WAYS TO REDUCE CO_2 EMISSIONS IN IRON AND STEELMAKING IN EUROPE

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ABSTRACT

The key ways to reduce CO_2 emissions in iron and steelmaking can be summarized under the general terms “Smart Carbon Usage” (SCU) and “Carbon Direct Avoidance”. SCU covers on the basis of carbon carriers as reductant incremental measures at the conventional blast furnace converter route and the CO_2 mitigation measures by applying so-called “end-of-pipe” technologies like CCS (CO_2 Capture and Storage) and CCU (Carbon Capture and Usage). CDA covers the scrap based electric arc furnace route and the iron ore based steelmaking route via direct reduction plant and electric arc furnace by the use of natural gas and/or hydrogen as reducing agent, which means the complete avoidance of coal and coke for the reduction of iron ores. The application of CCU at the conventional blast furnace converter route, which means the conversion of process gases into chemical raw materials, as well as the implementation of the direct reduction technology with hydrogen and subsequent smelting of the DRI (Direct Reduced Iron) to steel in an electric arc furnace require an immense amount of hydrogen and CO_2-free electric energy.

INTRODUCTION

The council of the European Commission has decided already in 2011 a roadmap for attaining a competitive low-carbon economy by 2050. According to this the European industry would have to cut back its CO_2-emissions below 1990 levels by 80 to 95 % by the year 2050. On 28 November 2018 the European Commission published on occasion of the UN climate agreement in Paris a long-term strategic vision for a climate neutral economy by 2050. On 11 December 2019 the European Commission announced by the European Green Deal the target, that the European Union will become the first climate neutral continent and has therefore presented an action plan. EU council, European Parliament and EU Commission have announced on 21 April 2021 in the context of the trilogue a preliminary agreement, which foresees within the climate protection law a mitigation of greenhouse gases of at least 55 % by 2030 compared to 1990. The realization of the 55 % target shall be achieved by a European „Fit for 55“ law with the revision of many enegy and climate related EU guidelines. The EU will present this law in June 2021.

The steel industry is in line with the target, to reach greenhouse gas neutrality by 2050 and will bring substantial CO_2 mitigations on the way by 2030. Such a comprehensive decarbonization will be an enormous challenge for the European steel industry. To reach this target, policy boundary conditions have to be realized in due time to afford necessary investments for CO_2-free iron and steelmaking technologies. The EU steel industry has, for many years, been at the forefront of R&D into breakthrough technologies via a large number of projects. An environmentally friendly, innovative and competitive steel industry plays a decisive role in achieving long term climate targets.

In this context, EUROFER – the European Steel Association – placed an order to the Steel Institute VDEh to update the steel roadmap of the year 2013 [1], in which the Steel Institute VDEh was also involved. Steel Institute VDEh just took over the pure technical part for this study, which started in March 2018 and ended in March 2019. The main results were presented at the 4th European Steel Technology and Application Days in June 2019 in Düsseldorf [2].

CO_2 EMISSIONS OF THE STEELMAKING PRODUCTION ROUTES IN EUROPE

Figure 1 presents the applied production routes for steelmaking in Europe with its current specific CO_2 emissions [3].

In the blast furnace converter route the CO_2 emissions of 1880 kg/t crude steel (CS) are generated directly in the production processes coke plant, sinter plant, blast furnace, converter and the subsequent process steps casting and rolling (not shown in the figure). The main CO_2 amount in this route comes from the blast furnace. The reduction of iron ores in the blast furnace with carbon or carbon monoxide (CO) respectively inevitably leads to carbon dioxide (CO_2). The chemical used carbon in the blast furnace process will be emitted as CO_2 to the atmosphere after energetic conversion/use of the carbon monoxide and carbon dioxide containing blast furnace gas and by processing of the carbon containing hot metal. In the integrated blast furnace converter route the blast furnace produces a liquid hot metal with a temperature of 1.500°C from which the main amount of the iron ore gangue materials are separated via a liquid slag. The produced blast furnace slag is mainly granulated and used for cement production replacing Portland clinker and with this reducing huge amounts of CO_2 emissions. An operation of a blast furnace without coke is not possible due to physical reasons [18]. The main physical tasks of the coke are to guarantee the gas permeability of the furnace in the shaft area, where the iron ores are softening and melting (cohesive zone), the drainage of hot metal and slag in the hearth and to build a supporting grid for the overlying burden layers above the cohesive zone.

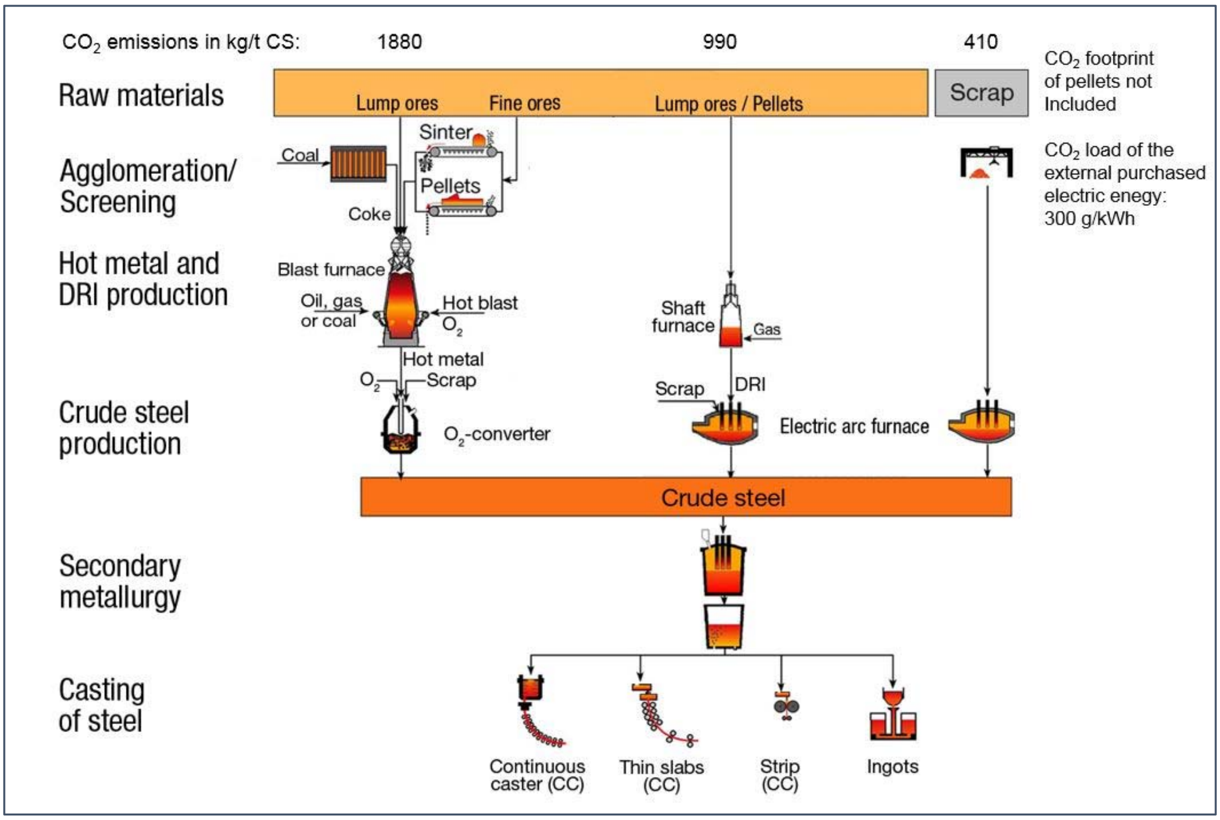


Figure 1: Process routes for steelmaking in Europe [3]

The process gases of the coke plant, the blast furnace and the converter steel shop are amongst others used for the production of electric energy in a subsequent power plant. By this the CO content in the gases are oxidized by burning into CO_2 and emitted with power plant waste gas to the atmosphere. This route is completely supplying its need for electricity by own production.

In the scrap based electric steelmaking route just a part of the CO_2 emissions is generated by the processes itself. The main part of the CO_2 emissions comes from the CO_2 load of the external purchased electric energy for the processes, as the electric arc furnace route does not produce process gases which are energetic applicable for electricity production. The CO_2 emission of this route is in the range of 410 kg/t CS at a CO_2 load factor of 330 g/kWh.

Using iron ore reduction technology as a pre-step for steelmaking, hydrogen is the only alternative reducing agent to carbon monoxide. Since the beginning of the 1970ies hydrogen rich natural gas is used as reducing agent for the reduction of iron ores in industrial applied direct reduction technology. Sponge iron/DRI is produced for example in a shaft furnace process. In this process most of the oxygen is removed from the iron ores to produce DRI but the DRI is solid and still contains all the gangue materials of the iron ores. The processing of the DRI to crude steel with smelting and slag metallurgy occurs in an electric arc furnace. The CO_2 emissions of this route are in the range of 990 kg/t CS.

CO_2 EMISSIONS OF THE EU 28 STEEL INDUSTRY IN 2015 COMPARED TO 1990

The specific and total CO_2 emissions for the EU28 steel industry were calculated for 1990 to get the correct number for the base year as well as for 2010 from the study in 2013 [1] and for 2015 for this follow-up study to highlight the CO_2 mitigation for the last two and a half decades.

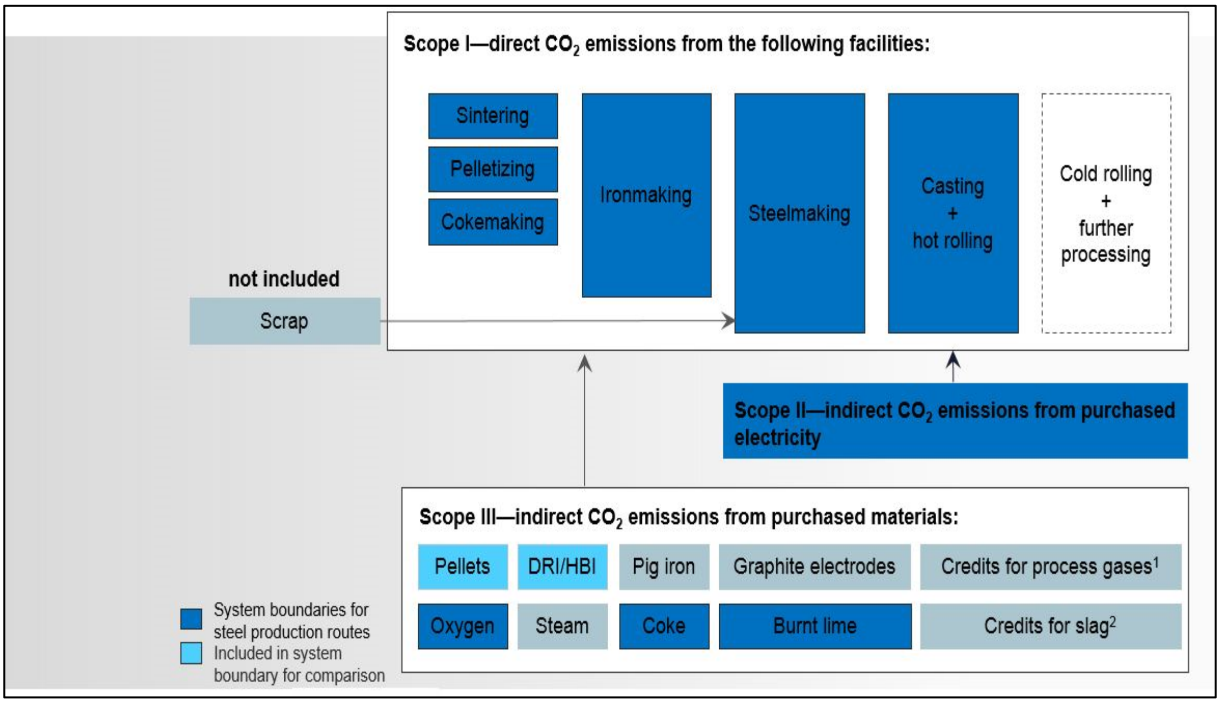


Figure 2: System boundaries to evaluate the CO_2 footprint of the EU 28 steel industry [2]

The system boundaries for the calculation of the CO_2 emissions of the steel industry in Europe were agreed upon in a way, that the CO_2 emissions of the process steps are in the balance as direct emissions (Scope I), **Figure 2**. The CO_2 emissions generated by the energetic use of the process gases of the integrated route, which supplies electric power, are already in the balance of the individual process steps. Regarding the scrap and also the DRI based electric arc furnace route, which does not produce any energetic usable process gases for power production, the CO_2 load of the external supplied electric power is going as indirect emissions into the balance (Scope II). For comparison the CO_2 load of purchased materials, like iron ore pellets or DRI (Direct Reduced Iron) were partly for some scenarios considered in the balance (Scope III).
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). So, no credits could be considered for this in the CO_2 balance. The aspect of granulated

blast furnace slag which leads by its use in cement production to CO_2 mitigation was not investigated further in this study as a CO_2 credit to avoid double counting.

The evaluation of 1990 and 2015 shows a drop of the total CO_2 emissions of the steel industry by 28 % from 298 to 216 million t as shown in the green bars on the right site of the **Figure 3**.
In the same period the crude steel production in the EU decreased from 197 million t to 166 million t in 2015 by 16 %, shown with the red bars under crude steel production.
The specific CO_2 emission per t crude steel decreased by 14 % from 1.5 to 1.3 t, shown with the yellow bars below Avg. CO_2 intensity.

The share of electric steelmaking at total steelmaking increased from 28 % to 39 % in 2015, bars under production share. The CO_2 load of the externally purchased electricity for electric steelmaking dropped in the same time from 585 g CO_2/kWh to 300 g CO_2/kWh.

Finally, the production decrease in Europe contributed to almost by 50 % of the total CO_2 mitigation of 28 % absolute.

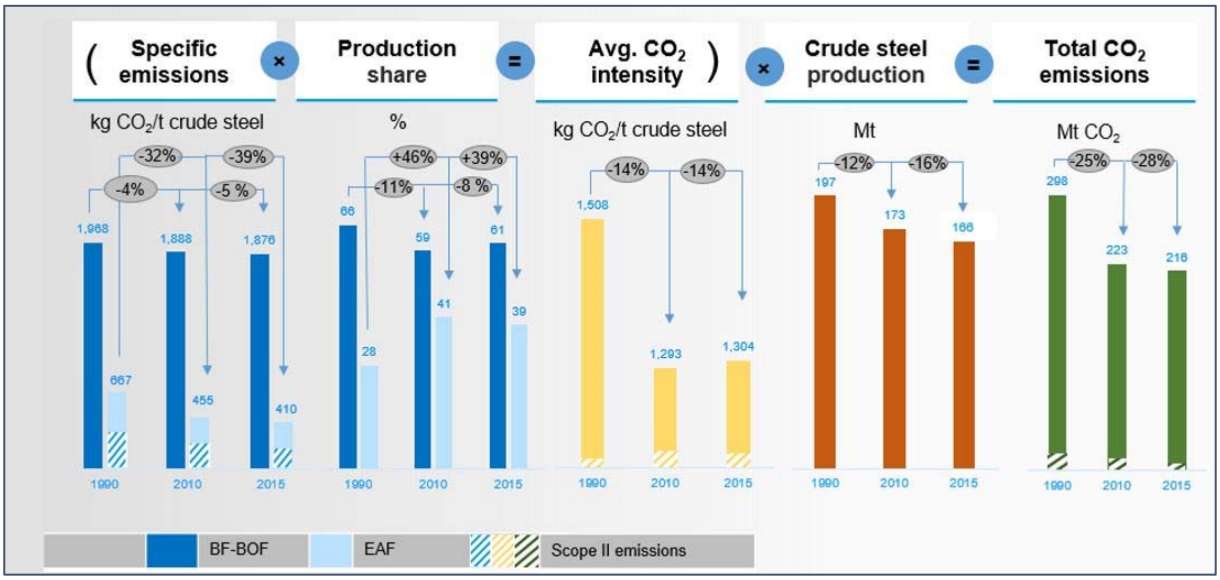


Figure 3: Results of the evaluation of CO_2 emissions of the European steel industry in 1990, 2010 and 2020 [2]

OPTIONS TO REACH THE CO_2 MITIGATION TARGETS BY 2050

The key options for CO_2 mitigations of the EU steel industry can be summarized in the two pathways: Smart carbon usage (SCU) and carbon direct avoidance (CDA), **Figure 4**.
SCU includes under process integration with reduced use of carbon the incremental measures of the conventional blast furnace converter route to reduce CO_2 emissions. This may also include so-called end-of-pipe technologies like CCS (CO_2 Capture and Storage) and CCU (Carbon Capture and Usage).

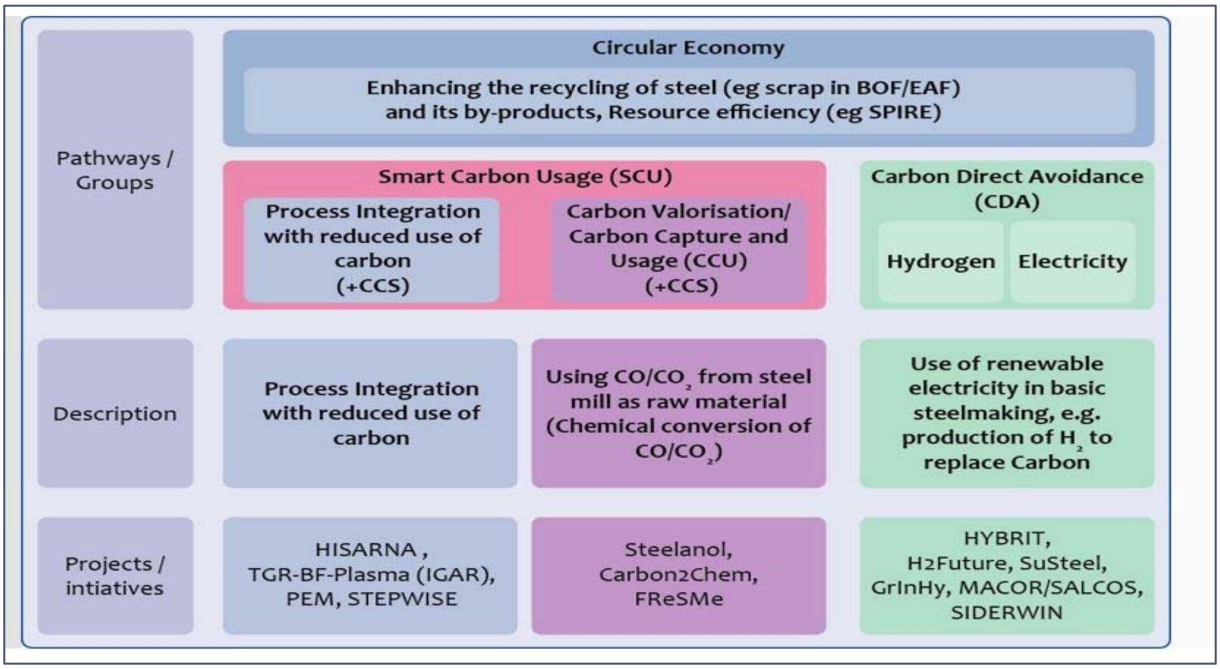


Figure 4: Projects and initiatives for mitigation of CO_2 emissions in the EU steel industry
(Source: EUROFER, 2017)

The group of carbon direct avoidance (CDA) includes the process routes scrap based EAF with CO_2-free electricity and the DRI-EAF route based on natural gas and hydrogen and CO_2-free electricity.

The change from integrated carbon based blast furnace/converter route to DRI/EAF route would result in no further need for coke and sinter, but instead the need for natural gas, hydrogen and pellets.

One main assumption for the study is that there will be no carbon leakage for the steel industry in Europe. This means that the whole agglomerated iron ore burden materials for the processes should be produced within Europe and accounted as direct emissions.

SMART CARBON USAGE (SCU)

The incremental measures at the existing iron and steel works have CO_2 mitigation effects, but do not lead to massive CO_2 mitigation without the application of CCS and CCU.

Projects combined with CCU are Carbon2Chem and Steelanol, the project combined with CCS is the HIsarna smelting reduction process, **Figure 5** [4].

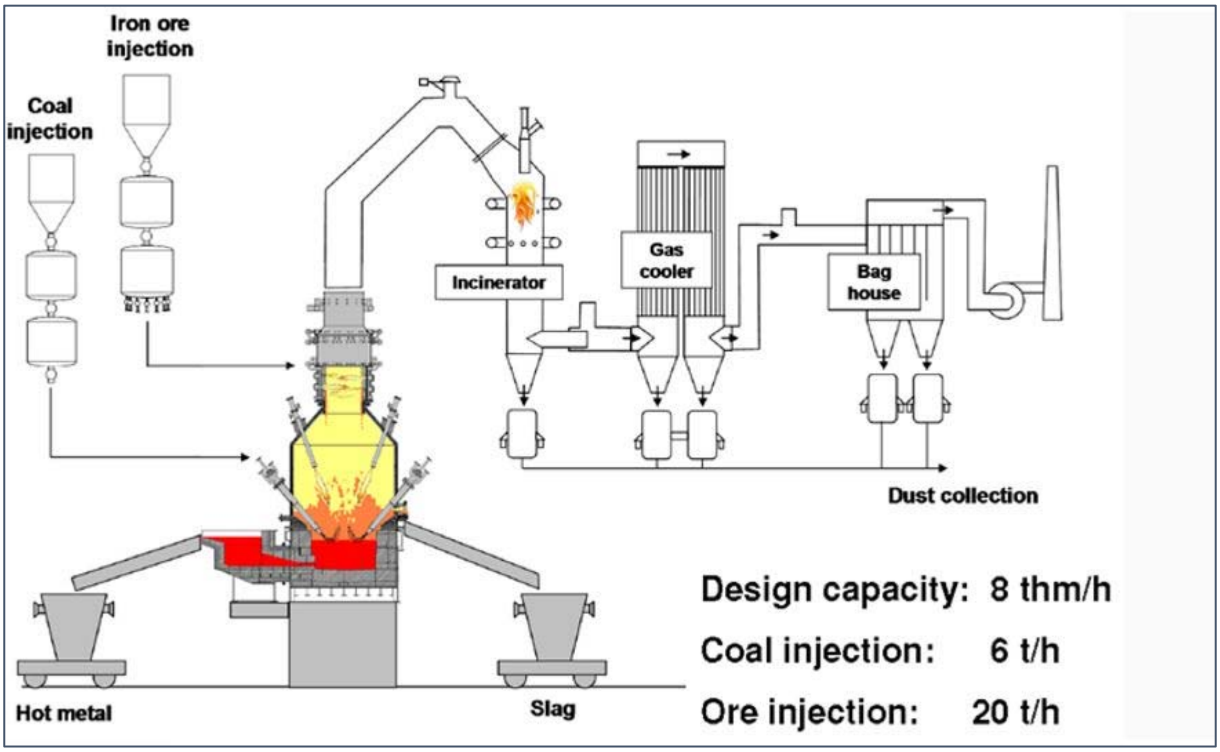


Figure 5: HIsarna smelting reduction process at Tata Steel in Ijmuiden [4]

In the HIsarna process, fine ores and non-coking coal and oxygen are used to produce liquid hot metal. The HIsarna-BOF route does not need any cokemaking and ore agglomeration steps.
The high CO_2 concentration of the off-gas will be beneficial for combining HIsarna with CCS.

Steelanol is converting the CO and H_2 in the blast furnace gas by using microbes into ethanol. In this way carbon is bound into chemicals (CCU) which would otherwise be incinerated to CO_2. What is left after Steelanol is a CO_2-rich stream which can directly be used in the IGAR technology (which stands for Injection de Gaz Réformé) to reform natural gas in a plasma torch to obtain a hot reducing gas composed of CO and H_2, **Figure 6** [5].

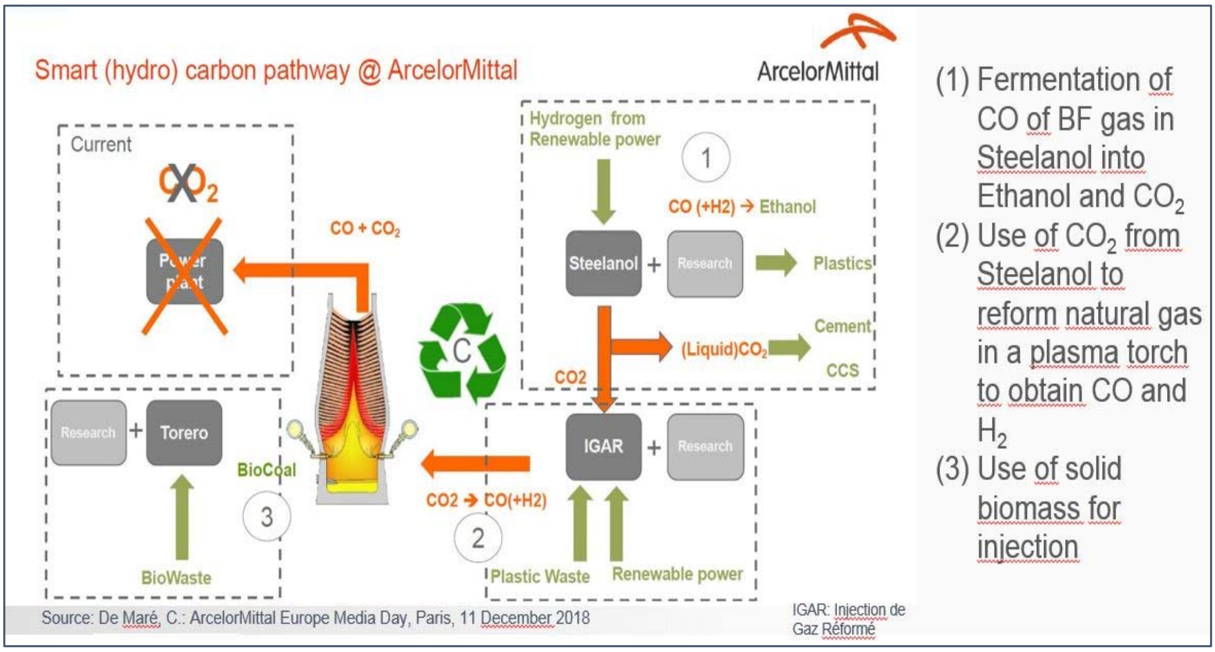


Figure 6: IGAR Steelanol process combination [5]

This reducing gas is injected through tuyeres into the blast furnace. Carbon lean electricity will be used for plasma gas processing. As the process is running on oxygen only (no hot air), high injections rates of solid carbon containing waste materials (as solid biomass and plastic) in combination with the hot reducing gas are minimizing the coke rate of the blast furnace.

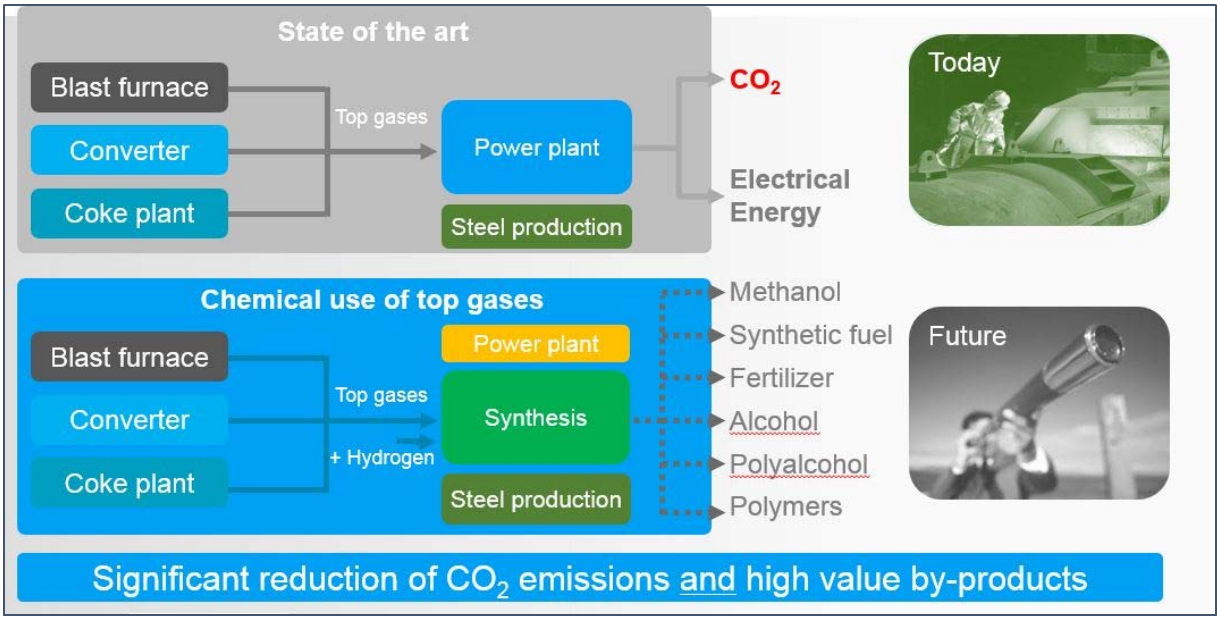


Figure 7: thyssenkrupp project Carbon2Chem – chemical use of process gases [6]

The Carbon2Chem initiative of thyssenkrupp aims to use process gases of the integrated iron and steelworks, like coke oven gas, blast furnace top gas and converter gas, as a starting material for chemical products avoiding the CO_2 emissions when these gases would be burnt in a power plant for the generation of electricity. Thus, the project is an essential contribution to climate protection as well as energy transition. On the other hand, the amount of the gases used for the production of chemical products are no longer available for the production of electricity needed by the integrated works. The missing electric energy then needs to be supplied from external sources which must CO_2 free. The Carbon2Chem concept needs additional hydrogen from green energy sources for the chemical processes involved in ammonia and methanol production.

As all the carbon is at maximum recycled or converted into chemicals, this combination of technologies is illustrating how also carbon and CO_2 can be reused in a circular way.

CARBON DIRECT AVOIDANCE (CDA)

The focus of Carbon Direct Avoidance will be set on the process route with direct reduction of iron ores and the use of the DRI in an electric arc furnace, **Figure 8**. For the direct reduction of iron ores with hydrogen shaft furnace processes will be used.

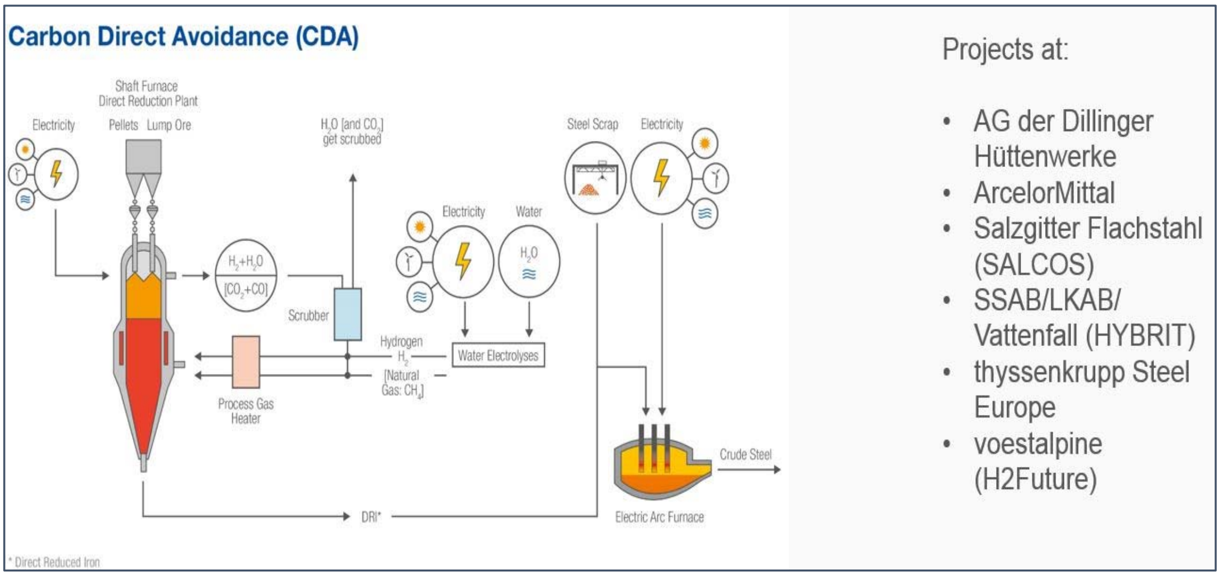


Figure 8: Production of "green steel" with hydrogen as reductant

In 2018 around 110 DRI shaft furnace plants (Midrex, HyL/Energiron) were operated worldwide with a production volume of 79.4 Mio. t DRI which is 79 % of the worldwide DRI production [7]. Maximum annual capacity of a single module is 2.5 million t DRI. They are still mostly located and operated where low cost natural gas is available. Only one plant is operated in Europe at ArcelorMittal Hamburg [7].

In these furnaces the iron ores, mostly in the form of pellets, are reduced in the "dry" stage by CO and H_2 from cracking of natural gas. No liquid phases occur, no slag metallurgy is done and no coke is needed. The produced DRI contains all the gangue materials from the iron ores, so that the slag metallurgy must be done in the subsequent electric arc furnace during crude steel production. To keep the slag volume at low level so-called DR pellets, which have compared to blast furnace pellets lower gangue components, are charged to the DR plant. The used fine ores for producing DR pellets need more intensive beneficiation. The slag of the electric arc furnace cannot be used for production of granulated slag like the blast furnace slag. Another process option for using the DR technology on the hydrogen basis is melting of the DRI to liquid hot metal in a submerged arc furnace (SAF) applying slag metallurgy and refining of the hot metal to liquid steel in the oxygen converter [17]. This option enables the production of granulated slag in the submerged arc furnace and the use of the existing oxygen converter with its metallurgical advantages. The reducing gas fed to the industrial direct reduction shaft furnaces already contains 60 to 80 % hydrogen. The idea of CDA is to inject up to 100 % hydrogen.

Figure 9 sums up the projects for CO_2 mitigation in Europe. For the CCU projects IGAR/Steelanol and Carbon2Chem in the smart carbon usage pathway, the CO_2 emissions released to the atmosphere may come down to levels below 600 kg CO_2/t crude steel [2]. But one has to keep in mind that carbon is still in the CCU products.
The HIsarna process with CCS in combination with basic oxygen steelmaking converter may come to CO_2 emissions of also less than 600 kg CO_2/t crude steel [2].

All other projects are in the pathway carbon direct avoidance. The hydrogen based DRI production combined with electric arc furnace is developed at ArcelorMittal, Dillinger, Salzgitter and thyssenkrupp in Germany, at SSAB/LKAB/Vattenfall in Sweden and at voestalpine in Austria.

voestalpine is also working on a project on iron ore reduction with hydrogen in a plasma smelting reduction reactor in laboratory scale.
The CDA processes may reach CO_2 emissions of below 340 kg CO_2/t crude steel.

Smart Carbon Usage	ArcelorMittal	IGAR/Steelanol	CO/H_2 as reductant (CCU)	[5]
	Tata Steel Europe	HIsarna	CO as reductant (CCS)	[4]
	thyssenkrupp	Carbon2Chem Water electrolysis	CO/H_2 as reductant (CCU]	[6]
Carbon Direct Avoidance	AG der Dillinger Hüttenwerke	COG to BF DR (H_2)/EAF	H_2 as reductant	[8, 9]
	ArcelorMittal	DR (H_2)/EAF Water electrolysis	H_2 as reductant	[10, 11]
	Salzgitter Flachstahl	DR (NG, H_2)/BF/EAF Water electrolysis	H_2 as reductant	[12]
	SSAB/LKAB/ Vattenfall	DR (H_2)/EAF Water electrolysis	H_2 as reductant	[13]
	thyssenkrupp Steel Europe	H_2 to BF DR (NG, H_2)/BF/SAF Water electrolysis	H_2 as reductant	[14, 15, 17]
	voestalpine	DR (NG, H_2)/BF/EAF Plasma smelting Water electrolysis	H_2 as reductant	[16]

Ideas from European steel producers for CO_2 abatement: Electric power intensive

Figure 9: Projects of the EU steel industry on CO_2 mitigation

All projects mentioned here need huge amounts of CO_2-free hydrogen and CO_2-free electric energy.

COMPARISON OF THE CO_2 MITIGATION OPTIONS (CCU/CCS NOT INCLUDED)

Figure 10 summarizes the results for CO_2 mitigation for the different alternative routes in comparison with the blast furnace converter and the scrap based EAF routes, whereby the options with the end-of-pipe-technologies CCU and CCS where not considered.

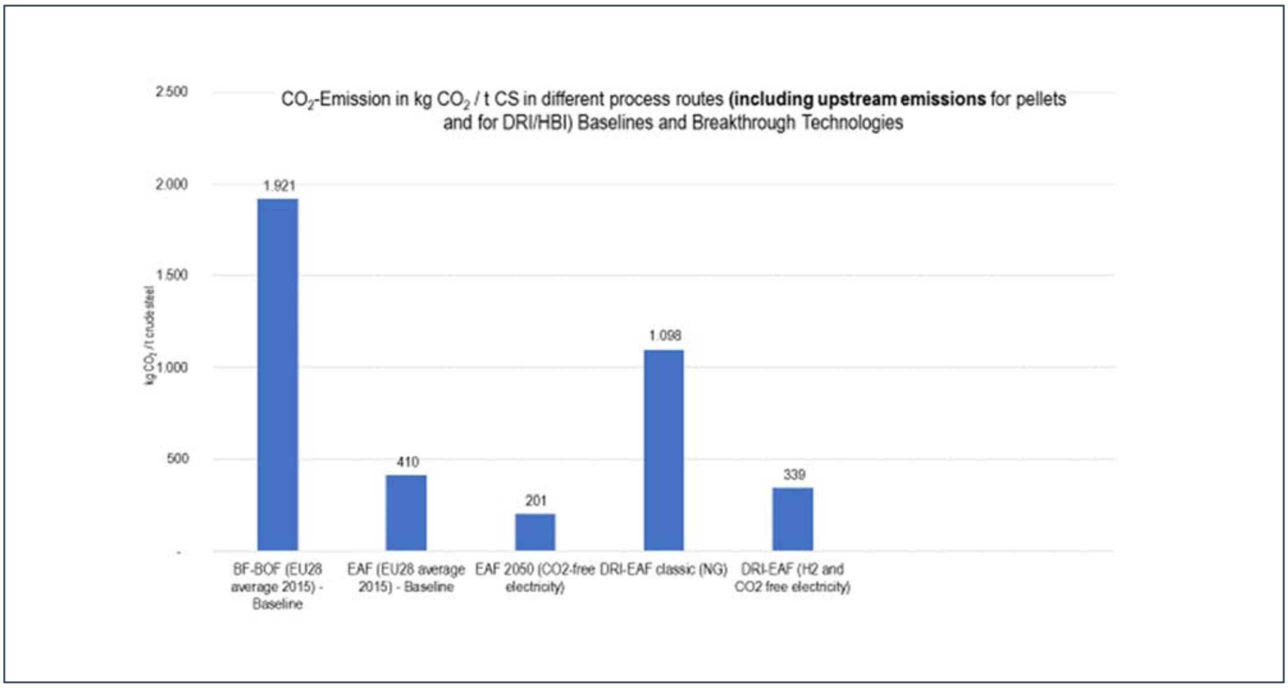


Figure 10: CO_2 emissions of different options [2]

The results include upstream CO_2 emissions for pellets charged to the blast furnace and to the DRI shaft. For all routes the CO_2 emissions of the downstream plants continuous casting and rolling are considered.
The BF-BOF route has a CO_2 emission of 1921 kg/t crude steel. The scrap based EAF baseline route with a CO_2 load of electricity in 2015 of 300 g/kWh has a CO_2 emission of 410 kg/t crude steel.

The assumption of the use of CO_2-free electricity reduces the baseline steel scrap EAF route to just only 201 kg CO_2/t crude steel. One could not conclude from this, that a solution of the CO_2-mitigation challenge could be simply the change over from the blast furnace converter route to the scrap based EAF route. It has to be kept in mind, that not all steel grades can be produced via the scrap based EAF route. To produce high grade flat steel products virgin iron ores or very clean scraps are needed as iron bearing input materials.

The natural gas based DRI-EAF route emits with the current CO_2 load of the electricity 1,098 kg CO_2/t crude steel. The availability of CO_2-free electricity is also the prerequisite for the DRI/EAF route based on hydrogen for iron ore reduction resulting in CO_2 emissions down to 339 kg/t crude steel.

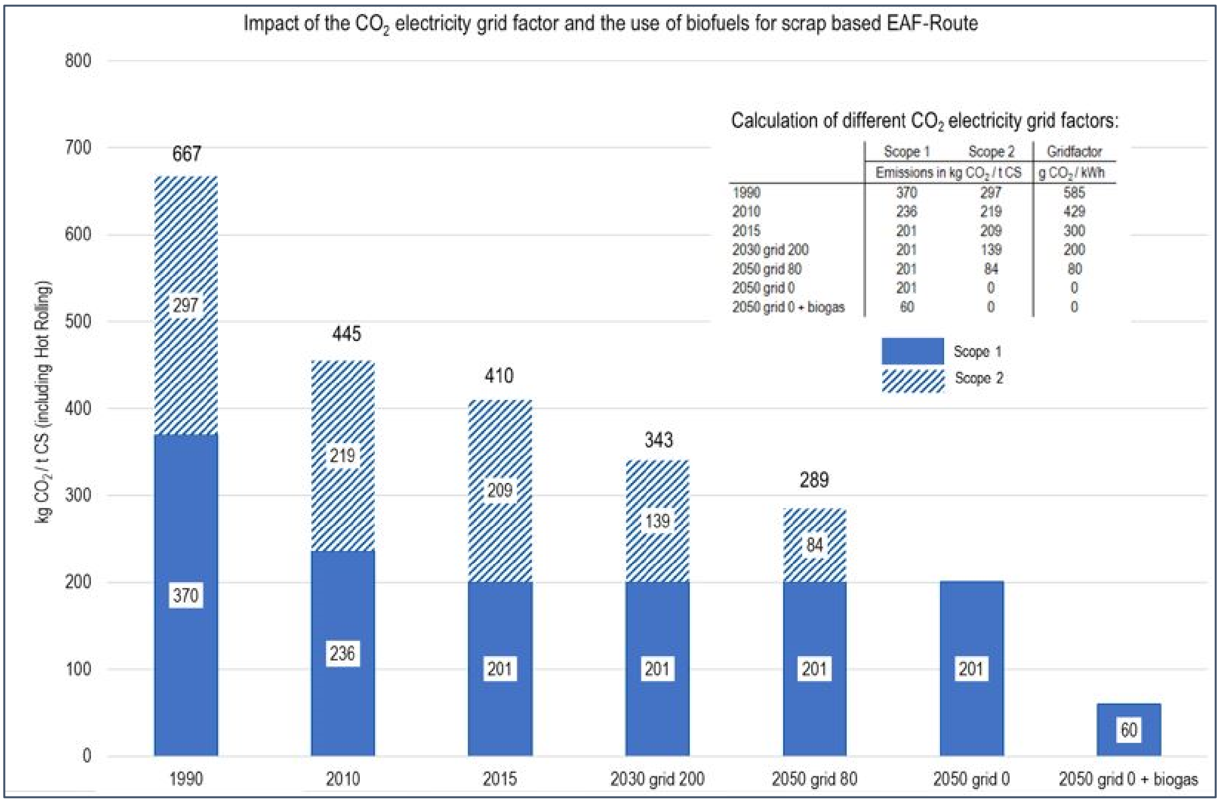
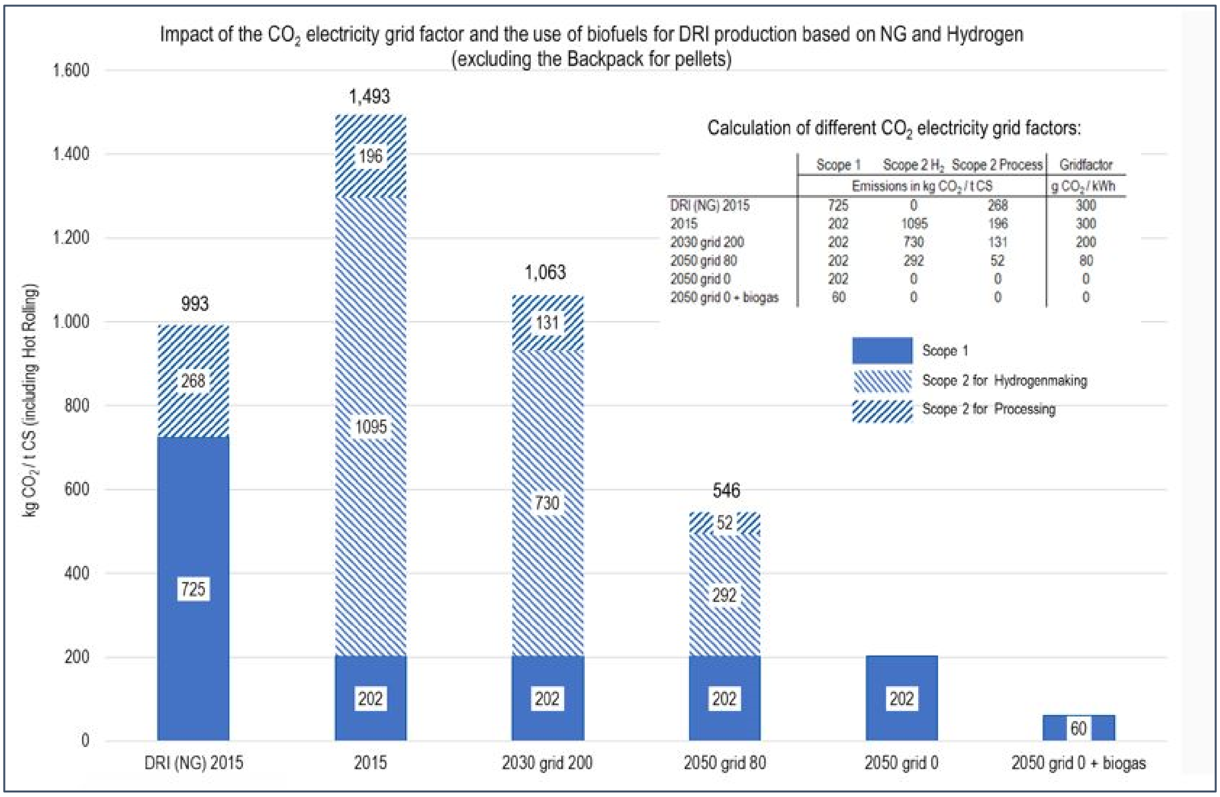


Figure 11: Direct and indirect emissions of the scrap based EAF route [2]

The impact of the CO_2 electricity grid factor over the years from 1990 to 2050 on the scrap based EAF route is shown in **Figure 11**. Massive CO_2 emissions reduction of this route is dependent on the CO_2 load of the electrical energy. The “International Energy Agency” has forecast for the year 2050 a CO_2 grid factor of 80 g/kWh. This leads for the scrap based EAF route to a CO_2 mitigation down to 289 kg/t crude steel which is minus 57 % in 2050 compared to 1990 level. If the supplied energy is based on CO_2 neutral fuels and CO_2-free electricity, then the CO_2 emissions could be decreased to 60 kg/t crude steel which is a CO_2 mitigation of 91 % compared to 1990 levels. The remaining CO_2 emissions are coming inevitably from electrode consumption and from the charged additions and alloying elements.



	Scope 1	Scope 2 H_2	Scope 2 Process	Gridfactor
	Emissions in kg CO_2 / t CS			g CO_2 / kWh
DRI (NG) 2015	725	0	268	300
2015	202	1095	196	300
2030 grid 200	202	730	131	200
2050 grid 80	202	292	52	80
2050 grid 0	202	0	0	0
2050 grid 0 + biogas	60	0	0	0

Figure 12: Direct and indirect emissions of the DRI natural gas and DRI hydrogen based EAF route [2]

The same effect of the CO_2 intensity of electricity is to be seen for the natural gas and hydrogen based DRI-EAF route, **Figure 12**. At a grid factor of 80 g CO_2/kWh the CO_2 emissions may come down in 2050 by 73 % to 546 kg CO_2/t crude steel compared to the BF-BOF baseline in 1990 which was 1968 kg CO_2/t crude steel (see Figure 3). The hydrogen based DRI-EAF route is on the same CO_2 intensity level of 202 kg/t crude steel as the scrap based EAF rout in the case of zero CO_2 load of electricity. A possible backpack for the charged pellets to the DRI plant was not considered.

When also using CO_2 neutral fuels for upstream and downstream processes, the resulting CO_2 intensity is also only 60 kg/t crude steel for the hydrogen based DRI/EAF route. The CO_2 mitigation achieved compared to the 1990 level of the blast furnace converter route is 97 %. To achieve this goal also pellets need to be produced CO_2-free.

CO_2 EMISSIONS OF THE EU 28 STEEL INDUSTRY IN 2050 FOR REACHING THE SET TARGETS

What does it mean under the targets given by the EU of CO_2 mitigation levels of 80 or 95 % in 2050 compared to 1990 levels for maximum allowable CO_2 emissions, if the total crude steel production of the EU 28 steel industry remains on the 2015 level of 166 million t?

As to be seen in **Figure 13**, the total emissions need to be reduced for the EU steel industry from 298 million t in 1990 to 60 million t in 2050 for the 80 % scenario and to 15 million t in the 95 % scenario. This means specific CO_2 emissions of 361 kg and 90 kg/t crude steel respectively. The 95 % mitigation target is achievable by the availability of huge amounts of CO_2-free electricity and CO_2-free produced hydrogen, CO_2-neutral carbon based fuels (biomass) and/or the application of CCU and CCS for carbon based iron ore reduction routes.

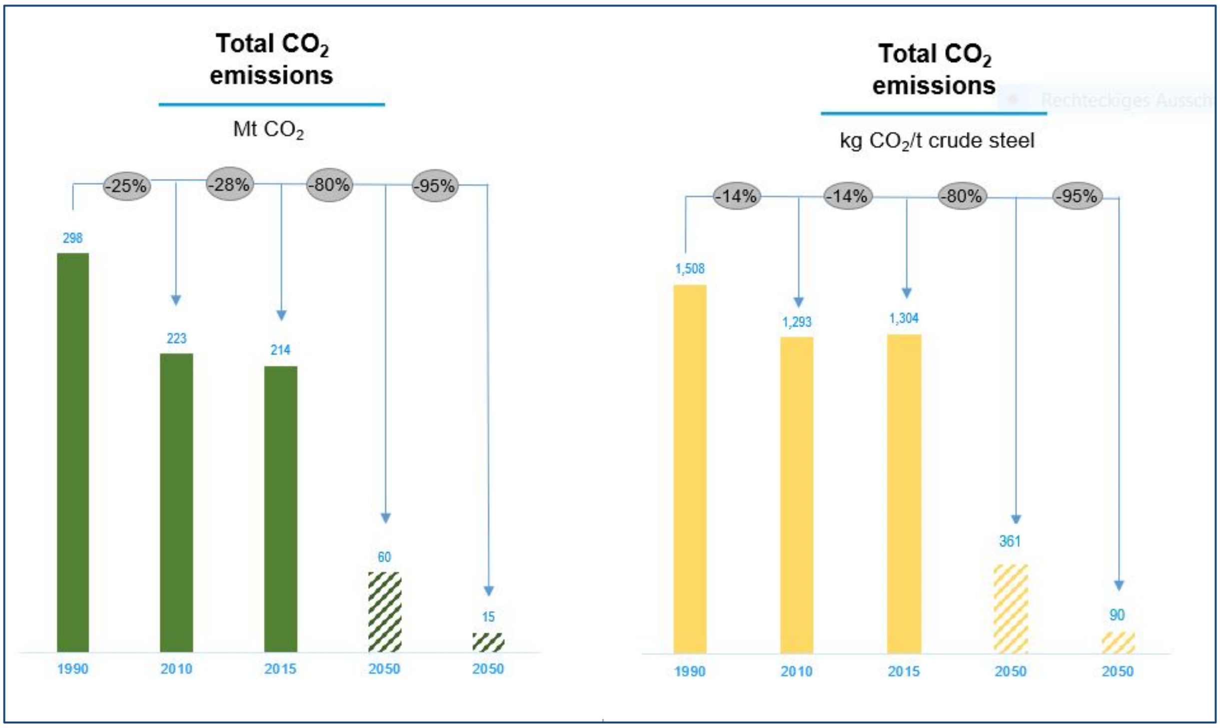


Figure 13: Maximum allowable CO_2-emissions in 2050 to reach the 80 % and 90 % mitigation target

The demand for green electricity for the EU steel industry only could raise in 2050 to a level of approximately 450 to 500 TWh/a.

CONCLUSIONS

The new ways for reaching massive CO_2 mitigation in steel production can be subdivided in the sectors "Smart Carbon Usage" (SCU) with processes based on carbon for steelmaking and "Carbon Direct Avoidance" (CDA), which use electricity and hydrogen for steelmaking. For all processes and scenarios to reach the 95 % CO_2 mitigation target by 2050 compared to 1990 level an extreme huge amount of green electric energy, green hydrogen and biomass is necessary and for the carbon based routes CCS and/or CCU technologies as well. The new ways for low-carbon steelmaking require tremendous financial resources for "Capex" and "Opex" for new plants and a lot of time.

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