



Reaching zero carbon emissions from **Steel**

Consultation
Paper

WHO ARE WE?

The [Energy Transitions Commission](#) (ETC) is a **global coalition of 30 leading executives from across the energy landscape** (energy companies, energy-intensive industries, investors, environmental NGOs and academics). Its mission is to define how to most effectively transition to low-carbon energy systems while also delivering the large increases in energy supply needed in many developing countries to enable economic prosperity, and to accelerate required action from public and private decision-makers.

In 2017, the ETC published [Better Energy, Greater Prosperity](#), a report that outlines four strategies to cut carbon emissions by half by 2040. It argues in particular for an energy productivity revolution and a rapid decarbonization of electricity generation combined with the electrification of a wider range of economic activities.

OUR WORK ON “HARD-TO-ABATE” SECTORS

In 2018, the ETC is focusing its analytical and influencing efforts on **those sectors which are likely to be harder to decarbonize in heavy duty transport – trucking, shipping and aviation – and industry – steel, cement and plastics**. Together these sectors represent 40% of carbon emissions from the energy systems today, but this share will grow to 60% of remaining emissions by 2040 in a 2°C scenario, as other high-emitting sectors are decarbonized and demand for mobility and materials grows in emerging economies. Our aim is to **assess whether and how these sectors can be fully decarbonized and to accelerate action** from key policy, industry and finance players.

WHAT IS THE PURPOSE OF THIS PAPER?

In June 2018, the ETC will be releasing a series of **consultation papers** which lay out pathways to reach zero carbon emissions for these 6 different sectors. In addition, there will be 3 consultation papers covering key cross-cutting technologies: electricity and hydrogen, biomass, and carbon capture, utilization and storage. These 9 consultation papers will form the basis of a series of targeted stakeholder engagement with industry players and civil society in order to refine our analysis and conclusions. This process will then **feed into an integrated report on the decarbonization of “hard-to-abate” sectors in industry and heavy-duty transport**, to be published in November 2018. The ETC also carries out actions to influence key decision-makers, which have begun with the ongoing consultation process and will intensify after the publication of the integrated report.

JUNE 2018 JULY 2018

**DECARBONIZING
HEAVY-DUTY TRANSPORT**



**DECARBONIZING
HEAVY INDUSTRY**



**CROSS-CUTTING
TECHNOLOGIES FOR DEEP
DECARBONIZATION**



HOW WAS THIS PAPER DEVELOPED?

This consultation paper was **developed by the ETC Secretariat**, with the support of its members. It draws heavily on analysis from our research partners Material Economics, McKinsey and SYSTEMIQ, as well as on a review of the existing literature. It integrates feedback received through a **consultation workshop and bilateral exchanges with industry experts and representatives**, whom we would like to thank for their contributions.

Please note that the analysis and conclusions presented in this paper are still **being refined and should therefore be treated as being “work in progress”**. The members of the Commission and the institutions with which they are affiliated have not been asked to formally endorse this paper.

HOW CAN YOU PROVIDE FEEDBACK?

We warmly welcome feedback on this paper until 31st August 2018. Please send comments, questions and requests for follow-ups to pmo@energy-transitions.org. We are particularly interested in feedback on the feasibility and cost of different decarbonization options, and on the recommendations to policymakers, industries, businesses and investors. This feedback will be integrated in the final report to be published in November 2018.

TABLE OF CONTENTS

- Reaching zero carbon emissions from steel 4**
 - Supporting analysis and reports5
- 1. Overview of the challenge 6**
 - A. Demand trends to 20506
 - B. Carbon emissions7
- 2. Reducing carbon emissions through circularity 9**
 - A. Reducing primary steel production through increased recycling9
 - B. Reducing total steel demand via a shift to a more circular economy 12
 - Automotive sector: impact of a shared mobility system 13
 - Buildings construction: improving materials efficiency 14
 - C. Assessing the demand reduction potential 15
- 3. Decarbonizing primary steel production 16**
 - A. Opportunities for energy efficiency improvement 16
 - B. Decarbonization options: description & technology readiness 17
 - C. Decarbonization options: Cost trade-offs and overall economic impact 19
- 4. Emerging conclusions and existing initiatives 22**
 - A. Emerging conclusions and policy implications22
 - B. Existing policy and industry initiatives23
- 5. Recommendations 24**
 - Research, development and investment projects.....24
 - Public policy25
 - Industry action: Role of steel producers and consumers26

REACHING ZERO CARBON EMISSIONS FROM STEEL

Energy-related emissions from the steel and iron industry currently amount to circa 2.8 Gt of CO₂ per annum accounting for almost 8% of total global energy system emissions, but, under a business as usual scenario, they would grow to 3.1 Gt by 2040 representing 7.5% of global emissions and 34% of the industry sector emissions¹.

To tackle the major impact of these emissions on the economy, it is essential to assess **whether total demand for steel could be reduced**, or whether demand could be met by **more recycled secondary steel** and less primary production. However, as production per capita is still expected to grow strongly in most developing regions – with the exception of China –, it will not be possible to achieve necessary emissions reductions without **a shift towards low or zero-carbon production routes for primary steel**. A substantial but capped energy efficiency improvement potential is to be grasped, but more radical process changes are required. The two main routes to decarbonization will certainly be hydrogen-based reduction and carbon capture and storage or use (CCS/U), but optimal pathway will differ by location in the light of electricity prices and CCS cost and feasibility.

The ETC is confident that **a complete decarbonization of the steelmaking industry is achievable by mid-century**, with a modest impact on end-consumer prices and cost to the overall economy, although an uneven transition on a global scale may create competitiveness issues. An internationally coordinated carbon price coupled with downstream levers, like the implementation of “green steel” standards and labels across the steel value chain are therefore essential to mitigate competition risks. Increased R&D spending in decarbonization technologies as well as to improve the quality of secondary steel through better scrap management will also be essential, alongside a combination of voluntary commitments and regulations to encourage recycling and more efficient steel use, in particular in the automotive and construction sectors.

Top 3 actions to accelerate the transition for...		
<p>... R&D</p> <ul style="list-style-type: none"> • Develop and pilot hydrogen-based DRI • Develop and pilot new technologies to reduce cost of CCS on BF-BOF • Develop innovations that enable higher-quality and higher-value recycling of steel 	<p>... Industry/Businesses</p> <ul style="list-style-type: none"> • Support “green steel” standards design and implementation, as well as collective industry targets for carbon emissions • Develop commitments on “green steel” purchase in steel-using sectors, starting with the automotive industry • Initiate collaborative projects between producers and users to increase and improve quality of steel recycling 	<p>... Public policy</p> <ul style="list-style-type: none"> • Enforce a carbon tax on steel production reaching \$50-\$70 by 2030 • Commit to 100% zero-carbon steel in all publicly-funded construction by 2040 • Develop regulations on steel production and steel-using sectors to encourage better recycling

¹ IEA, 2016, *Energy Technology Perspectives*

SUPPORTING ANALYSIS AND REPORTS

The Energy Transitions Commission work on steel has drawn extensively on inputs from **two knowledge partners**:

- A report by **Material Economics** on the potential for greater materials circularity, which particularly focused on Europe – *The circular economy: a powerful force for climate mitigation* (2018);
- A report by **McKinsey & Company** on supply-side decarbonization options across several industrial sectors – *Decarbonisation of the industrial sectors: the next frontier* (2018).

This consultation paper presents a synthesis of the relevant conclusions from those reports supplemented by some additional analysis.

1. OVERVIEW OF THE CHALLENGE

A. DEMAND TRENDS TO 2050

Total global steel production is forecasted to **grow by 30% by 2050², with recycled secondary steel growing faster than the primary production³**, but with major differences by country and region.

Demand for primary steel is driven by the accumulation of steel stocks – in particular in buildings, infrastructure and transport vehicles – which deliver consumer benefits throughout their life. **Developed countries typically have stocks of around 12 to 13 tonnes per capita⁴** and, with this level no longer increasing significantly, demand for steel in developed economies is now driven primarily by the replacement of buildings and equipment and could in principle be met through recycling of existing steel stocks. By contrast, **steel stocks per capita in India and Africa are only 1 tonne per capita⁵**, and therefore likely to grow for many decades, creating significant primary steel demand. China's rapid expansion of steel production over the last 20 years has supported a rise in its stock to over 5 tonnes per capita, but once the country reaches developed country levels, demand for primary steel will fall significantly.

Today, **about 95% of primary steel is produced in blast furnaces (BF-BOF)** which use coking coal as both the reduction agent and the source of heat energy. Only around 5% new steel is produced via direct reduction (DRI) combined with electric arc furnaces (EAF). In DRI-EAF, syngas (a combination of CO and H₂) achieves the reduction process, with this syngas in turn primarily derived from methane gas (though with some coal-based DRI in India). **Secondary steel recycling typically occurs in electric arc furnaces (EAF).**

The interaction of the changing balance of primary and secondary demands for steel – and the different production routes of each – drives **current and future projected volumes of steel produced by the different routes overall and by region** [Exhibit 1]. According to IEA forecasts, between now and 2050, Chinese total steel demand could fall from 800 Mt to 550 Mt, which together with a shift from BF-BOF primary production to EAF steel recycling, could see coal-based production fall by 60%. Africa and India, by contrast, are expected to see huge increases in steel production, and in particular in coal-based primary production, as steel stocks per capita rise. Forecasts for Europe, where it would be possible to shift to a heavily EAF-based approach to support steel demand, still assume significant primary production because of exports⁶.

The IEA Reference Technology Scenario's projection suggests that **total global steel demand could rise from 1.6 Gt per annum in 2015 to 2.2 Gt by 2050⁷, but with primary production flat** as reductions in China offset increases elsewhere in developing economies.

² World Steel Association, 2018, World steel in figures 2018

³ 40% growth between 2015 and 2050 for the main route for recycled steel (Electric Arc Furnace), vs. 2% growth on the same period for the conventional primary steel production route (Basic Oxygen Furnace). Reference Technology Scenario, IEA, 2017, *Energy Technology Perspectives*

⁴ McKinsey & Company, 2018, *Decarbonization of industrial sectors: the next frontier*

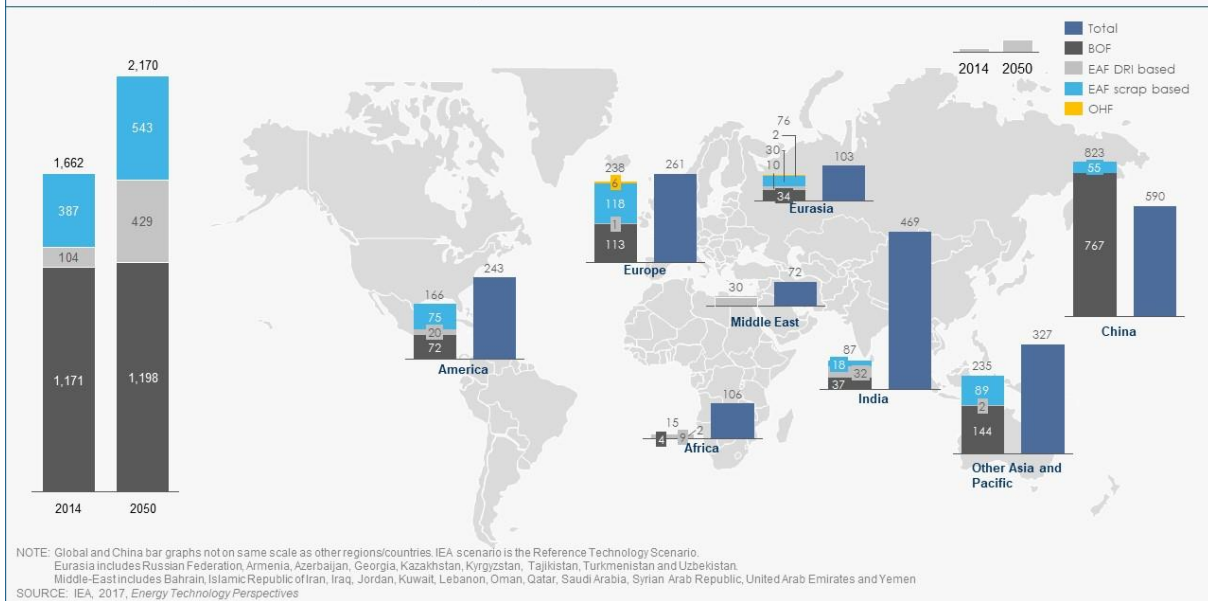
⁵ McKinsey & Company, 2018, *Decarbonization of industrial sectors: the next frontier*

⁶ McKinsey & Company, 2018, *Decarbonization of industrial sectors: the next frontier*

⁷ IEA, 2017, *Energy Technology Perspectives*

Exhibit 1 – Steel production projections by geographic area

Million tonnes per year, 2014 and 2050, total steel production



B. CARBON EMISSIONS

Global carbon emissions from iron and steel production are **currently around 2.8 Gt per annum**, about 8% of global energy system emissions. Business as usual scenarios suggest that this **could rise to 3.1 Gt per annum by 2050**⁸, with the growth in global steel demand driven by regions that are more unlikely to make significant progress on the decarbonization front.

The growth of emissions and the balance between different countries **will be strongly driven by the changing mix of different production processes**. While average BF-BOF furnaces produce emissions of about 2.3 tonnes of CO₂ per tonne of steel produced, DRI with gas as the input produces about 1.1 tonnes, while EAF produces about 0.4 tonnes, and less still if the electricity used comes from zero-carbon sources⁹ [Exhibit 2].

Given these different intensities, the predicted shift in the mix of steel production from primary to secondary and from BF-BOF to EAF explains why **forecasted emissions grow only 10% even while total steel demand grows over 25%**.

But if the world is to have any chance of meeting the Paris climate objective of keeping the global temperature increase to well below 2°C, total emissions from global energy use across all economic sectors must be cut from today's 36 Gt to 20 Gt by 2040, below 15 Gt by 2050¹⁰ and reach net zero around 2070¹¹. It is therefore essential to develop a strategy to dramatically reduce steel industry emissions by 2050 and to eliminate them by 2070.

⁸ International Energy Agency, 2016, *Energy Technology Perspectives*

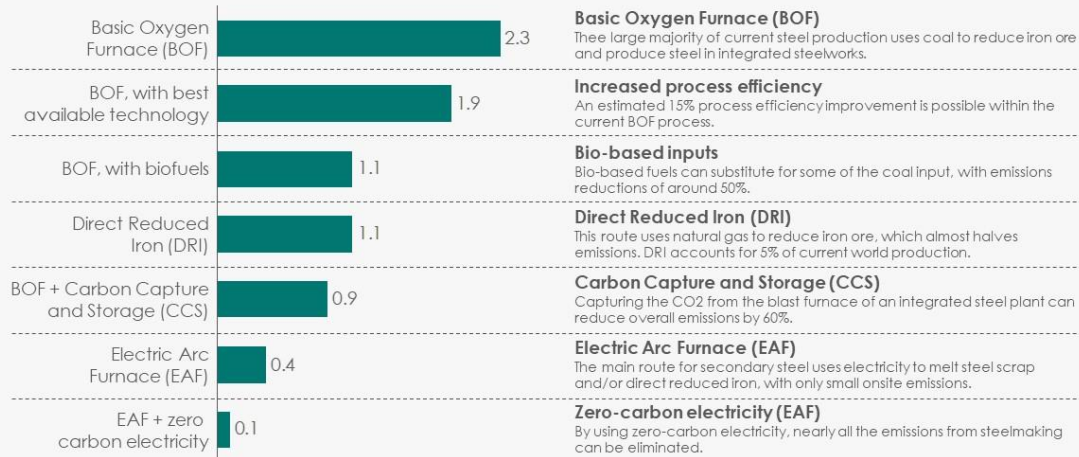
⁹ Material Economics, 2018, *The Circular Economy, a powerful force for climate mitigation*

¹⁰ International Energy Agency, 2016, *Energy Technology Perspectives*

¹¹ Energy Transitions Commission, 2017, *Better Energy Greater Prosperity*. Also targeted by Shell's Sky scenario (Shell, 2018, *Sky: Meeting the Goals of the Paris Agreement*)

Exhibit 2 – CO₂ intensity of steel production

tCO₂ per ton of steel



Source: Material Economics, 2018, *The Circular Economy: a powerful force for climate mitigation*

2. REDUCING CARBON EMISSIONS THROUGH CIRCULARITY

As Section 3 will discuss, while decarbonization of steel production is undoubtedly technically possible, it may entail significant cost and will take considerable time, since some of the technologies are not yet fully developed and existing assets may have long lives. **To reduce the cost to the economy and to ensure early progress on emissions reductions**, it is therefore essential to assess whether total demand for steel could be reduced, or whether demand could be met by more recycled secondary steel and less primary production.

Our knowledge partner Material Economics has analyzed the potential to reduce the demand for all major industrial materials in a report on *The Circular Economy – a powerful tool for climate mitigation* (2018). In total, they estimate that **total annual carbon emissions from steel production in 2100 could be reduced by 52% relative to business as usual** if changed practices and policies allowed us to maximize:

- Opportunities for greater recycling of steel, with total demand met from more secondary and less primary production;
- Opportunities for delivering the same standard of living with a lower stock of steel per capita, thus cutting total annual steel production both primary and secondary.

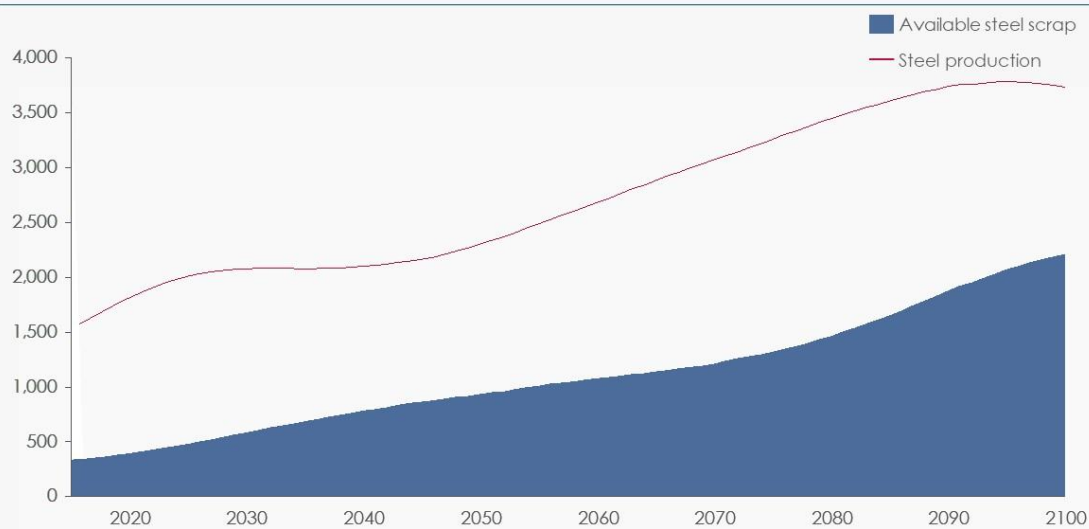
A. REDUCING PRIMARY STEEL PRODUCTION THROUGH INCREASED RECYCLING

The vast majority of steel is already recycled at end-of-life. Material Economics estimate that 83% of steel is recycled at end-of-life globally and as high as 90% in some countries. Even if the percentage of steel recycled at end-of-life did not increase, **the proportion of secondary steel in total steel production will automatically rise during the 21st century**, as stocks of steel per capita reach maturity, and as the flows of steel reaching end-of-life increase.

- If all countries eventually reached a stable level of stocks (at 12 tonnes per capita) and if all steel was recycled at end-of-life, then **eventually 100% of all steel would come from recycled sources**. If recycling rates remain at around current levels with 83% of steel was recycled, then in this long-term steady-state 83% of annual steel production would come from recycled sources.
- In practice, both population and stocks per capita will continue to rise in many countries throughout the century, but **the proportion of total steel demand which could theoretically come from available steel scrap will nevertheless increase from around 22% today to around 60% by 2100** [Exhibit 3].

Exhibit 3 – Global steel production to meet demand and available steel scrap

Million tonne steel per year



NOTE: EXCLUDING SCRAP EXPORTED OR USED IN INTEGRATED STEELMAKING.
Source: Material Economics, 2018, *The Circular Economy: a powerful force for climate mitigation*

The percentage of steel demand actually met by secondary production will depend on the recycling rate achieved and, if recycling rate could be driven up from today's 83%, important reductions in primary production would result. But **to achieve increased recycling, three problems must be overcome:**

- Losses of steel which are not recycled:** These can result from (i) end-of-life structures which are inaccessible or too corroded to use, (ii) old scrap which is simply lost or ends in landfill, (iii) new scrap lost in fabrication but not collected and recycled, (iv) losses in the remelting process. Material Economics estimate that, in total, these losses could amount to 150 Mt of steel in Europe only today, with primary production therefore unnecessarily increased by that amount [Exhibit 4].
- The “downcycling” problem:** Recycled steel is typically lower-quality and lower-value than the steel from which it originally came, with much of it, for instance, ending life as rebar for construction purposes. This downcycling is made unavoidable because of “tramp elements” in the recycled steel. While it is not a barrier to recycling as long as there is sufficient demand for the more basic steel categories, it would become an important barrier to achieving anything like 100% recycling.
- The copper contamination problem:** Steel scrap usually suffers from a high copper content, which limits its capacity to be used for the production of some alloy categories. Copper contamination is one of the key drivers of downcycling. It also requires the diluting of scrap steel with inputs of primary steel to lower copper content of the recycled material.

If these problems could be overcome, primary production could be very significantly reduced¹². Material Economics estimate that **primary production could be 20% lower in 2050 and 30% lower in 2100 compared with baseline levels if a stretching but credible increase in recycling was achieved** [Exhibit 5].

¹² Thus, for instance, in the eventual steady-state situation with stable stocks of steel per capita, a recycling rate of 95% would mean 75% less primary production than a recycling rate of 80%.

Exhibit 4 – Losses in steel production

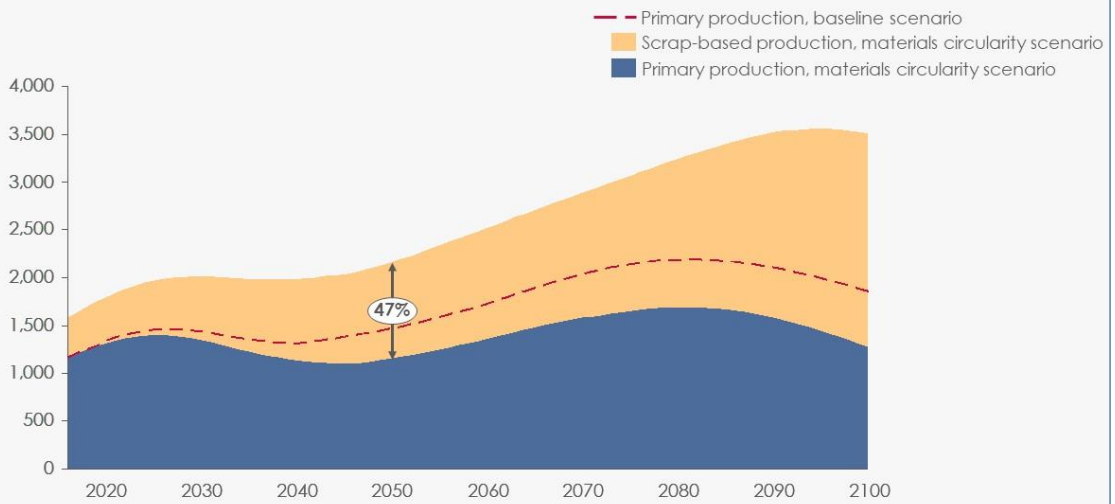
Million tonne steel 2015



Source: Material Economics, 2018, *The Circular Economy: a powerful force for climate mitigation*

Exhibit 5 – Global steel production by route

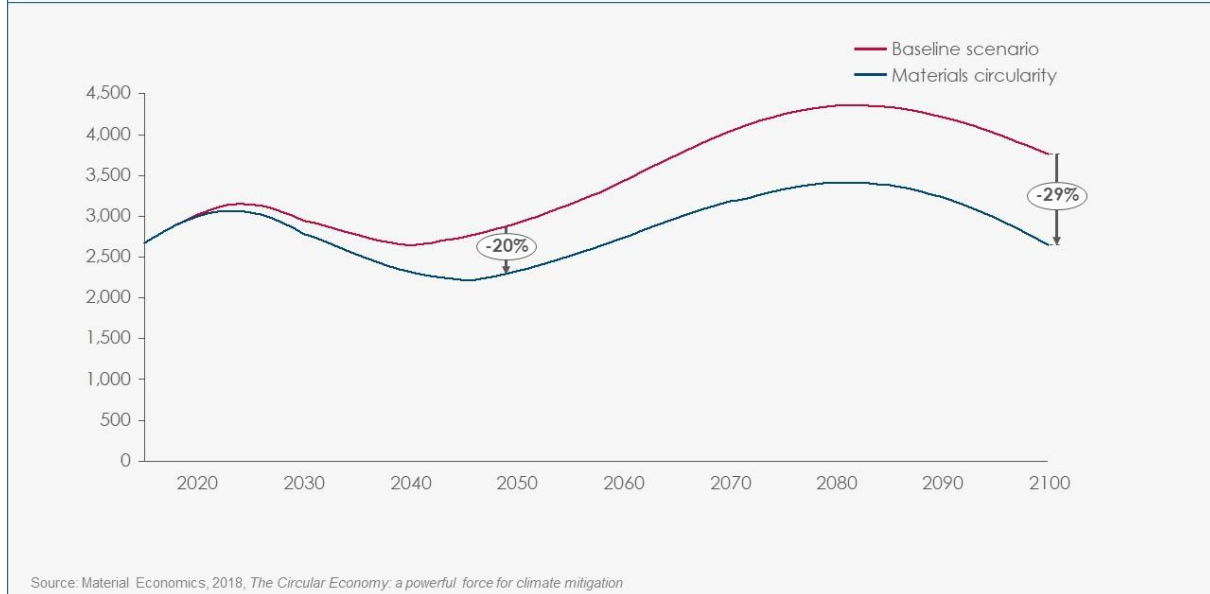
Million tonne steel per year, 2015-2100



Source: Material Economics, 2018, *The Circular Economy: a powerful force for climate mitigation*

Exhibit 6 – Global CO₂ emissions from steel production

Million tonne CO₂ per year, 2015-2100



This shift from primary production to secondary would in turn produce a large cut in emissions, given the very different carbon intensities of secondary versus primary production illustrated in Exhibit 2. Material Economics estimate that **greater recycling could cut global annual emissions by 20% by 2050 and by 29% by 2100 relative to business-as-usual levels** [Exhibit 6].

Achieving this increase in recycling will however require significant changes in industry practices, supported by changes in regulation. In particular, a more circular approach to steel production requires:

- Improved systems for collection of end-of-life materials, including more careful separation of iron and steel when buildings are demolished;
- Reduced new scrap creation by better product design, potentially enabled by 3D printing and powder metallurgy;
- Reduced remelting losses, which may be made easier through the better separation of different alloys prior to remelting;
- Improved alloy-to-alloy sorting to reduce downcycling; and
- Product designs and end-of-life recycling processes which make it easier to separate copper from steel.

The role which public policy might play in encouraging these changes is considered in Section 5 on recommendations.

B. REDUCING TOTAL STEEL DEMAND VIA A SHIFT TO A MORE CIRCULAR ECONOMY

In principle it is possible to **reduce total steel stocks per capita** and thus required steel production while continuing to deliver the same end services from which customers benefit. Such opportunities could exist in all steel-using sectors, for instance via more lightweight product design, but **the greatest opportunities lie in the automotive and construction sectors which together account for around two thirds of all steel use.**

AUTOMOTIVE SECTOR: IMPACT OF A SHARED MOBILITY SYSTEM

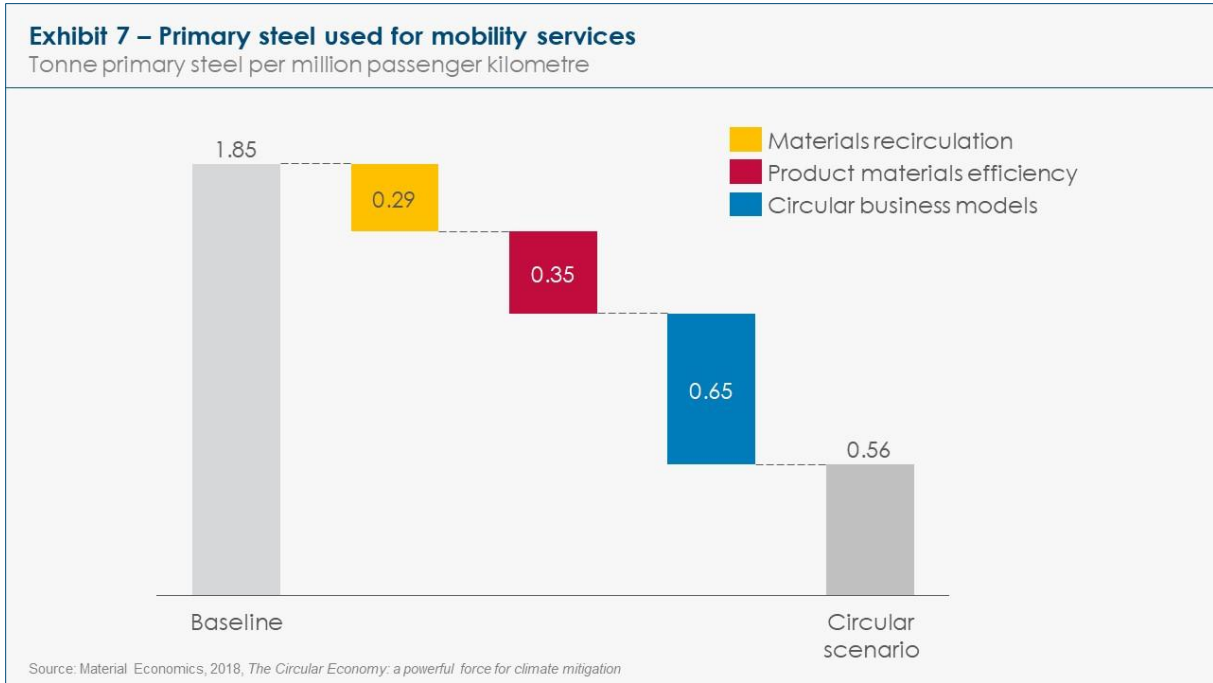
Today 77% of the passenger car emissions reflect emissions arising from the use of the vehicle and 23% from its production¹³. But as the shift to electric vehicles cuts in-use emissions, eventually 90% of surface transport related emissions could derive from the manufacture of vehicles and the underlying material inputs¹⁴.

In principle, these emissions related to manufacturing and material inputs could be dramatically reduced through **a shift from individual car ownership to a shared mobility system**. This shift may in any case occur as a natural result of the development of electric and autonomous vehicles since (i) EVs have higher capital and lower operating costs, which increases the economic benefits of a shared approach, (ii) autonomous driving makes possible a shared, “order-when-needed” approach to buying transport services.

A shift to a more shared approach will have both **direct and indirect effects on materials use**:

- The direct impact is a dramatic increase in the utilization of vehicles and thus **dramatic reduction in the number of vehicles required** to meet any given level of transport demand. With the total utilization of privately-owned passenger vehicles currently around 2 to 5%, the scope for improvement is massive.
- In addition, a shared or hire-on-demand approach to road passenger transport will likely lead to **a reduction in the average size of car**, since many family cars are currently sized for occasional multiple passenger trips, but with the average space requirement much lower.

It is possible, therefore, that a shift to a shared mobility system could produce a dramatic fall in required material inputs to auto manufacture. Specifically, for steel and considering the combined opportunities for improved recycling, better material efficiency and shared business models, Material Economics estimate that **the tonnes of primary steel required per million passenger kilometers could fall by 70%** [Exhibit 7].



¹³ Material Economics, 2018, *The Circular Economy, a powerful force for climate mitigation*

¹⁴ Material Economics, 2018, *The Circular Economy, a powerful force for climate mitigation*

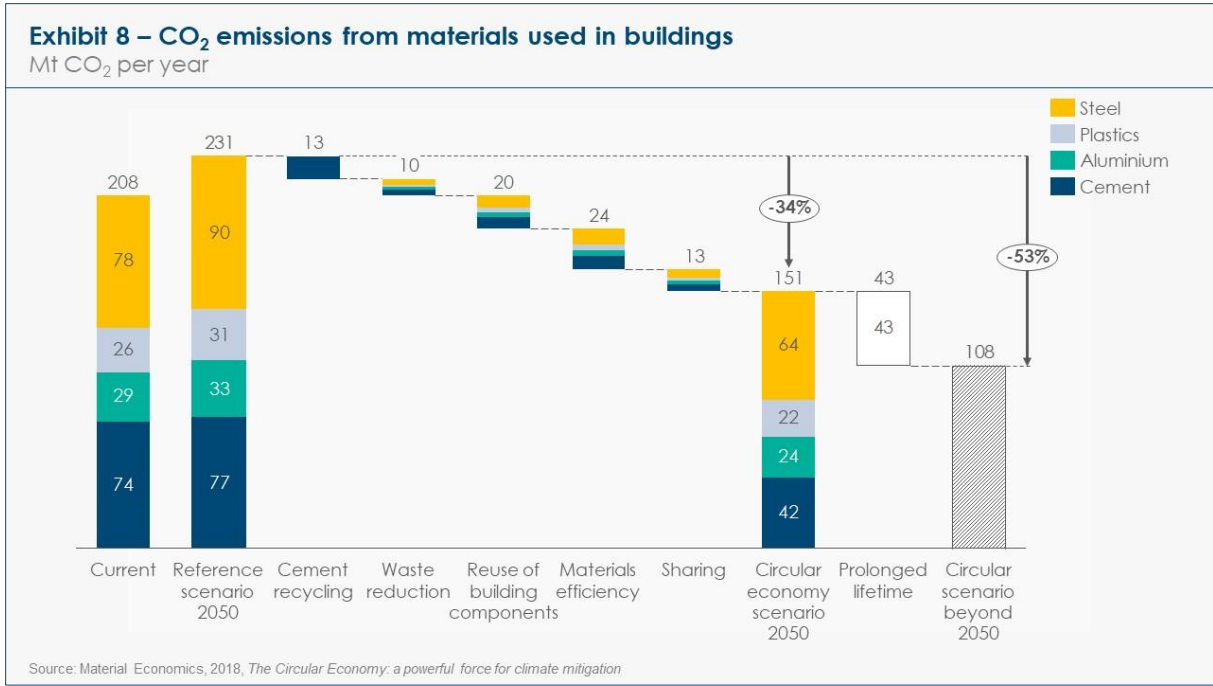
BUILDINGS CONSTRUCTION: IMPROVING MATERIALS EFFICIENCY

Construction accounts for about 50% of all steel demand, and here too there may be significant opportunities to reduce required steel use while continuing to deliver the end customer service of residential or commercial space.

Key opportunities considered in the Material Economics report – in addition to reduced construction waste and increased recycling – are:

- **Greater direct reuse of building components**, with for instance steel used in its existing form rather than remelted into new steel;
- **Greater materials efficiency in building construction**, with better designs and less over-specification of steel (or concrete) in excess of structural requirements; and
- More speculatively, a small shift to a **“shared” approach to commercial office use**.

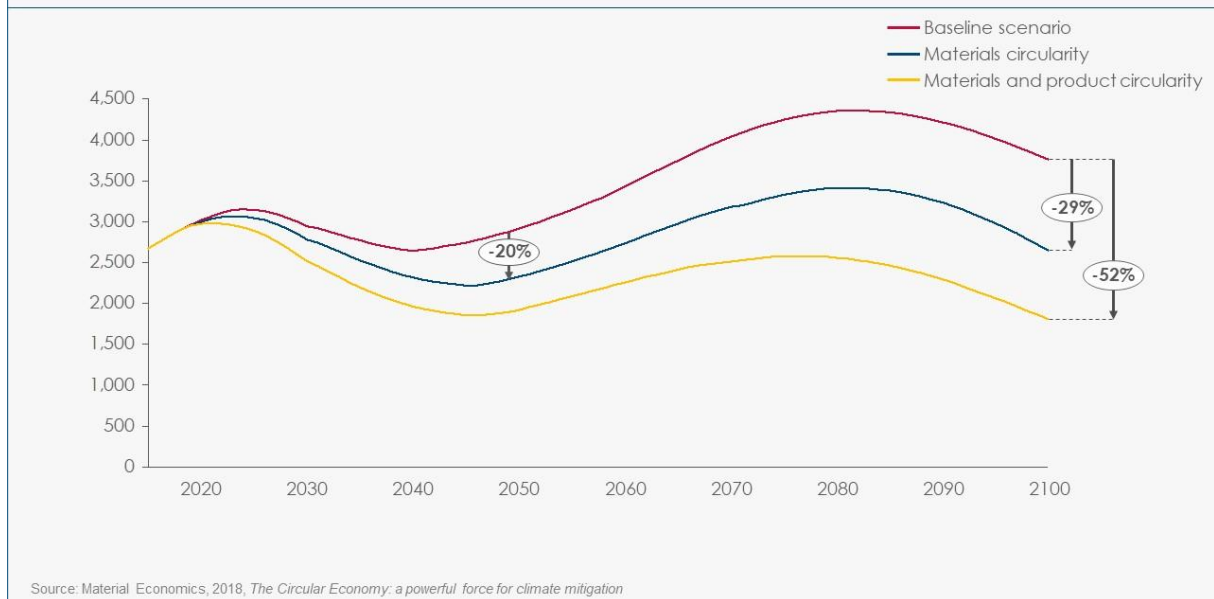
In total for all materials, and considering also some benefits from improved recycling, Material Economics estimate **potential emission reductions from all materials input to the buildings sector (steel, plastics, aluminum and cement) of 34% by 2050** if all opportunities for improved construction efficiency could be achieved [Exhibit 8].



For steel specifically, and including both the benefits of improved recycling and reduced steel demand, across all sectors of the economy, the Material Economics analysis suggests that **total emissions could be cut by 34% by 2050 and 52% by 2100** relative to a business as usual trajectory, if all opportunities to reduce demand could be achieved [Exhibit 9].

Exhibit 9 – Global CO₂ emissions from steel production

Million tonne CO₂ per year, 2015-2100



C. ASSESSING THE DEMAND REDUCTION POTENTIAL

The extent to which these demand reduction opportunities can in practice be achieved is inevitably a matter of judgement. But the scale of the theoretical potential suggests that policies to contain demand must play a key role in the decarbonization of the steel sector.

However, Material Economics estimates suggest that, even if these demand reduction opportunities can be grasped, if production methods remained unchanged, emissions from steel production would still remain close to or above 2 Gt CO₂ per annum throughout the 21st century. Strategies to decarbonize primary steel production are therefore also essential.

3. DECARBONIZING PRIMARY STEEL PRODUCTION

This section draws on analysis which McKinsey & Company have conducted into supply-side decarbonization options for each of the major industrial sectors, now published in the report *Decarbonization of industrial sectors: the next frontier* (2018). This input has been complemented by other analysis, discussions with steel companies, and a workshop with a range of industry participants.

Our emerging conclusions are that:

- **There is a range of feasible routes to near-total steel decarbonization**, but the optimal route in different locations will be determined by local electricity prices and the local feasibility and cost of carbon capture and storage, and
- **The cost implications for end product consumers and the overall economy are relatively small**, although they might be more significant for individual industry players.

A. OPPORTUNITIES FOR ENERGY EFFICIENCY IMPROVEMENT

There is considerable potential to improve energy efficiency of steel production even without fundamental changes in process. Analysis by the OECD for instance suggests that **many steel companies currently are underexploiting positive-return opportunities to reduce energy input per tonne**. This situation is likely explained by pressure on margins in an internationally competitive sector and thus by the difficulty for individual industry players to bear the upfront costs of investments with medium-to-long-term payback periods.

Examples of existing technologies that could have a significant impact on energy efficiency of blast furnaces include:

- Coke Dry Quenching (CDQ): cooling using an inert gas instead of sprayed water (achieving an up to 40% energy reduction¹⁵);
- Capturing high-pressure gas leaving the furnace and using it to power other equipment.

But while achieving such improvements is important, there is a limit to the scale of achievable energy efficiency improvement with current technologies, which McKinsey estimates at around **15-20% of present energy consumption**¹⁶. More radical changes in process will therefore be required to achieve deep decarbonization.

¹⁵ Industrial Efficiency Technology Database website (<http://ietd.iipnetwork.org/content/coke-dry-quenching>)

¹⁶ McKinsey & Company, 2018, *Decarbonization of industrial sectors: the next frontier*

B. DECARBONIZATION OPTIONS: DESCRIPTION & TECHNOLOGY READINESS

Primary steel production could be fully decarbonized in 4 ways:

- **(1) Bioenergy:** Using charcoal instead of coal as a feedstock for BF-BOF plants is a mature technology, which has been applied in Brazil on a significant scale. The total potential for this across the world is however severely limited by supply of sustainable biomass (see the forthcoming ETC consultation paper on *Bio-based products in a zero-carbon economy* for analysis of issues relating to sustainable biomass resources across multiple economic sectors). An alternative use of bio-energy would be to use biogas (methane generated from biomass sources), as against fossil fuel derived methane, as an input to DRI production, although the availability of may be limited, compared to the scale of demand from the steel sector, in many regions of the world.
- **(2) Carbon capture and storage/use:** CCS/U could be retrofitted on existing BF-BOF production without significant changes to existing equipment. But there are also a range of innovative technologies – including top gas recycling and the Hlsarna process – which reduce required coal inputs and increase the percentage of CO₂ in exhaust gases, thus lowering carbon capture costs. These approaches however do entail significant changes to existing plants and are still at pilot plant stage of development. Supported by the ULCOS group research program (discussed in sections 4 and 5), a Hlsarna pilot plant was constructed in 2010 at Tata Steel IJmuiden, hosting 5 experimental campaigns, the last of which started in 2017. This pilot project aims at a 20% decrease in CO₂ emissions and energy use as well as process cost reductions¹⁷.
- **(3) Hydrogen as the reduction agent:** Hydrogen already plays a role as a reduction agent in DRI primary steel production, since the methane gas input is first converted to syngas – which is a mix of H₂ and CO – and that syngas then acts as the reduction agent. Existing DRI facilities could therefore be gradually converted to pure hydrogen rather than methane/syngas and the German steel producer Salzgitter has set out a proposed pathway which would achieve 80% emissions reductions by 2050 [Exhibit 10]. In parallel, steel companies could replace existing BF-BOF plant with newly built hydrogen-based DRI. Swedish steel maker SSAB, in association with power company Vattenfall and iron ore producer LKAB, has developed a project (HYBRIT) to achieve this by the early 2040s [Exhibit 11].
- **(4) Electrolysis.** Finally, it is in theory possible to reduce iron ore via direct electrolysis (the technology already extensively used in aluminium production). Processes being researched include ones where iron ore is dissolved in a mixture of calcium oxide, aluminium oxide and magnesium oxide at temperatures of around 1600°C, and an electric current then passed through. This technology however is still at the laboratory research phase.

In addition, to these full decarbonization options, there may be options to significantly reduce carbon emissions from the existing BF-BOF fleet by **partially replacing coking coal with hydrogen even within blast furnaces**. This would produce only partial decarbonization, and would have to be accompanied by CCS to achieve complete decarbonization, but could be a useful transitional option for existing plants, especially in emerging economies. Nippon Steel is currently working on developing this technology¹⁸.

¹⁷ Tata Steel, 2017, *Hlsarna: game changer in the steel industry*

¹⁸ Patent application from Nippon Steel, 2016, *Method for operation of blast furnace*

Exhibit 12 summarizes the technology readiness of different decarbonization routes with charcoal based production already in use, CCS and hydrogen reduction now entering pilot stage, while electrolysis is at the basic research stage.

Exhibit 10 – Hydrogen based decarbonisation: “SALCOS” – Salzgitter low CO₂ steelmaking

Technical transition

- Gradual shift from BF-BOF to “Direct reduction process”(DRP) by ~2050
- Initially with natural gas input and in-situ reforming to CO + 3H₂
- Gradually increasing percentage of hydrogen input produced from electrolysis
- Application to all of European steel-making requires 260 TWh of additional renewable electricity

Emissions reduction

- Current production 4.6 million tonnes of steel, with ~8 million tonnes CO₂ emissions
- Target reduction
 - 18-26% in 2020s
 - 50% by 2040s
 - 82% by ~2050

Technical challenges

- Migration from existing integrated and energy optimised facility
- DRP with increased hydrogen input
- Hydrogen storage

SOURCE: Presentation by Dr Volker Hille, October 2017


Exhibit 11 – Hydrogen-based decarbonization: HYBRIT fossil-free steel

Objective

- Fossil-free steel production by early 2040s
- Switch to electric melting between 2025 and 2040
- Replacing coking plant and blast furnace with hydrogen electrolysis and direct reduction
- Electricity from renewables (primarily wind)
- Hydrogen storage in lined rock cavern

Key parameters

- ~4 tonnes of steel production currently emitting ~6 million tonnes of CO₂ (1.6 Gt CO₂ per tonne of steel)
- Additional electricity requirement: 15 TWh
- Electricity cost ~€35 per MWh
- Increased production cost of 20-30%: from \$400 per tonne to \$480-520 per tonne
- Construction started in 2018



Cost per tonne of CO₂ saved: ~\$50-75

... competitive with GCCSI estimate of NOAK CCS costs

SOURCE: Vattenfall website, Energy Transitions Commission, based on expert interviews

Exhibit 12 – Technological maturity of decarbonization options

Conventional option	Applied at industrial-scale sites	Technology to be applied in pilot sites	Research phase
<ul style="list-style-type: none"> • BF-BOF with coal as fuel and feedstock • DRI-EAF with natural gas as feedstock • Mixed options (e.g. liquid iron in EAF or DRI in BF or BOF) 	<ul style="list-style-type: none"> • BF-BOF with charcoal as fuel and feedstock (small furnaces) • DRI-EAF with biogas as feedstock 	<ul style="list-style-type: none"> • DRI-EAF with hydrogen as feedstock • Conventional BF-BOF with CCS on all exhaust gases • Hlsarna-BOF and CCS on all exhaust gases • BF-BOF with top-gas recycling, coke oven gas rerouting, and CCS on all exhaust gases 	<ul style="list-style-type: none"> • BF-BOF with hydrogen as feedstock • Electrolysis for iron ore reduction

C.DECARBONIZATION OPTIONS: COST TRADE-OFFS AND OVERALL ECONOMIC IMPACT

Since biomass in the form of charcoal is unlikely to be a feasible route on a large scale except in specific locations with large biomass resources, **the key drivers of the optimal path to deep decarbonization will be:**

- (i) The costs of capturing carbon from BF-BOF furnaces,
- (ii) The local feasibility, political acceptability and cost of carbon transportation and storage,
- (iii) The cost of renewable electricity to produce hydrogen via electrolysis.

Estimates from the Global Carbon Capture and Storage Initiative (GCCSI) suggest that **current costs for capturing CO₂ from steel furnaces could be around \$65-70 per tonne of CO₂¹⁹**, potentially falling to around \$55 in future (see the forthcoming ETC consultation paper on *Carbon capture in a zero-carbon economy* for discussion of why and how carbon capture costs vary by different industrial sectors).

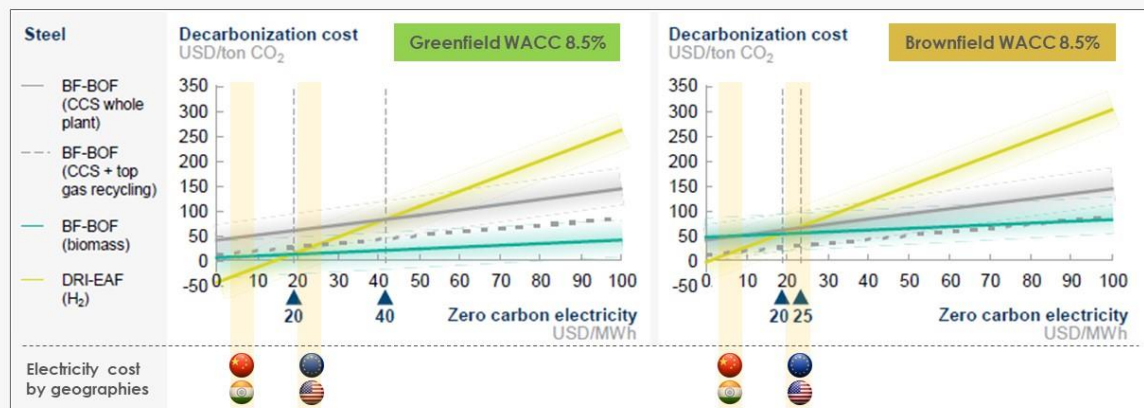
McKinsey analysis [Exhibit 13] suggests that, if the total cost of carbon capture and storage varies from around \$50 to \$100 per tonne of CO₂ as the electricity price increases, **electricity prices would have to be below \$40/MWh before hydrogen reduction became more economic than the carbon capture for greenfield plants (\$20/MWh for plants using biomass)**. For brownfields plants, this breakeven point between hydrogen reduction and carbon capture with BF-BOF goes down to \$25/MWh (\$20/MWh for plants using biomass).

¹⁹ Global CCS Institute, 2017, *Global costs of Carbon Capture and Storage*

The SSAB Hybrit project, however, assumes that an economic path to hydrogen-based steel production is foreseeable, if the electricity price is around current Swedish wholesale rates (e.g. \$41 per MWh) with a carbon price of \$50-\$75 per tonne²⁰. The Salzgitter Salcos project also assumes that the hydrogen route would be preferred in the German situation, even though electricity prices there are likely to stay considerably higher than \$20/MWh, in part because Salzgitter assumes that CCS is not politically feasible in Germany²¹.

Exhibit 13 – The most likely routes for decarbonizing virgin steel are CCS and hydrogen-based DRI, although biomass use in blast furnaces might be a cheaper option in some geographies

Cost comparison of different steel production decarbonization technologies depending on price of zero-carbon electricity



SOURCE: McKinsey & company, 2018, Decarbonization of industrial sectors: the next frontier

The way forward will therefore most likely vary by location, in line with (significant) differences in the price of renewable electricity, and both the technical feasibility and political acceptability of CCS. There are indeed huge differences between regions in the inherent renewable solar and wind resources, and the ETC believes that, **in some parts of the world, renewable electricity will be available at below \$20/MWh** even while prices are significantly higher elsewhere²². There are also major differences in the currently known availability of underground CO₂ storage capacity, either onshore or offshore, making CCS technically feasible in some locations but infeasible in others at any cost. Biomass resources also vary significantly by region²³.

But, whatever the balance of different routes chosen, **the costs to consumers and to the global economy of total steel decarbonization appear to be manageable**. In McKinsey & Company's "Reference case" for electricity prices, the total cost of decarbonizing steel production averages around \$60 per tonne of CO₂, resulting in a cost increase of around \$115 per tonne of steel [Exhibit 14]. This cost impact could fall to around \$25 per tonne of CO₂ and \$50 per tonne of steel if very low renewable electricity prices were generally available²⁴.

²⁰ Hybrit Fossil Free Steel Summary of Findings, 2017

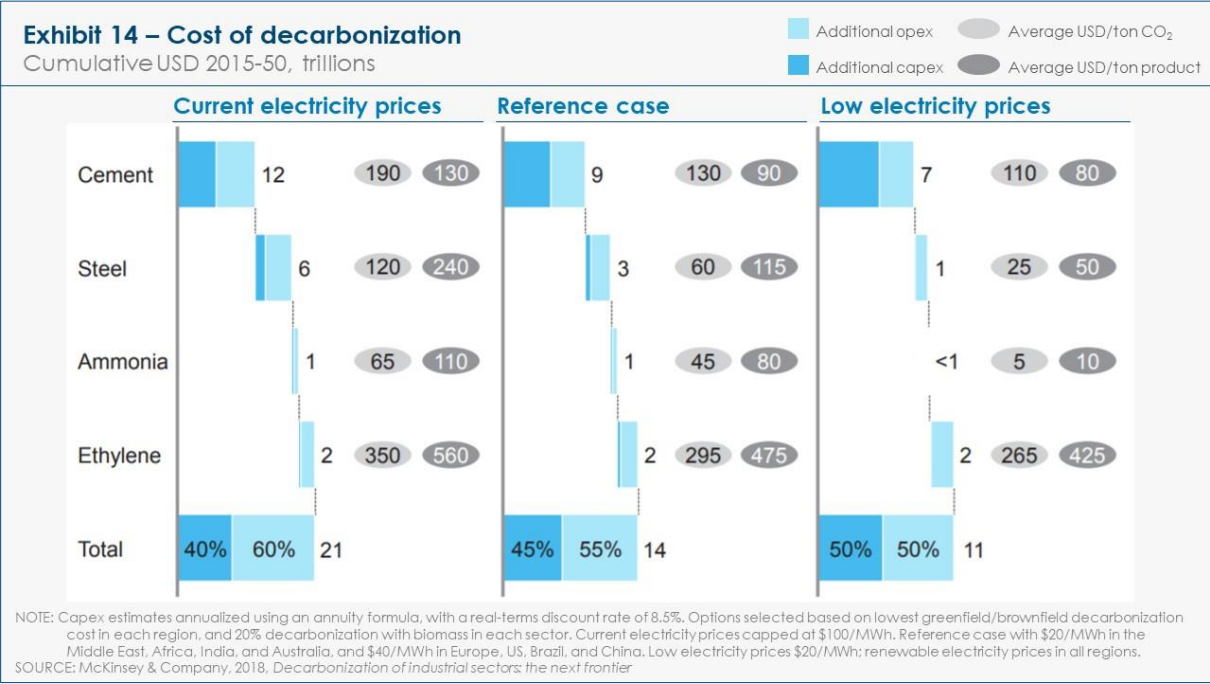
²¹ Salcos, Salzgitter Low CO₂ Steelmaking, Presentation by Dr. Ing Volker Hille, Brussels, 18/10/2017

²² Energy Transitions Commissions, 2017, *Better Energy Greater Prosperity*

²³ See our forthcoming cross-cutting papers on *Electricity and hydrogen in a zero-carbon economy*, *Bio-based products in a zero-carbon economy*, *Carbon capture in a zero-carbon economy* which will consider the issue of geographical variations in resource relevant to each of these options.

²⁴ McKinsey & Company, 2018, *Decarbonization of industrial sectors: the next frontier*

The “Reference case” would in turn imply that a typical automobile weighing 1 tonne be just \$150 more expensive if made from zero-carbon “green steel” – an increase of less than 1% in the price paid by the consumer. McKinsey estimate that the total cost to the global economy of decarbonizing steel would be a cumulative \$3 trillion over 30 years – i.e. about \$100 billion per annum and less than 0.1% of global GDP.



The key challenge in steel decarbonization is therefore not cost to the global economy, nor the implications for end consumer prices, but **how to deal with the industrial competitiveness problem** at the commodity price level. The implications for end consumers are minor, but, if steel producers in one country face carbon prices of \$60 per tonne and thus a production cost penalty of \$115 per tonne of steel, they may be undercut if producers in other countries do not face a similar carbon price. The implications of this for appropriate policy are considered in Sections 4 and 5.

4. EMERGING CONCLUSIONS AND EXISTING INITIATIVES

A. EMERGING CONCLUSIONS AND POLICY IMPLICATIONS

The analysis above leads us to the following emerging conclusions and policy implications:

- There is **very significant potential to reduce total steel demand and to shift the balance from primary to secondary (recycled) production** via increased recycling and improved efficiency of materials use. It is essential to grasp these opportunities to reduce the economic cost of supply-side decarbonization and to accelerate emissions reductions. Public policy for steel decarbonization should include focus on how to overcome the barriers to recycling and more efficient steel use, in particular in the automotive and construction sectors.
- There are **a number of technically feasible routes to achieve near-total decarbonization of primary steel production** over a 30-year period at only moderate average cost per tonne of CO₂ saved (e.g. \$60). Targets for steel decarbonization should therefore aim for very significant reductions in emissions reductions – e.g. 80% or 90% – by mid-century.
- **The impact of steel decarbonization on end consumer prices will be very modest and the cost to the overall economy clearly manageable.** But the fact that decarbonization may significantly increase steel prices (e.g. by \$100 per tonne or more) creates a potential competitiveness problem on a global commodity trade scale. This could be overcome by either:
 - Imposition of a **carbon price** agreed and applied on a globally coordinated basis – or at least between major producing regions;
 - The use of **downstream policy levers**, e.g. requirements for an increasing percentage of steel used to manufacture automobiles in any given country or region (for instance Europe) to come from zero-carbon production.
- **The optimal decarbonization route will differ by location** in the light of electricity prices and the feasibility and costs of carbon transportation and storage, and the overall balance cannot be and does not need to be predicted. But given that the two main routes will almost certainly be CCS and hydrogen-based reduction, public policy and industry investment should focus on driving down the cost and developing the infrastructure required for the deployment of these two solutions (as described in more details in Section 5).

B. EXISTING POLICY AND INDUSTRY INITIATIVES

A number of Government and industry initiatives have been launched to reduce steel emissions, but what appears to be lacking is an agreed way forward to the radical long-term reductions which our analysis suggests can be achieved at a modest cost.

- **In China**, government policy is for now focused on the elimination of the oldest most polluting plants and on reducing sulphur dioxide and nitrogen oxide emissions in order to cut particulate pollution, rather than on CO₂ emissions per se²⁵. Given the major contribution of China to total emissions (as China accounts for half of the world steel production, and produces 90% of its steel in blast oxygen furnaces), a clear strategy to decarbonize Chinese steel production is essential.
- **In Europe**, the ULCOS (Ultra-Low CO₂ Steelmaking) partnership of 48 companies and organizations from 15 European countries has set a target to reduce CO₂ emissions per tonne of steel produced by at least 50% by 2050. But the 50% target does not reflect the relatively low-cost potential for far more dramatic emissions reductions.

In parallel, **Responsible Steel** is currently developing a social and environmental sustainability standard for primary and secondary steel production, in partnership with both steel producers and steel users, which will include a minimum threshold as well as more ambitious targets for greenhouse gas emissions from steel production.

Public policy and industry investments indeed need to be designed to achieve more significant reductions over the next 30 years and aim for zero-carbon emissions shortly after 2050.

²⁵ Reuters, 2018, *China to cut more coal, steel output to defend "blue skies"*

5. RECOMMENDATIONS

Given the analysis above, achieving a low- and eventually zero-carbon steel sector will require action by governments and by industry, with public-private partnerships required specifically in R&D and key infrastructure developments.

RESEARCH, DEVELOPMENT AND INVESTMENT PROJECTS

Given that the two main routes for primary steel production decarbonization will almost certainly be **CCS and hydrogen-based reduction**, public and private R&D spending, as well as investment in pilot plants, should focus on:

- Driving down the cost and increasing the efficiency of electrolysis equipment (the implications of this are discussed in the forthcoming ETC Consultation Paper on *Electricity and hydrogen in a zero-carbon economy*);
- Piloting and driving down the cost of hydrogen-based reduction;
- Ensuring the feasibility and driving down the cost of innovative BF-BOF designs which would reduce CCS costs;
- Helping to increase the feasibility and reduce the cost of CCS – in those locations where storage capacity is available and where higher electricity prices are likely to make the hydrogen route a more expensive option.

Additional R&D priorities would also include:

- Driving down the cost of energy efficiency and carbon efficiency technologies that can drive down carbon emissions from existing plants;
- Developing iron electrolysis as a potentially lower-cost solution in the very long term;
- Developing innovations that enable higher-quality and higher-value recycling of steel (including potentially making recycled steel with higher levels of copper contamination usable in a broader set of applications than it currently is).

The primary role in R&D and investment will be played by individual companies, but there is also **a potential important role for governments in:**

- Supporting specific pilot projects designed to achieve early decarbonization of a country's steel industry;
- Supporting early-stage R&D in technologies which are currently further away from commercial readiness – such as electro-chemical approaches to iron ore reduction;
- Supporting the development of shared CO₂ transportation networks which may be required to make CCS a feasible solution in those locations where it is likely to be significantly cost advantaged.

PUBLIC POLICY

In addition to **RD&D support**, Governments must set up a favourable policy framework to encourage private sector action, combining **push levers**, such as carbon pricing and regulations on steel production, with **pull levers**, such as public procurement and regulations on industry sectors that use steel, in particular the automotive, buildings and infrastructure sectors.

Explicit or implicit carbon pricing: Effective carbon pricing must play a crucial role in driving both decarbonization of primary steel production, and increased recycling and reuse of steel. If steel producers and users faced a carbon price of roughly \$50-\$70 per tonne by 2030, major changes would be unleashed in both the steel production and steel-using industries. The challenge is to introduce effective carbon prices while not causing excessive competitiveness and relocation effects on a global scale. Governments should therefore ideally deploy some mix of the following policies:

- Seeking international agreement – between all countries or a subset of countries – to impose a common carbon price on steel;
- Unilaterally imposing more modest carbon prices sufficient to provide significant incentives to action, but low enough to minimize competitiveness and relocation effects;
- Imposing product regulations which require major steel users (e.g. in the automotive industry) to use a rising percentage of low/zero-carbon steel, thus effectively imposing a carbon tax on steel use within an economy irrespective of the location of production;
- Accordingly, developing a standard for low/zero-carbon steel on which to base end-product regulations, which could build on existing industry initiatives like the Responsible Steel standard currently being developed.

Regulation to drive increased recycling and reuse: Governments should develop strategies explicitly focused on the need for increased recycling and reuse, and for improved material efficiency. Specific regulatory policies which might achieve this could include:

- Building codes which require improved efficiency in the use of steel and other materials;
- Regulations on building demolition which require rigorous separation of different materials;
- Increased landfill taxes to discourage unseparated landfill;
- Producer responsibility regulations which increase incentives for product design compatible with complete recycling.

Public procurement: Governments should use public procurement to create initial demand for lower-carbon steel, for instance by requiring a rising percent of low/zero-carbon steel to be used in all publicly-funded construction, and by setting clear targets for this increase over the long run, thus creating long-term incentives for both demand- and supply-side action.

In addition, given the probable role of electric arc furnaces (either for DRI-based primary production or for secondary production), hydrogen-based reduction and potentially, in the longer term, electricity-based reduction, it is essential that Governments continue driving down the cost of renewable electricity to **reduce the carbon intensity of electricity** and therefore of both recycled steel and primary steel produced by DRI.

These public policies are relevant to governments across the world. But some **country-specific priorities** can also be defined:

- In the European Union, further **tightening of the EU emissions trading scheme (EU-ETS)** is a priority, but the EU Commission should also assess the case for underpinning the fluctuating EU-ETS price with a minimum carbon tax, creating greater certainty about the future price trajectory.
- **In China, it is vital to develop the regulations and other policies which will drive increased recycling and reuse** in a country now approaching developed country steel stocks per capita, and vital also to ensure that **Belt and Road Initiative investments** support the decarbonization of the steel industry, through direct support to the steel industry and/or demand for green steel infrastructure projects.

INDUSTRY ACTION: ROLE OF STEEL PRODUCERS AND CONSUMERS

Steel producers will respond, via research, development and investment, to the incentives set by public policy, but should in addition play a leadership role by supporting the design and implementation of **“green steel” standards**, which would best be positioned as part of the broader sustainability standard currently being developed by Responsible Steel.

- Such a standard would establish clear targets – both individually and collectively across the industry – for the steady reduction in carbon intensity per tonne of steel.
- It would also make it possible for steel consumers to track and demonstrate the carbon intensity of steel supplied – and therefore endeavor to get a premium price at consumer level for produced based on green steel, which could then be passed on to green steel producers. Such a label could also play in favor of steel in the eyes of consumer industries when considered in competition with potential substitute materials like aluminium.

Accordingly, **steel users, in particular in the automotive and construction sectors**, could play a major role in driving decarbonization by buying decreasingly carbon-intensive steel, and could potentially use tightly monitored commitments to “green steel purchase” in their marketing of end products. This is particularly true in the short term for the automotive industry, because the additional cost of green steel compared to carbon-intensive steel would only marginally impact the cost of a car and because consumer good purchase may be more receptive to green marketing than the business-to-business market.

Collaboration between steel producers and steel users would therefore be key to creating an initial market for green steel. Similarly, it would play a major role in the development of a more circular approach to steel consumption, addressing the barriers to higher recycling rates – in product design and material separation – discussed in Section 2.

Finally, the steel industry also has an interest in **actively proposing and supporting international agreement on significant carbon prices (either across all countries or subsets of countries)**, in order not to face the competitiveness risks of more unilateral policy measures.

The Energy Transitions Commission welcomes feedback on this consultation paper until 31st August 2018 at pmo@energy-transitions.org. We are particularly interested in feedback on the feasibility and cost of different decarbonization options, and on the recommendations to policymakers, industries, businesses and investors. This feedback will be integrated in the ETC's final report to be published in November 2018.

For more information, please visit www.energy-transitions.org or contact pmo@energy-transitions.org.