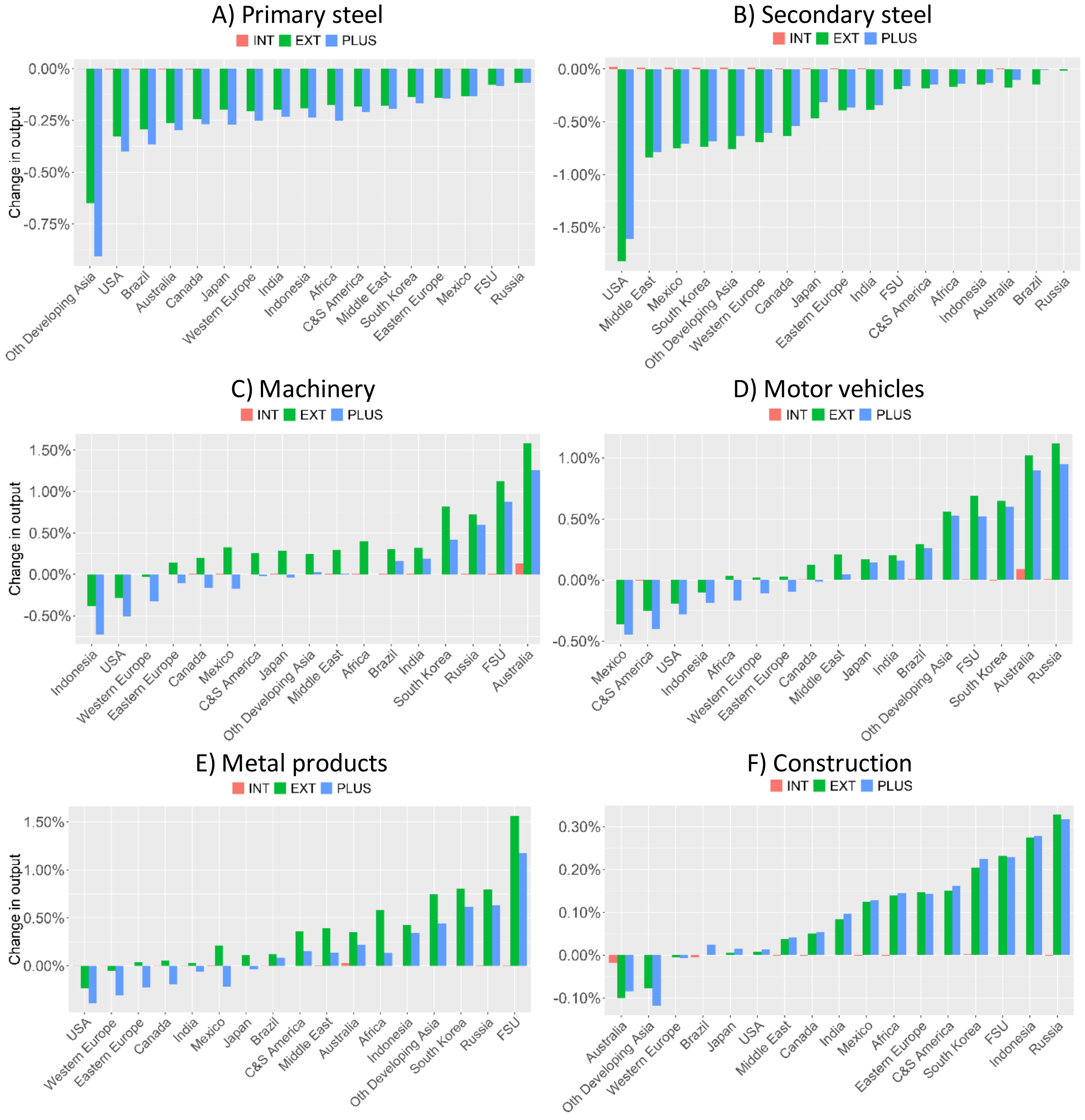


Figure 11 – Output changes in steel-related sectors across regions in 2030. Changes are determined as deviations from the multi-annual baseline

The increased adaptability of Chinese downstream sectors (PLUS) further increases the demand for secondary steel and decreases that for primary steel. The associated impacts on steel production outside China are uniform across regions through a further reduction in primary steel- and an increase in secondary steel production relative to EXT.

The downstream steel-intensive sectors generally benefit from lower steel prices in EXT as their output increases by more than 1% with many cases outperforming Chinese sectors for this scenario (Figure 11 C-F). Nevertheless, some output losses relative to the baseline are obtained - industrialised regions (USA, Western Europe) and some developing and emerging regions (Indonesia, Mexico, C&S America). The higher adaptability of downstream sectors to use secondary steel (PLUS) reduces the competitive advantage coming from lower steel prices outside China as more regions face a decrease in output, especially for machinery, motor vehicles and metal products.

4. Discussion

The results in our analysis show that the deeper the reform towards a more circular use of steel in the Chinese economy, the higher the economic opportunities for the country. The level of gains cumulated over the 2019-2030 time period with a progressive but accelerated penetration of secondary steel (from 10% of EAF production capacity in 2018 to 30% in 2030) could be between USD 589 billion and USD 819 billion representing 4.2% and 5.8% of its GDP in 2018 respectively.

These outcomes very much depend on the capacity of downstream sectors, notably the more advanced ones such as the automotive industries, to absorb an increasing amount of secondary steel. These figures are of the same level of magnitude as the economic benefits obtained in other applications of the circular economy in China – EMF (2018) obtain a USD 5.1tr savings for business and households for measures in the area of the built environment, mobility and nutrition. Furthermore, the gains in the present study are not calculated based on *ceteris paribus* assumptions but are obtained by accounting for the economy-wide impacts of general price changes implied by the Chinese industrial transformations explored in our scenarios. The multi-regional CGE model used in our analysis, ENGAGE-materials, also allows for the identification of the other winners of this transition but also the losers affected by changes in international trade flows.

The aggregate GDP increases can hide the differentiated impacts across Chinese economic sectors – a higher availability of secondary steel at lower prices could lead to a competitive advantage for manufacturing and particularly for construction. At the same time, this shift would lead to a reduction in domestic iron mining and primary steel production, an impact which would demand policies to ensure that the workers affected in the lagging industries are not left behind. Therefore, from a geographical perspective, a more circular steel industry could imply an intensification of steel production around areas with a high scrap availability. These are regions in China that have already benefited from economic development, implying a further increase in employment opportunities in these areas. Another secondary impact would be the increased labour costs for some downstream sectors due to a crowding-out effect of a higher employment in steel-intensive activities.

The level of industrial restructuring in China resulting from our scenarios is comparable to practices already found in industrialized countries. The penetration of EAF to 30% of total capacity in 2030 is still smaller than the shares found in Western Europe and the USA. Downstream, the increased absorption of secondary materials by steel-intensive sectors is also in line with the current shares of secondary steel used in automotive and appliances sectors from industrialised economies (Stadler et al., 2018). Therefore, although China would follow the path already taken by other economies, the quantification of the opportunities to greening the steel sector in China could help justify a pro-active industrial restructuring. The scrap use targets in China's Central Government Thirteenth Plan (2016-2020) of an increase by 20% of scrap use by 2020 is already covered in the INT scenario which yields low economic benefits. Therefore, a more ambitious increase in secondary steel production could be envisaged for the next Five-Year Plan or the years ahead. In its national legislation, China is already putting great emphasis on the circular economy principles in manufacturing (McDowall et al., 2017) but more actions need to be taken upstream in the primary industries (Mathews & Tan, 2016) and systemically at the level of industrial parks in order to enhance benefits from industrial symbiosis (Huang et al., 2019). On environmental grounds, given that larger steel plants can be more energy efficient, small retiring BOF-based plants could be replaced with larger similar facilities. While we acknowledge energy efficiency as a driver for the industrial transformation in China (Li et al., 2019) which will likely materialise for the short-run, the latest government regulations on steel capacity replacement in the Beijing, Tianjin and Hebei areas and the Yangtze and Pearl River more favourable to EAF adoption (OECD, 2019) hint at a strategy towards more circular steel production for the longer run.

The economic opportunities for China revealed in this study may also come with uncertainties, risks and unwanted effects which would need to be considered in an integrative manner. An important uncertainty would be the availability of obsolete scrap. As opposed to iron ore reserve estimations which are determined through geological surveys, future scrap availability is calculated by means of modelling of current operational steel stock using assumptions regarding product lifetimes. Since most of scrap supply in the next decade is expected to be supplied from existing infrastructure and building depreciation (Pauliuk et al., 2012), more detailed stock modelling is needed at urban scales. Some important factors which could constrain the medium-term supply of steel are past construction practices and future regulations for steel reuse and recycling in buildings. Nevertheless, our trade flow results show that China would still play a minor role in global scrap trade by 2030 hence, it could rely on international markets for any domestic scrap shortages.

The expected medium-term changes in the overall steel demand structure (a decline for construction and an increase for the automotive industry, Pauliuk et al., 2012) could have impacts on the quality of scrap for the longer term. With this view, measures to extend producer responsibility for eco-design and recycling in the automotive industry should already be put in place to help address the risk of increased copper contamination in scrap steel beyond 2030 (Daehn et al., 2017). This could be aligned with a shift towards e-mobility and thus be in time with innovation within the automotive industry and their supply chain. Other medium-term issues could be related to the structure of the recycling sector in China which would require consolidation to leverage the efficiencies of scale in the collection, treatment and supply of steel scrap.

The greening of the steel sector through more secondary production would reduce the use of iron ore and therefore could enable a partial decoupling of resource extraction from the expansion of industrial activity and related GHG emissions. However, our results suggest that the increase in electricity demand required to satisfy a growing secondary steel production could potentially result in an increase in Chinese coal production with implications for global CO_2 emissions and local environmental impacts from coal mining. As China also relies on coal imports, the environmental pressure could also be augmented in the other coal exporting regions. One may note that such unintended consequences of a green shift stem from a regional shift in existing supply chains, and not from a 'pollution haven' of dirty industries relocating to less regulated parts of the world. These statements should nonetheless be interpreted carefully as they are the result of the high share of coal inputs in the electricity sector resulting from the model, which is not necessarily consistent with scenarios developed by relevant international institutions (e.g. the New Policy Scenario in IEA, 2018a). Therefore, the increased circularity of steel production needs to be aligned with policies for increased energy efficiency (Hasanbeigi et al., 2013) and energy transition towards low-carbon technologies in China as well as in other regions to reap the potential environmental benefits from increasingly meeting the future demand of steel from secondary sources.

The move to a more circular steel production in China has mixed implications for other countries. On the one hand, it imposes losses for other regions coming from lower iron ore extraction (Australia, Brazil, India) and a slight decline in steel production. Nevertheless, regions outside China could generally benefit from lower global steel prices through lower production costs of the downstream sectors. Our analysis shows competitive gains for steel-intensive products in many emergent and developing regions. In the scenario of a deeper circularity in China (PLUS), to keep their production advantages, these regions would need to take further steps at their turn for a higher adaptability to the downstream use of secondary steel – again, it illustrates the need for a green industrial policy alignment through international cooperation aimed at steel but also other key materials.

Anticipating a green shift in China with deflationary impacts on world steel prices, regions in which steel demand has already peaked (Western Europe, USA, Japan, South Korea) could increase their support for zero-carbon steel technologies in the primary route aiming for a faster deployment of hydrogen-based reduction and carbon capture technologies. In this respect, policy-makers could seek to stimulate the creation of premium zero-carbon steel markets for high-purity alloys. In these markets, domestic steel producers could become key innovators, gaining competitive advantage and preparing for a complete decarbonisation of the global steel sector as implied by the UNFCCC Paris Agreement.

A global environmental risk could come from the evolution of iron ore and coal prices going downwards, which may encourage investment in CO_2-intensive primary production in regions with a high growth in steel demand (India, Other Developing Asia and Africa). While in many of these economies there is still a mismatch between obsolete scrap supply and steel demand due to the currently insufficient in-use stocks of steel, the production along the primary route could be exacerbated on cost grounds. Looking at the demand for steel, one may also take into account requirements coming from energy transitions (wind energy, distribution), e-mobility, and sustainable cities. Therefore, a global partnership to coordinate investment in steel capacity, implement circular economy principles in steel making and reduce CO_2 emissions across the supply chain could be critical in avoiding rebound effects and the creation of new pollution hotspots. While there is an emerging discussion on global partnerships for the circular economy (Geng et al., 2019), we leave the topic of coordinated efforts towards a globalised greening of the sector for future work.

This study assesses the gains for China and the implications for other regions at a macro scale, thus not considering the geographical and plant-level heterogeneities regarding steel production. A more comprehensive analysis would thus be required to capture the spatial constraints of the underlying steel supply chains when moving to a more circular production in China. Furthermore, an analysis on the employment effects considering potential production relocation within the regions considered here would also be welcome.

5. Conclusions

Our study assesses a shift towards a circular economy in steel for China – a latecomer to secondary steel production among the largest economies. The results reveal potential macro-economic gains in China dependent on the speed of change and adaptability of downstream sectors. The economic opportunities are significant and in line with findings for other areas of application of circularity principles in the Chinese economy. The international implications are also relevant but mixed, implying both gains and losses for the other world regions. The largest negative impacts would occur in major iron ore producing regions (Australia, Brazil, India, Other Developing Asia, Russia), however, these are counterbalanced by general cost reductions for development associated with lower steel prices.

While broader environmental gains from an industrial policy towards a less resource- and energy-intensive production are obvious, a major implication for green development in steel production is an increasing demand of coal, if such shift is not aligned with an energy transition in electricity generation. Our study, therefore, pledges for policy alignment combining a circular economy with low carbon pathways in China and internationally through coordinated action.

Our article should also underline the strengths of using a global economy-wide model with environmental extensions. ENGAGE-materials has been set up to model the full supply chain of steel in all relevant world regions, which is up to now a unique feature. More modelling, however, needs to be done to integrate technological change and innovation, and to assess environmental implications at regional scales. Such advancement and modelling interlinkages are not only relevant for this line of research, but also for empirical policy analysis, for industry and planners, and for foresight exercises. With a world undergoing massive disruptions due to geopolitics and green developments, there is clearly a need for evidence-oriented research from an international perspective.

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