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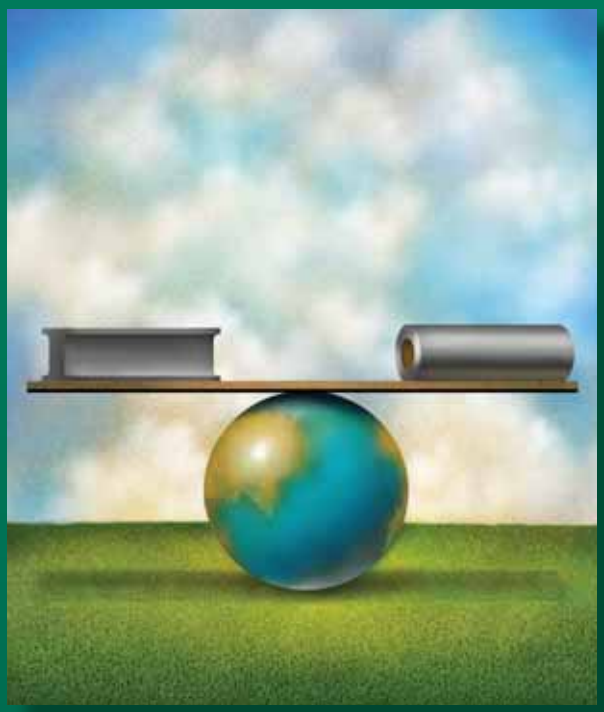

Steel's Contribution to a Low-Carbon Europe 2050

TECHNICAL AND ECONOMIC ANALYSIS OF THE SECTOR'S CO_2 ABATEMENT POTENTIAL

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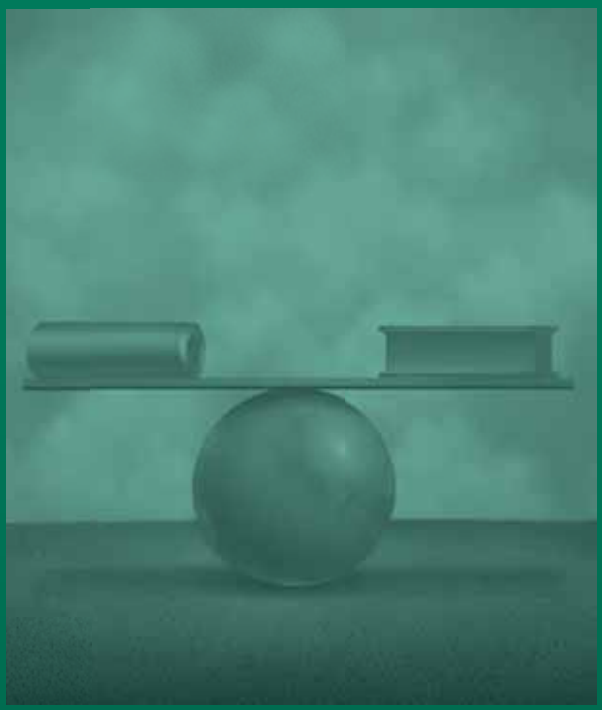

The aim of the Steel Institute VDEh, which is in the legal form a registered association, is to encourage technical, scientific, and technical economical cooperation between engineers of steel producing companies with a view to advancing steel technology and promoting steel as a material. Currently 59 steel producers in Germany, 16 steel producers in other European countries, and 81 plant manufacturing and supplier companies are members in the Steel Institute VDEh. The joint cooperation takes place in 16 organized technical committees dealing with all aspects of iron and steel making including the production steps sintering, pelletising, cokemaking, blast furnace ironmaking, direct reduction, smelting reduction, basic oxygen furnace and electric arc furnace steelmaking, continuous casting, forming and rolling, and open die forging to the finished products. A focus is set to the application of steel. The Verlag Stahleisen is the publishing house of Steel Institute VDEh, where the latest developments and newest technologies in the field of steel technology and economics are made available to the public. The promoting of research is done on the one hand with applied research via the VDEh-Betriebsforschungsinstitut BFI and on the other hand with fundamental research work via the Max Planck Institute for Iron Research (MPIE). Steel Institute VDEh also promotes young engineers and further training by organizing seminars and it promotes the education of students at universities. For more information please visit www.stahl-online.de.

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SUMMARY OF FINDINGS

This report provides a realistic view of how the steel industry can respond to one of the most important challenges facing humankind—climate change.

In particular, it addresses the European steel industry's response to the long-term target, defined by the European Council in 2009, of diminishing greenhouse-gas emissions by 80 to 95 percent of 1990 levels by 2050, as part of the reductions needed by developed countries as a group. This target is in line with the Intergovernmental Panel on Climate Change (IPCC) recommendations to decrease global emissions by 50 percent by 2050 so as to keep global warming below a difference of 2.1 degrees Celsius from the preindustrial age. (IPCC, 2007)

In March 2011, the European Commission published its roadmap for attaining a competitive low-carbon economy by 2050. That document examines possible cost-efficient paths toward reducing European Union (EU) domestic greenhouse-gas emissions by 80 percent by 2050. According to the commission's report, European industry would have to cut back its emissions below 1990 levels by 34 to 40 percent by 2030 and by 83 to 87 percent by 2050.[1] In this context, the commission and the European Parliament invited industrial sectors to develop their own low-carbon roadmap. (European Commission, 2011)

Aside from the ecological impact, carbon dioxide (CO_2) emissions—and the direct and indirect costs associated with them—are likely to have a continuing economic impact on the industry.

The sector is subject to the EU Emissions Trading System (ETS), introduced in 2005. The reduction target is 21 percent of 2005 levels by 2020, assuming an annual reduction of 1.74 percent of total emissions from the participating sectors as of mid-2010. (ETS directive, 2009) This means a below-2005-level target of 38.4 percent by 2030, 55.8 percent by 2040, and 73.2 percent by 2050. A review of the 1.74 percent per year is foreseen for 2020, with a possible adaptation for 2025.

The steel sector currently receives free CO_2 allowances based on performance benchmarks, and member states may grant partial compensation for the increase in electricity prices resulting from the ETS because it was determined that increased CO_2-related costs would make European steel uncompetitive and trigger potential migration to countries with less-restrictive carbon-emission policies (carbon leakage). The decision is up for review in 2014. The current directive foresees that in 2021 carbon leakage sectors would receive a maximum of 25 percent of its benchmarks in free CO_2 allowances, a figure decreasing to zero percent in 2027. The steel industry would then have to buy all allowances needed to cover its CO_2 emissions on the market. (ETS directive, 2009)

This report provides a realistic technical view of steel's CO_2-mitigation potential, examining which reduction technologies are available and how much impact they can make between now and 2050. It also examines the economic dimension and how far such considerations will affect decisions on investment in emission-reducing technologies.

The scenarios developed for, and examined in, our study are therefore designed to elucidate the true techno-economic potential for the industry. As such, they are not designed to provide data relevant to benchmarking and must not be taken that way.

The report is targeted at decision makers and sustainability experts in the steel industry—the people who make the key investment decisions in an asset-intensive business that needs a degree of stability before substantial investment decisions can be made. Keeping this need in mind, this document addresses policymakers who need to both define realistic targets that balance ecological and economic interests and provide stable investment conditions. Without these stable conditions it will be difficult for the steel industry, with an investment horizon of 15 years or more, to start the steps necessary for a low-carbon Europe 2050.

After presenting an overview of the steel industry and its development, the report assesses the *steel sector's own impact*—that is, the emission-reduction potential within the steel sector. Steel is an asset-intensive industry that has made significant changes over the past 50 years, including the virtual elimination of traditional blast furnace open-hearth furnace (BF-OHF) production, a doubling in the proportion of production through the scrap-based electric arc furnace (Scrap-EAF) route, and an almost complete switch from traditional casting methods to continuous casting. Given those developments, the specific CO_2 emissions (taking Germany as an example) fell by about one-third between 1960 and 1990. (Dahlmann & Lüngen, 2012)

In evaluating the potential for emissions reduction within the steel sector, we looked first at the sector's historical development (the base line). Absolute emissions of CO_2 in the 27 European Union countries (EU27) fell by 25 percent, from 298 million tons (Mt) to 223 Mt, in the two decades from the base year 1990. This drop was driven mainly by declining production and a partial shift from the blast furnace-basic oxygen furnace (BF-BOF) to the Scrap-EAF production route, together with further efficiency gains. CO_2 emissions per ton of crude steel decreased by 14 percent between 1990 and 2010.

We also assessed future development—that is, various abatement scenarios. Crude steel production is expected to rise between now and 2050 as a result of growing demand, assuming there is a stable degree of industrialization in the EU27 and no delocalization of the steel industry. Thus, efficiency gains will, to a large extent, be offset against higher volumes. We will show that technologically there will be a broad range of outcomes regarding the potential CO_2 abatement, possibly leading to maximum savings of 38 percent by 2050. However, this would entail a radical restructuring of production that requires not only highly expensive investment but also the availability of cheap natural gas and electricity. Thus, from an economic point of view, an absolute CO_2 reduction of about 10 percent from 1990 levels is the most likely outcome. This objective can be achieved by an improvement of current production routes and an additional shift (from 41 percent to 44 percent) toward more Scrap-EAF steel. Depending on the scenario, by 2050 the average specific emissions per ton of crude steel could be reduced from 1990 levels by between 14 and 48 percent.

Using carbon capture use and storage (CCUS) in addition to the other technologies, as an end-of-pipe technology, could bring absolute emissions down by almost 60 percent of 1990 levels—reducing specific CO_2 emissions by over 60 percent. But economic practicalities and uncertainty over the availability and public acceptance of CCUS render this option highly speculative.

It is worth mentioning that, to reach the European Commission's climate goal, the steel industry is investing continuously in research and development of innovative CO_2 emission-reducing technologies (for example, ULCOS or Ultra–Low Carbon dioxide (CO_2) Steelmaking) even beyond the technologies described and evaluated in this report.

The report also assesses *steel as a mitigation enabler*—that is, the emission-reduction potential due to steel use in other sectors. It is clear that steel's impact on CO_2 emissions is not confined to the production processes. Analysis of eight cases in which there is virtually no alternative to steel for the particular application, found a positive ratio of 6 to 1 between CO_2 savings from these uses in the EU27 and emissions resulting from production of the corresponding steel. The following eight applications were considered: efficient fossil-fuel power plants, offshore wind power, other renewables, efficient transformers, efficient e-motors, weight reduction—cars, weight reduction—trucks, and combined heat and power. These eight applications alone create a total net saving of 350 Mt CO_2 per year from 2030 onward. This amount would offset the potential CO_2 emissions of the whole steel sector in Europe. The highest absolute savings would come from the production of lighter cars.

NOTE

1. For ease of reading, the target is referred to as an "80 percent reduction target" throughout the rest of this report.

STEEL INDUSTRY OVERVIEW AND DEVELOPMENT

Steel is essential to the modern world. Thanks to its strength and its properties of formability, it is one of the most versatile and adaptable engineering materials. It is the material of choice for a wide range of applications ranging from the construction of bridges and buildings to automotive and machine parts, as well as packaging of food, generation of power, and uses in aerospace engineering. The major end-use industries include construction (35 percent), automotive (18 percent), and mechanical engineering, as well as metal goods (14 percent each).[1] (EUROFER, 2013) Steel's recyclability also makes it a key material for sustainable development.

The steel industry is an essential part of Europe's economy. In 2009, the total sales (GVA) of the steel sector amounted to €170 billion (€80 billion), accounting for 1.4 percent (0.7 percent) of the GDP of the European Union's 27 members, according to the EUROFER member survey conducted in 2010. Large parts of other industries depend on the availability of a reliable-quality steel supply. The EU27 steel industry directly employs around 360,000 people, and several millions are to some extent dependent on it. The sector produced 177 Mt of crude steel in 2011, or 11.7 percent of global steel production. The EU27 constitutes the first steel-importing region in the world (36 Mt) and the third exporting one (38 Mt) after China and Japan. (Worldsteel, 2012)

Overview of the Steel Production Process

Steel is a heavy-duty material consisting of an alloy made by combining iron with carbon and other chemical elements. Different grades of steel are produced by varying the chemical composition, the microstructure, and the surface conditions, all of which determine the steel's specific characteristics. There are more than 2,500 types of steel, with different properties available for a broad range of applications.

Two basic methods of production exist:

- *Primary route:* steel that is produced from virgin iron extracted as iron ores out of the earth in mines
- *Secondary route:* steel that is produced from scrap—that is, home scrap, new scrap, and obsolete scrap from end-of-life products

Scrap can be melted to directly produce new steel. However, iron ores—which are iron oxides with an iron content of above 60 percent—must be first reduced into iron.[2] This means extracting the iron by removing the oxygen (O_2) bound to it with the help of re-

ducing agents (mainly carbon monoxide, or CO, and, to a lesser extent, hydrogen, or H_2). The hot metal produced can then be converted into steel. This is why the processes using virgin iron units are often referred to as *iron making* and *steel making*. Exhibit 1 gives a simplified overview of different iron- and steel-making processes.

One process shown in Exhibit 1 is the blast furnace converter (BF-BOF) or integrated route.[3] This process for producing steel is described just below.

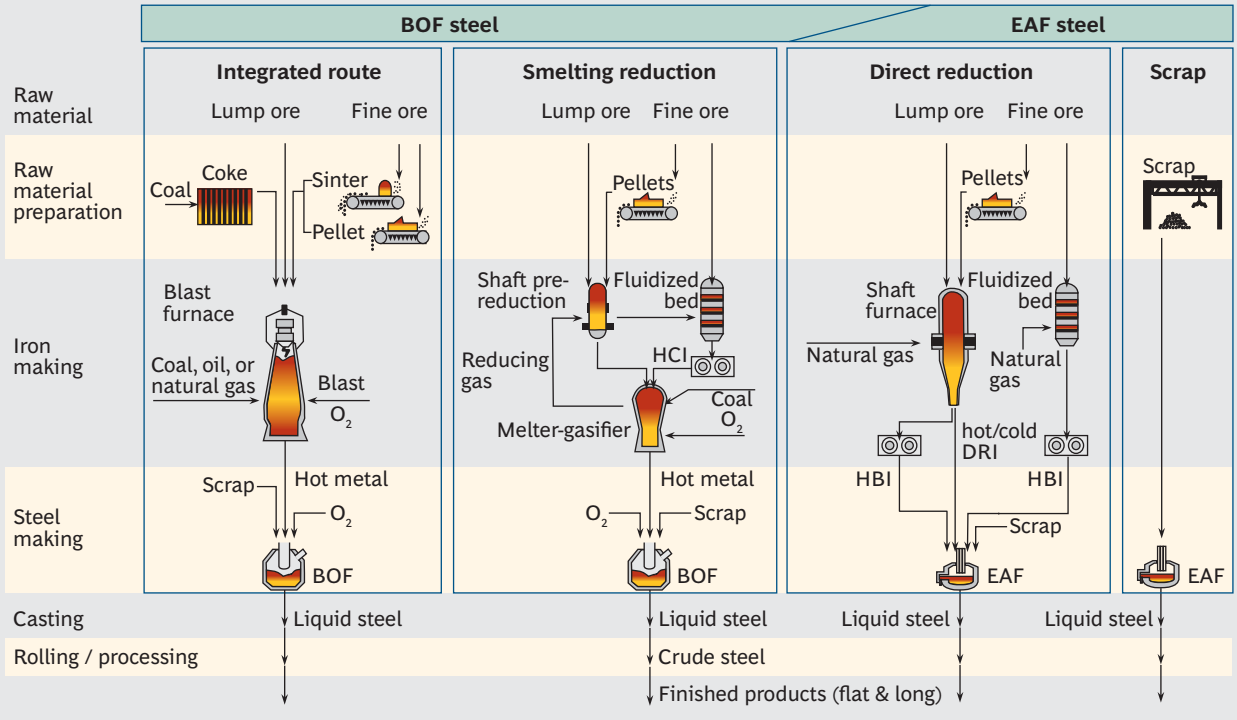
- *Iron making.* Iron ores in the form of lump ores, pellets, and sinter are reduced in the blast furnace (BF) using, predominantly, coal and coke as reducing agents. The reducing gas CO is generated by the reaction of carbon from coke or coal (known as *pulverized coal injection*, or PCI) with O_2 from the injected blast. The reduced liquid iron is called *hot metal* (*pig iron* refers to its solidified state).[4] During the transition to the liquid phase, impurities in the iron ores, coke, and coal ash (gangue elements) are separated from the hot metal to form a liquid slag. Pellets, sinter, and coke are agglomerated products, whereas lump ores and injection coals can be used directly in the BF in the defined grain-size fractions.

- *Steel making.* After the oxide has been removed from the iron, the hot metal is charged to a basic oxygen furnace (BOF)—or *converter*, as it is often called—where O_2 is injected to remove any remaining unwanted elements and as much of the residual carbon in order to convert the metal into steel of the required quality (the carbon content typically being below 2 percent). Because the process is exothermic—releasing energy—it requires coolants. Mostly, scrap is used for this purpose, but sometimes cold pig iron or direct reduced iron (DRI, explained in the paragraphs that follow) is added into the BOF.

An alternative method for producing steel is the smelting reduction converter (SR-BOF) route. This process is described just below.

- *Iron making.* The BF is replaced by a two-stage process. In the first stage, the

Exhibit 1 | Overview of Iron- and Steel-Making Processes



Sources: Steel Institute VDEh; Wirtschaftsvereinigung Stahl; World Steel Association; project team analysis.

iron ores are prereduced through the use of off-gases from the melter-gasifier. In the second stage, the prereduced iron ores are melted in the melter-gasifier, using coal as a reducing agent. CO is generated by the carbon from the coal and the pure O_2 injected to convert the iron into hot metal and separate most of the unwanted elements (gangue) of the iron ores and the coal ash into a liquid slag. Two main technologies exist for smelting reduction: Corex, where pellets and lump ores are prereduced in a shaft, and Finex, where fine ores are prereduced in a multistage fluidized bed reactor.

- *Steel making.* The hot metal is charged to a BOF. (See the discussion above for details.)

A third iron- and steel-making process shown in Exhibit 1 is the direct reduced-iron electric arc furnace (DRI-EAF) route. The process is described just below.

- *Iron making.* Iron ores remain solid, rather than being melted as in BF and SR (smelting reduction), through the entire process. Oxygen is removed by a chemical reaction with the hot reducing gas—mostly reformed natural gas—which is high in H_2 and CO content. The hot DRI can either be fed right to the EAF or be compacted as hot briquetted iron (HBI), which allows better storage and transportation of the pyrophoric material.[5] Midrex and HYL, both shaft based, are the predominant technologies for the direct-reduction (DR) process. Unlike hot metal, DRI still contains residual O_2 and other unwanted materials (gangue) from the iron ores that need to be eliminated in the steel-making stage.

- *Steel making.* The DRI or HBI is fed to an EAF, where it is melted into liquid steel. Scrap may still be added to improve the operational performance of the EAF.

The fourth process for producing steel, as shown in Exhibit 1, is the Scrap-EAF route.

- *Steel making.* Ferrous scrap is melted by the energy supplied by an electric arc often assisted by O_2 injection, oxy-fuel burners, or both. Other iron-bearing materials, such as DRI may be added to the scrap charge.

EU27 crude steel production is almost entirely divided between the BF-BOF and the Scrap-EAF routes. In 2010, BF-BOF accounted for 59 percent of EU27 production, and Scrap-EAF the remaining 41 percent. Although other iron- and steel-making processes are used in different parts of the world, they have little to no significance for Europe. The open-hearth furnace in combination with the blast furnace (BF-OHF) played a role in Europe until the 1990s, but by 2010 only one OHF remained, in Latvia, accounting for 0.4 percent of the EU27's crude steel production. This plant has meanwhile been dismantled and replaced by an EAF. Since 1971, there has also been one DR facility in Hamburg, Germany; as of 2010, it had an annual production of around 0.45 Mt. (Midrex, 2011)

Contrary to the three iron- and steel-making processes based on virgin ores that can produce any type of steel quality required by the user, Scrap-EAF has two limitations:

- The general availability of scrap within a country or region (net scrap imports and exports) serves as the natural limit to scrap use.

- The quality of available scrap restricts the range of steel qualities the process can produce. This is why carbon steel from Scrap-EAF typically serves the construction industry rather than automotive and other customers who require high-quality steel. Higher qualities of carbon steel can be produced in an EAF only if DRI or pig iron is substituted for scrap. Exceptions are high-alloy and stainless-steel grades, produced exclusively via the EAF route, which enables the recovery and recycling of high-value high-alloy and stainless steel scrap.

An overview would not be complete without also looking at casting, rolling, and further processing, as shown in Exhibit 1. Liquid steel is cast to certain shapes, dimensions, and

weights of crude steel (billets, blooms, slabs, ingots, or other semifinished products) for further processing. Casting transforms the liquid steel into crude steel. Since the 1950s, continuous casting has evolved as the casting technology of choice, accounting for over 90 percent of the world's crude steel production (CSP). (Thomas, 2004)

Crude steel is first formed through "hot rolling" at a temperature of about 1,300 degrees Celsius (above the recrystallization temperature). Hot rolled steel may afterward go through various processing steps such as heat treatment, cold rolling, or surface treatment.

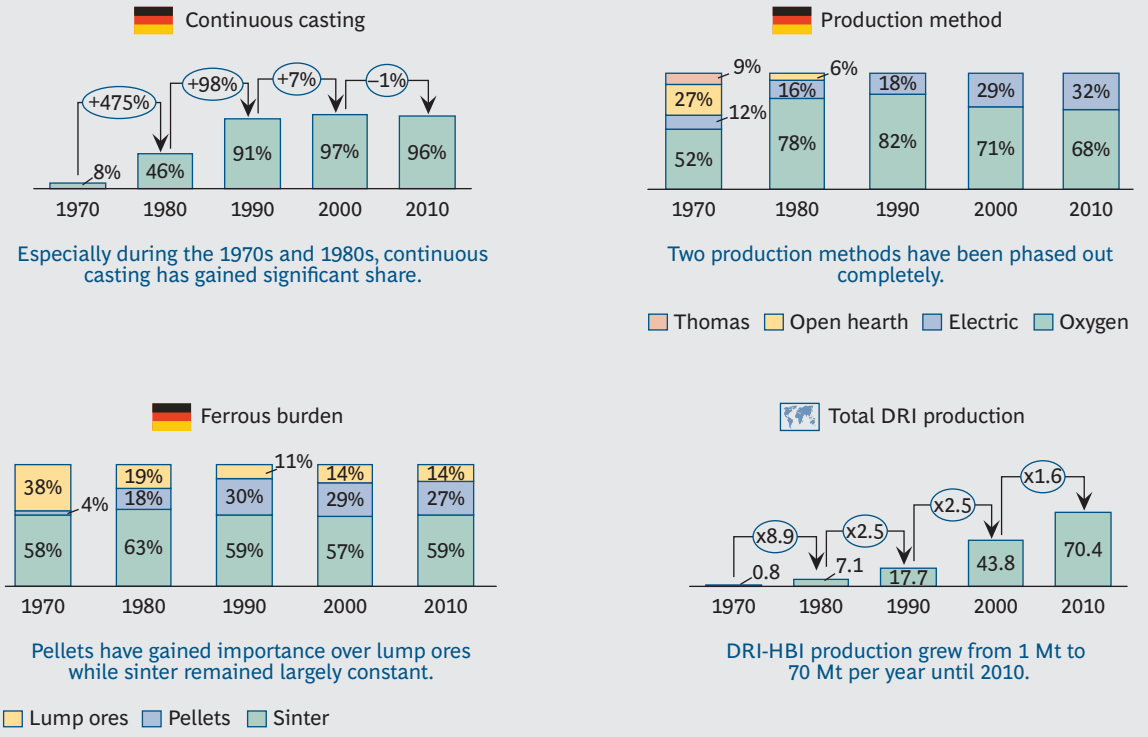
Evolution of the Steel Industry in General

In trying to project the possible development paths of the steel industry—and hence its carbon dioxide (CO_2) emissions—in the coming 37 years, it is helpful to look back over a similar time span. Since the mid-1970s, the steel industry—which, as a highly capital-intensive industry with long investment cycles, does not change rapidly—has gone through a number of quite significant technological evolutions. (See Exhibit 2.)

- Ingots were once formed by traditional casting but are now formed by continuous casting. This change has been the largest to occur since the middle of the past century. In Germany, for example, continuous casting had a penetration of only 8 percent in 1970 but rose rapidly to 96 percent in 2010. Ingot casting in the EU is now confined to specific applications (for example, forgings). The worldwide share of continuous casting is around 90 percent.

- The EAF share of production has grown significantly, doubling from 1970 to 2010. In Germany, for example, it rose from below 12 percent at the end of the 1970s to 32 percent today. Despite this shift, BF-BOF remains the predominant method of steel making. Additionally, most old OHFs, especially in Eastern Europe, have been shut down.

EXHIBIT 2 | Overview of Significant Technological Changes in the Steel Industry Since 1970



Sources: Midrex; Steel Institute VDEh; project team analysis.

- The ferrous burden mix has altered slightly. For instance, although in Germany the share of sinter has remained largely constant at around 58 to 60 percent, pellets have gained importance over lump ores: their share has grown from only 4 percent in 1970 to 27 percent in 2010, whereas the share of lump ores declined from 38 percent to 14 percent.

- The worldwide production of DRI has increased from about 1 Mt to 70 Mt since 1970. At the same time, hot metal production more than doubled from about 600 Mt to over 1,400 Mt. (Midrex, 2011; Worldsteel, 2012) DR now accounts for 6 percent of the world's iron production, with a strong regional focus on Asia, the Middle East, and northern Africa. The reason for this regional concentration is relatively low local prices for natural gas and electricity.

The steel industry is very capital-intensive and has extended investment cycles. Furthermore, steel plants are often very large compounds with complicated intertwined material and energy flows. The industry, therefore, is not prone to radical technological change.

Notes

1. Metal goods include steam generators, forging, pressing, stamping, roll-forming of metal, powder metallurgy, treatment and coating of metals, manufacture of cutlery, tools, general hardware, locks and hinges, steel drums and similar containers, light metal packaging, wire products, chains and springs, fasteners, screw machine products, and other fabricated metal products, manufacture of furniture. (NACE Rev. 2, 2008).
2. Mined iron ores with an iron content below 60 percent typically have to be beneficiated—to increase their iron content—before they are reduced.
3. The term refers to BF-BOF steel plants where all processes for iron making and steel making are located at one site, forming an "integrated" steel plant.
4. The term pig iron originated from the shape of the molds into which the hot metal was poured in order to form solid, transportable ingots. Today hot metal is usually directly transported to the converter (BOF) in its liquid phase.
5. If the DRI is not briquetted, it reacts when in contact with oxygen (for example, from the air). This results in unwanted chemical reactions as extreme as self-ignition.

THE STEEL SECTOR'S OWN IMPACT ON CO_2 EMISSIONS

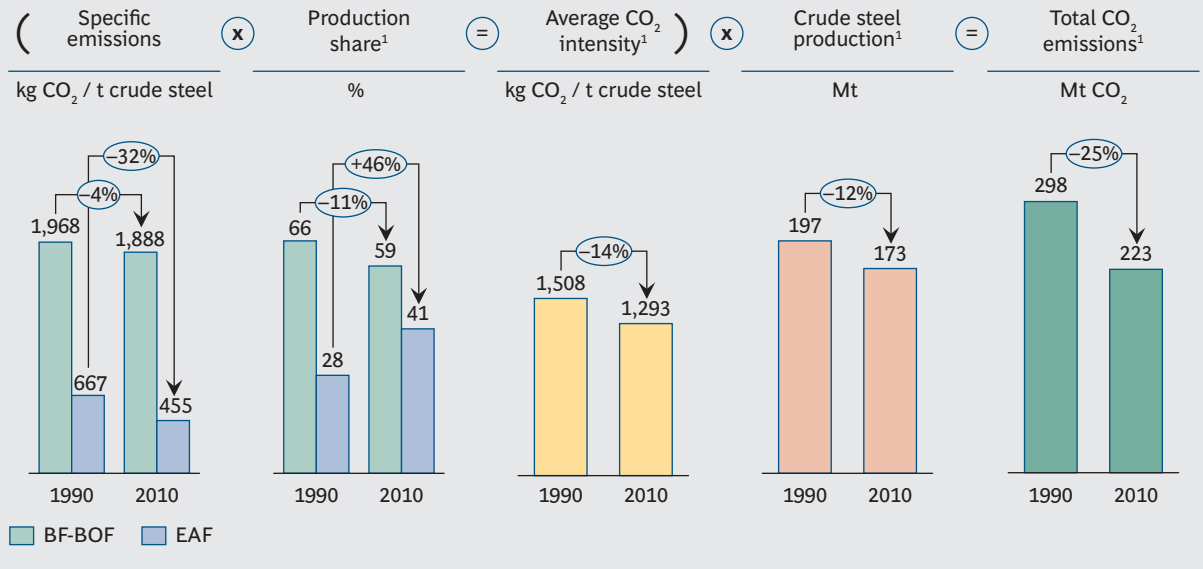
We will now turn our focus to assessing the extent to which innovative CO_2 abatement efforts can meet the EU's middle- and long-term CO_2-reduction milestones.

Establishing a Base Line

Between 1990 and 2010, total CO_2 emissions in the EU27 steel industry fell by about 25 percent, from 298 Mt to 223 Mt. The same period saw overall crude steel production drop from 197 Mt to 173 Mt, a decline of 12 percent. When we calculate a weighted average for emissions per ton of crude steel produced, we see a decrease of 14 percent over the period. (See Exhibit 3.)

In computing this finding, the numbers are based heavily on data reported by companies and on bottom-up emission calculations de-

Exhibit 3 | EU27's Specific CO_2 Intensity Decreased 14 Percent, Whereas Absolute Emissions in 2010 Dropped by 25 Percent, from 1990 Figures



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
Note: Figures include the process of hot rolling.
[1]Includes BF-OHF share of 6 percent in 1990 and 0.4 percent in 2010, accounting for 3 and 0.2 Mt CO_2, respectively.

rived from material flows along the value chain. We provide additional information on our methodology later in this section.

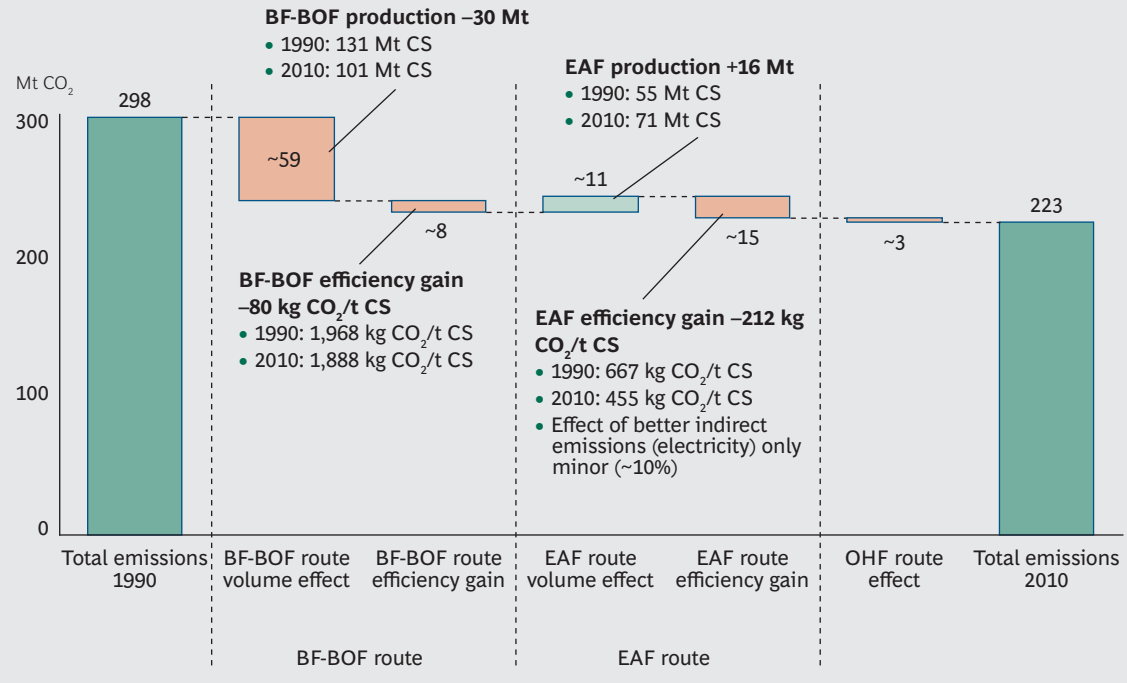
The absolute decline in total emissions from the EU27 steel industry had three causes:

- The overall production level declined (from 197 Mt in 1990 to 173 Mt in 2010). When disaggregating the abatement effects, volume changes—that is, the fall in BF-BOF—were by far the largest contributor (around 65 percent) to the absolute decline. (See Exhibit 4.) The descent in production from 1990 was driven by structural changes in Eastern European countries (see the last section of this chapter, "Steel and Scrap Forecast," for more details) as well as the overall decline that was due to the economic downturn in 2009 and the slow recovery in the years following the crisis.

- A shift from primary to secondary steel making—that is, from high- to lower-emission-generating types of production—occurred. (Scrap-EAF's share of production went up from 28 percent in 1990 to 41 percent in 2010.) The limiting factor, as mentioned earlier, is twofold: the availability of scrap and its quality, the second of which restricts the range of steel qualities the process can produce. BF-BOF production declined by 23 percent, whereas the antiquated BF-OHF virtually disappeared.

- Efficiency gains took place—resulting in a decline in overall specific CO_2 emissions by 14 percent. In the Scrap-EAF route, CO_2 emissions per ton of EAF production were reduced by 32 percent. Most of this came from the decrease in indirect CO_2 caused by the consumption of electricity (from 585 g CO_2 per kWh in 1990 to 429 g CO_2 per kWh in 2010), which makes up around half of all emissions associated with this route.[1] Further benefits came from almost complete replacement of hot metal charged directly to the EAF by an almost 100 percent scrap feed. The integrated route achieved a 4 percent cut per ton. This was driven by burden mix changes and the reduction of the coke rates. One may wonder about the relatively low improvement of about 4 percent, but

Exhibit 4 | The Reduction of CO_2 Emissions from 1990 to 2010 Mainly Driven by Volume Effects



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
Note: Includes all direct and upstream emissions as well as casting and hot rolling; BF-OHF route volume 1990: 11 M; CS = crude steel; small differences due to rounding.

additional efficiency gains in the plants may have been obscured by the negative effects of deteriorating raw-material qualities. It must be stated that with the methodology used (the self-sufficiency assumption), any efficiency gains from power plants are not included.

To put these numbers into perspective, let's take a look at the underlying methodology. The numbers calculated represent the total carbon footprint of the EU27 steel industry. The footprint can be understood as equating to all CO_2 emissions that would not take place if there was no steel industry. (See Exhibit 5.) It was calculated using data from the 15 countries that were EU members in 1990 (EU15), using company reports to the VDEh data exchange. Numbers for the 12 more recent members were calculated through a set of real data and scaling based on figures from the original 15.

CO_2 emissions were determined by the amount of input material consumed and output material produced within each process step attributed to each material's carbon content. Netting input with output CO_2 flows (carbon balance) yields the direct CO_2 emissions for each step. Emissions from previous process steps are included in the next step as upstreams ("rucksack") weighted with the amount of material needed.

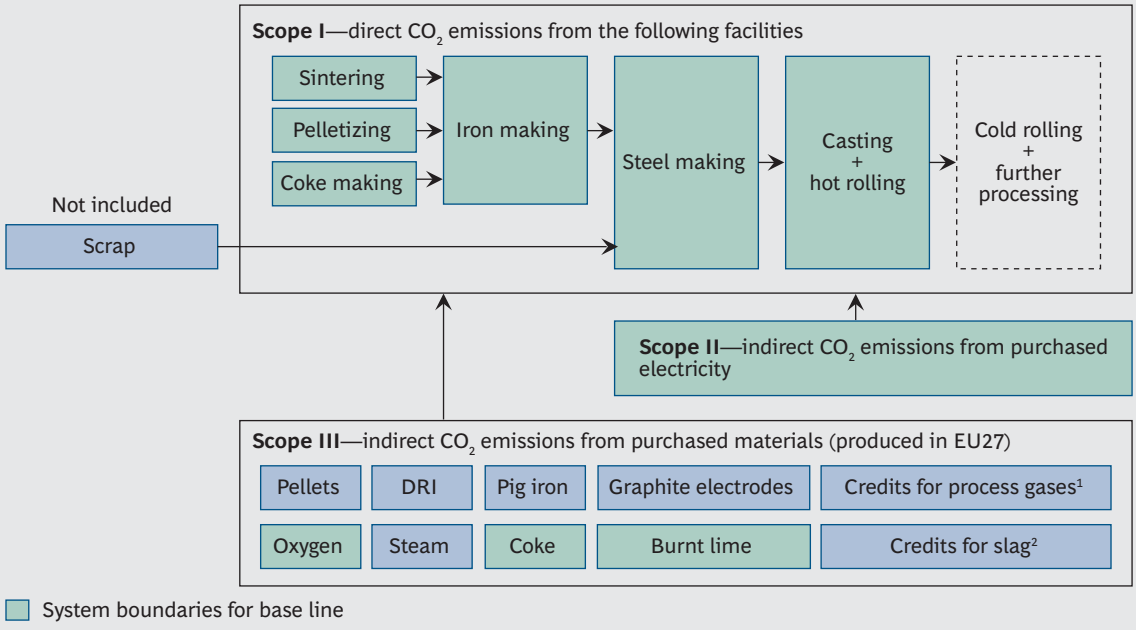
For BF-BOF, most emissions are generated directly by production processes that run from agglomeration through iron making and steel making to casting and hot rolling. Process gases generated along the value chain are used to produce electricity and heat, rendering *sufficient* power to satisfy the electricity demand in an integrated plant (the self-sufficiency assumption).[2]

For a discussion about the use of byproducts from the BF-BOF route please see the sidebar "The Use of Byproducts from the BF-BOF Route."

For Scrap-EAF, only around 50 percent of the CO_2 emissions are generated by production processes, with the remainder coming from indirect emissions.

- Indirect emissions from purchased electricity needed during steel making in

Exhibit 5 | System Boundaries Mirror Steel's CO_2 Footprint Originated in EU27



Sources: World Steel Association; project team analysis.
[1]The utilization of byproducts, such as process gases or waste heat, is not counted as a credit, because such use helps reduce the energy consumption within the process steps. Only byproduct gases that are sold to a second party can be counted as a credit, because they help to reduce emissions of a different sector.
[2]Currently no credits are given for the CO_2 savings through slag usage in cement production.

THE USE OF BYPRODUCTS FROM THE BF-BOF ROUTE

The BF-BOF iron- and steel-making processes are closely intertwined, making synergies possible. Most of the residues can be recycled within integrated steel plants (for example, mill scale, flue dust, and coke breeze, which can be fed into the sinter plant), making for the efficient use of residues. Other residues, notably process gases and slag, even constitute byproducts.

In the BF-BOF route, process gases occur at the coke plant, BF, and converter; in the SR-BOF route, they occur at the smelting facility and BOF. Because of their calorific value, they are, in most cases, recovered and used to generate electricity and steam or to substitute for natural gas in the furnaces. In our analysis, we have assumed the self-sufficiency of an integrated steel plant—that is, no additional electricity or steam is bought in from the outside.

Slag is a byproduct created by chemical reactions during the iron-ore-reduction process, or during the steel-making process. Its composition is adjusted through the addition of fluxes. Its main users are the cement and the building material (road construction) industries. (Jahrbuch Stahl, 2013) Granulated slag from the BF is used in the cement industry, where it replaces input materials that are CO_2 intensive (Portland clinker) in production. According to de Lassat de Pressigny, 557 kg CO_2 of the overall BF emissions can be assigned to the production of one ton of granulated slag. (de Lassat de Pressigny, 2005) Average production of around 215 kg granulated slag per ton of hot metal in 2010 (VDEh data exchange, 1990/2010) resulted in total emissions of 11 Mt CO_2. In the cement industry, the use of one ton of granulated slag reduces CO_2 emissions by 945 kg. (Ehrenberg & Geiseler, 2001) The corresponding emission savings due to slag use in the cement industry amounted to 19 Mt CO_2 in 2010. Because these savings pertain to activities carried out beyond the steel sector's perimeter, the aspect of slag was not investigated further in this study.

EAF, casting, and hot rolling, a route requiring the energy to be imported because no coupling energy (as in the integrated route) is generated

- Indirect emissions from materials purchased within the EU27—such as coke, burnt lime, and O_2—included for both routes but making only a limited impact

Because of the lack of reliable data and the high dependency on company-specific product portfolios, cold rolling and further processing have not been included in the scope of this study. However, our analysis still covers more than 90 percent of steel-production emissions. Emissions associated with the mining and transportation of raw materials are not included.

Abatement Scenarios for 2050

Predicting the future entails much uncertainty. One need only look back a few years to predictions of how life would be in the early twenty-first century to understand this. The objective of this report is, of course, not to make hard and fast predictions about how the future will look from now on, but to outline possible scenarios based on today's knowledge and to identify those that are the most likely ones from a technical as well as an economic perspective.

The *upper boundary*—projecting 305 Mt CO_2 emissions in 2050—is a base-line scenario assuming that nothing changes in terms of performance. The sector would move on with the same specific emissions per route and the same relative split between BF-BOF and Scrap-EAF production. The production volume in this scenario is the sole variable.

The *lower boundary without carbon capture use and storage (CCUS)*—projecting 184 Mt CO_2 in 2050—is the maximum-abatement scenario. It assumes that BF-BOF production is gradually replaced by an alternative route with

lower specific CO_2 emissions and that low-carbon technologies available for existing routes are implemented to their technological limits.

Both of these scenarios are essentially theoretical. The base-line scenario assumes that emission-reducing trends will halt, whereas the maximum-abatement scenario rests on a massive replacement of the existing BF-BOF route whether the implementation of carbon dioxide-reducing technologies is economically viable or not.

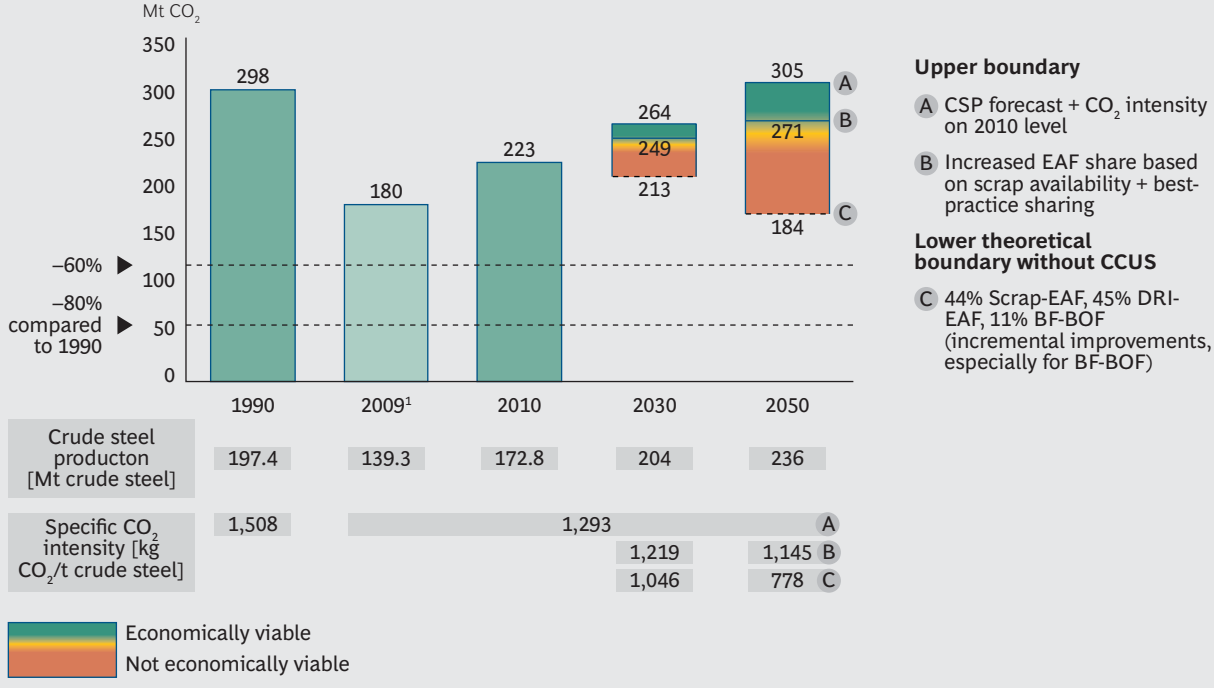
Realistically, neither of the two scenarios is likely. Therefore we have also calculated a Point B version of the upper boundary, at 271 Mt. This assumes that current best practice will be shared, and adopted generally, along with continuing improvement in CO_2 emissions for purchased electricity.

All three scenarios are illustrated in Exhibit 6. Readers may wonder why we include results for 2009 as well as for every 20 years from 1990 to 2050. This is because they illustrate a key truth in this debate, which is that even at the lowest point of production during the economic downturn, CO_2 emissions from the EU27 were well above a 60 percent reduction of the 1990 level, and even further away from the called-out 80 percent target.

Assuming the CSP projected for 2050 (236 Mt), all likely outcomes lie in the option margin between Point B and the maximum-abatement Point C. A scenario close to Point B is much likelier because, as our economic scenarios in the paragraphs that follow show, the large-scale replacement of BF-BOF by the less CO_2-intensive DRI-EAF route is not economically viable.[3]

End-of-pipe technologies for storing or using the CO_2 (CCUS) are multisector and not steel-specific options. CCUS is often referred to as potentially an extremely important driver for CO_2 mitigation, in particular in the power sector. However, there is also much uncertainty about when it will be commercially available. Furthermore, because of strong concerns about public acceptance in many EU countries, storage sites might not be available throughout the EU. Our examination of the possible impact of CCUS on CO_2 emissions is discussed at the end of this section.

Exhibit 6 | Option Space for Possible CO_2 Abatement Scenarios in 2050



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
[1]2009 crude-steel production with 2010 CO_2 intensity and 2010 Scrap-EAF share.

What follows is an explanation of how the scenarios are calculated—that is, the upper boundary, which includes Point A and Point B in Exhibit 6, and the lower theoretical boundary without CCUS, which is shown by Point C in that exhibit.

Upper Boundary Point A (Base-Line Scenario). The projection for the upper boundary scenario (point A in Exhibit 6) is 305 Mt CO_2 in 2050. This assumes a continuation of the 2010 production split—59 percent BF-BOF, 41 percent Scrap-EAF—with the average 2010 CO_2 intensity of about 1.3 t CO_2 per ton of crude steel.

Upper Boundary Point B (Continued Improved Efficiency Scenario). The projection of 271 Mt CO_2 in 2050 assumes the following:

- Scrap-EAF's share will increase to its upper limit, based on scrap availability, of 44 percent by 2050—reducing total emissions by around 8 Mt.
- Emissions for both existing routes are assumed to improve to the weighted average of the current top 50 percent of performers through shared best practice.
- For BF-BOF, this will lead to a 6 percent decrease in specific emissions—from 1.89 t CO_2 (in 2010) to 1.78 t CO_2 per ton (in 2050) of CSP—reducing total emissions by 14 Mt.
- For Scrap-EAF, the key change will be a further 25 percent reduction in specific emissions—from 455 kg (in 2010) to 341 kg (in 2050)—bringing total emissions down by almost 12 Mt. The reduction in CO_2 emissions will be driven mostly by improvement in the CO_2 load of electricity consumed. The improvement is due to the predicted decline from 429 g CO_2/kWh (in 2010) to 210 g CO_2/kWh (in 2050).[4] This decarbonization of the power industry equates to a decrease of over 60 percent from 1990 levels (585 g CO_2/kWh in 1990).[5] The effect of best-practice sharing will be minimal.

Our modeling assumes that regardless of the way input-factor prices develop, the growing amount of scrap put on the market is fed to the BOF to a maximum rate of 20 percent in 2050, the remaining volumes being processed by the EAF plants. According to our estimation, the current BF-BOF and EAF production capacities are able to absorb the predicted 0.8 percent yearly production increase. Furthermore, the existing EAF production capacity is also able to cope with the predicted rise of the EAF share, in particular through the normal pace of incremental productivity increases and installation overhaul. Our modeling also assumes that scrap quality issues will not be a limiting factor in the partial shift from iron-ore-based steel to scrap-based steel. However, this assumption could be challenged because the continued increase in EAF steel is likely to lead to a degradation of the quality of domestic scrap.

Lower Boundary Point C (Theoretical Maximum-Abatement Scenario without CCUS). The projection of 184 Mt CO_2 assumes the implementation of all available technologies to the maximum technological extent possible (without CCUS). Because scrap EAF is the route with the lowest specific-CO_2 emissions, we project the maximum share possible—44 percent—on the basis of the availability of scrap. Although it might appear that producing all the EU27's steel from scrap would be the best way to cut emissions, this is materially impossible. First, there is not enough scrap, and second, its composition (that is, the quality mix) does not enable the production of certain steel qualities required by, for instance, the automotive industry. This leaves 56 percent to be divided among BF-BOF, DRI-EAF, and SR-BOF.

Over the past four decades the BF-BOF route has made significant progress in energy and material efficiency as well as in process control. Best performers in the EU are operating at close to optimum levels. This leaves only limited room for further improvement. Among the alternatives to the BF-BOF route, DRI-EAF stands out, with a CO_2 intensity about 36 percent lower than BF-BOF. Smelting reduction—without CCUS—is not an option, as it shows a higher CO_2 intensity. Detailed specific emissions per ton of crude steel for each production route can be found below.

Our assumptions for the lower boundary (see Point C in Exhibit 6) are as follows:

- DRI-EAF is the only technologically feasible CO_2-emission-reducing alternative steel-making technology based on virgin ores. Smelting reduction without CCUS has to be ruled out because its CO_2 intensity is higher than that of BF-BOF.[6]

- For the technological frontier (lower boundary), DRI-EAF is assumed to gradually replace BF-BOF, by 2050, accounting for 80 percent of production by the two routes—45 percent of total output, as opposed to 11 percent for BF-BOF. DRI-EAF will have a specific CO_2 intensity of 1.2 t CO_2 per ton (36 percent lower than that of BF-BOF) in the base-line year of 2010 in the operation mode, with 80 percent cold DRI and 20 percent scrap charge to the EAF.

- The DRI-EAF process of steel making is based on the reduction of pellets and lump ores. Pellets are not usually produced inside EU27 nations; generally they come from close to mining sites in other parts of the world. A shift from BF-BOF to DRI-EAF would lead to the closure of EU27 sinter plants, because sinter cannot be used in DRI production. So as not to "sugarcoat" the emissions of the DRI-EAF, the pellets likely to be produced outside the EU27 are included with an upstream burden of 105 g CO_2 per ton of pellet, according to EUROFER computations.

- The shift from BF-BOF to DRI-EAF, without efficiency improvements in the DRI-EAF route, would reduce total emissions in 2050 by 62 Mt CO_2 compared to Point B (realistic upper boundary).

- Hot charging of DRI is assumed to be a common practice by 2050,[7] saving around 100 kWh at the EAF process step and leading to an emission reduction of roughly 2 percent. Because of a larger share of renewables in the energy mix, improved electrical emissions per kWh electricity enable a further 15 percent reduction in specific emissions, to 1.0 t CO_2 per ton by 2050. In total, this would reduce absolute emissions by a further 21 Mt CO_2.

Although the route shift would account for the bulk of the reduction in emissions, there would also be efficiency gains from existing routes:

- In Scrap-EAF, a 45 kWh improvement in process efficiency would shrink specific emissions from 341 kg per ton at Point B to 330 kg. This 3 percent reduction would produce a saving of about 1 Mt CO_2.

- In BF-BOF several incremental technologies are available, ranging from heat recovery at sinter plants to better use of process gases. These technologies enable the generation of electricity or savings in input materials such as natural gas. (See the section "Technology Assessment" later in this chapter for more details.) They would cut specific emissions from BF-BOF from 1.78t CO_2 per ton (upper-boundary Point B) to 1.66t by 2050, a reduction of 6.7 percent. But the decrease in BF-BOF production volume over this period means that the absolute saving would be only about 3 Mt CO_2.

Even in the unlikely event that this maximum-abatement scenario is fully implemented, the reduction in absolute emissions to 184 Mt by 2050 represents an improvement of 38 percent, barely halfway to the EU target of 80 percent. This makes it clear that the EU's goal cannot be attained by route shifts or efficiency gains alone. Shifts in volume could also have an impact. Lowering production by 1 Mt of crude steel would, we calculate, reduce emissions by 1.14 Mt at Point B and 0.78 Mt at Point C. But even if EU27 output were to fall back to 2009 levels by 2050—an outcome we regard as neither likely nor desirable—the maximum-abatement scenario, which would also become less likely because a declining industry would struggle to justify the investment needed to make it reality, would still fall short of the 80 percent European target.

Our calculations of upper and lower boundaries for 2030 represent much more than a tidy midpoint of the period under examination. They indicate an improvement of around 28 percent over 1990 under the best-case, lower-boundary scenario. The vital point underlined

by this result is that CO_2 abatement is not linear. This is because the adaptation of new technologies, best-practice sharing, and incremental improvements is not instant. Instead, CO_2 abatement follows an S-curve, with slow adaptation in the beginning, rapid progress once a critical point is reached, and a slowing once saturation is attained.

The year 2050 might seem a long way ahead, but given slow adaptation (the S-curve), it is not. In other words, 2050 is just a couple of investment cycles away. This is underlined by considering the implications of Points A, B, and C in our projections for 2050. The two upper boundaries represent efficiency gains and shifts within the steel industry that are covered within general investment strategies and cycles. They, and in particular Point B, represent the continuation of current trends and strategies.

There are additional considerations regarding the specific CO_2 intensities of the different routes that should be noted. (See the sidebar "Considerations About the Comparison of the Routes' Specific CO_2 Intensities.")

Economic Scenarios. Although the previous section explains what is theoretically possible, any potential changes will be subject to the basic test applied to any innovation in a market economy: economic feasibility. The limitation imposed by the availability of high-quality scrap on the most CO_2-effective route—the Scrap-EAF—leaves two realistic means of further reducing CO_2 emissions:

- Replace the existing BF-BOF route with other, low-carbon routes.
- Implement incremental technologies in order to lower CO_2 emissions in the existing routes.

Any analysis of economic feasibility must take into account Europe's current overcapacity in the BF-BOF route. (SBB, 2013) This means that existing capacity is likely to be more than sufficient to meet demand in the EU27, so a technological switch to DRI-EAF would entail massive investment, not only in new DRI-EAF plants but also in the decommissioning of existing BF-BOF facilities. A further consideration is that Europe's high population and building density, combined with existing plant infrastructure, means that any new plant is likely to be a brownfield construction on a current site rather than to be situated on scarce greenfield space. So, existing facilities would have to be dismantled first to allow new facilities to be installed. Even where greenfield construction is possible, there would still be significant shutdown costs—many of them due to environmental regulations—for existing plants.

Alternative Steel-Making Routes. Our economic feasibility assessment is focused on the cost side, comparing operating expenses (OPEX) and the capital expenditures (CAPEX) for the alternative technologies. They assume, given a similar product portfolio, that revenues are the same.

First, let's take a closer look at OPEX:

- Although the operating costs of smelting reduction are only marginally higher, they are significantly higher for alternative production via DRI-EAF than for BF-BOF.[8] (See Exhibit 7.)
- Additionally, DRI-EAF has a greater share of input factor costs (raw materials, electricity, natural gas, and so forth)—more than 90 percent as opposed to roughly 75 percent for the BF-BOF and SR-BOF. Therefore input-material price increases would influence DRI-EAF OPEX in a disproportionally high way.
- BF-BOF and SR-BOF are influenced heavily by the price and availability of raw materials, such as coal to be used directly or for coke production, sinter feed for sinter production, and pellets or lump ores for the production of hot metal.
- DRI-EAF, by contrast, depends on pellet prices, along with the price and availability of natural gas and electricity.
- Electricity-intensive process routes, namely EAF, will be affected on the way to 2050 by the possible increases in the price of power that are related to the

CONSIDERATIONS ABOUT THE COMPARISON OF THE ROUTES' SPECIFIC CO_2 INTENSITIES

The specific CO_2 intensities for the different routes used to calculate the emissions for the different scenarios (Points A through C) are derived through bottom-up calculations using the same approach and boundaries as in the base line. (See the preceding section of this chapter, "Establishing a Base Line.") The results are conservatively calculated and consistent with previous findings. (Schenk, 2012) In addition to the numbers we have calculated, the following five additional factors influencing the routes' CO_2 intensity should be noted.

Byproduct Slag. As stated in the previous section of this chapter "Establishing a Base Line," slag is generated during the iron- and steel-making processes through the addition of fluxes so as to host impurities (in the form of oxides) separated from the iron burden. Slag from the BF and smelting reduction can be granulated for use in the cement industry, with subsequent CO_2 savings. The DRI-EAF process, on the other hand, does not generate such slag and therefore cannot claim such cross-sectoral CO_2 savings. Although there are processes that may help convert the DRI-EAF slag into more usable form (for example, the Zero-Waste ZEWA process), industrial-scale use and economic feasibility are still unproved. (Fleischanderl, 2004)

Approximately 215 kg of granulated slag was produced per ton of hot metal from the BF-BOF route in 2010. If the use of granulated slag is credited for specific CO_2 mitigation during cement production (557 kg CO_2 per ton of granulated slag), this would reduce specific CO_2 emissions per ton of crude steel by roughly 120 kg CO_2 per ton of hot metal or 108 kg CO_2 per ton of crude steel, assuming a hot-metal charge of 880 kg to the converter (BOF) and a yield factor from liquid to crude steel of about 98 percent. Smelting reduction generates larger amounts of slag (around 330 kg per ton of hot metal), leading to a reduction of 184 kg of CO_2 per ton of hot metal by way of slag credits.

Upstream Emission Factor for Iron Ores. As explained in the chapter "Steel Industry Overview and Development," iron- and steel-making processes depend on different types—lump ores, sinter, pellet feeds—and quantities of iron ores. Each generates differing CO_2 emissions from mining, grinding, and beneficiation. Lump ores and sinter feed have a similar emission factor of 41 kg CO_2 per ton of product, whereas pellet feed generates more than twice as much—94 kg CO_2 per ton of product. (Roth et al., 1999; VDEh analysis) This is because pellet feed must be ground into smaller grid sizes and it needs further chemical beneficiation.

So if these upstream emissions were to be taken into consideration, the specific emissions of the DRI-EAF—the highest user of pellets (80 percent)—would increase on average by 107 kg CO_2 per ton of crude steel (9 percent), whereas those of BF-BOF (32 percent pellets) and SR-BOF (100 percent fine ores) would go up only by 82 kg CO_2 per ton of crude steel (4 percent) and 54 kg CO_2 per ton of crude steel (2 percent), respectively.[1]

If the boundaries were extended to the scope described by the three aspects just mentioned, the specific CO_2 intensity of the DRI-EAF would be only 30 percent instead of 36 percent lower than the average BF-BOF of 2010. If it were to be compared with the best performing BF-BOF, the difference would only be 21 percent. (See the exhibit "Overview of How Different Modes of Operation Affect the Specific CO_2 Intensity of DRI-EAF and BF-BOF.")

Scrap Share. Because the emissions originating from the scrap charge are close to zero, specific emissions from any route can be lowered by increasing the scrap share. But there are bounds to this practice. As mentioned before, scrap availability is limited in quantity and quality: only a proportion of high-quality

CONSIDERATIONS ABOUT THE COMPARISON OF THE ROUTES' SPECIFIC CO_2 INTENSITIES (CONTINUED)

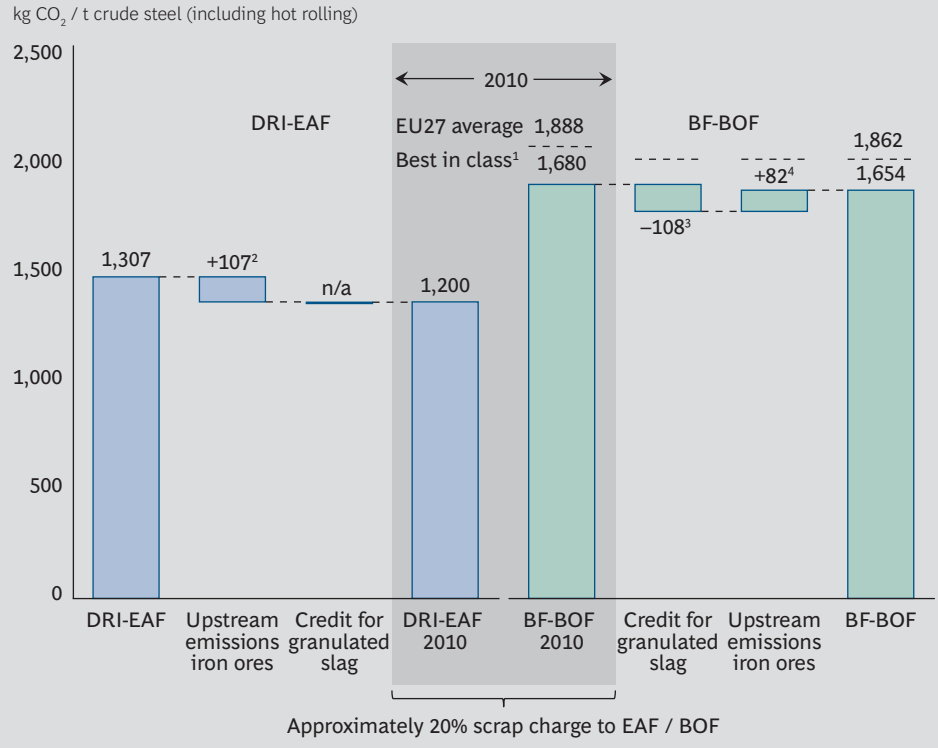
scrap exists for the steel grades required by certain customers.

Scrap is also required for the BF-BOF and SR-BOF routes as a coolant for the exothermic conversion process. The maximum acceptable scrap share is somewhere between 20 percent and 30 percent, with slightly below 20 percent being used in current practice. The lowest coolant share is around 6 percent.

Steel making by way of an EAF can equally be fed by scrap or DRI, so the amount of scrap or DRI can vary from zero percent to 100 percent. As shown in the 2010 base line, 100 percent scrap-feed EAF generates 455 kg CO_2 per ton of crude steel. An operation with 100 percent DRI would more than triple these emissions (1,376 kg CO_2 per ton of crude steel). To compare routes on an equal basis, we assume an across-the-board scrap share of 20 percent.[2]

Injection of Natural Gas into the Blast Furnace. The DR process relies heavily on natural gas as a reducing agent. Natural gas may also be used in the BF, replacing PCI. Its lower carbon and higher H_2 content leads to lower specific emissions for the BF

Overview of How Different Modes of Operation Affect the Specific CO_2 Intensity of DRI-EAF and BF-BOF



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
Note: The yield for casting liquid steel into crude steel is assumed at around 98 percent.
[1]BF operated in oil injection mode.
[2]Charge for direct reduction of 1,400 kg with 80 percent pellets and 20 percent lump ores leading to 117 kg CO_2 per ton of DRI and 105 kg CO_2 per ton of liquid steel.
[3]Assuming an average granulated slag volume of 215 kg per ton of hot metal and a credit of 557 kg CO_2 per ton of granulated slag.
[4]Assuming a BF charge of about 1,570 kg with 8 percent lump ores, 32 percent pellets, and 60 percent sinter leading to 91 kg CO_2 per ton of hot metal or 80 kg CO_2 per ton of liquid steel.

process step. However, keeping the flame temperature above 2,000 degrees Celsius requires the injection of more O_2. This leads to a reduction of specific CO_2 intensity of only 2 to 2.5 percent for the BF-BOF route.

Charging of HBI to the Blast Furnace. The use of HBI in a BF operation decreases the consumption of reducing agents in the BF process. The exchange rate between HBI and coke is approximately 0.27. This results in a coke reduction of 0.27 kg per ton of hot metal in case of one kg HBI per ton of hot metal being charged into the BF instead of other iron oxides. HBI can be used in a range of up to 250 kg per ton of hot metal. The smaller CO_2 emissions at the BF have to be netted against the CO_2 emissions from the HBI production. This limits the CO_2 saved at the BF—assuming a charge of 180 kg HBI—to about 55 kg CO_2 per ton of hot metal. (Buergler, 2012)

NOTES

1. The 2 percent applies to Finex, which is based solely on fine ores. For Corex, where 35 percent lump ores and 65 percent pellets are used, the specific CO_2 intensity would increase by 3 percent.
2. In the base-line year 2010, the BOF is charged with 81 percent hot metal and 19 percent scrap. In 2050, the scrap charge is assumed to be 20 percent.

continuing decarbonization of the power sector.

Second, let's look more closely at CAPEX:

- BF-BOF's greater infrastructure needs (coke, sinter, BF, and BOF plants) render its CAPEX for greenfield higher. (See Exhibit 8.)
- But because these plants already exist, they need only to be maintained through, for example, repairs, renewal of refractory linings, and modernization of the installations. (In this report we call this *retrofit BF-BOF*.)
- Thus, for practical purposes, retrofit BF-BOF requires less CAPEX than other routes.
- All prices exclude decommissioning costs for existing facilities. These can vary from €50 to €500 per ton of installed capacity, depending on the age and layout of the plant as well as on local construction and environmental regulations.

Under current conditions, replacing the integrated route in Europe is not economically feasible. This could be changed only if the following occurred:

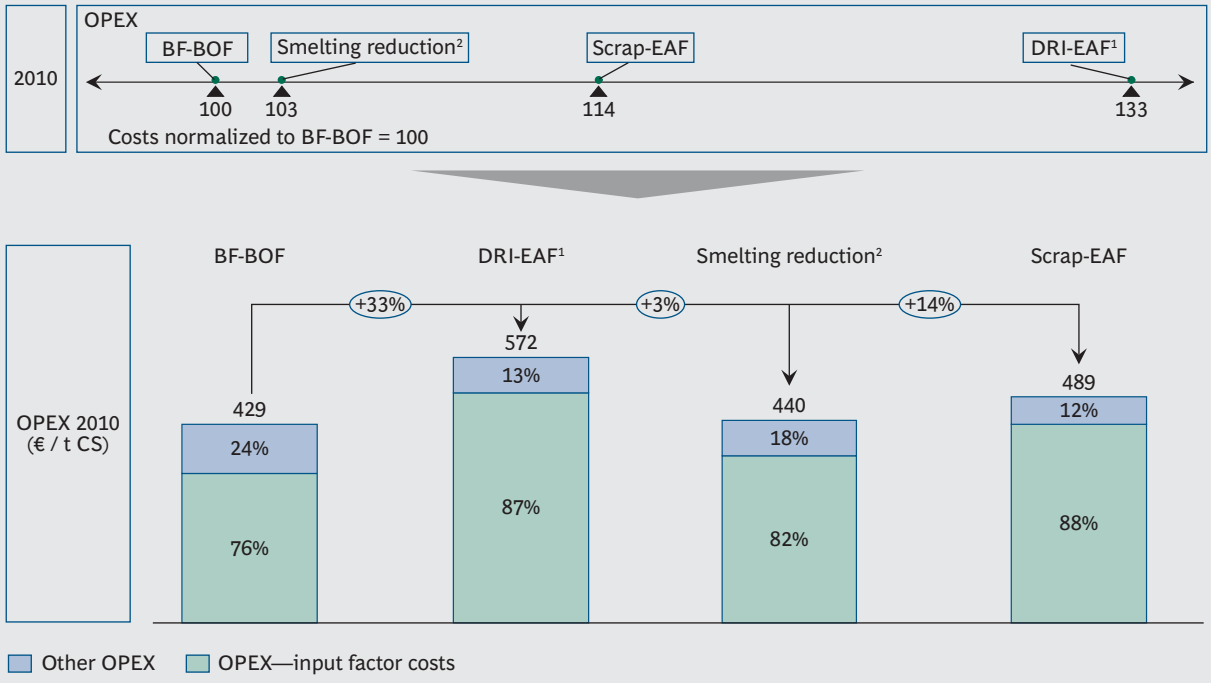
- Significant shifts in the prices of input materials
- CO_2 abatement costs offsetting the CAPEX/OPEX advantage of the BF-BOF route with the reduced emissions of the DRI-EAF

The latter would likely have an asymmetric effect on Europe alone. European steel could lose competitiveness if its CO_2 emissions had a price tag that did not apply elsewhere.

As already noted, the DRI-EAF route relies heavily on the price and availability of power and natural gas. Both input factors have a relatively high price in Europe but are cheaper in other countries, such as the United States, where shale gas extraction has led to rapidly declining natural-gas prices and pressure on the electricity price. However, this technology is heavily debated and environmental concerns are high.

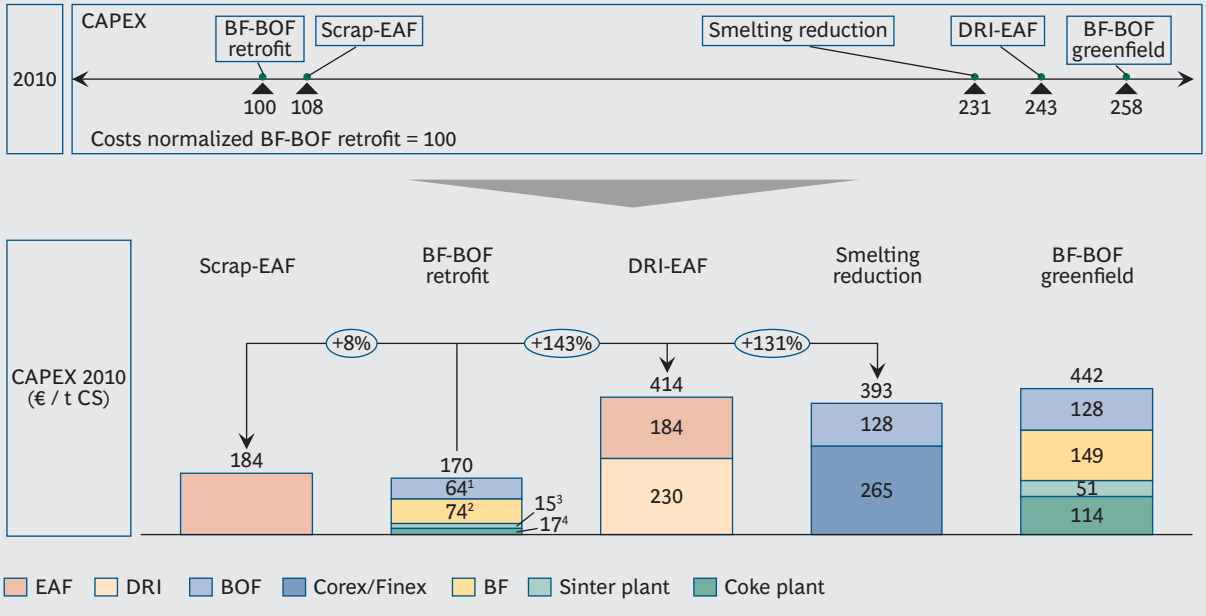
If we compare costs over an investment cycle of 15 years, with weighted average costs of capital (WACC) of 10 percent, and assume prices for natural gas and electricity at current U.S. levels, the OPEX difference would diminish, but not by enough to offset the CAPEX disadvantage. This would require the natural gas and electricity price to be even

EXHIBIT 7 | A Comparison of the Operating Expenses of Alternative Steel-Making Technologies



Sources: Steel Institute VDEh; project team analysis.
Note: CS = crude steel.
[1]Based on Midrex direct reduction technology.
[2]Based on Finex smelting reduction technology.

EXHIBIT 8 | A Comparison of Capital Expenditures for Alternative Steel-Making Technologies



Sources: Diemer et al., 2011; Steel Institute VDEh; project team analysis.
Note: CS = crude steel.
[1]BOF: 50 percent of Greenfield investment.
[2]BF: 50 percent of Greenfield investment.
[3]Sinter: 30 percent of Greenfield investment.
[4]Coke: 15 percent of Greenfield investment.

lower, close to zero—below zero, if we include decommissioning costs.

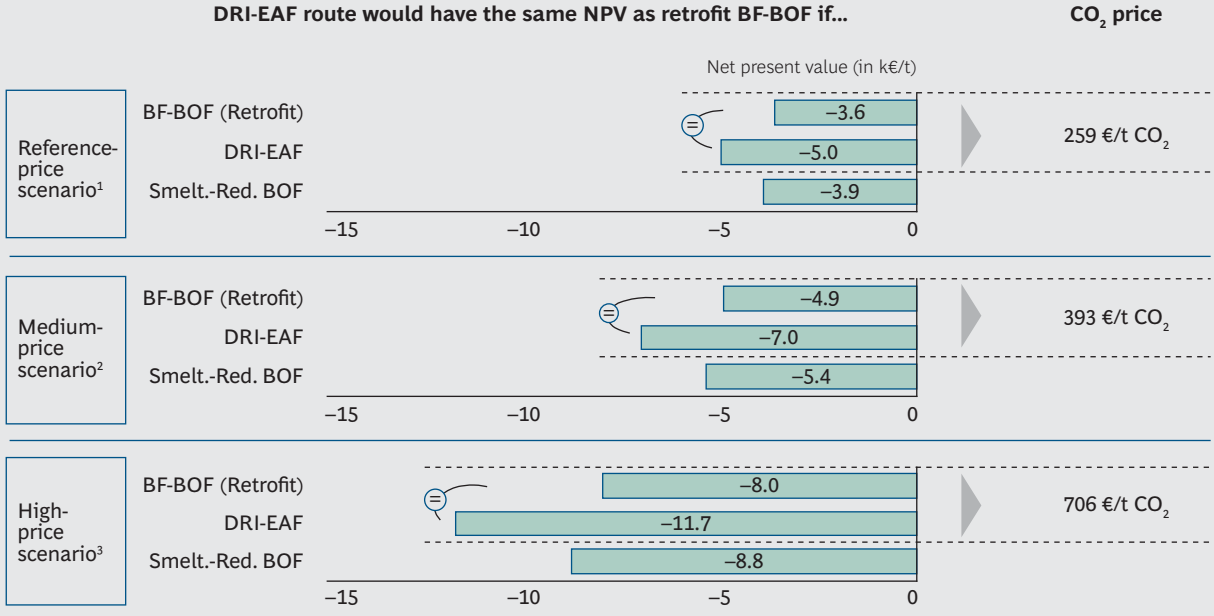
Europe is unlikely to see U.S. price levels, let alone levels close to or below zero. Electricity prices in Europe are high and may increase steadily in light of the EU decarbonization objective and the corresponding investments in infrastructure and renewables. Gas prices in Europe also remain highly uncertain, especially considering public acceptance of shale gas explorations.

The abatement costs for CO_2 for the same investment cycle would have to range between €260 and €700 per t of CO_2, depending on the input-factor price increase (also excluding decommissioning costs). The higher input factor prices go, the higher CO_2 abatement costs need to be to offset the CAPEX and OPEX disadvantage of the DRI-EAF route. Exhibit 9 shows the comparison of the different production routes and the corresponding CO_2 abatement cost per scenario.

Incremental Technologies That Improve Existing Routes. Incremental technologies build on existing technology, improving the CO_2 balance of BF-BOF or Scrap-EAF steel production. Their application goes beyond the best-practice sharing considered for Point B (realistic upper boundary), thus helping further reduce emissions in the option space. For a detailed description of these technologies, see the next section, "Technology Assessment."

- Of the eight potential technologies considered, seven are already commercially available and partly implemented, and we assume the other (top gas recycling blast furnace, or TGR-BF) will be commercially available in 2035.
- Only one incremental technology—the improvement of process efficiency, reducing electricity consumption by up to 45 kWh per t of steel produced—has been identified for the Scrap-EAF route.
- The other technologies apply to the integrated route. Either they save natural gas or electricity by (1) recovering heat or chemical energy (sinter-plant-cooler heat

EXHIBIT 9 | DRI-EAF Comparable to Retrofit BF-BOF for CO_2 Price Between ~260€/t–~700€/t, Depending on Price Scenario



Source: Project team analysis.
Note: NPV calculated assuming weighted average cost of capital (WACC) of 10 percent and an investment cycle of 15 years.
[1]Input factor prices adjusted for inflation.
[2]Doubling of (real) input-factor prices from 2010 until 2050.
[3]Fivefold increase of (real) input-factor prices from 2010 to 2050.

recovery, coke dry quenching [CDQ], and BOF gas recycling) or (2) generating electricity (BF top gas pressure recovery turbine), or they improve the process by reducing input factors (injection of natural gas or of coke-oven gas [COG] as an H_2 rich reductant, 100 percent pellet-operated BF, or TGR-BF). Efficiency gains in process-gases-fired power plants are not included in the scope of this study.

- We analyzed likely outcomes using two-step logic: We first determined economic feasibility under different price scenarios. We then gradually implemented the economically feasible technologies on the basis of varying adaptation curves for the different scenarios.

- We computed the economic feasibility of the four energy-recovery measures and the EAF process-efficiency improvement by comparing the costs (CAPEX and OPEX) with the potential savings over an investment period of five years with a WACC of 10 percent, depending on different price scenarios. The scenarios included inflation only (reference-price scenario), a doubling of real input factor costs (medium-price scenario), and a fivefold increase of input factor costs (high-price scenario).

- We found that sinter-plant-cooler heat recovery, BF top gas pressure recovery turbine (TRT), and EAF process-efficiency improvement are feasible in any of the scenarios, whereas BOF gas recycling and CDQ become feasible only in the high-price scenario where input factor prices increase fivefold in real terms by 2050.

- We assumed that the remaining three productivity improvements (Optimization of pellet ratio to BF, injection of H_2 rich reductants, and TGR-BF) will be implemented as incremental modernization measures. We calculated their feasibility on the assumption that the extent of adaptation will depend on prices.

Summary of All CO_2 Abatement Scenarios Without CCUS. In the maximum-abatement scenario, 38 percent of CO_2 emissions can be saved compared with 1990 levels, largely through a massive shift from the BF-BOF route to DRI-EAF steel production. The economic assessment clearly showed that this shift is not economically feasible in any of the scenarios investigated for two main reasons: First, large investments in new infrastructure and decommissioning of existing plants would be needed. Second, under current price scenarios, the operating costs of the DRI-EAF route are about one-third higher than those of the traditional BF-BOF route.

Hence, in the absence of DRI-EAF being economically viable, the emission reduction over Point B is driven by incremental improvements of EAF and BF-BOF steel making, leading to an additional improvement of up to 5 percent by 2050. This, though, equates to an absolute emission figure for 2050 that is only 10 to 13 percent lower than in the1990s. (See Exhibit 10.)

Exhibit 11 summarizes the change in average specific CO_2 intensity for each of the scenarios already described. By neutralizing the volume effect, it is possible to see that specific emissions can be reduced by about 25 to almost 50 percent from the base-line year of 1990.

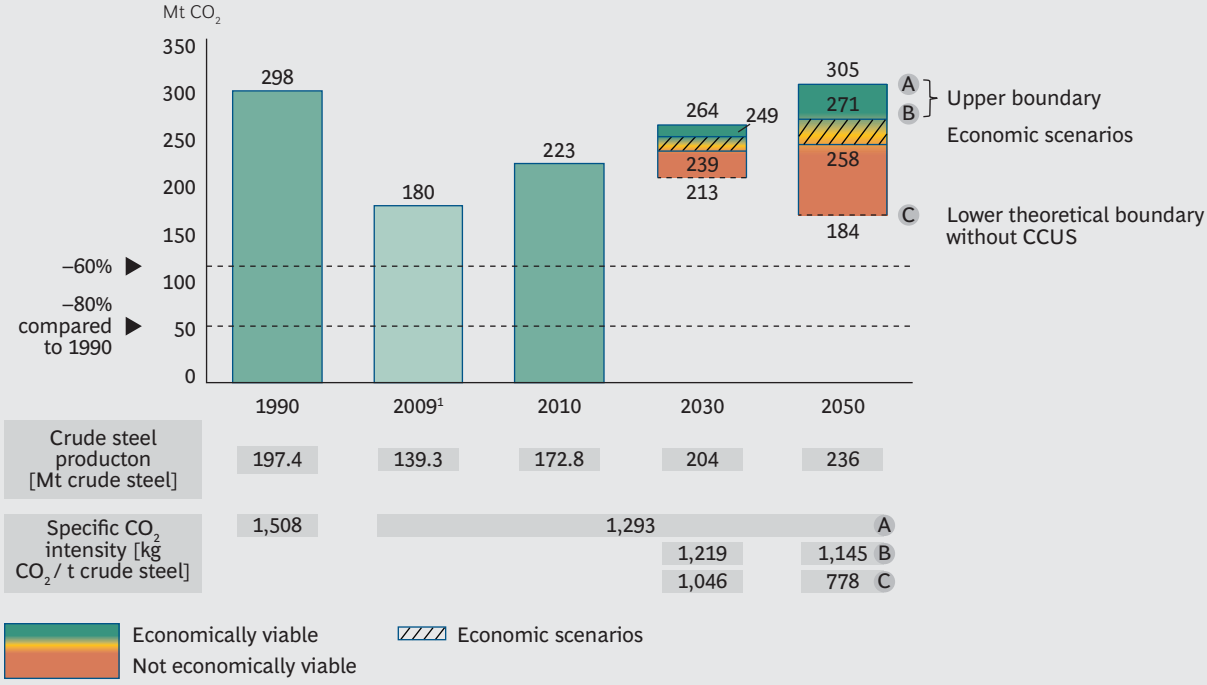
CO_2 Abatement Scenarios with CCUS. CCUS is widely regarded as a potential big driver for CO_2 emission reduction. For a number of reasons, the analysis of its impact, however, suggests only limited potential in the steel industry.

For one thing, not all routes are equally susceptible to CCUS. That is, the relative decrease of the specific CO_2–emission-reduction potential per ton of crude steel is not equal.

- While smelting reduction offers the greatest potential for CO_2 emission reduction in relative terms (about 70 percent)—because the gas in the reduction process has a high CO_2 content, making it easier to separate, store, or use—it has higher CO_2 emission amounts than other routes to start with.

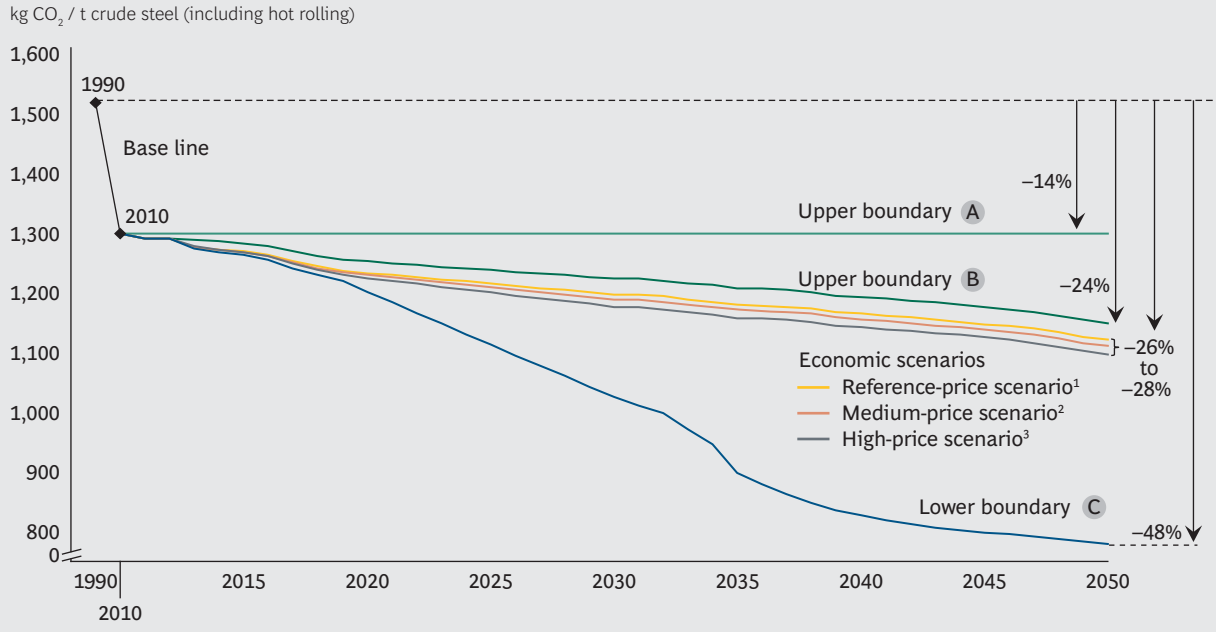
- The potential for CO_2 emission reduction in DRI-EAF is comparatively low, because

EXHIBIT 10 | CO_2 Abatement Economic Scenarios for 2050: Around 10–13 Percent as Compared with 1990s (Close to Point B)



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
[1]2009 crude-steel production with 2010 CO_2 intensity and 2010 Scrap-EAF share.

EXHIBIT 11 | Development of Average Specific CO_2 Intensity for Different Scenarios Without CCUS



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
Note: All scenarios are without CCUS.
[1]Input factor prices adjusted for inflation.
[2]Doubling of (real) input-factor prices from 2010 until 2050.
[3]Fivefold increase of (real) input-factor prices from 2010 to 2050.

the EAF process step is assumed to have no CCUS opportunities, the DR process offers savings similar to those of smelting reduction, and the total DRI-EAF process, with CCUS, could achieve about a 25 percent savings.

- Although the Scrap-EAF starts with the lowest specific emissions, we assume it offers no further potential with the help of CCUS.

- The potential for CO_2 emission reduction in BF-BOF ranges from 25 percent for existing plants to about 50 percent for TGR-BFs, for which cleaning of off-gases to be stored or used is fairly easy. (Birat et al., 2008)

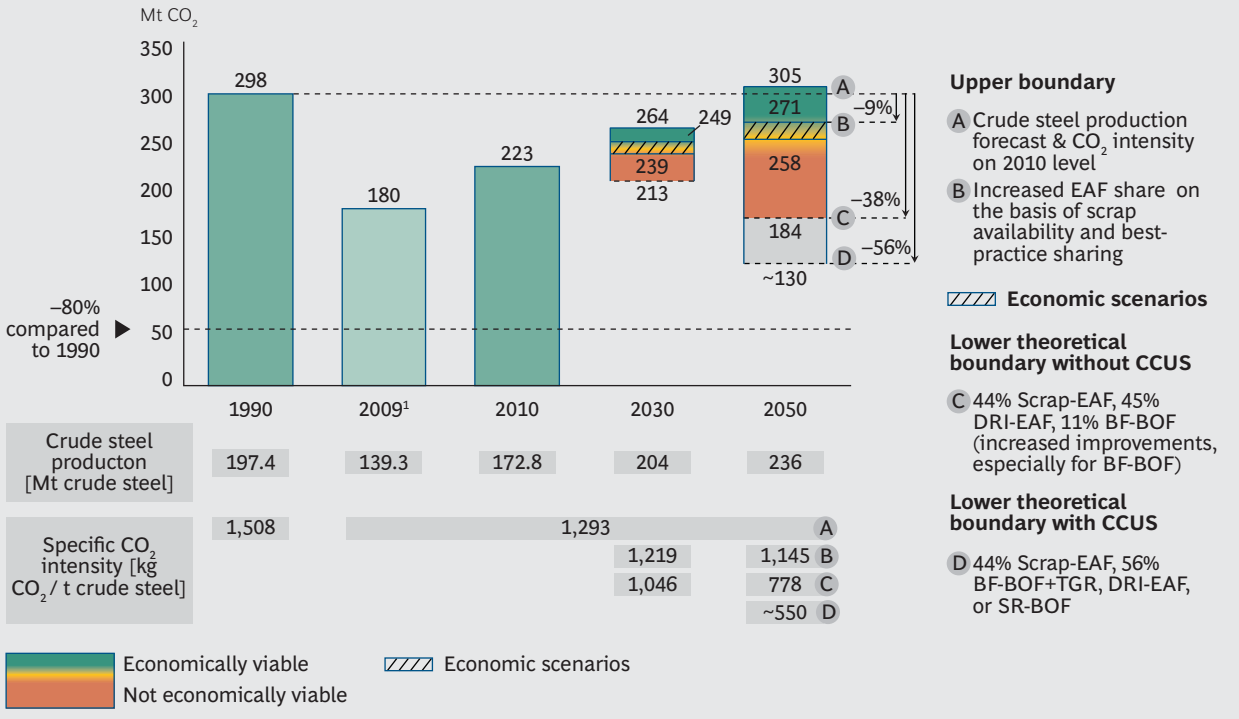
However, in absolute terms, the relative specific final CO_2 emissions per ton of crude steel produced with CCUS is almost the same for all production routes: for BF-BOF and DRI-EAF, about 750 kg CO_2 / t of crude steel, and for SR–BOF, about 700 kg CO_2 / t of crude steel.

Everything stated here assumes the availability and full implementation of CCUS in 2050. This is itself a very optimistic assumption, given that availability is not expected until around 2030 and a relatively long S-curve adaptation would apply. Using this assumption as a basis, the maximum reduction potential with CCUS would lead to about 130 Mt in CO_2 emissions in 2050, independent of the production route, in addition to the 44 percent Scrap-EAF production. (See Exhibit 12.) This is equal to average specific emissions of about 550 kg CO_2 / t of crude steel produced.

The overall potential of CCUS on top of the other technological improvements is unlikely to be sufficient, in light of the 80 percent reduction target. It should also be considered that in some areas of the EU27, the storage of CO_2 can be implemented more easily than in others, largely depending on geographic and geological conditions.

As mentioned, all three virgin-iron unit-based technologies under consideration lead to sim-

EXHIBIT 12 | Absolute CO_2 Emissions in 2050 Could Be Almost 60 Percent Lower Than in the 1990s with the Full Implementation of CCUS



Sources: EUROFER Benchmark 2007/2008; VDEh data exchange 1990/2010; project team analysis.
[1]2009 crude-steel production with 2010 CO_2 intensity and 2010 Scrap-EAF share.

ilar specific CO_2 intensities and similar abatement potentials with CCUS.

However, the implementation of carbon capture and storage (CCS) technology relies on the availability of a widespread safe infrastructure (pipelines and storage facilities) that is highly capital intensive. Besides the investment cost for such technologies, ongoing operating costs would also have to be considered. Placing the burden solely on EU27 steel producers would have asymmetric and significantly adverse effects on the global competitiveness of EU27 steel players, as shown in Exhibit 9. Even for Scrap-EAF, the deployment of CCS technology could lead to significant cost increases, if costs are passed on through electricity prices by the power sector. As a consequence, the implementation of CCS may be possible only through a joint effort by all industries as well as public authorities, given the high investment needs. With regard to CCU (carbon capture and usage, or sequestration of carbon into chemical products), the uncertain economics and the rather limited range of applications suggest that the corresponding abatement opportunities will remain modest.

The Possible Effect of a Significant Drop in CSP. It is important to consider the potential consequences of a substantial drop in CSP.

- If production fell to the level of the crisis year 2009—that is, 139 Mt crude steel—the lower boundary would be at 108 Mt CO_2—a 64 percent reduction from the 1990 levels.
- With CCUS available, this would be around 86 Mt CO_2 (71 percent of 1990 levels).
- Volume would have to fall to 96 Mt crude steel, 70 percent of production in 2009, to reach the 80 percent target.

Such a drop in CSP is neither realistic nor desirable, because it would either mean that there is a lower steel demand and consequently a lower level of industrialization in Europe or that the demand is still high but the steel is instead sourced from outside the EU27. As mentioned before, the latter is likely to be even worse in terms of global CO_2 emissions (carbon leakage).

Technology Assessment

In this section, we give an overview of the technologies underpinning the CO_2 abatement scenarios just discussed. We explain how each scenario works, as well as its corresponding impact on CO_2 emissions. The scenarios can be divided into two categories: incremental technologies and alternative steel-making technologies.

- *Incremental technologies.* These build on existing technology, improving the CO_2 balance of BF-BOF or Scrap-EAF steel production, usually by enhancing energy efficiency. Their application goes beyond the best-practice sharing considered for Point B (realistic upper boundary), thus helping further reduce emissions in the option space. They can be installed "on top" of each other, but not all may be compatible with each other.
- *Alternative steel-making technologies.* These are large-scale innovations in the steel-making process—or combinations of them—that would require the replacement of existing capacity, the construction of new capacity, or both. Their application is essential in order to reduce total emissions below Point B and in the direction of Point C (lower boundary without CCUS), as shown in Exhibit 6 and Exhibit 12. But the extent of their adoption is likely to be determined by financial criteria because of the large capital investment implied.

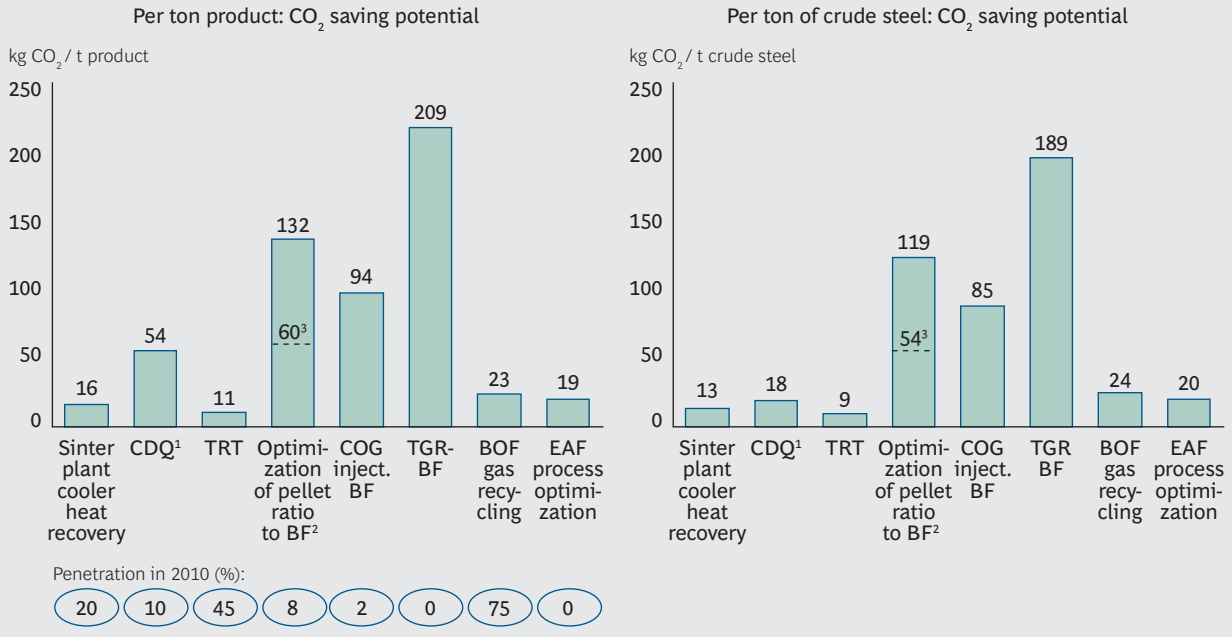
Because alternative steel-making technologies were described in the previous chapter ("Steel Industry Overview and Development") and analyzed for their abatement potential in the previous section of this chapter ("Abatement Scenarios for 2050"), we concentrate here on incremental technologies. In this conservative approach, we have not included technologies that are still being researched or developed, because these lack reliable data or may not be available on an industrial scale, and because their potential impact on emissions is uncertain.

Incremental Technologies. Exhibit 13 gives an overview of the potential impact of incremental technologies on the specific CO_2 intensity of the BF-BOF and Scrap-EAF routes. The values displayed represent EU27 averages for the base year 2010.

Agglomeration—Sinter-Plant-Cooler Heat Recovery. Sinter-plant-cooler heat recovery is a state-of-the-art technology already implemented in 12 out of 53 sinter strands in the EU27, accounting for approximately 20 percent of sinter production. The thermal energy from hot sinter can be recovered during cooling, generating approximately 280 MJ per ton of sinter. The energy can be used in several ways: preheating the raw-material mix fed to the sinter plant, preheating the combustion air of the ignition hood or blast-furnace hot stoves, and generating steam. Assuming that natural gas with an emission factor of 56 kg CO_2 per GJ is being saved through the recovered energy, a reduction of around 16 kg of CO_2 per ton of sinter would be achieved.

Agglomeration—Coke Dry Quenching (CDQ). Hot coke leaving the oven has traditionally being cooled by water (wet quenching). This leads to a loss of thermal energy. With CDQ, part of this energy can be recovered. Hot coke is loaded into a cooling chamber, where gas (nitrogen) is used to bring its temperature down. The nitrogen is used to produce high-pressure steam for electricity or other purposes. Between 100 and 150 kWh per ton of coke can be recovered through CDQ. On average, about 54 kg CO_2 can thus be recovered per ton of coke, assuming the average CO_2 intensity in 2010 of 429 g CO_2 per kWh. The limited use of coke in CSP by way of BF-BOF means that the overall effect per ton of crude steel is only one-third at 18 kg CO_2 per ton of crude steel. Abatement potential will also decline as the CO_2 intensity of the power sector decreases over time.

Exhibit 13 | Overview of the CO_2 Abatement Potential of Incremental Technologies



Sources: BFI; Steel Institute VDEh; project team analysis.
Note: The saving potential per ton of crude steel is calculated on the basis of respective material-input amounts as well as yield factors for each process step.
[1]It is sometimes argued that during wet quenching around 1 percent of the coke produced is lost because of burning when the coke is in contact with the surrounding air during transport to the quenching facility. This would reduce CO_2 savings from 54 to 22 kg CO_2 per ton of coke for 2010. Assuming a CO_2 intensity of 210 g CO_2 per kWh, this would even result in a negative CO_2 balance for CDQ of about 6 kg CO_2 per ton of coke.
[2]We assumed a 100 percent pellet ratio for calculations.
[3]If credits for slag were to be taken into consideration, this would reduce the effect of 100 percent pellet-operated BFs by 72 kg CO_2 per ton of hot metal (or 65 kg CO_2 per ton of crude steel) because of a lower slag volume of around 130 kg (based on operational plant data). Depending on the grade of pellets, fluxes—which normally are bound into the sinter–may have to be charged directly into the BF, which could increase CO_2 emissions from blast furnace operations. In optimizing the pellet ratio the tradeoff between operational benefits due to lower slag volumes and less CO_2 savings in the cement industry pertaining to slag have to be considered.

CDQ is employed in 5 of 128 coke batteries, accounting for approximately 10 percent of Europe's coke production, but it is more prevalent in Japan, South Korea, China, and Russia. The application of CDQ in Japan, South Korea, and China is driven by the scarcity of electricity within the countries themselves. In Russia it is propelled by the expected low temperatures in the winter time.

It can be argued that during dry quenching around 1 percent of the coke produced is lost to burning when the coke is in contact with the surrounding air during transport to the quenching facility. This would reduce CO_2 savings from 54 to 22 kg CO_2 per ton of coke for 2010. Assuming a CO_2 intensity of 210 g CO_2 per kWh, this would even result in a negative CO_2 balance for CDQ of about 6 kg CO_2 per ton of coke.

Blast Furnace—Top Gas Recovery Turbine (TRT). The blast furnace gas (BFG) at the top of the BF can have around 0.6-3 bars over pressure. Using an expansion turbine, this gas can be used to generate electricity at a rate of approximately 35 kWh per ton of hot metal. TRT is usually found in larger BFs and is incompatible with the TGR BF technology. Approximately 45 percent of hot metal is produced in BFs with TRTs. These current TRTs operate at 8 to 33 kWh per ton of hot metal, resulting in a weighted average of 18 kWh per ton of hot metal. Assuming the improvement of operational TRTs and construction of new ones, an average of 25 kWh per ton of hot metal can be recovered. Thus 11 kg CO_2 per ton of hot metal can be saved, assuming the average CO_2 intensity in 2010 of 429 g CO_2 per kWh. Abatement potential will decline as the CO_2 intensity of the power sector decreases over time.

Blast Furnace—Optimization of Pellet Ratio to BF-BOF. BFs are usually charged with an iron unit mix of lump ores, pellets, and sinter. Because the agglomeration of sinter is almost three times more CO_2 intensive than that of pellets, a substitution of pellets for sinter would decrease emissions. Several smaller plants within Europe (approximately 8 percent of the hot metal production) currently run on 100 percent pellets. Approximately 7 percent or 132 kg CO_2 could be saved per ton of hot metal.[9]

However, there are two restrictions on this technology. It has yet to be proved for larger BFs (greater than a 12m hearth diameter), and abandoning sinter production would mean a loss of flexibility in material handling and create the need for alternatives in order to handle iron, carbon, and flux-containing residual that are currently recycled in the sinter plant. Depending on the grade of pellets, fluxes—which normally are bound into the sinter—may have to be charged directly into the BF, and thus could increase CO_2 emissions from BF operations.

Blast Furnace—Injection of H_2-Rich Reductants (For Example, Natural Gas or COG). Using H_2 or H_2-rich gases instead of coke and injected coal as reducing agents in the BF can lower CO_2 emissions. For example, natural gas or COG from the coke plant, the latter of which has a high H_2 content (more than 50 percent), can be used for this purpose. Over 90 kg CO_2 per ton of hot metal can be saved through this method, which is currently used for less than 2 percent of hot metal production. The injection rate of H_2 gases is limited by the high H_2 content. The gas injected reduces the raceway adiabatic flame temperature (RAFT), which needs to be kept above 2,000 degrees Celsius, in the BF. Approximately 40 percent of COG is currently used as a fuel in the coke oven, with the rest usually fueling equipment such as boilers and reheating furnaces. If the COG has already been used for other purposes, it may increase emissions in other process steps. This depends on the layout of the steel mill and would have to be assessed individually.

Blast Furnace—Top Gas Recycling (TGR). Part of the blast furnace process gas (BFG) containing CO and H_2 can be recycled and injected, replacing coke or injected coal as a reducing agent in the BF. The technology is still under development and is not expected to be industrially available before 2035. Early indications are that it would reduce BF emissions by almost 20 percent, an overall effect of about 10 percent per ton of crude steel. Since BFG is cleaned to separate CO and H_2 for injection from the CO_2, TGR offers even greater potential once CCUS is available, because the CO_2 can be stored or used. With CCUS the specific CO_2 intensity can be cut by up to 50 percent.[10]

Converter—BOF Gas Recovery. The BOF process gas (BOFG) released in the conversion of hot metal into liquid steel in the BOF can be recovered and used to make high-pressure steam (the combustion method) and fuel to displace natural gas in other parts of the installation (the noncombustion method). In the combustion method, CO leaving the furnace is allowed to combust using large amounts of air, and the resulting hot gas is used to produce high-pressure steam. In the noncombustion method, conversion of CO to CO_2 (that is, combustion) is prevented. The sensible heat of the CO-rich off-gas is recovered in a waste-heat boiler, generating high-pressure steam. The gas is then cleaned, stored, and used as fuel; thus 0.77 GJ per ton of liquid steel can be recovered.

For more than 70 percent of Europe's steel production, BOFG is being recovered. The actual recovered energy for those plants amounts, on average, to 0.49 GJ per ton of liquid steel. Assuming both improvements of existing plants and construction of new ones, on average 0.42 GJ per ton of liquid steel can be recovered. This leads to an abatement potential of 23 kg CO_2 per ton of liquid steel, assuming that BOFG is replacing natural gas as a fuel with specific emissions of 56 kg CO_2 per GJ.

EAF—Process Optimization. Modern automation systems, based on dynamic-process models and continuous measurement of process data, are essential to the energy- and resource-efficient operation of EAF plants. Efficiency can be enhanced by improving the following: control of the chemical energy input, the post-combustion process inside the EAF; continuous online monitoring of the EAF energy balance; end-point control of the EAF tapping temperature; and content and process temperature control for the entire EAF route. Approximately 45 kWh per ton of liquid steel can be saved. This corresponds to an abatement potential of about 19 kg CO_2 per ton of liquid steel, assuming an average CO_2 intensity of 429 g CO_2 per kWh for 2010. The abatement potential decreases as the CO_2 intensity of the power sector diminishes over time.

Alternative Technologies. There are two main alternatives to BF-BOF and Scrap-EAF for reducing iron ores and producing steel: smelting reduction in combination with a converter (SR-BOF), and DR in combination with an electric arc furnace (DRI-EAF). These processes were explained in the previous chapter ("Steel Industry Overview and Development"), so we focus here on different technologies within each route.

Direct Reduction (DR). Two processes can be differentiated according to the raw materials used, as shown in Exhibit 1. Either lump ores and pellets are reduced in a shaft (Midrex, HYL), or fine ores are reduced in a fluidized bed (Finmet, Circored). Midrex, HYL, and Finmet use natural gas as a reducing agent, whereas Circored uses "pure" H_2. H_2 is not usually available, and its production uses energy (for instance, in the form of electricity), so it may be an alternative to natural gas only if the electricity is virtually CO_2 free. The melting process in the EAF also has to be adapted for Circored, as no carbon is transferred into the iron during reduction.

Although only one EU27 DRI plant exists, in Hamburg, there are 71 Midrex and 24 HYL plants worldwide. Because of this high penetration, Midrex and HYL were chosen to calculate the emissions of the "representative" DR route in the previous section of this chapter ("Abatement Scenarios for 2050"). Another shaft DR technology, ULCORED, is being developed by the ULCOS project. By changing process steps and modes of operation, ULCORED could potentially lower emissions. An experimental unit is under construction in Lulea, Sweden, but industrial scale and feasibility are yet to be proved.

One Finmet plant operates in Venezuela, and a Circored facility has been built in Trinidad but is not yet operating. Because of the limited penetration of these technologies and the consequent lack of reliable data, they have not been included in the abatement scenarios.

Smelting Reduction (SR). Smelting reduction processes depend on coal instead of coke (although some coke is still used for productivity and permeability reasons). Two processes, built on a shaft prereduction that is based on lump ores and pellets (Corex) and a fluidized bed prereduction that is based on fine ores

(Finex) in combination with a melter-gasifier, can be differentiated, as shown in Exhibit 1. For permeability reasons, the prereduced iron of the Finex plant must be compressed into hot compacted iron (HCI) before it can be charged to the melter-gasifier.

The process gas generated during smelting reduction can be used to generate electricity. It can be assumed that enough electricity can be generated along the value chain to make the SR-BOF route more than self-sufficient. Finex was chosen as the "representative" technology in the previous section of this chapter ("Abatement scenarios for 2050") because the specific CO_2 intensity of Finex is about 20 percent lower than that of Corex. Without CCUS both processes produce higher emissions than the BF-BOF route, but they have other advantages over DR and BF, particularly in dust generation (NO_x, SO_x) and waste water emissions. Seven industrial Corex plants are operating in China, India, and South Africa, and two Finex plants are in Pohang, South Korea.

The ULCOS project is also developing another smelting-reduction technology, HIsarna, based on fine ores. (The pilot plant is in IJmuiden, Netherlands). If industrial scale and feasibility can be proved, HIsarna could reduce process-specific emissions from smelting reduction by about 20 percent. (Meijer, 2011) In combination with CCUS, HIsarna's specific CO_2 emissions are expected to lessen by up to 80 percent. (Meijer, 2011)

Combination of Processes. There is some potential for combining different iron- and steelmaking processes. For example, COG could be used as a reducing agent in a gas-based DR plant. Similarly, process gas from smelting reduction could be utilized for the same purpose. Combining is being tested by ArcelorMittal in Saldanha Bay, South Africa. Any CO_2 saving is highly dependent on the complete energy balance of the site. If the process gas is used for DR, electricity may have to be purchased for other process steps.

Other Technologies Not Considered. Electrolysis is being examined as a possible iron-making technology by the ULCOS project (Ulcolysis, Ulcowin). However, because electrolysis processes rely exclusively on electricity, they would result in effective CO_2 savings only if the generation of electricity is virtually CO_2 free. It would produce "pure" iron, so carbon would have to be added in the steel-making phase. It is also worth stressing that in order to run a plant with a productivity equivalent of a midsize integrated plant, a power supply capacity of about 1 GW would be needed. As these projects are still in the laboratory stage, a pilot plant needs to be erected in order to give preliminary indications of technical feasibility and economic viability. Economic viability would rely on a competitive decarbonized power supply, among other things, in order to avoid cost distortions favoring global competitors.

Steel and Scrap Forecast

What follows is an assessment of steel consumption and production as well as scrap availability in the EU27 through 2050. The discussion includes the basis for each assessment and the methodology used to arrive at the forecasts.

Steel: The Context. One way to reduce CO_2 emissions in the EU27 would be to move steel production—or at least the liquid phase of steel making, which generates most of the emissions—out of Europe. But this is neither likely nor desirable.

The EU target has been set in response to global environmental concerns. Shifting steel production elsewhere would do nothing to reduce global emissions and could even increase them, because the resource efficiency of steel production in the EU27 is higher than in most other parts of the world.

We believe that steel is, and will continue to be, an important part of Europe's industry. Demand for steel is growing in absolute terms but with flattening speed. Countries will neither wish to deindustrialize nor be dependent on imported steel, although they will continue to value the employment and economic-output benefits a domestic industry brings.

Nor does steel offer the option, available in some manufacturing sectors, of concentrating on high-quality premium products and leav-

ing mass production to others. Cherry-picking of this sort would be short-sighted in strategic terms and risky for the industry as a whole, because it would reduce the ability to innovate while not guaranteeing sufficient long-term-capacity use levels.

Steel: The Forecast. We estimate that crude steel production in the EU27 (173 Mt in 2010) will grow to 204 Mt in 2030 and 236 Mt in 2050. (See Exhibit 14.) This represents an overall compound annual growth rate (CAGR) of 0.8 percent, driven by increased demand. It assumes that there will be no shift in steel production, with general industrial structures remaining the same, and no deindustrialization in the EU27, hence no "carbon leakage" outside Europe.

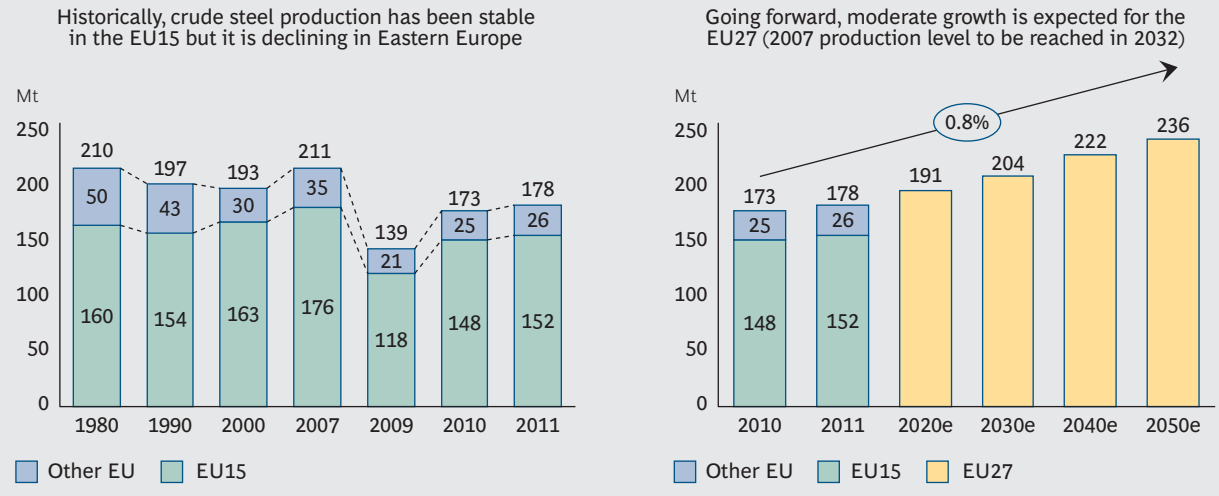
The figure is a conservative one. We do not believe that EU27 production will regain 2007 levels until 2032. Although a figure of 236 Mt for 2050 may appear high, it represents only limited growth—0.8 percent annually—over a 40-year period and can be achieved by productivity increases, as shown in Exhibit 14. It compares with the annual GDP growth for the EU27 projected by the Economist Intelligence Unit (EIU) at 1.6 percent over the same period, implying some efficiency increases and substitution of materials. (EIU, 2012) It is also small enough to suggest that existing capacity would be sufficient, assuming capacity creep—that is, productivity increases based on small modernizations.

There are also likely to be variations among different countries. Between 1990 and 2007, the EU15 showed a small but steady growth of 0.9 percent CAGR, whereas production elsewhere declined by almost a third because of the breakdown in the Eastern European countries. We predict very slow future growth for the EU15, whereas production elsewhere will increase as investment is made in Eastern Europe. For example, Polish steel consumption is projected to grow at 2.1 percent annually between 2010 and 2050, with still more rapid growth in other Eastern European EU nations. From its position as a net importer, we assume for simplification purposes that the EU27 will grow into a self-sufficient consumer of steel.

Steel: Methodology. To calculate these forecasts, we have applied the proven BCG methodology of steel intensity (SI) curves. Unlike a traditional steel per capita calculation, the SI curve has the advantage of accounting for the industrial structure of individual countries rather than only individual consumption by their residents. (See Exhibit 15.)

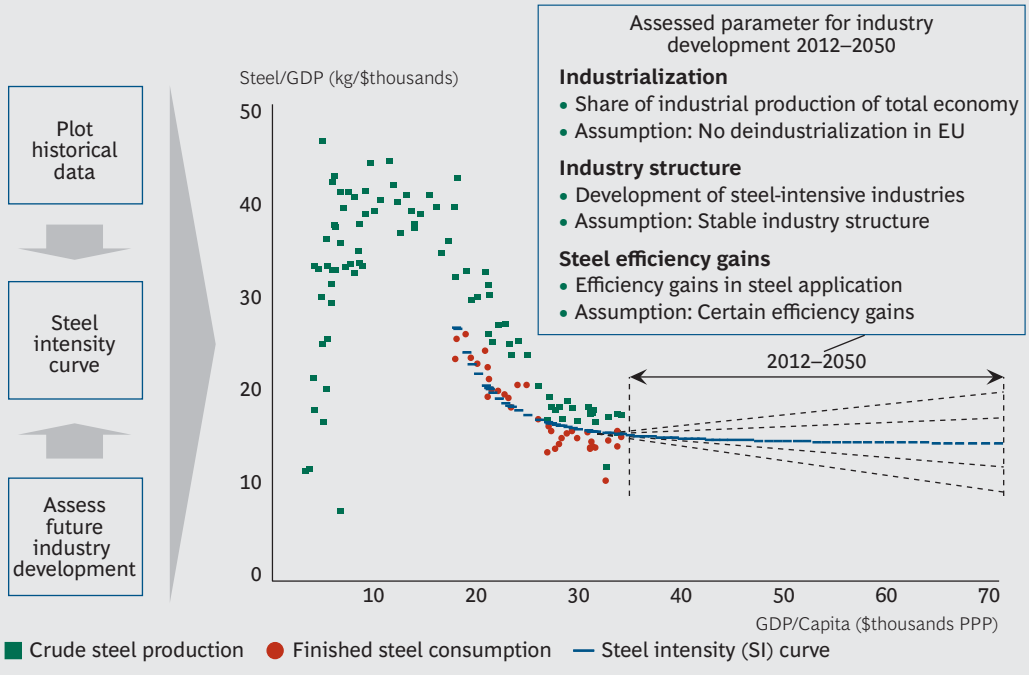
The methodology assumes that steel consumption follows a distinct path that depends on the affluence of an economy (measured in

Exhibit 14 | Moderate Annual Growth of Crude Steel Production Expected (0.8 Percent from 2010 until 2050)



Sources: World Steel Association; project team analysis.
Note: e = estimate.

Exhibit 15 | Steel Intensity Curves Used to Forecast Finished Steel Consumption per Country



Sources: World Steel Association; EIU; project team analysis.
Note: PPP = purchasing power parity

GDP per capita, shown on the x-axis). During its early development, steel consumption grows more rapidly than GDP, increasing the slope of the curve; but as affluence grows, steel consumption increases more slowly than the overall economy, decreasing the slope. This is because a country at the beginning of industrialization invests heavily in infrastructure, but at later stages, GDP has a wider range of drivers, including services.

SI curves were calculated for each country by using historical figures for finished steel consumption (FSC) in relation to GDP per capita and population. Our forecasts for FSC in 2030 and 2050 were calculated on the bases of population and GDP forecasts by the EIU and the United Nations (UN). The EIU and the UN predict that the EU27's population will stagnate between now and 2050. For GDP, the EIU projects modest growth until 2030. Extrapolating these figures until 2050, we project GDP growth of around 1.6 percent per year. (EIU, 2012)

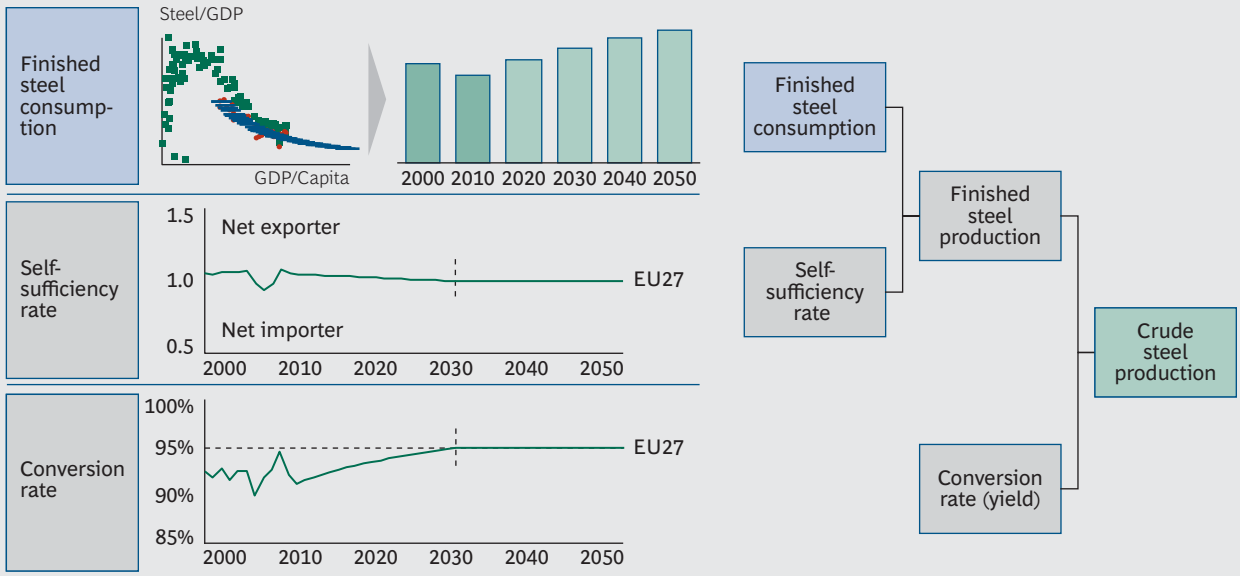
CSP and finished steel production (FSP) are both calculated from FSC. (See Exhibit 16.) We assume that the EU27 will move from its current position as a net exporter of finished steel to become self-sufficient from 2030 on, meaning that FSP and FSC will be identical in this period.

The difference between CSP and FSP depends on the conversion rate. The less steel is wasted during the process of manufacturing finished steel, the higher the conversion rate is and the lower this difference. We assume that the EU27 conversion rate will rise to 95 percent in 2030 and remain constant until 2050.

Scrap: The Context. Scrap is integral to steel production. Steel is, in principle, indefinitely recyclable and the world's most recycled material. Scrap is essential to low-carbon or low-CO_2-emission steel production, but the maximum share of scrap in steel making is limited because of the quantity and quality of scrap available. Aside from being melted directly in electric arc furnaces, scrap can be used as a coolant for high-quality production through the BF-BOF route (with a maximum of 20 to 30 percent scrap input).

Scrap: The Forecast. We project an annual growth in scrap availability of 0.9 percent in

EXHIBIT 16 | Overview of the Methodology Used to Compute Crude Steel Production from Finished Steel Consumption



Sources: World Steel Association; EIU; project team analysis.

the EU27 to 2050. (See Exhibit 17.) This would lead to 135 Mt being available that year, or 40 Mt more than in 2010. The projected annual growth rate for scrap is also a little faster than the predicted growth for steel production, creating some leeway for emission-reducing increases in the relative share of Scrap-EAF production or use as a coolant in BF-BOF. Increases will not, however, be spread equally across different types of scrap. We assume for our scrap availability forecast that Europe will be self-sufficient in scrap—that is, for simplification purposes (as scrap trade balances are difficult to estimate), being neither a net exporter nor a net importer from 2030 onward. It needs to be noted that the prospective scrap availability is subject to changes in the underlying trade conditions. As for scrap usage—discussed earlier—we assume the scrap is consumed first in the BOF (up to 20 percent) before additional EAF capacity is created.

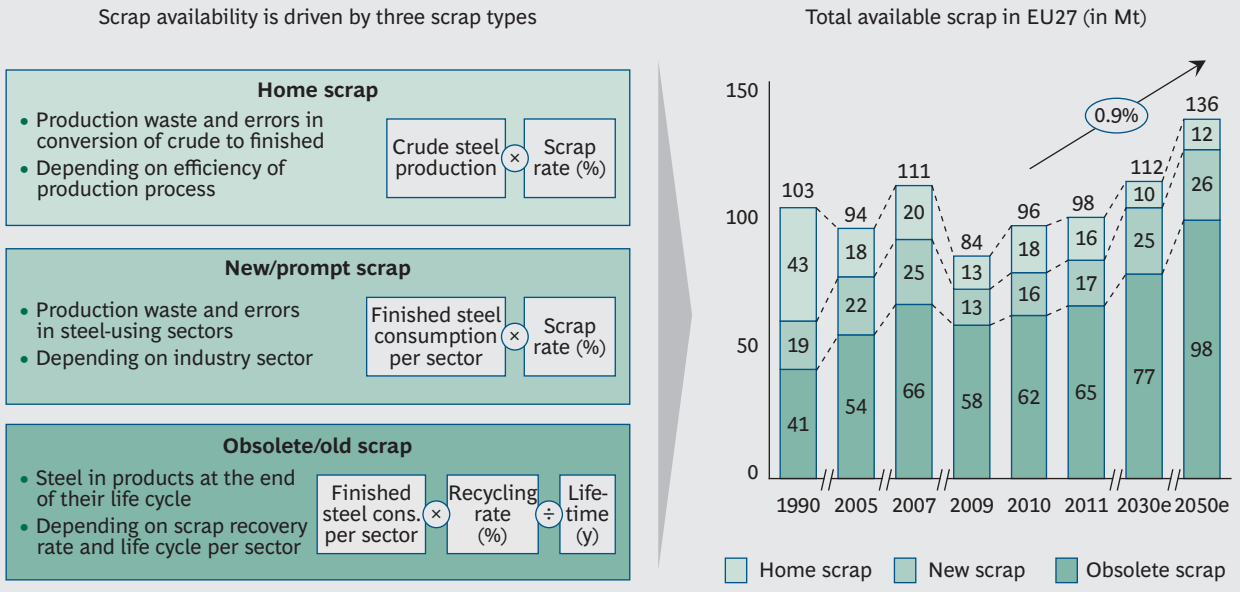
Scrap: Methodology—A Scrap Typology. Our forecast takes account of all the various important sources of scrap—obsolete, new, and home scrap—plus the balance of the scrap trade.

Obsolete Scrap. Obsolete scrap is defined as material from industrial applications—houses, cars, ships, and so forth—after the end of their economic lifetime. It accounts for around two-thirds of all steel scrap. Availability is expected to grow, largely because of increased finished steel consumption, with a surge starting in 2020 from an influx of construction scrap originated in the 1960s boom. Our calculations assume constant recycling rates (between 80 and 100 percent, depending on industry sector and region) and standard lifetimes (averages include 15 years for cars, 49 years for ships, and 75 years for construction) for each industry sector. This is a reasonable assumption because the high value of steel scrap creates incentives to maintain high levels of recycling.

New (or Prompt) Scrap. New scrap results from steel-based industrial manufacturing (for example, cut-off scrap). It currently accounts for about one-sixth of the total available scrap. We expect the availability of new scrap to rise steadily until 2030, when it will reach precrisis levels and then level off. New scrap growth rates vary sharply from industry to industry—as high as 25 to 30 percent in the automotive sector but close to zero in construction.

Home Scrap. Home scrap arises from steel production and therefore depends on the conversion factor, as shown in Exhibit 17. Be-

Exhibit 17 | Scrap Availability Forecasted to Grow by 0.9 Percent Annually until 2050, Mainly Driven by Obsolete Scrap



Source: Project team analysis.

cause we expect the conversion rate to rise to 95 percent by 2030, the availability of home scrap is likely to decline despite increased production of steel.

The reuse of steel products was not explicitly investigated for this report. Although Cooper and Allwood suggest that about 27 percent of finished steel could be reused instead of being melted and recycled, they also acknowledge that there are currently no reliable figures or analyses on the actual extent of reuse. Because of the uncertainty regarding the current and future state of reuse, the possibility of steel reuse was not considered in modeling scrap availability and subsequent scrap use for steel making. (Cooper & Allwood, 2012)

Notes

1. This BCG analysis is based on information from the International Energy Agency (IEA) historic, 2012 and IEA outlook, 2012.
2. This assumption can be quite complex in the specific case of a particular steel plant where a comprehensive assessment of the individual energy balance that considers the plant's specific layout and process depth is required. In the case of smelting reduction (SR-BOF), the route even produces excess process gas that can be sold, for example, to the power industry.
3. Investment decisions for alternative technologies might be feasible for a particular steel mill, depending on its process configuration as well as feedstock availability and price.
4. This BCG analysis is based on information from IEA historic, 2012 and IEA outlook, 2012.
5. An even larger decarbonization of the power sector would lead to further improvements in the steel industry.
6. Smelting reduction, however, offers other advantages—for instance, in terms of dust generation (NO_x, SO_x) and waste water emissions. See the section "Technology Assessment" in this chapter for more details.
7. The DRI is charged to the EAF immediately after reduction to take advantage of the thermal energy. Solutions already exist and are used in practice for both Midrex and HYL.
8. This statement applies to Finex as OPEX for Corex are higher.
9. This assumes that pellets are produced on-site, even if they are purchased outside the EU27. If credits for slag were to be taken into consideration, this would reduce the effect of BFs that are 100 percent pellet operated by 72 kg CO_2 per ton of hot metal (or 65 kg CO_2 per ton of crude steel) because of a lower slag volume of around 130 kg (based on operational plant data).
10. According to ULCOS computations.

STEEL AS MITIGATION ENABLER

Steel's emission impact does not end with its production process. As one of the most flexible and durable materials, it is used across an immense range of industries, thus affecting emissions related to all of them.

Innovative steel-based emission-saving applications may help reduce CO_2 emissions, through either the use of newly developed steel for efficiency improvements in existing applications (such as fossil-fuel power plants) or its utilization in innovative applications (such as offshore wind power). The amounts of CO_2 saved thereby are quite substantial compared with the emissions released by the steel-making processes. Therefore a holistic analysis of the actual impact of steel making on CO_2 emissions has to reconcile both aspects.

It is important not to overclaim for such impacts and to make sure that only savings that are 100 percent attributable to steel are taken into account. This chapter follows the practices laid down in BCG's earlier study of German steel CO_2 emissions, conducted jointly with the Steel Institute VDEh in 2009, but extends them to the whole of the EU27. (BCG & VDEh, 2009)

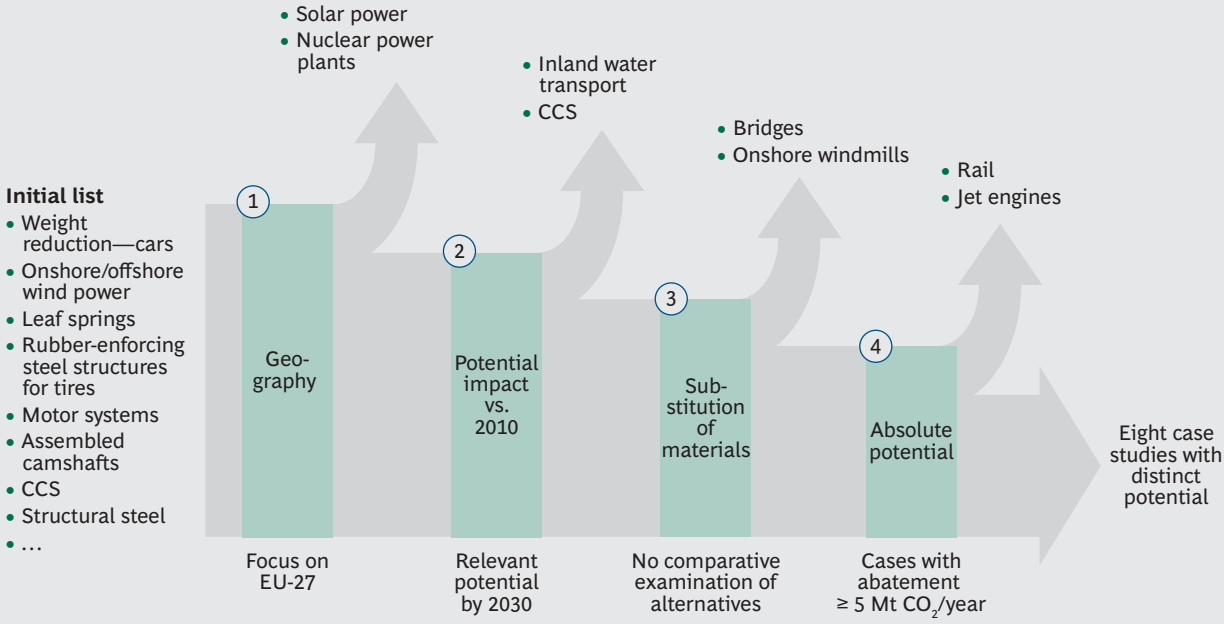
What Is Measured. The argument is limited to eight case studies that provide examples in which, to the best available knowledge, there is no alternative to steel for the application. (See Exhibit 18.) However, steel has an impact that goes beyond the eight case studies. For example, one could claim that steel contributes to energy-efficient building, yet it remains unclear if there are other, alternative materials available to accomplish the same thing. In this report, we kept to the narrower scope, taking into account, for instance, offshore wind parks, which can be built only from steel, but leaving out onshore windmills, which can be built from other materials as well.

We examined the cases over the period from 2010 (in line with our base line) to 2030. This is because reliable data is available only until 2030, and any extrapolation beyond that could have overestimated potential savings.

The eight case studies included the following: efficient fossil-fuel power plants, offshore wind power, other renewables (geothermal, biomass, hydro), efficient transformers, efficient e-motors, weight reduction—cars, weight reduction—trucks, and combined heat and power.

How It Is Calculated. The projection was derived by comparing savings in emissions resulting from the introduction of new or more efficient applications with the emissions arising from making the steel involved.

EXHIBIT 18 | Stringent Four-Step Logic Applied to Isolate the Case Studies for Evaluating Steel's Own Mitigation Potential



Sources: Steel Institute VDEh; project team analysis.

Production is assumed to be through the BF-BOF integrated route, generating an average of 1.89 t CO_2 per ton of crude steel produced. (See the section "Establishing a Base Line" in the preceding chapter for details.) BF-BOF production is assumed because of the high quality of steel needed, but it also generates a conservative estimate because the aforementioned figure is the emission rate for 2010. Efficiency improvements for the BF-BOF route are not assumed to use a conservative figure for CO_2 emissions by 2030.

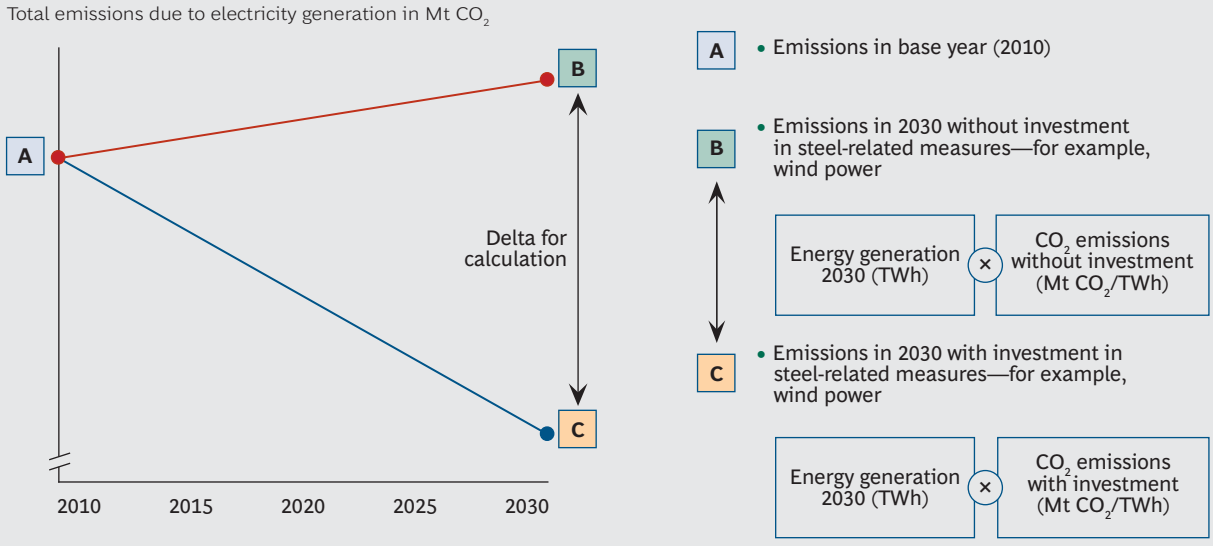
Exhibit 19, shows the computations conducted to assess potential steel-induced CO_2 savings relating to offshore wind power and renewables. Point A shows emissions in 2010. Point B shows a projected figure for 2030 if there are no steel-related measures to reduce emissions. And Point C shows what would happen if those measures (such as investing in a wind turbine) were implemented. The difference between Points B and C is the basis for calculating steel-related savings, although not all of the effect is attributed to steel because a combination of different materials may be used for certain applications.

The Results. Our projection is that the eight case studies combined would produce annual emission savings across the EU27 of around 440 Mt by 2030. (See Exhibit 20.) This savings has to be balanced against the additional 70 Mt of emissions resulting from production, which would create a positive net CO_2 balance of around 370 Mt.

The reduction-emission ratio in the region of 6 to 1 (440/70) echoes the outcome of a study on the impact of the steel industry on CO_2 emissions in Germany that BCG conducted on behalf of the Steel Institute VDEh in 2009. (BCG & VDEh, 2009) (See the sidebar "CO_2 Balance—Our EU27 Findings Compared with Our 2009 Study on Germany.") The greatest absolute saving would be generated by weight reduction in cars. The greatest proportionate improvement—that is, the relationship of saving from use and the emissions from the corresponding production—comes from efficient fossil-fuel power plants.[1]

EXHIBIT 19 | The Logic Underlying the Calculation of Steel-Induced CO_2 Savings

Example: CO_2 savings due to changes in energy mix—increased share of offshore wind-power plants



Sources: IEA, *World Energy Outlook 2012;* Steel Institute VDEh; project team analysis.

EXHIBIT 20 | Case Studies for EU27 Show Annual CO_2 Savings of About 440 Mt and Only 70 Mt of Extra CO_2 Emissions

Sources: Steel Institute VDEh; project team analysis.
Note: PP = power plant.
[1]Bioenergy.
[2]Net reduction refers to reduction attributable to steel.
[3]Refers to the emissions related to the amount of steel needed for the specific application.

CO_2 BALANCE—OUR EU27 FINDINGS COMPARED WITH OUR 2009 STUDY ON GERMANY

In 2009, in cooperation with the Steel Institute VDEh, BCG conducted a study of the impact of the steel industry on CO_2 emissions in Germany. The 2009 study employed a similar methodology, focusing on eight case studies and a consistent net balance of CO_2 reduction potential in a comparison of 2010 emissions figures with likely emissions in 2030.

The 2009 study, which was widely cited by industry leaders and policymakers, projected a similar overall 6 to 1 reduction-emission ratio (74 Mt/12 Mt), but with differences in the makeup of the benefits.

The EU27 employs more nuclear energy than Germany does, and gas plays a larger part in its fossil-power mix. As a result, there is a lower relative base for emission savings potential in the EU27.

The 2009 study on Germany found that efficient fossil-fuel power plants offered both the greatest absolute saving (29.5 Mt, close to half of the total for the eight cases) and the highest ratio of reductions to extra emissions (400 to 1). By contrast to the EU27 results, Germany offered little leeway for car weight reduction. This is because its car fleet is comparatively new and offers only limited potential for weight reduction, as opposed to the car fleets in some other countries (notably the newer EU members), which have a higher proportion of older vehicles.

NOTE

1. Although the greatest proportionate savings are associated with fossil power plants, their share in energy generation within the overall energy mix is expected to decline steadily until 2030. (IEA outlook, 2012)

A LOW-CARBON EUROPE 2050 IN TEN KEY POINTS

In conclusion, we highlight the ten key points presented in this report.

The following points capture the findings, documented by technical and economic analysis, that form the basis of our assessment of steel's contribution to a low-carbon Europe 2050.

Steel sector's own impact—base line

1. Emissions of CO_2 have fallen by around 25 percent in the EU27, from 298 Mt in 1990 to 223 Mt in 2010.

2. The reduction in CO_2 emissions was driven mainly by lower steel production volumes and the partial switch from BF-BOF to Scrap-EAF, which brought the Scrap-EAF share to 41 percent. It was caused—to a limited extent—by efficiency gains.

Steel sector's own impact—abatement scenarios for 2050

3. Steel production is expected to grow around 0.8 percent per year between now and 2050 (below the projected annual GDP growth rate) in order to meet the demand for steel in the EU27. This expectation assumes that the steel industry will continue to play a vital role in Europe (no deindustrialization, no carbon leakage).

4. The future scenarios for reduction in CO_2 emissions lie somewhere between two extremes: At one extreme, a continuation of the status quo, with specific CO_2 intensity and route splits remaining at 2010 levels—that is, 305 Mt CO_2, or an increase of absolute emissions by 2 percent over 1990 levels. At the other extreme, a theoretical, technologically possible but not economically viable, maximum-reduction scenario—that is, 184 Mt CO_2, or a 38 percent decrease over 1990 levels. In the maximum-reduction scenario without CCUS, this means a reduction from 1,293 kg CO_2 / t of crude steel produced (in 2010) to 778 kg CO_2 / t of crude steel produced (in 2050).

5. The Scrap-EAF route, which has the lowest specific CO_2 emissions, will increase its production share to a maximum of 44 percent by 2050, limited by the availability and quality of scrap.

6. The potential for incremental technologies to improve the specific CO_2 emissions of existing routes is limited. For BF-BOF, a maximum of around a 12 percent reduction would be possible. For Scrap-EAF, the maximum reduction is around 27 percent, driven mostly by the upstream emission factor for purchased electricity, which is expected to decrease by 50 percent from 2010 until 2050, or by more than 60

percent compared with 1990 levels (because of a higher share of renewables).

7. Only a massive shift from BF-BOF to DRI-EAF as an alternative steel-making technology could lower emissions to the theoretical lower boundary of 38 percent over 1990 levels. But such a shift is not economically feasible—not only because of the extensive investment needs but also because of higher operating costs (due to comparatively high natural gas and electricity prices in Europe).

8. From an economic perspective—in current circumstances—emissions could be reduced only by a combination of the following: shifting to Scrap-EAF (within the limits already described here), adopting best-practice sharing, and pursuing the improvement of existing routes through incremental technologies. This would bring absolute CO_2 emissions down from 1990 levels by a maximum of 10 to 13 percent and specific CO_2 emissions down per ton of crude steel produced by 26 to 28 percent.

9. The potential of carbon capture use and storage (CCUS) to further decrease emissions—beyond the maximum abatement scenarios without CCUS—is limited to another 54 Mt CO_2 in absolute terms (in addition to the scenarios already discussed here). In total, therefore, a reduction of almost 60 percent over 1990 levels could be achieved. The technological and economic feasibility of CCUS, as well as its ecological effects and public acceptance, are highly uncertain, though—especially in Europe.

Steel as mitigation enabler—emission reduction potential due to steel use in other sectors

10. Steel can make a real difference as a mitigation enabler. With its strength and durability, it enables savings in other industries. The eight conservative case studies demonstrate that CO_2 savings in other industries outweigh the emissions created by the production of the necessary steel at a ratio of 6 to 1—resulting in net savings of 350 Mt CO_2 per year by 2030. When looking at the potential emissions of the steel industry of 260 Mt to 305 Mt in 2050, the net savings (as illustrated by the eight case studies) fully enabled by steel alone are likely to exceed the total emissions of the steel sector.

LIST OF ABBREVIATIONS

BF	Blast furnace
BF-BOF	Blast furnace-basic oxygen furnace
BOF	Basic oxygen furnace
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture use and storage
CDQ	Coke dry quenching
CO	Carbon monoxide
CO_2	Carbon dioxide
COG	Coke-oven gas
CS	Crude steel
CSP	Crude steel production
DR	Direct reduction
DRI	Direct reduced iron
EAF	Electric arc furnace
EIU	Economist Intelligence Unit
ETS	Emissions trading system
EU	European Union
EU15	Member states of the European Union as of December 31, 2003
EU27	Member states of the European Union since January 1, 2007
EUROFER	European Steel Association
FSC	Finished steel consumption
FSP	Finished steel production
GDP	Gross domestic product
GJ	Giga joule
GVA	Gross value added
H_2	Hydrogen
HBI	Hot briquetted iron
HCI	Hot compacted iron
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kWh	Kilowatt hour
Mt	Million tons
O_2	Oxygen
OHF	Open-hearth furnace
OPEX	Operating expense
PCI	Pulverized coal injection
PPP	Purchasing power parity
RAFT	Raceway adiabatic flame temperature
SI	Steel intensity
SR	Smelting reduction
SR-BOF	Smelting reduction-basic oxygen furnace
t	Ton
TGR	Top gas recycling
TRT	Top gas recovery turbine
ULCOS	Ultra–Low Carbon dioxide (CO_2) Steelmaking
UN	United Nations
VDEh	Steel Institute VDEh
WACC	Weighted average cost of capital

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NOTE TO THE READER

This study was prepared independently by The Boston Consulting Group (BCG) and the Steel Institute VDEh on behalf of EUROFER, the European Steel Association.

The purpose of the study is to provide an objective evaluation of steel's contribution to a low-carbon Europe 2050. Although all appropriate measures have been taken to ensure the accuracy of the information presented herein, BCG and VDEh make no representations or warranties about the correctness of the statements and assume no liability for errors or omissions. The results of this study should not be used unrestrictedly without independent analyses, for which BCG and VDEh assume no liability.

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