MISSION POSSIBLE

REACHING NET-ZERO CARBON EMISSIONS FROM HARDER-TO-ABATE SECTORS BY MID-CENTURY

ENERGY TRANSITIONS COMMISSION

SECTORAL FOCUS

STEEL

The **Energy Transitions Commission (ETC)** brings together a diverse group of leaders from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics from the developed and developing world. Our aim is to accelerate change towards low-carbon energy systems that enable robust economic development and limit the rise in global temperature to well below 2˚C and as close as possible to 1.5˚C.

In November 2018, the ETC published ***Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century***. This flagship report is available on our website. This report describes in turn:

- Why reaching net-zero CO_2 emissions across heavy industry and heavy-duty transport sectors is technically and economically feasible;
- How to manage the transition to net-zero CO_2 emissions in those harder-to-abate sectors of the economy;
- What the implications of a full decarbonization of the economy are for the energy system as a whole, in particular in terms of demand for electricity, hydrogen, bioenergy/bio-feedstock, and fossil fuels, as well as carbon storage requirements;
- What policymakers, investors, businesses and consumers must do to accelerate change.

This Sectoral Focus presents in more details the underlying analysis on steel decarbonization that fed into the ETC's integrated report *Mission Possible*. It constitutes an updated version of the consultation paper with the same title published by the ETC in July 2018.

We warmly thank all experts from companies, industry initiatives, international organizations, non-governmental organizations and academia, who have provided feedback on this consultation paper. Their insights were instrumental in shaping the *Mission Possible* report and this updated Sectoral Focus.

The *Mission Possible* report and the related Sectoral Focuses constitute **a collective view of the Energy Transitions Commission**. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report. The list of our Commissioners at the time of publication can be found in the *Mission Possible* report.

In 2019, the Energy Transitions Commission will continue to engage actively and work with key policymakers, investors and business leaders around the world, using our analysis and the unique voice of the ETC to inform decision-making and encourage rapid progress on the decarbonization of the harder-to-abate sectors. We are keen to exchange and partner with those organizations who would like to progress this agenda. Please contact us at info@energy-transitions.org.

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REACHING NET-ZERO CARBON EMISSIONS FROM STEEL

Energy-related emissions from the iron and steel industry currently amount to circa 2.3Gt CO_2, accounting for 7% of total global emissions from the energy system. However, under a business-as-usual scenario, they would grow to 3.3Gt by 2050, representing 7.5% of global emissions and 34% of the industry sector emissions[1].

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 scrap-based (recycled) steel**, which is less carbon-intensive than ore-based (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 the necessary emissions reductions without developing and deploying **zero-carbon ore-based production routes**, through radical process changes. The **two main routes to decarbonization will certainly be hydrogen-based reduction and carbon capture**, combined with either storage or use (CCS/U), but the optimal decarbonization pathway will differ by location depending on local 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 a limited cost to the overall economy. However, given that steel is an internationally-traded commodity, 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 the risks of competition distortion.

SUPPORTING ANALYSIS AND REPORTS

The Energy Transitions Commission work on steel has drawn extensively on the existing literature (cited throughout this document), and more particularly 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) and a follow-up analysis replicating this work at a global scale (commissioned by the ETC);
- A report by **McKinsey & Company** on supply-side decarbonization options across several industrial sectors – *Decarbonisation of the industrial sectors: the next frontier* (2018).

[1] IEA (2017), *Energy Technology Perspectives*

HOW TO REACH NET-ZERO CO_2 EMISSIONS FROM STEEL

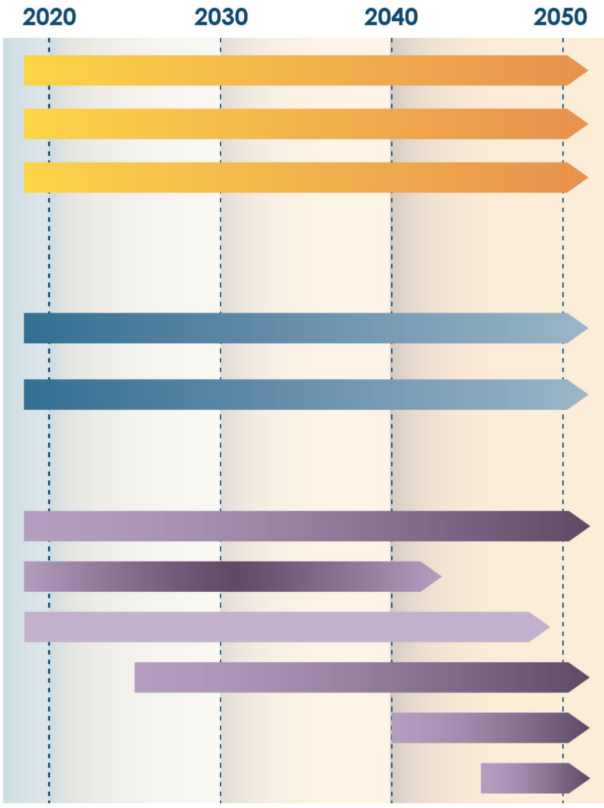
7% OF TOTAL GLOBAL EMISSIONS

TODAY	2050 BAU
2.3 $GtCO_2$	3.3 $GtCO_2$

REACHING NET-ZERO CO_2 EMISSIONS FROM STEEL IS POSSIBLE BY COMBINING 3 MAJOR DECARBONIZATION ROUTES:

		MAXIMUM CO_2 EMISSIONS REDUCTION POTENTIAL
1 DEMAND MANAGEMENT	Greater and better scrap recycling Redesigning products for materials efficiency and circularity More intensive use of steel-based products (e.g, sharing)	-38%
2 ENERGY EFFICIENCY	Use high-pressure gas leaving the furnace to power other equipment Coke dry quenching	-15/20%
3 DECARBONIZATION TECHNOLOGIES	Scrap-based EAF	-100%
	Gas-based DRI (transition fuel)	-50%
	Charcoal in BF/BOF (localized)	-100%
	Carbon capture	-90%
	Hydrogen-based DRI	-100%
	Electrolysis of iron	-100%

TECHNOLOGY APPLICABILITY / AVAILIBILITY OVER TIME



MAXIMUM DECARBONIZATION COST

COST PER TONNE OF CO_2	B2B COST	COST TO END CONSUMER
CO_2 +$25/60	+$120 +20% PER TONNE OF STEEL	+$180 +1% ON A CAR

TOP 3 ACTIONS TO ACCELERATE THE TRANSITION FOR...

INNOVATION

- Develop and pilot hydrogen-based DRI
- Develop and pilot new technologies to reduce cost of carbon capture on BF-BOF
- Develop metallurgy to enable higher-quality and higher-value recycling of steel

POLICY

- Coalition of governments: agree on a carbon tax on steel production reaching $50-70 by 2030
- Create and progressively tighten regulations on the embedded carbon intensity of steel-based produced, like cars
- Commit to 100% "green steel" in all publicly-funded infrastructure and buildings by 2040

INDUSTRY/BUSINESSES

- Steel industry: support "green steel" standards design and implementation
- Automotive industry: take commitments today on "green steel" purchase targets by 2040
- Steel producers and users: initiate collaborative projects between producers and users to increase and improve quality of steel recycling

1. OVERVIEW OF THE CHALLENGE

A. DEMAND TRENDS BY MID-CENTURY

Total global steel production is forecasted to **grow by 30% by 2050**[2]**,** with production following two major trends**:** a shift from ore-based to scrap-based steel and from BF-BOF to Electric Arc Furnace production (EAF), with major differences by country and region [Exhibit 1]. According to the IEA Reference Technology Scenario, this growth will result in a **total global steel demand increase from 1.6Gt per annum in 2015 to 2.2Gt by 2050**[3]**, but with ore-based production flat** as reduction of primary production in China offsets increases elsewhere in developing economies.

Demand for ore-based steel is driven by the accumulation of steel stocks – in particular, in buildings, infrastructure and transport vehicles – which deliver consumer benefits, and on the lifetime of these stocks. **Developed countries typically have stocks of around 12 to 13 tonnes per capita**[4] 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 capita**[5], and are therefore likely to grow for many decades, creating significant ore-based 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 ore-based steel will fall significantly.

Today, **about 95% of ore-based steel is produced in blast furnaces (BF-BOF),** which use coking coal as both the reduction agent and the source of heat energy[6]. 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 H_2) achieves the reduction process, with this syngas in turn primarily derived from methane gas (though with some coal-based DRI in India). By contrast, **scrap-based steel recycling typically occurs in electric arc furnaces (EAF).** In their Reference Technology Scenario, the IEA forecasts a 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)[7].

Current and future projected volumes of steel produced through different routes, globally and by region, therefore depend upon the changing balance of ore-based vs. scrap-based production, and upon the trade-offs between different production routes for ore-based production itself [Exhibit 1]. According to IEA forecasts, between now and 2050, the Chinese steel demand could fall from 800Mt to 550Mt, which, together with a shift from ore-based to scrap-based steel and from BF-BOF to EAF, could see coal-based production fall by 60%[8]. Africa and India, by contrast, are expected to see huge increases in steel production, and in particular, in coal-based ore-based 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 ore-based production because of exports[9].

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[2] IEA (2017), *Energy Technology Perspectives*
[3] IEA (2017), *Energy Technology Perspectives*
[4] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*
[5] Material Economics (2018), *The circular economy: a powerful force for climate mitigation*
[6] IEA (2017), *Energy Technology Perspectives*
[7] IEA (2017), *Energy Technology Perspectives*
[8] IEA (2017), *Energy Technology Perspectives*
[9] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

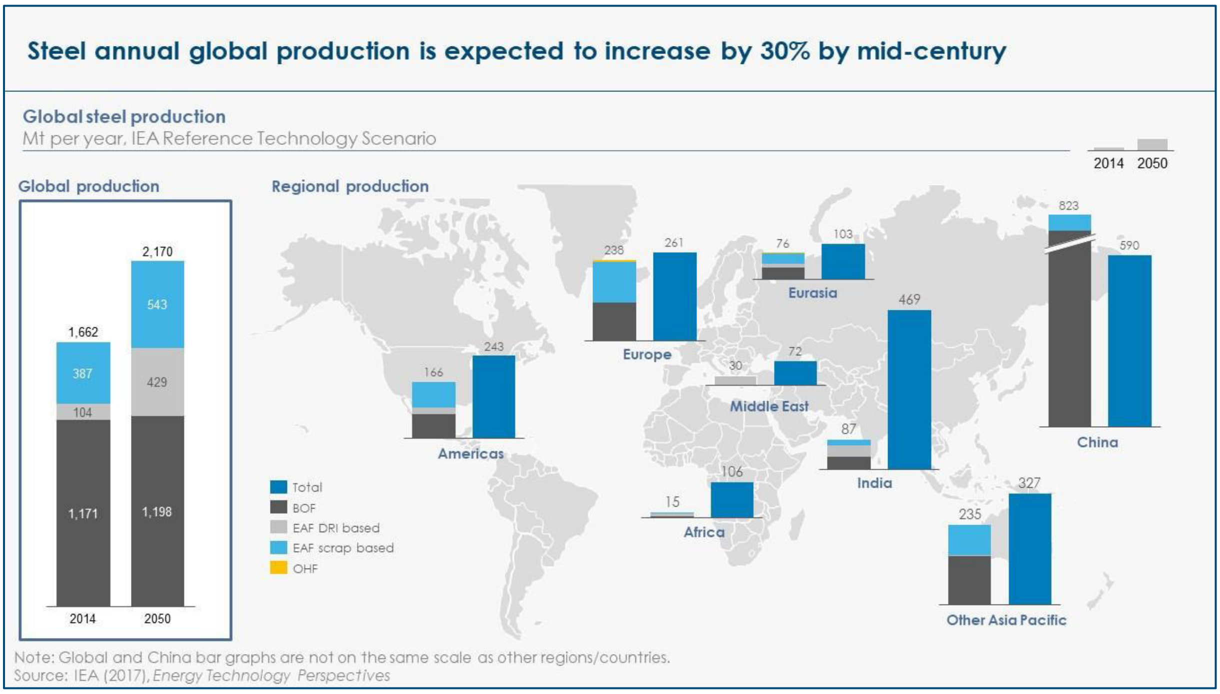


Exhibit 1

B. CARBON EMISSIONS

Global carbon emissions from iron and steel production are **currently around 2.3Gt per annum**, about 7% of global energy system emissions. Business-as-usual scenarios suggest that this **could rise to 3.3Gt per annum by 2050**[10] [Exhibit 2], with the growth in global steel demand driven by developing regions, where the adoption of low-carbon technologies is likely to be slower than in other regions.

The carbon emissions trajectory from the steel industry **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 CO_2 per tonne of steel produced, DRI with gas as the input produces about 1.1 tonnes, while the EAF process (based on scrap or direct reduced iron) produces about 0.4 tonnes, and less still if the electricity used comes from zero-carbon sources[11] [Exhibit 3].

Given these different levels of carbon intensity, a significant reduction in the direct CO_2 footprint of crude steelmaking could take place due to an extensive migration in the industry from BF-BOF to EAF technologies. In their well below 2°C and 2°C scenarios, the IEA forecasts carbon intensity levels as low as 0.12 and 0.55 tonnes direct CO_2 per tonne of crude steel by 2050, respectively a 60% and 92% reduction from current levels[12], allowing sharp emissions reduction (47% and 91%) even while total steel demand grows (by 35% and 7%)[13].

However, if the world is to have any chance of meeting the Paris climate objective of keeping global temperature rise well below 2°C and as close as possible to 1.5°C, total emissions from global energy use across all economic sectors, including iron and steel, must reach net-zero by mid-century. It is therefore essential to develop a more ambitious strategy

[10] IEA (2016), *Energy Technology Perspectives*
[11] Material Economics (2018), *The Circular Economy, a powerful force for climate mitigation*
[12] Carbon intensity in 2050 in the IEA's beyond 2°C scenario IEA (2017), Energy Technology Perspectives
[13] IEA (2017), Energy Technology Perspectives

to not only reduce, but actually reach net-zero emissions from steel production by mid-century.

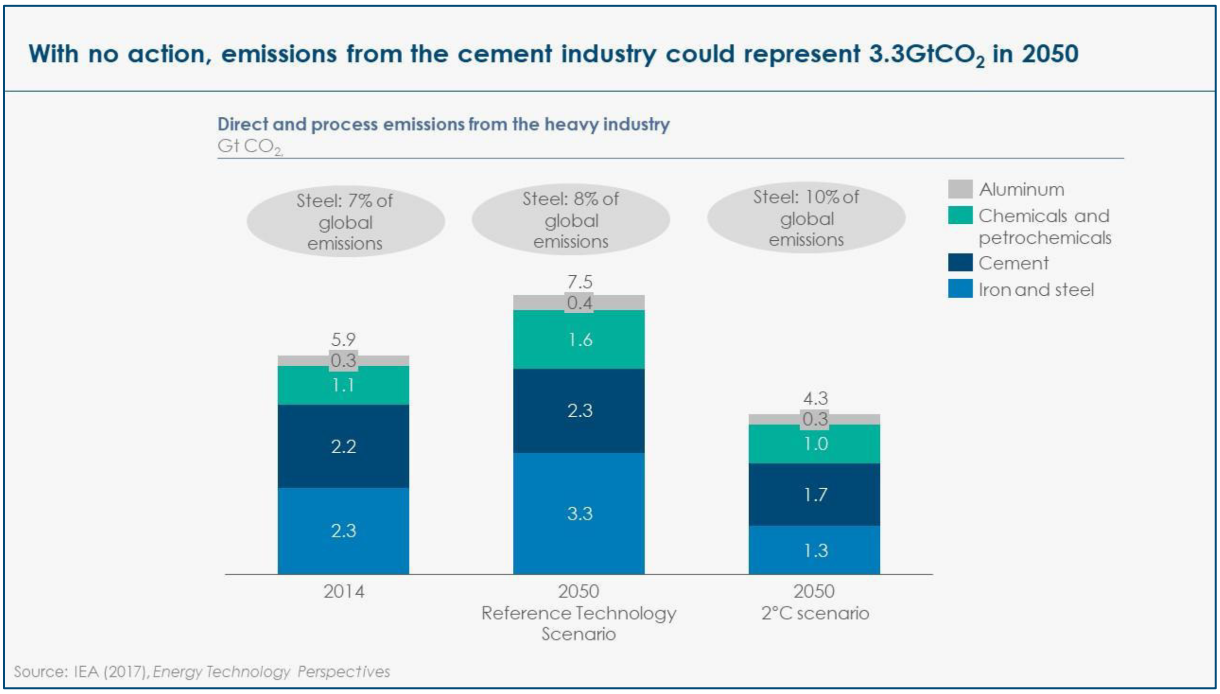


Exhibit 2

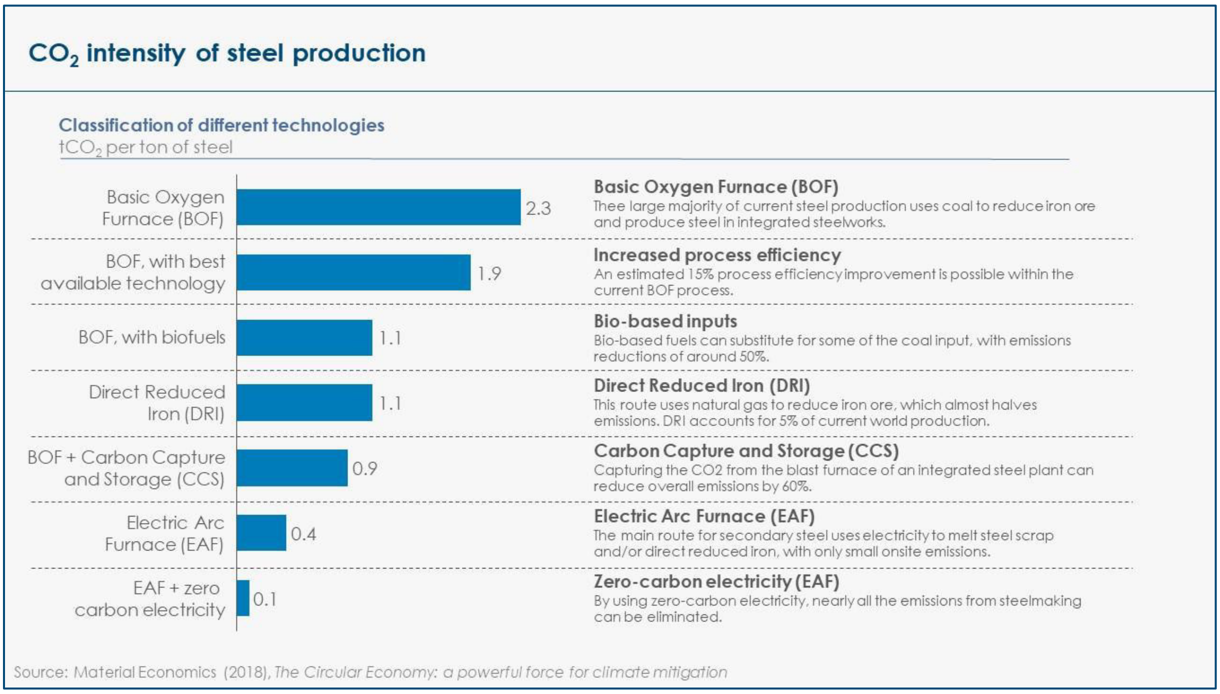


Exhibit 3

2. REDUCING CARBON EMISSIONS THROUGH CIRCULARITY

As Section 4 will discuss, while decarbonization of ore-based steel production is undoubtedly technically possible, it may entail significant investment and time, since some of the technologies required are not yet fully developed and the lifecycle of existing industrial assets may slow down retrofitting. **To reduce the total 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 scrap-based recycled steel and less ore-based primary production.

In the report *The Circular Economy: a powerful force for climate mitigation* (2018), our knowledge partner Material Economics assesses the potential to reduce the demand for all major industrial materials in Europe. Commissioned by the ETC, they then replicated this work at a global level. In total, they estimate that **global annual carbon emissions from steel production could be reduced by 37% relative to business as usual by 2050 (and 52% by 2100)** if changed industry practices and policies maximized:

- Opportunities for greater recycling of steel, with a greater share of total demand met by scrap-based rather than ore-based production;
- Opportunities for delivering the same standard of living with a lower stock of steel per capita, thus cutting total annual demand for both ore-based and scrap-based steel.

A. REDUCING ORE-BASED 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 scrap-based 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.

- In principle, if all countries eventually reached a stable level of stocks (at the OECD level of 13 tonnes per capita) and if all steel was recycled at end-of-life, then **eventually 100% of all steel could 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 could 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 scrap availability in proportion of steel demand will increase from around 22% today to around 40% by 2050** (up to 80% in Europe)[14]. This could result in important reductions in ore-based production.

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

[14] Material Economics analysis for the Energy Transitions Commission (2018) and Material Economics, (2018), *The Circular Economy: a powerful force for climate mitigation*

globally amount to 150Mt of steel annually today, with ore-based production therefore unnecessarily increased by that amount.

- **The "downcycling" problem:** Recycled steel is typically lower-quality and lower-value than the steel from which it originally came, which significantly limits the variety of applications for which scrap-based steel can be used. Much recycled steel, for instance, ends life as rebar for construction purposes. This downcycling is made unavoidable because of "tramp elements" in the recycled steel. While this is not a barrier to recycling if there is sufficient demand for the more basic steel categories, it would become an important barrier to achieving 100% recycling.
- **The copper contamination problem:** In particular, 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 ore-based steel to lower copper content of the recycled material.

If these problems could be overcome, ore-based production could be very significantly reduced. Material Economics' scenario estimates that **ore-based production could be 21% lower in 2050 compared with baseline levels if a stretching but credible increase in recycling was achieved** (increase of scrap-based production from 36% in a current practice scenario to 48% of total production in a materials circulation scenario).

This shift from ore-based production to scrap-based would in turn produce a **large cut in emissions**, given the very different carbon intensities of scrap-based versus ore-based production illustrated in Exhibit 3. Material Economics estimates that, with the adoption of known best available technology, the average CO_2 intensity of ore-based steel production could amount to 1.94tCO_2/t, and the CO_2 intensity of scrap-based production to 0.08tCO_2/t. Therefore, any shift from ore-based to scrap-based production would represent a 95% reduction in emissions on the corresponding production volume.

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

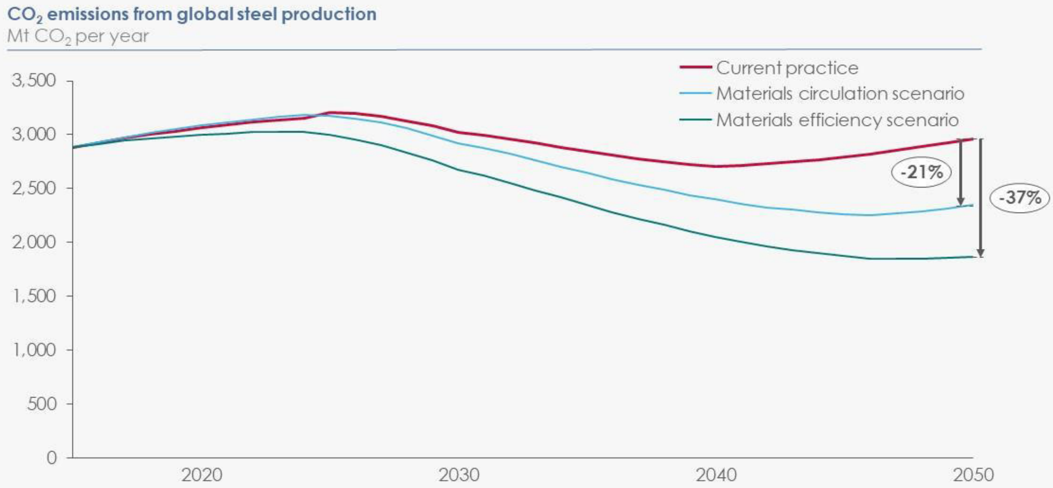
- Improved systems for collection of end-of-life materials, including more careful separation of iron and steel when buildings are demolished;
- Reduced new scrap creation by better product design, potentially enabled by 3D printing and powder metallurgy;
- Reduced remelting losses, which may be made 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.

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**.

The Material Economics analysis suggests that, relative to a business-as-usual trajectory, **total emissions from steel production could be cut by 21% in a “materials circulation” scenario** (i.e. maximizing recycling opportunities described above) and **by 37% in a “material efficiency” scenario** (i.e. maximizing recycling opportunities and reducing steel demand across multiple sectors of the economy) by 2050 [Exhibit 4]. This trajectory would result in a 38% reduction of ore-based steel production by 2050 compared to a current practice scenario [Exhibit 5].

Materials efficiency can reduce emissions from steel production by 37% by mid-century

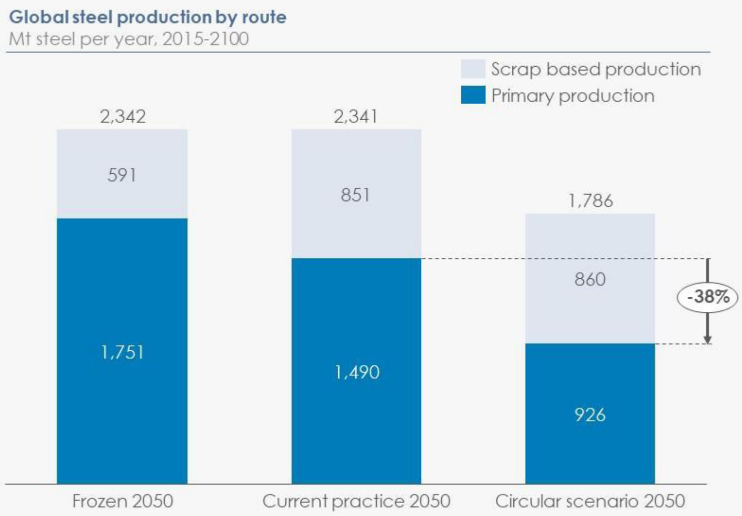


Note: Current practice scenario: increase in steel stock per capita, adoption of best available technology by 2050, increase of scrap based production; Materials circulation scenario: reduced steel losses and reduced downgrading of steel; Materials efficiency scenario: besides materials circulation, the circular scenario also builds on demand reduction from value chains, resulting in reduced steel per capita by 25%

Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 4

A circular scenario can reduce significantly primary steel production globally



Source: Material Economics analysis for the Energy Transitions Commission (2018)

Exhibit 5

AUTOMOTIVE SECTOR: IMPACT OF A SHARED MOBILITY SYSTEM

Today 77% of passenger car emissions arise from the use of the vehicle and 23% from its production[15]. 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 inputs[16].

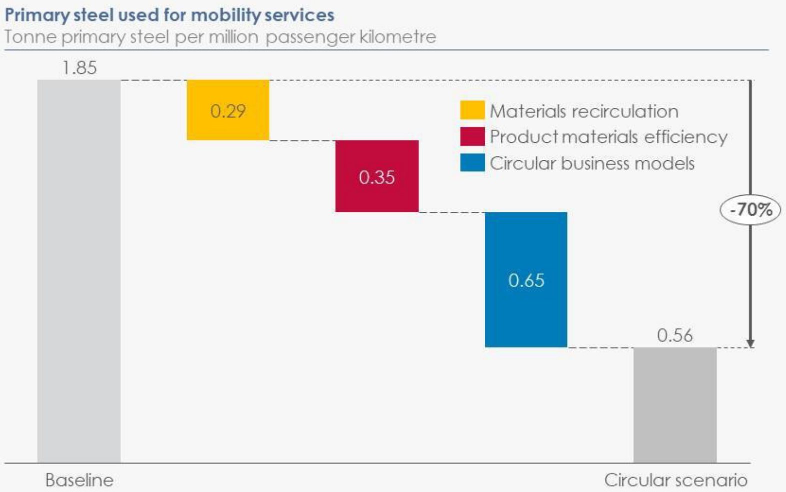
In principle, these emissions related to manufacturing and material inputs could be dramatically reduced through **a shift from individual car ownership to a shared mobility system**. This shift may, in any case, occur as a natural result of the development of electric and autonomous vehicles since (i) 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 shared approach to mobility will have both **direct and indirect effects on materials use**:

- The direct impact would be 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 cars**, since many family cars are currently sized for occasional multiple passenger trips, whereas the space requirement for the average trip is 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, considering the combined opportunities for improved recycling, greater materials efficiency and shared business models, Material Economics estimate that **the volume of ore-based steel required per million passenger kilometers could fall by 70% by 2050** [Exhibit 6].

Global emissions from steel used for mobility services could be reduced by circa 70% by 2050 in a circular scenario



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

Exhibit 6

[15] Material Economics (2018), *The Circular Economy, a powerful force for climate mitigation*
[16] Material Economics (2018), *The Circular Economy, a powerful force for climate mitigation*

BUILDINGS CONSTRUCTION: IMPROVING MATERIALS EFFICIENCY

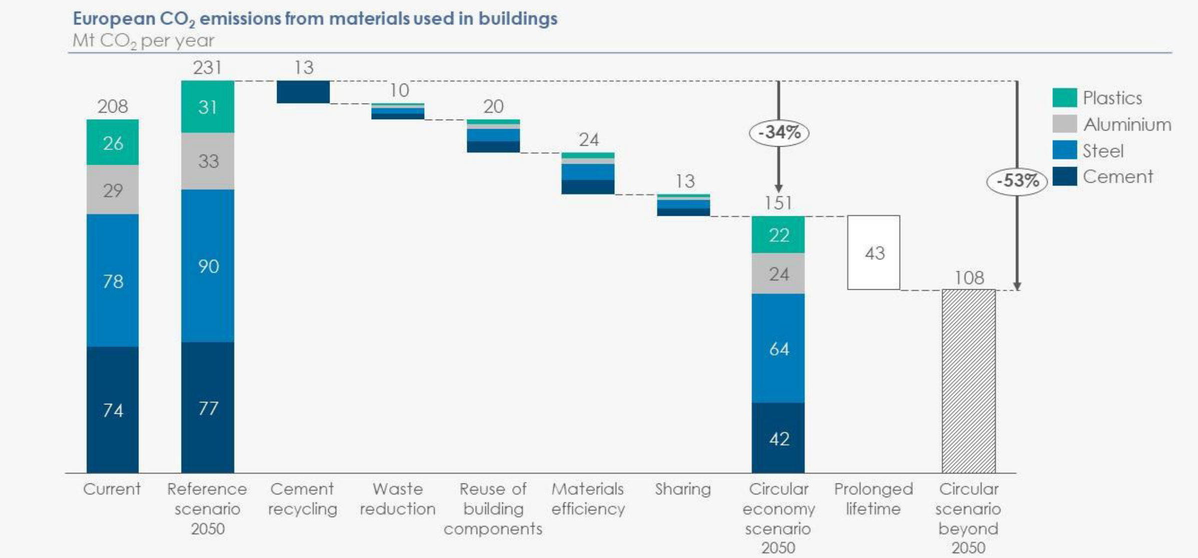
Construction accounts for about 50% of all steel demand, and here too there may be significant opportunities to reduce required steel use while continuing to deliver the end customer service of residential or commercial space.

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 re-melted 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, Material Economics estimate that **emissions from all materials input to the buildings sector (steel, plastics, aluminum and cement) could be reduced by 34% by 2050** if all opportunities for improved construction efficiency could be achieved in Europe and if also taking into account benefits from improved recycling [Exhibit 7]. This potential could be even greater if the lifetime of the buildings was significantly prolonged.

In Europe, CO_2 emissions from materials used in buildings could be reduced by up to 53% due to greater materials efficiency



Source: Material Economics (2018), *The Circular Economy: a powerful force for climate change*

Exhibit 7

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, as they require profound reshuffling in the manufacturing and construction value chains. 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, even if these demand reduction opportunities can be grasped, if production methods remained unchanged, emissions from steel production would remain close to or above 2Gt CO_2 per annum throughout the 21st century[17]. Strategies to decarbonize ore-based steel production are therefore also essential.

[17] Material Economics analysis for the Energy Transitions Commission (2018)

3. IMPROVING ENERGY EFFICIENCY

There is considerable potential to improve energy efficiency of steel production even without fundamental changes in process. Analysis by the OECD 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): It is a heat recovery system in which heat of the red hot coke from a coke oven is recovered and utilized for power generation or as steam used for other purposes. This is not a new technology, it has been used in different facilities since the 1970s, and it is capable to deliver up to 40% energy consumption reduction[18]. As an example, in 2017, Tata Steel, the 10th global largest steel producer, established India's largest Coke Dry Quenching facility, located at their steel plant at Kalinganagar Industrial Complex. It can handle 200 metric tonnes per hour[19].
- **Production gases reuse for power production**: The steel production process emits three types of gases: coke gas, blast furnace gas and furnace gas. All of them can be used to create hot water, steam and electricity. The hot water and gases from the engines can then be fed into boilers, and the steam produced can be used in the steel production process itself. Additionally, it can be used to produce electricity that can either be used on-site or fed to the public grid. These processes can theoretically achieve up to 37% higher energy efficiency in the steel production process[20].

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** on average globally[21]. This potential is limited because retrofit is not always feasible: for example, the reuse of gas leaving furnace to power other equipment is applicable to greenfield sites only. More radical changes in process will therefore be required to achieve deep decarbonization.

Many of these energy efficiency improvements could in principle deliver attractive rates of return, thus creating opportunities to abate CO_2 emissions at negative marginal cost and significantly reducing the average abatement cost in the harder-to-abate industrial sectors. However, they often entail high upfront capital costs that individual industry players cannot always bear, especially in developing economies. It is therefore vital to create strong incentives to grasp these opportunities, and the policies required to drive more radical decarbonization – such as carbon pricing – will also help achieve this lower cost abatement potential. But energy efficiency improvements alone will be inadequate to achieve full decarbonization.

[18] Industrial Efficiency Technology Database website (http://ietd.iipnetwork.org/content/coke-dry-quenching)
[19] The Economic Times (2017), *Tata Steel sets up Coke Dry Quenching facility at Odisha*
[20] Clarke Energy (2018), https://www.clarke-energy.com/steel-production-gas/
[21] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

4. DECARBONIZING ORE-BASED STEEL PRODUCTION

Drawing on the report by McKinsey – *Decarbonisation of the industrial sectors: the next frontier* (2018), as well as additional literature review and inputs from industry experts, our conclusion is that **there is a range of feasible routes to zero-carbon steel production**, 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. **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. DECARBONIZATION OPTIONS: DESCRIPTION & TECHNOLOGY READINESS

Ore-based steel production could be fully decarbonized in 4 ways, which are at different stages of development:

- **(1) Using hydrogen as the reduction agent:** Hydrogen already plays a role as a reduction agent in DRI ore-based steel production, since the methane gas input is first converted to syngas – which is a mix of H_2 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. The German steel producer Salzgitter has set out such a decarbonization pathway, which would achieve 80% emissions reductions by 2050 [Exhibit 8]. 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 9]. After an initial research phase and pre-feasibility study during 2016-2017, the project is now entering the second phase to construct world-first fossil-fuel free steel pilot plant in Sweden, expected to be ready by 2020.
- **(2) Carbon capture and storage/use**: CCS/U could be retrofitted on existing BF-BOF production without significant changes to existing equipment, which could make it easier to deploy. The cost of carbon capture, however, decreases with the purity of the CO_2 stream. There are therefore a range of innovative technologies – including top gas recycling and the HIsarna process – which would reduce required coal inputs and increase the percentage of CO_2 in exhaust gases. These approaches do entail significant changes to existing plants and are still at pilot plant stage of development. Supported by the ULCOS group research program, a HIsarna 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 CO_2 emissions and energy use as well as process cost reductions, and could achieve 80% reduction in its carbon footprint if carbon capture and storage (or use) was added to the pilot[22].
- **(3) Biomass use:** Using charcoal instead of coal as a feedstock for BF-BOF plants is a mature technology, applied for instance in Brazil on a commercial scale. An alternative use of biomass would be to use biogas (methane generated from biomass sources) instead of fossil fuel derived methane, as an input to DRI production, although the availability of biogas may be limited. The total potential of all biomass-related routes across the world is indeed severely limited by supply of sustainable biomass (see Chapter 6 of the ETC's *Mission Possible* report for analysis of issues relating to sustainable biomass resources and prioritization of their use across multiple

[22] Tata Steel (2017), *HIsarna: game changer in the steel industry*

economic sectors). Alternatively, using plastics waste as a reductant in the blast furnace is a practice that has been applied in the past in a number of European steel plants. However, as described in the ETC's Sectoral Focus on plastics[23], reducing emissions of end-of-life plastics should also be a priority, which pleads in favor of plastics recycling and against plastics incineration in industry.

- **(4) Electrolysis.** Finally, it is in theory possible to reduce iron ore via direct electrolysis, which is the technology already extensively used in aluminum production. Processes being researched include ones where iron ore is dissolved in a mixture of calcium oxide, aluminum oxide and magnesium oxide at temperatures of around 1600°C, and an electric current then passed through. For steel, however, this technology is still at basic research phase.

In addition, to these full decarbonization options, there may be options to significantly reduce carbon emissions from the existing BF-BOF fleet in the short to medium term 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 technology[24].

Exhibit 10 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.

Hydrogen based decarbonisation: "SALCOS" – Salzgitter low CO_2 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 + $3H_2$
- 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 CO_2 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 (Oct. 2017)

Exhibit 8

[23] Energy Transitions Commission (2019), *Reaching net-zero carbon emissions from plastics*
[24] Patent application from Nippon Steel (2016), *Method for operation of blast furnace*

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 CO_2 (1.6 Gt CO_2 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 CO_2 saved: ~$50-75

... competitive with GCCSI estimate of NOAK CCS costs

Source: Vattenfall website/ Energy Transitions Commission/ based on expert interviews

Exhibit 9

Technological maturity of decarbonization options

Conventional option

- 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)

Applied at industrial-scale sites

- BF-BOF with charcoal as fuel and feedstock (small furnaces)
- DRI-EAF with biogas as feedstock

Technology to be applied in pilot sites

- DRI-EAF with hydrogen as feedstock
- Conventional BF-BOF with CCS on all exhaust gases
- HIsarna-BOF and CCS on all exhaust gases
- BF-BOF with top-gas recycling, coke oven gas rerouting, and CCS on all exhaust gases

Research phase

- BF-BOF with hydrogen as feedstock
- Electrolysis for iron ore reduction

Exhibit 10

B. DECARBONIZATION OPTIONS: COST TRADE-OFFS

Since biomass is unlikely to be a feasible route on a large scale except in specific locations with large sustainable 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 CO_2 from steel furnaces could be around US$65-US$70 per tonne of CO_2**[25], potentially falling to around US$55 in future (see Chapter 4 of the *Mission Possible* report for discussion of why and how carbon capture costs vary by different industrial sectors[26]).

McKinsey analysis [Exhibit 11] suggests that, as the total cost of carbon capture and storage varies from around US$50 to US$100 per tonne of CO_2 as the electricity price increases, **electricity prices will have to be below US$40/MWh before hydrogen-based DRI become more economic than carbon capture on BF-BOF for greenfield plants.** For brownfields plants, this breakeven point would go down to US$25/MWh (US$20/MWh for plants using biomass).

The HYBRIT project assumes that an economic path to hydrogen-based steel production is foreseeable, if the electricity price is around current Swedish wholesale rates (e.g. US$41/MWh) with a carbon price of US$50-US$75 per tonne of CO_2[27]. 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 US$20/MWh, in part because Salzgitter assumes that CCS is not politically feasible in Germany[28].

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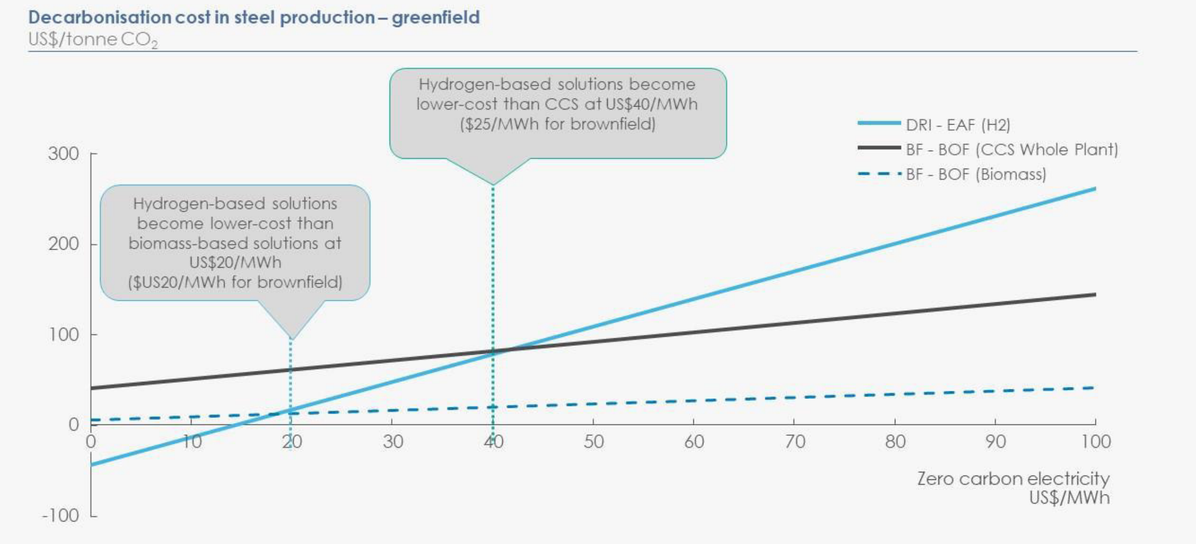
[25] Global CCS Institute (2017), *Global costs of Carbon Capture and Storage*

[26] Energy Transitions Commission (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century*

[27] Hybrit Fossil Free Steel Summary of Findings (2017)

[28] Salcos, Salzgitter Low CO_2 Steelmaking, Presentation by Dr. Ing Volker Hille, Brussels (2017)

Hydrogen-based steel production becomes lower-cost than fossil fuel-based production with CCS if electricity is cheaper than US$40/MWh



Source: McKinsey & Company (2018), *Decarbonization of the industrial sectors: the next frontier*

Exhibit 11

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 US$20/MWh** even while prices are significantly higher elsewhere[29]. There are also major differences in the currently known availability of underground CO_2 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 region[30].

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's "Reference case" for electricity prices, the total cost of decarbonizing steel production averages around US$60 per tonne of CO_2, resulting in a cost increase of around US$115 per tonne of steel. This cost could fall to around US$25 per tonne of CO_2 and US$50 per tonne of steel if very low renewable electricity prices were generally available[31].

[29] Energy Transitions Commissions (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century* – Chapters 6 and 7

[30] Energy Transitions Commissions (2018), *Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century* – Chapter 6

[31] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*

5. COST OF FULL DECARBONIZATION OF STEEL

Sections 2 to 4 show that it is technically possible to achieve full decarbonization of the steel sector "within itself", i.e. without purchasing offsets from other sectors. This full decarbonization is likely to come at a very **low cost to the economy and to end-consumers**. However, it still represents a significant increase in cost of intermediate products purchased by businesses (B2B cost) which must be taken into account when designing decarbonization policies like carbon pricing.

Therefore, this chapter considers in turn:

- The cost to the economy derived from the abatement cost per tonne of CO_2 saved,
- The implications for the cost of intermediate products purchased by businesses and of end products purchased by consumers.

A. COST TO THE ECONOMY

Actual abatement costs – and the least-cost routes to decarbonization – will depend on future technological developments and cost trends and will vary by region in the light of natural resource endowments, but McKinsey's 2018 report[32] gives a reasonable indication of where the highest costs and the cheapest opportunities are likely to lie. Steel appears to be the cheapest to decarbonize of all harder-to-abate heavy industry sectors, with an average abatement cost of US$115 per ton of steel and US$60 per ton CO_2[33]. The availability of low-cost, zero-carbon electricity would make a major difference to the cost of steel decarbonization.

The abatement cost on the demand side is considerably lower: Material Economics estimates the demand-side abatement cost of steel at US$7/t$CO_2$, half for materials circulation levers (e.g. recycling), half for product circulation levers (e.g. sharing economy)[34]. This pleads for maximizing materials efficiency as a cheaper decarbonization route than supply-side decarbonization.

An initial estimate of the maximum annual cost to the global economy of achieving net-zero CO_2 emissions within the steel sector (with no use of offsets) can be generated by multiplying these abatement costs with the volume of CO_2 emissions projected by mid-century in a business-as-usual scenario. This indicative "cost to the economy" is very low in the case of steel: running a fully decarbonized steel industry could amount to 0.02% of global GDP in 2050, or less than US$80 billion per annum [Exhibit 12].

This could be significantly reduced by three factors:

- **Lower renewable energy costs**: if zero-carbon electricity was available at US$20/MWh instead of US$40/MWh, the total cost of decarbonizing steel would be reduced by more than 50% – from US$60/t$CO_2$ if zero-carbon electricity is available at US$40/MWh to US$25/tCO_2.
- **Demand management**: greater recycling and reuse of materials could reduce the total decarbonization cost by 9-26%, bringing the total cost to lower than 0.01% of global GDP.
- **Future technological development**: the cost of decarbonization could be dramatically reduced or even eliminated by new and unanticipated technologies.

[32] McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[33] Based on the reference case scenario in McKinsey & Company (2018), *Decarbonization of industrial sectors: the next frontier*
[34] Material Economics (2018), analysis for the Energy Transitions Commission

For instance, if technological improvements make hydrogen-based DRI cost-competitive even without a carbon price, or make electrolysis a feasible and cost-competitive route, the cost of steel decarbonization could be driven down even more.

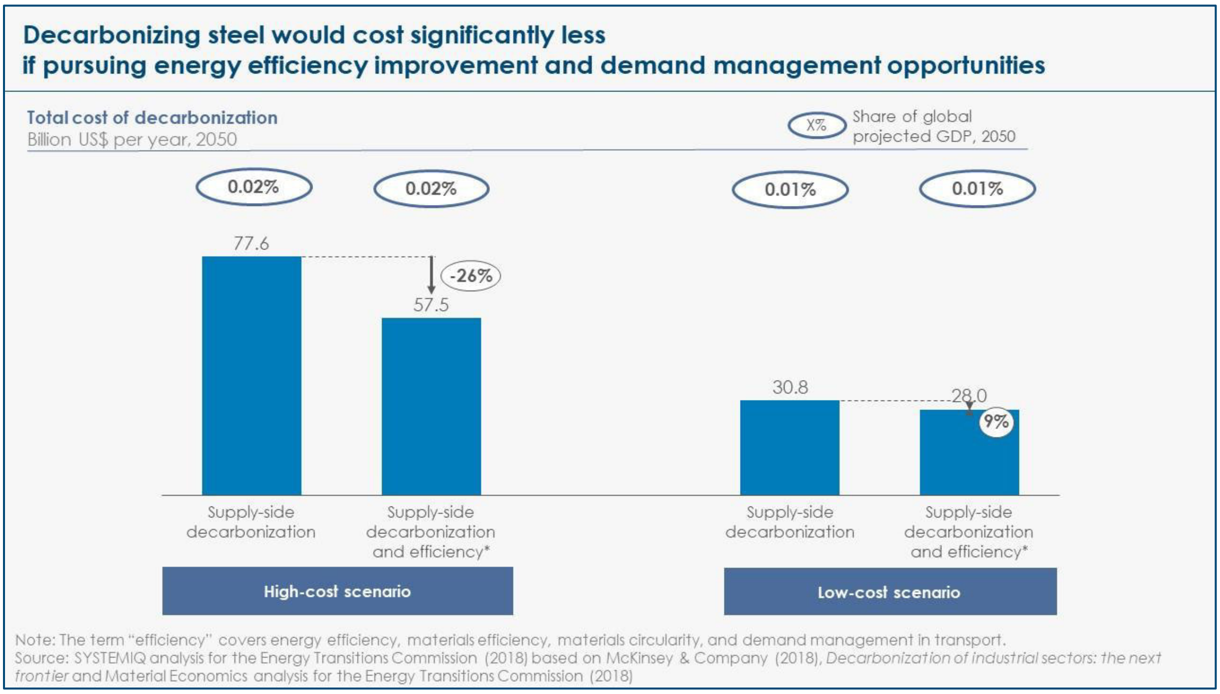


Exhibit 12

B. B2B COST AND END-CONSUMER COST OF DECARBONIZATION

The very reasonable total cost of full decarbonization of steel gives us a useful argument to push for proactive and ambitious decarbonization actions, but is very much a theoretical indicator. It is therefore useful to consider what the impact of decarbonization might be on the price of intermediate products purchased by businesses, and end products purchased by consumers [Exhibit 13]:

- If we consider the impact of steel decarbonization on the **end consumer price** of a typical 1.5 tonne automobile priced US$15,000, it would add around 1% or $180 to the price of the car (using an assumption of 2tCO_2 per tonne of steel and the high-range abatement cost of supply-side decarbonization of US$60/t$CO_2$). This makes it highly likely that consumers would be willing to support policies – whether carbon prices or "green steel" mandates – which would drive decarbonization.
- However, at the **intermediate product** level, the impact on the price of a tonne of steel could be as much as +20%. Steel companies could therefore be severely disadvantaged if policy requirements did not apply equally to all relevant domestic and international competitors.

The key challenge in steel decarbonization is therefore not the 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 US$60 per tonne and thus a production cost penalty of about US$120 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 5 and 6.

6. CONCLUSIONS AND POLICY IMPLICATIONS

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

- There is **very significant potential to reduce total steel demand and to shift the balance from ore-based to scrap-based (recycled) production** via increased recycling and improved efficiency of materials use, especially in developed economies with high steel stocks. 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 a 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 decarbonization of ore-based steel production** over a 30-year period at only a moderate average cost per tonne of CO_2 saved (e.g. US$60). Targets for steel decarbonization should therefore aim to achieve net-zero carbon emissions within the sector (without offsets) 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 US$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 in automobiles sold in any given country or region (for instance Europe) to come from zero-carbon production, regardless of where the raw material or the car is produced.

- **The optimal decarbonization route for ore-based production will differ by location** in the light of local electricity prices and the feasibility and costs of carbon transportation and storage. The overall balance cannot be and does not need to be predicted. But, given that the two main decarbonization routes will almost certainly be CCS/U 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 6).

7. EXISTING 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 CO_2 emissions per se[35]. 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 CO_2 Steelmaking) partnership of 48 companies and organizations from 15 European countries has set a target to reduce CO_2 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, **ResponsibleSteel** is currently developing a social and environmental sustainability standard for ore-based and scrap-based 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.

[35] Reuters (2018), *China to cut more coal, steel output to defend "blue skies"*

8. RECOMMENDATIONS

In light of the technical and economic feasibility of the transition to a zero-carbon steel industry, the Energy Transitions Commission recommends the following key innovation, industry and policy actions to accelerate decarbonization.

A. RESEARCH AND DEVELOPMENT

Given that the two main routes for ore-based steel production decarbonization will almost certainly be **CCS/U 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;
- 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 CO_2 capture costs.

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 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).

B. 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 steel production, and increased recycling and reuse of steel. If steel producers and users faced a carbon price of roughly US$50-US$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 ResponsibleSteel standard currently being developed.

REGULATION TO DRIVE A CIRCULAR STEEL ECONOMY

Governments should develop strategies explicitly focused on increasing recycling and reuse of steel, and improving materials 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;
- Increasingly tight regulations on the recycled steel content of specific products that do not require very high-quality steel;
- Increased landfill taxes to discourage unseparated landfill;
- Producer responsibility regulations which increase incentives for product design compatible with high-quality recycling.

PUBLIC PROCUREMENT

Governments can 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 decarbonization.

R&D AND DEPLOYMENT SUPPORT FOR NEW TECHNOLOGIES

The role of governments to support the R&D priorities described above will be more specifically to:

- **Support early-stage R&D** in technologies which are currently further away from commercial readiness – such as electrolysis for iron ore reduction;
- Support specific projects designed to achieve early decarbonization of a country's steel industry by way of **large-scale demonstration projects and pilots**;
- Support the development of shared **CO_2 transportation and storage** infrastructure which may be required to make CCS a feasible solution in those locations where it is likely to be significantly cost advantaged.

LOW-COST POWER DECARBONIZATION

Given the probable role of electric arc furnaces (either ore-based production, or for scrap-based production), of hydrogen-based iron reduction and potentially, in the longer term, electricity-based iron reduction, it is essential that Governments continue **reducing the carbon intensity of electricity and driving down the cost** of renewable electricity.

REGIONAL SPECIFICITIES

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.

C.ACTION FROM 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 ResponsibleSteel.

- 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 with the aim of reaching net-zero carbon emissions by mid-century (2060 at the latest).
- 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 aluminum.

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 3.

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.

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