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Power-to-Steel: Reducing CO_2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry

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Abstract: This paper analyses some possible means by which renewable power could be integrated into the steel manufacturing process, with techniques such as blast furnace gas recirculation (BF-GR), furnaces that utilize carbon capture, a higher share of electrical arc furnaces (EAFs) and the use of direct reduced iron with hydrogen as reduction agent (H-DR). It is demonstrated that these processes could lead to less dependence on—and ultimately complete independence from—coal. This opens the possibility of providing the steel industry with power and heat by coupling to renewable power generation (sector coupling). In this context, it is shown using the example of Germany that with these technologies, reductions of 47–95% of CO_2 emissions against 1990 levels and 27–95% of primary energy demand against 2008 can be achieved through the integration of 12–274 TWh of renewable electrical power into the steel industry. Thereby, a substantial contribution to reducing CO_2 emissions and fuel demand could be made (although it would fall short of realizing the German government's target of a 50% reduction in power consumption by 2050).

Keywords: power-to-steel; CO_2 reduction in steel industry; sector coupling; renewable energy for steelmaking; alternative steelmaking processes

1. Introduction

The growth of the global economy and population is strongly associated with a continuous increase in primary energy demand. In 2012, 81% of energy was generated by fossil fuels, which emitted around 30.2 billion tons of CO_2 [1]. In its World Energy Outlook 2012 [1], the International Energy Agency (IEA) outlines in the "450 Scenario" that the average increase of global temperature could be limited to 2 °C if CO_2 emissions could be reduced to 22 billion tons a year by 2035. This would mean that annual global CO_2 emissions must be reduced by approximately 30% from the year 2012 until 2035. As a worldwide leader in climate protection-focused policy, the targets of the German government are more ambitious. In its energy concept 2010/2011, it set out the goal of reducing greenhouse gas emissions in Germany by 80–95% by 2050 against 1990 levels, with a simultaneous reduction of electrical power demand by 25% and primary energy demand by 50% by 2050 against

2008 levels. The primary means foreseen for achieving this is the expansion of renewable energies, which are intended to provide 60% of final energy consumption and 80% of power production by 2050 [2]. Therefore, the German landscape has seen a continuous expansion of wind turbines during 2003 to 2015 from 14 to 45 GW and photovoltaic installations in the same time from 0.5 to 39 GW for power production [3].

However, both technologies are characterized by fluctuating electrical power provision due to the volatile nature of wind and solar radiation, so that there are times when supply of electricity is scare and times when it is abundant. To integrate a high proportion of wind and solar power into the energy system, a large-scale storage solution is required to compensate for the temporal imbalances between production and demand. For this task, power-to-gas technologies that convert surplus power into other forms of final energy such as thermal or chemical energy (e.g., hydrogen or synthetic methane) are suitable, even though electrical power has the highest degree in energy [4–6]. The production of gases using excess electrical power at times when more electricity than needed is produced offers different opportunities. On the one hand, the gas can be reconverted into electrical power with gas turbines or fuel cells during periods when demand for electrical power is higher than production. On the other hand, conventional gas power plants can be used for backup power to compensate gaps in electricity production, with the gases produced being used in other applications, such as fuel for transportation or for heating in several sectors [5,7,8]. The direct or indirect use of electrical power from renewable energies to provide heat, cold and operating power across all sectors is also known as sector coupling [9], which is shown in simplified form in Figure 1. Furthermore, synthetic methane or hydrogen can be used directly as a feedstock in the chemical industry [10]. The integration of renewable energies into different shapes, applications and sectors can lead to a reduction in CO_2 emissions beyond the power sector [6,11,12]. Although the step of converting hydrogen to methane incurs additional energy (η = 80%) [4,5], an advantage of synthetic methane is that it can be fed directly into the natural gas grid so that existing infrastructure and technologies for heat generation can be used.

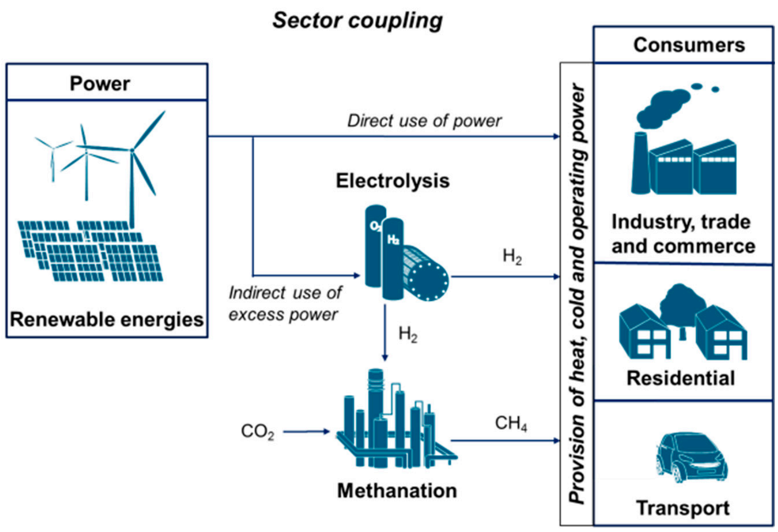


Figure 1. Principle of sector coupling, description from [9].

However, renewable power is not always directly convertible, especially in certain industrial processes. This is exemplified by the steel industry, which is mainly dependent on coal or coke, not only as an energy source but also for necessary process engineering [13]. In a conventional blast furnace, coal or coke serves as a reducing agent, heat provider and ensures the mechanical stability of the different layers of coke and iron ore inside the furnace (see also Section 4.1). For the need to reduce CO_2 emissions is particularly acute in steelmaking, as it constitutes one of the most energy- and carbon dioxide-intensive industrial processes worldwide; Germany, serving as a case study in this paper, is no exception (see Section 3) [14]. The literature contains many studies that deal with the overall potential of CO_2 reduction in the steel industry in terms of increasing efficiency [15–18]. Fujii and Managi (2015) [19] for example proposed and measured optimal production resource reallocation using data envelopment analysis. Their research clarifies the effect of optimal production resource reallocation on CO_2 emissions reduction, focusing on regional and industrial characteristics [19]. Nevertheless, studies that specifically pertain to alternative processes and the potential to integrate renewable power are lacking.

In a bid to contribute to filling this gap, this study evaluates blast furnace gas recirculation (BF-GR) [20,21], blast furnace carbon capture (BF-CC) [20,21], the possibility of a higher share of steelmaking being conducted with electrical arc furnaces (EAFs) [22] and the direct reduction of iron ore with renewable hydrogen (H-DR) [23] technologies and methods that not only have the potential to reduce sector CO_2 emissions, but also to shift the steel industry's energy demand away from coal to other energy carriers that can be provided by renewable energies. Therefore, the objective of the present study is to determine whether it is possible to integrate renewably-generated power into the conventional coal-based steel industry via alternative manufacturing technologies or measures and to analyze the effect on CO_2 emissions.

Additionally, the above-mentioned aims of the German Government regarding the simultaneous reduction of CO_2 emissions, as well as electrical power and primary energy demand are also taken into account and analyzed. As the German Government did not publish particular objectives of CO_2 and energy reduction for special sectors or processes, it is assumed at this point that the steel industry should achieve an 80–95% CO_2 reduction on 1990 levels by 2050 and simultaneously a reduction in electrical power demand by 25% and primary energy demand by 50% against 2008 by 2050. While this analysis is conducted within the context of Germany, the methodology and data on the technologies could be applied to similar analyses focused elsewhere, as the steel industry is similarly constructed around the world (see Section 3).

2. Method and Procedure

To achieve the objectives of the present study, the state-of-the-art conventional method of steelmaking is first described and its energy demand determined using data from the literature. On the basis of this data and the specific emission factors of fuels, feedstocks and electrical power, energy-related emissions are calculated. Emissions arising from plant construction, fuel procurement and maintenance are not considered. For the calculation of the energy as well as process-related emissions, only CO_2 was included because the greenhouse gas emissions of the relevant energy carriers consist of 98.8% CO_2 and the process emissions of steel manufacturing of CO_2 only [24,25]. Secondly, selected measures and alternative processes that have the potential to reduce CO_2 emissions and incorporate renewable energy into the integrated steelworks are considered. These potential CO_2-reduction technologies were analyzed in the same manner as conventional processes to determine energy demand and CO_2 emissions.

Finally, a comparison of the energy demand and CO_2 emissions between the conventional processes and alternative processes should indicate if it is possible to achieve the emission and energy consumption reduction aims of the German government, first without (Sections 6.1–6.3) and then with (Section 6.4) the integration of renewable energies into the steelmaking process. For this comparison, not only were blast furnaces investigated in isolation, but also connected processes, like coking plants, sinter production and blast furnace gas utilization processes were analyzed for their energy demand and CO_2 emissions. A detailed outline of the analytical framework can be found in Section 6. The method used in this study is based on common CO_2 and energy balance calculations derived from data in the literature.

Table 1 shows the CO_2 emission factors of the most important energy carriers and gases that are used for steelmaking. For the analyses of CO_2 emissions in Sections 4.1, 4.2, 5.1–5.4 and 6.1–6.3, the electricity use assumed is based on the German electricity mix from 2012, which had a CO_2 emission factor of 160 kg_{CO2}/GJ.

Table 1. CO_2 emission factors of fuels, electrical power and feedstocks [4,24,26–28].

Energy Carrier/Gases	Description/Assumptions	CO_2 Emission Factor
Natural gas (NG)	-	56 kg_{CO2}/GJ
Blast furnace gas (BF gas)	-	257.8 kg_{CO2}/GJ
Coke	-	105.0 kg_{CO2}/GJ
Hard coal	-	94.2 kg_{CO2}/GJ
Coke oven gas (COG)	-	40.0 kg_{CO2}/GJ
Basic oxygen furnace gas (BOF gas)	-	257.8 kg_{CO2}/GJ
German electricity mix 2012	-	160 kg_{CO2}/GJ
Oxygen	Energy demand of O_2 provision by cryogenic air separation: 0.745 MJ_{el}/kg_{O2} [27]	119.2 kg_{CO2}/t_{H2} (powered by the German electricity mix 2012)
Nitrogen	Energy demand of N_2 provided by cryogenic air separation: 0.576 MJ_{el}/kg_{O2} [28]	92.18 kg_{CO2}/t_{H2} (powered by the German electricity mix 2012)
Hydrogen produced through the steam reforming of natural gas (NG)	η = 84% [29] =>1.190 GJ_{NG}/GJ_{H2}	66.64 kg/GJ (8000 kg_{CO2}/t_{H2})
Hydrogen produced through water electrolysis powered by the German electricity mix 2012	η = 70% [4] =>1.428 GJ_{el}/GJ_{H2}	119 kg/GJ (27,418 kg_{CO2}/t_{H2})
	Used in Section 6.4 only	
Renewable electrical power	Only energy-related CO_2 emissions are considered	0.0 kg_{CO2}/GJ
Hydrogen produced by water electrolysis powered by renewable electrical power	η = 70% [4] =>1.428 GJ_{el}/GJ_{H2}	0.0 kg/GJ (0.0 kg_{CO2}/t_{H2})
Synthetic methane produced via power-to-gas with hydrogen from water electrolysis powered by renewable electrical power	Electrolyzer: η = 70% [4] Methanation: η = 80% [4] =>1.785 MJ_{el}/MJ_{CH4} Energy demand and CO_2 emissions of CO_2 provision are not considered	0.0 kg/GJ

Two different cases based on the use of hydrogen are also considered. In the first of these, hydrogen was produced by steam reforming [29], with an energy demand of 1.190 MJ_{NG}/MJ_{H2} and related CO_2 emissions of 66.64 kg_{CO2}/GJ_{H2}, while in the other case it was sourced by water electrolysis powered by the electricity mix [4] In Section 6.4, which deals with the integration of renewable energies, it is assumed that electrical power is exclusively provided by renewable sources such as solar cells or wind turbines. Hence, zero CO_2 emissions are assumed because only the energy-related CO_2 emissions are considered in this study. In this case, the CO_2 emissions arising from hydrogen provided via water electrolysis are zero as well. Furthermore, natural gas is substituted by synthetic natural gas, which is produced by a methanation process that entails the hydrogenation of CO_2, in which the necessary hydrogen is provided by water electrolysis powered by renewable electricity, as shown in Figure 1. Since the provision of CO_2 is not considered at this point, it is assumed that the CO_2 emission factor of the synthetic methane is also zero. Synthetic methane is considered for heat provision in this study because it can directly substitute natural gas without a change in the combustion technologies. At this point, a detailed description of the different technologies is omitted, because this would be beyond the scope of the present study. More information about the technologies can be found in Schiebahn et al. [4,5] and Agostinha et al. [29].

3. Global and German Steel Industry

In 2012, the global production of crude steel exceeded 1560 million tons [30], produced mainly in oxygen blast furnaces (BF-BOF) (70.49%) by iron ore and in EAFs with iron metal scrap (28.62%) [31]. Other crude steel production routes, such as open hearth furnaces (OHF), smelting reduction (SR) or direct reduction (DR) contributed only a minor portion to this, with a share of less than 1% of the total amount produced [31].

In 2012, crude steel manufacturing constituted 5.5% of global primary energy demand and was the source of 8.0% of total global CO_2 emissions (data based on Table 2). The largest manufacturer of crude steel is China, whose share amounts to approximately 47% followed by Japan, the USA, India and Russia (see Figure 2).

Although its production quantity is relatively low compared to China, Germany is the eighth largest producer in the world (see Figure 2). In 2012, it produced 42.7 million tons of crude steel, similar to the global average of 67.67% produced through the BF-BOF method and 32.32% via the EAF route, with a primary energy demand of 762.76 PJ and CO_2 emissions of 57.84 million tons, which corresponds to 5.67% of primary overall German energy consumption and 7.01% of German CO_2 emissions (see Table 2). The steel industry's manufacturing processes are the most energy- and carbon dioxide-intensive in Germany, accounting for approximately 24% of thermal energy demand and 28% of CO_2 emissions in German industry, although this is only "one" product of "millions" [32].

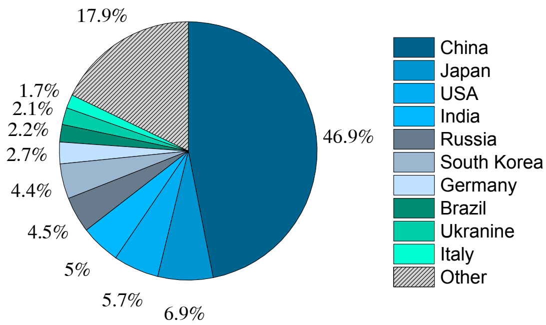


Figure 2. Share of countries in total steel production in 2012 [31]. The ten largest steel manufacturers in the world (2012). Total global production: 1560 million tons of crude steel.

Table 2. Data from the year 2012 used for calculation to classify the steel industry.

Steel Industry	Global	Reference	Germany	Reference
Primary energy demand (EJ/a)	559.82	[33]	13.45	[25]
Net power consumption (TWH/a)	22,668	[33]	540	[25]
CO_2 emissions (million t/a)	35,083	[34]	818	[35]
Manufacturing Process	**Crude Steel**			
Output (million t/a)	1560	[30]	42.7	[30]
Average primary energy demand ($GJ_{th}/t_{Crude\ steel}$)	20.0	[30]	17.88	[36]
Average CO_2 emissions ($t_{CO2}/t_{Crude\ steel}$)	1.8	[30]	1.356	[37]

The above-mentioned CO_2 emissions already include process-related emissions. The reduction of iron ore (Fe_2O_3) to pig iron, directly with coke (Equation (1)) or indirectly with carbon monoxide (Equation (2)), which is formed in situ with oxygen inside of oxygen blast furnace (simplified in Equation (1)), produces reaction-related CO_2 emissions. The specific process-related emissions are typically 0.588 $t_{CO2}/t_{pig\ iron}$ [35].

$$Fe_2O_3 + 1.5C \rightarrow 2Fe + 1.5CO_2 \quad (1)$$

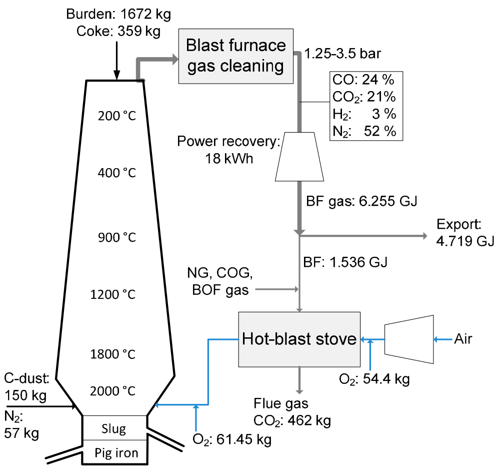
$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad (2)$$

4. Conventional Steelmaking Processes

In this section, the steel/iron industry is analyzed, beginning with a description of conventional steelmaking processes using blast furnaces, which is the most energy-intensive part of the steelmaking process, followed by steel production in an electric arc furnace. The SR and DR are not considered here because these methods make up only a negligible proportion of the global total and are not practiced in the German steel industry (see Section 3). The second part of this presents an analysis of measures and alternative processes that have the potential to reduce CO_2 emissions and integrate a higher share of renewable energy into steelmaking.

4.1. Conventional Blast Furnace Route

Figure 3 schematically displays a typical blast furnace for steelmaking. Before the feedstock iron ore is fed into the top of the blast furnace, it is pretreated in a sinter or pellet plant and mixed with additives such as limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). This mixture of sinter, pellets and additives is referred to as the burden. In the blast furnace, the iron of the burden, which comprises a mixture of hematite (Fe_2O_3) and magnetite (Fe_3O_4), is reduced and the resulting iron melted. For the separation of oxygen and iron in conventional blast furnaces, coke and coal dust are typically used as reduction agents. The burden and coke are fed into the top of the furnace in alternating batches, while at the same time coal dust and hot air, enriched with oxygen, are injected into the lower part of the furnace (see Figure 3). The blast furnace is a continuously operated shaft furnace that works on a countercurrent principle. The reducing agents coke and coal react with/burn the oxygen to mainly produce carbon monoxide (CO) and heat. The CO reduces the iron ore to metal iron, producing CO_2 (Equation (1)). The blast furnace gas leaves the furnace at the top, while the molten metal and slug are collected in the hearth at the bottom, where both are discharged at regular intervals. The BF gas, which is under pressure (1.25–3.5 bar) and still has a heat value, is first expanded over a turbine to recover electrical power (18 kWh/$t_{pig\ iron}$) and then a portion of it (1.536 GJ/$t_{pig\ iron}$) is used to heat up the air, which is then led to the furnace. The main part of the BF gas is thereafter exported to other processes of the integrated steelworks [38,39]. The energy demand of an average blast furnace (see Figure 3) is 15.95 GJ/$t_{pig\ iron}$. Considering the export of blast furnace gas (4.719 GJ/$t_{pig\ iron}$), the net energy requirement is 11.4 GJ/$t_{pig\ iron}$. These values include the power demand for the O_2 and N_2 provision via cryogenic air separation, but not the energy demand for coke and burden production, which are additional processes and considered in Section 6. For the calculations of the CO_2 emissions—through the use of emission factors from Table 1 and the energy data from Figure 3—only the upstream chain of N_2 and O_2, as well as the used electrical power, are considered.



Data per ton pig iron

Energy demand per ton of pig iron [39]	
Coke	10.303 GJ
Coal dust	4.67 GJ
Net power demand	0.202 GJ
Power demand for N_2 and O_2 allocation	0.119 GJ
To hot-blast stoves	
Natural Gas (NG)	0.213 GJ
Coke oven gas (COG)	0.284 GJ
Oxygen steel furnace gas (BOF gas)	0.168 GJ
Total energy demand	15.95 GJ
Export of blast furnace gas	4.719 GJ
Net energy demand (overall demand minus export of blast furnace gas)	11.24 GJ
CO_2 emissions of the blast furnace per ton of pig iron	
Directly from the process	514 kg_{CO2}
Inclusive CO_2 in exported BF gas	1099 kg_{CO2}

Figure 3. Simplified scheme of a blast furnace based on average data from UBA 2012 [39].

The CO_2 emissions of the process are 514 $kg_{CO2}/t_{pig\ iron}$ as a result of burning a part of the BF gas (462 $kg_{CO2}/t_{pig\ iron}$) for preheating the air and the emissions generated by the electrical power demand of the process and the N_2 and CO_2 provision (51.5 $kg_{CO2}/t_{pig\ iron}$). However, a large proportion of the CO_2, which is formed inside the blast furnace, exits the process in the form of exported BF gas. The CO_2 concentration in the gas is 21% and when this is also considered in the CO_2 balance, CO_2 emissions are 1099 $kg_{CO2}/t_{pig\ iron}$. Moreover, the process-related CO_2 emissions accruing from iron ore reduction are already a part of the BF gas. As shown in Figure 3, the largest part of the conventional blast furnace's energy demand is provided by coke and coal (94%), hence the integration of renewable energies to achieve a large reduction of CO_2 emissions is not possible.

4.2. Electrical Arc Furnace

In an EAF, materials that contain iron, such as scrap, are melted directly through the use of electrical power. The resulting product from this process is liquid steel rather than pig iron, as in blast furnaces. Initially, a natural gas burner assists with the melting process. For process engineering and metallurgical reasons, oxygen nitrogen and coal are inserted into the liquid steel [39]. The energy demand and resultant CO_2 emissions entailed by the production of one ton of crude steel are shown in Table 3. The specific energy demand, including the electrical power demand for the provision of N_2 and O_2, is 3.34 GJ/t_{LS}, which is only 30% of blast furnace energy demand. The CO_2 emissions are 508 kg/t_{LS}, which also includes the emissions for electrical power (German electricity mix) and N_2, O_2 provision and process-related CO_2 emissions caused by decarburization processes and electrode burn-off [39].

Table 3. Energy demand (average values based on UBA 2012 [39]) and calculated CO_2 emissions of an EAF.

Energy Demand per Ton of Liquid Steel	
Electrical power	2.07 GJ [a]
Natural gas	0.78 GJ
N_2	8 kg (4.6 MJ_{el}) [b]
O_2	50 kg (37.3 MJ_{el}) [b]
Coal	0.45 GJ
Overall energy demand	3.34 GJ
CO_2 Emissions per Ton of Liquid Steel	
Process-related: Decarburization and electrode burn-off	83.9 kg
Total CO_2 emissions including N_2 and O_2 provision	508 kg

Notes: [a] German electricity mix (2012); [b] see also Table 1.

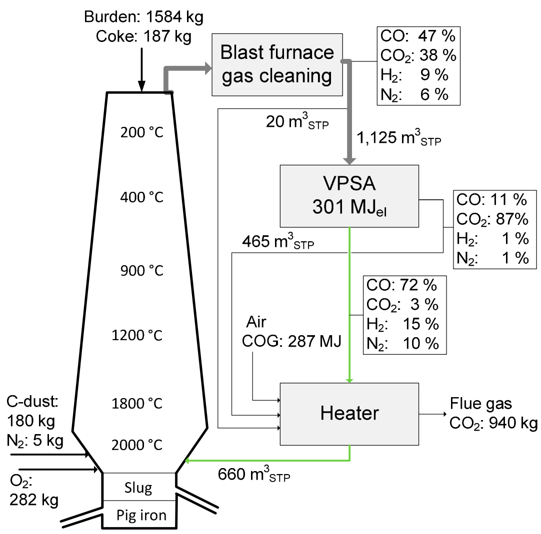
In contrast to blast furnaces, EAFs not only have the potential to reduce CO_2 emissions through lower energy demand, but also through the use of renewable electricity and synthetic methane instead of natural gas. Therefore, a higher share of steelmaking in EAF is discussed as an alternative means of CO_2 reduction and the integration of renewable energies in Sections 5.3 and 6.

5. Alternative Processes for Steelmaking

In this section, the following selected CO_2-reduction technologies or routes are evaluated for use in the steel industry: (Section 5.1) Blast furnaces with gas recirculation (BF-GR) [20,21]; (Section 5.2) blast furnaces with carbon capture capability (BF-CC) [20,21]; (Section 5.3) a higher share of steelmaking using EAFs at constant steel production volume [22]; and (Section 5.4) the direct reduction of iron ore using hydrogen as the reduction agent (Circored Process) [23]. These technologies were selected by the authors because all of them have the potential to reduce a huge amount of CO_2 through the implementation of one measure or technology, and all have already attained commercialization potential, or are on the verge thereof [20,40]. In addition, these technologies would enable greater independence from coal, such that energy demand can be met by other, less CO_2-intensive fossil sources like natural gas or directly with emission-free renewable sources such as renewable electrical power or renewable gases like synthetic methane or hydrogen. Furthermore, the CO_2 reduction potential of a higher share of steelmaking in EAFs at constant steel production is also considered in Section 5.3, because this could lead to a relatively simple reduction in CO_2 emissions without the implementation of new technologies. The analysis of other technologies like the electrochemical cleavage of iron [41] ore are not considered, because these technologies are still at the basic research stage and unlikely to be marketable before 2040 [20]. Furthermore, many possible efficiency measures relating to the whole integrated steelworks, which are described in Santos 2013 [21], for example, are not considered, because one of the targets of this study is to illuminate technologies and measures that lead to large reductions in CO_2 emissions and to determinate the possibility of integrating renewable energies.

5.1. Blast Furnace with Blast Furnace Gas Recirculation

Figure 4 outlines a blast furnace with BF-GR. Ultra-Low Carbon Dioxide Steelmaking (ULCOS), a consortium of 48 European companies and organizations [41], has developed and evaluated this technology [20,21,42,43]. BF-GR is intended as a replacement of air (hot blast) by nearly pure oxygen and pretreated BF gas. At the pretreatment stage, the BF gas is separated in a CO_2-rich and a CO-rich-gas by vacuum pressure swing adsorption (VPSA). The CO-rich gas stream is fed into the furnace and the CO_2-rich stream, which still contains CO and H_2 (see Figure 5), is used for preheating the CO-rich stream. Due to the recycling of CO to the furnace, coke demand drops by 45% compared to the conventional blast furnace (Figure 3).



Data per ton of pig iron

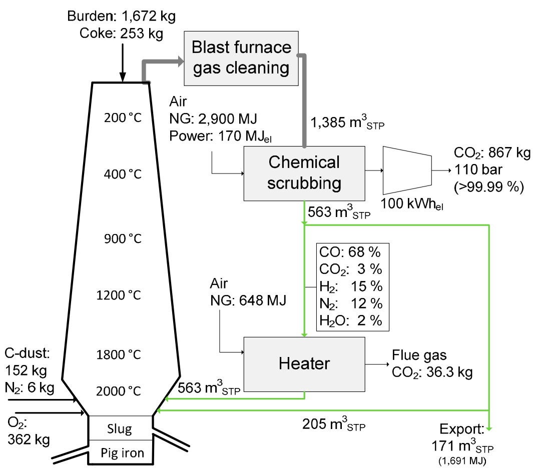
Energy demand per ton of pig iron [20,21,42]	
Coke	5.64 GJ
Coal dust	4.89 GJ
Total Power consumption inclusive of N_2 and O_2 allocation and VPSA; (assumption based on [20,21,27,39,43])	0.78 GJ
Hot-blast stoves	
Coke oven gas (COG)	0.29 GJ
Total energy demand	11.6 GJ
Export of blast furnace gas	0 GJ
Net energy demand (overall demand minus export of blast furnace gas)	11.6 GJ
CO_2 emissions of the blast furnace per ton of pig iron	
Directly at the process (inclusive electrical power demand)	1065 kg_{CO2}
VPSA = Vacuum pressure swing adsorption	

Figure 4. Simplified scheme of a blast furnace with blast furnace gas recirculation based on average data from Danloy 2009, Santos 2013 [20,21].

The reason for the reduction in coke demand is that CO, as well as coke, can act as a fuel and reduction agent of iron ore (see Equation (2)). With the help of data from Danloy 2009, Santos 2013 and Danloy 2008 [20,21,42], the net energy demand of the BF-GR, inclusive of the provision of N_2 and O_2, was determined to be 11.6 $GJ/t_{pig\ iron}$. The reason for the reduction in coke demand is that CO, as well as coke, can act as a fuel and reduction agent of iron ore (see Equation (2)). With the help of data from Danloy 2009, Santos 2013 and Danloy 2008 [20,21,42], the net energy demand of the BF-GR, inclusive of the provision of N_2 and O_2, was determined to be 11.6 $GJ/t_{pig\ iron}$. Although the coke demand is less than in the conventional process, net energy demand is slightly higher, because the conventional process exports the largest part of the BF gas, which is used in this technology. Moreover, the electrical energy demand increases due to the lack of power recovery due to BF gas expanding and the additional energy demand for VPSA and the higher amount of necessary pure oxygen. These circumstances lead to the result that CO_2 emissions (calculated with the emission factors of Table 1 and data from Figure 4) arising directly from blast furnaces with gas recirculation (1065 kg/$t_{pig\ iron}$) are higher than for the conventional process (514 kg/$t_{pig\ iron}$). However, when the CO_2 content of the exported BOF gas is also taken into account in the context of the conventional blast furnace, the emissions of the blast furnace with gas recirculation is slightly less (1065 kg/$t_{pig\ iron}$ vs. 1099 kg/$t_{pig\ iron}$). At this point, it should be pointed out again that the CO_2 emissions are only based on the combustions of fuels, and that CO_2 emissions for building the facilities were not considered. The extent to which the complete CO_2 reduction potential, as well as the potential to integrate renewable energy, is due to the reduction of coke and the lack of exported blast furnace gas becomes apparent under consideration of the entire integrated steelwork process, which is analyzed in detail in Section 6.

5.2. Blast Furnace with Carbon Capture

Figure 5 shows a schematic of a blast furnace with BF gas recirculation and carbon capture (BF-CC). This concept is also developed by ULCOS [21,44]. The main difference to the BF-GR is that the BF gas is separated by chemical scrubbing in an almost pure CO_2 stream (>99.99%) and a CO-rich stream is led back to the blast furnace. Because the CO_2-rich stream has no heat value, it cannot be used for preheating the CO-rich stream as in the case above (see Figure 4). Therefore, natural gas is used for the preheating of the stream, as well as for the additional thermal energy demand of the CO_2-separation unit via chemical scrubbing. To avoid CO_2 emissions to the air, the pure CO_2 stream must be geologically-stored or used as a feedstock for chemical products or synthetic gases [5,10]. According to the data on ULCOS (see Figure 5), the coke demand drops to 7.26 GJ/$t_{pig\ iron}$, which is 30% lower than in the conventional process. The coke drop is not as high as with the BF-GR, because part of the CO-rich stream (1.69 GJ/$t_{pig\ iron}$) is exported. The net energy demand of the blast furnace with carbon capture is higher than for both the other cases above (Figures 3 and 4) because of the lack of BF gas for preheating the air or the recirculated gas, and the additional thermal and electrical energy demand of the CO_2 separation unit. However, the direct CO_2 emissions from the furnace are very low (382 kg_{CO2}/$t_{pig\ iron}$) because of the separation of 867 kg_{CO2}/$t_{pig\ iron}$. Even taking into account the CO_2 content of the exported BF gas, the emissions are 392 kg_{CO2}/$t_{pig\ iron}$ and thus less than in a conventional blast furnace and the BF-GR. The entire CO_2 reduction potential, due to the reduction of coke and the less exported BF gas, as well as the potential to integrate renewable energy, becomes apparent under consideration of the entire integrated steelworks, which are analyzed in detail in Section 6.



Data per ton of pig iron

Energy demand per ton of pig iron [21,44]	
Coke	7.26 GJ
Coal dust	4.39 GJ
Total power consumption inclusive of N_2 and O_2 allocation and chemical scrubbing	1.07 GJ
Hot blast stoves	
Natural gas (NG)	3.59 GJ
Total energy demand	16.31 GJ
Export of blast furnace gas	1.69 GJ
Net energy demand (overall demand minus the export of blast furnace gas)	14.62 GJ
CO_2 emissions of the blast furnace per ton of pig iron	
Directly at the process (inclusive power demand)	382 kg_{CO2}
Inclusive CO_2 in exported BF gas	392 kg_{CO2}

Figure 5. Simplified scheme of a blast furnace with gas recirculation and carbon capture based on average data from Santos 2009 and UNIDO 2010 [21,44].

5.3. A Higher Share of Steelmaking in EAF

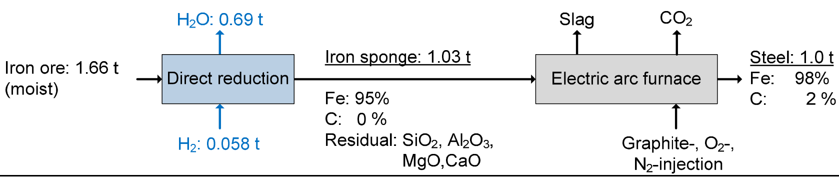
As was already shown in Section 4.2, steel manufacturing in an EAF is less energy and CO_2-intensive than in a blast furnace, because iron ore reduction is not necessary due to the use of scrap as feedstock. In additional, thermal and electrical energy demand can be easily substituted by renewable energies without changes in technology. Under the assumption that German steel production remains constant, it would be possible to reduce the energy demand by 12.61 GJ/t_S and the CO_2 emissions by 507 kg/t_S (related to the CO_2 emissions of the blast furnace inclusive CO_2 content in the BF gas), which is more produced in an EAF. However, the available quantity of scrap is limited. In the study "climate protection scenario 2050", which was conducted on behalf of the German Federal Government [22], the potential for additional steel production in EAF is limited to 6.1 Mt/a. Furthermore, with respect to the energy and CO_2-reduction potential mentioned above, there is a broader reduction in both due to the lack of coke and sinter as feedstocks. These effects are also analyzed in Section 6.

5.4. Direct Reduction of Iron Ore Using Hydrogen (Circored Process)

The Circored process [23,45] produces direct reduced iron briquettes from iron ore fines and uses pure hydrogen as a reduction agent. The first commercial-scale plant has operated in Trinidad since 1999 and has a capacity of 65 t/a. During the process, iron ore fines are dried and heated through the combustion of natural gas at temperatures of up to 850–900 °C. Finally, it is reduced by hydrogen produced via natural gas reforming. Using hydrogen as a reducing agent leads to the formation of water (see Equation (3)) rather than CO_2 as a byproduct (see Equation (2)).

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \tag{3}$$

The product of the Circored process is not pig iron, but a solid iron sponge in the form of briquettes or fines with a metallization of approximately 95%, which can be added to the charge of an EAF to produce steel. The reason for the reduction of the iron ore fines by hydrogen is the products of the Circored process contain no carbon. Therefore, an injection of coal into the iron bath of the EAF is also necessary for metallurgical reasons, particularly when the charge of the EAF has a share higher than 40% of direct reduction iron [45]. Figure 6 shows a simplified scheme of the Circored process and the subsequent treatment of iron sponge in EAF. The data on the Circored process are from Elmquist 2002 and Nubert 2006 [23,45], while, for the EAF part, the same values as for the conventional process were used. An additional amount of coal (0.574 GJ/t_{LS}) is also assumed and is needed for injection into the iron bath to achieve a carbon content of 2% and 100% charge of sponge iron in the EAF.



Circored process [23,45] Energy demand per 1.03 ton of hot briquetted iron (HBI)		Electric arc furnace (EAF) Energy demand per ton of liquid steel	
Electrical power	0.46 GJ	Electrical power	2.07 GJ
Natural gas for heat provision	5.62 GJ	Natural gas	0.78 GJ
Natural gas for H_2 provision	8.31 GJ (58.17 kg_{H2})[a]	N_2	8 kg (4.6 MJ_{el}) [a]
-	-	O_2	50 kg (37.3 MJ_{el}) [a]
-	-	Coal	1.024 GJ [b]
Total energy demand	14.39 GJ	Total energy demand	3.91 GJ
Total energy demand of the Circored process + EAF		18.3 GJ/t_{LS}	
Total CO_2 emissions of the Circored process + EAF (including N_2 and O_2 provision inclusive of process-related emissions (83.9 kg/t))		1.206 kg_{CO2}/t_{LS}	

Figure 6. Simplified scheme of the Circored process connected with an electrical arc furnace. [a] For more information, see Table 1. [b] Additional coal to achieve 2% carbon content in steel and 100% charge of sponge iron in the EAF.

The energy demand of the Circored process, together with the following EAF process, is 18.3 GJ/t_{LS} and the corresponding CO_2 emissions are 1.206 kg/t_{LS}. Both the total energy demand and CO_2 emissions are higher than for pig iron manufacturing in the conventional blast furnace (15.95 GJ/$t_{pig\ iron}$, 1099 kg_{CO2}/$t_{pig\ iron}$) inclusive CO_2 in exported BF gas, (see Figure 3). However, the Circored process has the advantage that no energy-intensive upstream processes such as a coke oven are necessary and no CO_2-intensive gases like BF gas are exported. The effects on energy demand and CO_2 emissions of the whole integrated steelworks with the use of fossil against renewable energies is also discussed in Section 6.

5.4.1. Direct Reduction of Iron Ore with Hydrogen from Electrolysis

In the Circored process, the requisite hydrogen is produced from natural gas by an external steam reformer (Section 5.4). It is also possible that the hydrogen is produced by water electrolysis. However in the case that the electrical energy demand of 12.5 GJ/t_{LS} (Table 4) is provided by the German electricity mix and only the heat is provided by natural gas, the CO_2 emissions total 2407 kg/t_{LS}, which are two-times higher than in the case with hydrogen production via the steam reforming of natural gas. Furthermore, the energy demand is higher due to the lower efficiency of the electrolyzer (η = 70%) compared to a steam reformer (η = 84) (Table 1).

To achieve a major reduction in CO_2 emissions, it is necessary that the electrical power is fully supplied by renewable sources. In this case, the CO_2 emissions are only 409 kg/t_{LS} and thus much lower than for the process via hydrogen from steam reforming. A further reduction in CO_2 could be achieved with the substitution of natural gas by synthetic methane for heat supply (Section 6.4).

Table 4. Energy demand and CO_2 emissions of the Circored process connected to an EAF for the hydrogen production via water electrolysis.

Circored Process [23,45]	
Energy demand per 1.03 tons of hot briquetted iron (HBI)	
Electrical power for plant operation	0.46 GJ [23,45]
Electrical power for hydrogen production	9.97 GJ (58.17 kg_{H2}) [a]
Natural gas for heat provision	5.62 GJ [23,45]
Overall energy demand	16.05 GJ
Total energy demand inclusive of further processing in EAF	19.96 GJ
CO_2 emissions per ton of liquid steel (Circored process + EAF)	
CO_2 emissions using electrical power from the German electricity mix and natural gas for the heat supply	2407 kg
CO_2 emissions using renewable electrical power and natural gas for the heat supply	409 kg
CO_2 emissions using renewable electrical power and synthetic methane for the heat supply	94 kg

Note: [a] Efficiency of the electrolyzer = 70%.

6. Evaluation of Alternative Processes under Consideration for the Integrated Steelworks

In the first part of this section, a balancing area of the most important processes in an average conventional integrated steelworks is defined. An example of the procedure and basic conditions for the evaluation of the alternative processes (see Section 5) is then defined in the context of the integrated steelworks outlined. In the second part, the effects on energy demand and CO_2 emissions, first by the use of conventional fossil fuels and the German electricity mix, and then with the integration of renewable energy sources, are investigated.

6.1. Definition of the Reference Case

The reference case of the conventional integrated steelworks, which is shown in Figure 7, was defined by the authors with the help of data from Sun 2012, UBA 2014 and Hensmann 2010 [25,35,46] and Section 4.1. The parts considered are the coke oven, sinter plant, blast furnace, a power plant for house requirements and export, as well as heat generation for export. The oxygen furnace is not considered a reason for the relatively low energy demand compared to the other processes, as well as for simplification of the balance area. Further processes in the integrated steelworks are considered with the export of heat and electricity over the balance area beyond. In the defined integrated steelworks (Figure 7), the incoming energy flows comprise coal and natural gas for the coke oven, sinter plant and blast furnace.

Because the coke demand in Germany is not completely produced by own coking plants, coke imported as an energy input is also part of the balance area. The energy flows inside the integrated steelworks are shown in Figure 7. For example, the coke oven uses BF gas as an energy input, but exports coke oven gas (COG) to the hot stoves of the blast furnace. The blast furnace and coke oven internally produce more gas than is needed.

The surplus gas is used to generate power and heat for export to other parts of the integrated steelworks, for example rolling mills, or to the public power or heating grid. As shown in Figure 7, 0.5 GJ electrical power and 3.9 GJ heat per ton of pig iron are exported. The CO_2 emissions considered are also shown in Figure 7. For example, during the production of 10 GJ coke, the coke oven emitted 165 $kg_{CO2}/t_{pig\ iron}$. All emissions that are inside of the balance are attributed to pig iron production. The CO_2 emissions of the exported power and heat are divided into two parts. All CO_2 emissions that exceed the German power mix or heat provision by natural gas are included in the pig iron production, because the high CO_2 emission factor of the BF gas (Table 1) leads to heat and power with a very high CO_2 footprint.

With respect to the balance area considered, the production of one ton of pig iron has a total energy demand of 19.18 GJ; however, 4.4 GJ are exported in the form of electrical power and heat. The CO_2 emissions that relate to the balance area are 1732 $kg_{CO2}/t_{pig\ iron}$ and the remaining 299 kg $_{CO2}/t_{pig\ iron}$ relates to the exported energy that is not attributed to the balance area.

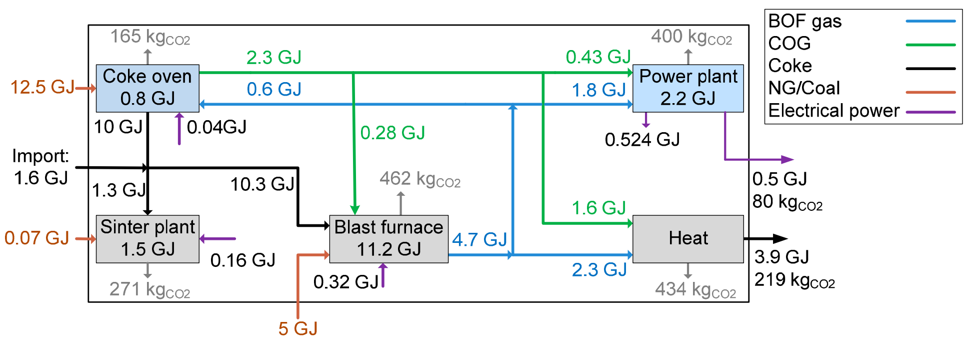


Figure 7. Defined balancing area of the integrated steelworks using data from Sun 2012, UBA 2014 and Hensmann 2010 [25,35,46] and Section 4.1. All data relating to the production of a ton of pig iron.

6.2. Example of the Procedure and Basic Conditions

In this section, the influences of the alternative processes on the integrated steelworks are shown in Figure 8 for the case that the blast furnace is equipped with a BF-GR (Section 5.1). Through the BF gas recirculation, coke demand drops by 45% compared to the conventional blast furnace. Assuming that the coke import is first terminated (in order to use the capacity of own plants) leads to a reduction of coke oven production of 31%. The reduction of coke production leads in turn to less production of COG, which is used for heat and power production. Under the condition that the export of electrical power and heat out of the balance area is constant, the lack of COG must be replaced by a substitute like natural gas.

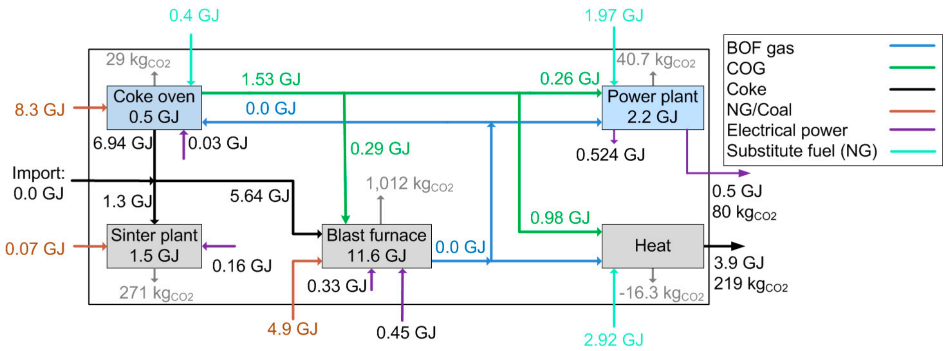


Figure 8. Considered balancing area of the integrated steelworks with a blast furnace with BF gas recirculation using data from Sun 2012, UBA 2014 and Hensmann 2010 [25,35,46] and Section 5.1. All data relate to the production of a ton pig iron.

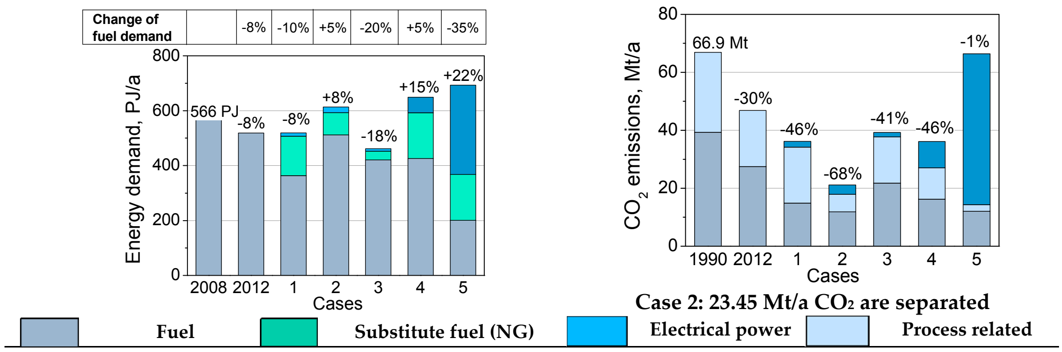
Furthermore, the blast furnace with BF-GR does not have a gas export. As a result, this missing gas has also been replaced by a substitute gas (Figure 8). The electrical power that is generated in the integrated power plant and used within the balance area is also kept constant. The saving of electrical power at the coke oven is used to cover the higher electrical power demand of the blast furnace with BF gas recirculation. The part that cannot be covered by this power is provided by the German electricity mix (0.45 $GJ_{el}/t_{pig\ iron}$).

The changes in the energy demand of the blast furnace and coke oven, as well as the additional energy demand for the provision of the substitute fuels to assure a constant export of electrical power (0.5 $GJ_{el}/t_{pig\ iron}$) and heat (3.9 $GJ_{th}/t_{pig\ iron}$), yields a total energy demand of 19.01 $GJ/t_{pig\ iron}$. This figure is approximately as high as the energy demand of the conventional integrated steelworks, but the energy input shifts from coal to natural gas and a higher share of electrical power. This opens up the options to meeting the energy demand with either conventional energy carriers or completely by renewables. Even if natural gas and the German electricity mix are used, the CO_2 emissions of the balance area are 1336 $kg_{CO2}/t_{pig\ iron}$ and hence 23% lower than in the reference case of the integrated steelworks. Therefore, as already mentioned above, the effect of the CO_2 reduction potential by alternative technologies is only apparent by considering the integrated steelworks in its entirety, especially because the isolated analysis in Section 5 could create the impression that the energy demand and CO_2 emissions of the blast furnace with BF gas recirculation are higher than for the conventional process.

6.3. Alternative Processes with Conventional Energy Provision

According to the same method as described in Section 6.2, the other alternative processes (Section 5) were analyzed with consideration to the integrated steelworks. Figure 9 shows on the left side the total energy demand and on the right side, the CO_2 emissions for the production of 27.048 t of pig iron by means of the conventional blast furnace and alternative processes. The production volume correlates with the amount produced in German blast furnaces in 2012 [35]. Pig iron production was chosen as a basis for the comparison because the idea of this study is to replace the blast furnace as the most energy-intensive part of steelmaking, even if processes such as the Circored process or EAF directly produce steel. Figure 9 also shows energy demand in the year 2008 and CO_2 emissions from the year 1990. These values were extrapolated with the help of data from 2012 and the corresponding years [21,25]. Total energy demand has decreased by 8% since 2008 and CO_2 emissions by 30% since 1990. The values of 2008 and 1990 were added to address one target of the study, namely to indicate whether it is possible to achieve a reduction in electrical power demand by 25% and primary energy demand by 50% against 2008 by 2050 and simultaneously GHG emissions by 80–95% against 1990 by 2050. Therefore, the relative change of fuel demand to the alternative processes is also shown in Figure 9.

In Figure 9, the bars of the energy demand of the alternative processes are divided into three different kinds of energy input. Firstly, conventional fuels that are needed for the process; secondly, additional electrical power, which is not covered by the integrated power plants; and thirdly, the fuel that is needed to replace missing COG and BF gas to keep the power and heat production output of the integrated steelworks constant (see Sections 6.1 and 6.2). In a similar manner, CO_2 emissions (Figure 9, right side) are divided into three different types, namely CO_2 emissions from fuel combustion, process-related emissions and indirect emissions through the use of electrical power from the German power gird.



Cases

Defined integrated steelworks (see Section 6.1) with:
- **2008:** Conventional blast furnace in 2008 only for comparison of the energy demand
- **1990:** Conventional blast furnace in 1990 only for comparison of the CO_2 emissions
- **2012:** Conventional blast furnace in 2012
- **1:** Blast furnace with blast furnace gas recirculation (see Section 5.1)
- **2:** Blast furnace with blast furnace gas recirculation and carbon capture (see Section 5.2)
- **3:** Reduced conventional blast furnace production and 6.1 Mt/a more steel production by EAF (see Section 5.3)
- **4:** Circored process with EAF using hydrogen produced by natural gas (see Section 5.4)
- **5:** Circored process wit EAF using hydrogen produced by electrolysis (see Section 5.4.1)

Figure 9. Energy demand and CO_2 emissions depending on the considered cases.

Case 1: Blast Furnace with Gas Recirculation

The energy demand of the conventional integrated steelworks in 2012 (corresponding to the definition in Section 6.1 and defined as case 2012), as well as steelworks with a BF-GR (see Section 5.1), is 8% lower than in 2008. However, in the case with BF gas recirculation, the energy demand consists of not only fuels such as coke, but also electrical power and a relatively high amount of substitute fuel to ensure power and heat generation for own use and export. Thus, the missing BF gas is replaced by a substitute fuel (natural gas) with a lower emission factor, achieving a CO_2 reduction of 46% on 1990. However, the saving in fuel is relatively low, with 10% against 2008 and additional power from the grid needed.

Case 2: Blast Furnace with Blast Furnace Gas Recirculation and Carbon Capture

In Case 2 (Figure 9), when the blast furnace is equipped with a BF gas recirculation and CO_2 separation (see Section 5.2), total energy demand is 8% higher than in 2008, but as a reason for the separation of 23.45 Mt_{CO2}/a and simultaneous reduction of coke, the CO_2 emissions are 68% lower than in 1990. Moreover, the remaining BF gas, which is used for heat and power production, has a lower emission factor due to the lower CO_2 concentration as a reason for the CO_2 separation (see Figure 5). As in Case 1, the substitution of GF gas by natural gas also leads to a reduction in CO_2 emissions.

Case 3: Reduced Conventional Blast Furnace Production and 6.1 Mt/a More Steel Production by EAF

The production of 6.1 million tons more steel per year in an EAF instead of a blast furnace (see Section 5.3) leads to a total energy reduction of 18% and a reduction in fuel demand of 20% against 2008 (Figure 9). The slight increase in electrical power demand is caused by the EAF itself, which needs four-times more electrical power for the production of one ton of steel/pig iron than the integrated steelworks that use a conventional blast furnace. Nevertheless, the CO_2 emissions are 41% lower than in 1990. In this case, it is also assumed that the power plant produces a constant amount of electricity for export and own use, as well as a constant amount of heat. It is for this reason that substitute fuel is still needed.

Case 4: Circored Process with EAF Using Hydrogen Produced by Natural Gas

In Case 4 (Figure 9), the iron ore is reduced by hydrogen via the Circored process, followed by further processing in an EAF (see Section 5.4). The necessary hydrogen is produced by the steam reforming of natural gas. Although the sinter plant, coke oven and conventional blast furnace are not necessary, the total energy demand increases by 15% and fuel demand, inclusive of substitute fuel, by 5%. The higher energy demand is primarily due to the hydrogen supply. Nevertheless, it is possible to achieve a CO_2 reduction of 46% against 1990, because the main part of the energy is provided by natural gas instead of coal or BF gas. Nevertheless, the process is not free of process-related CO_2 emissions, because these kinds of emissions occur during the steam reforming of natural gas for hydrogen production.

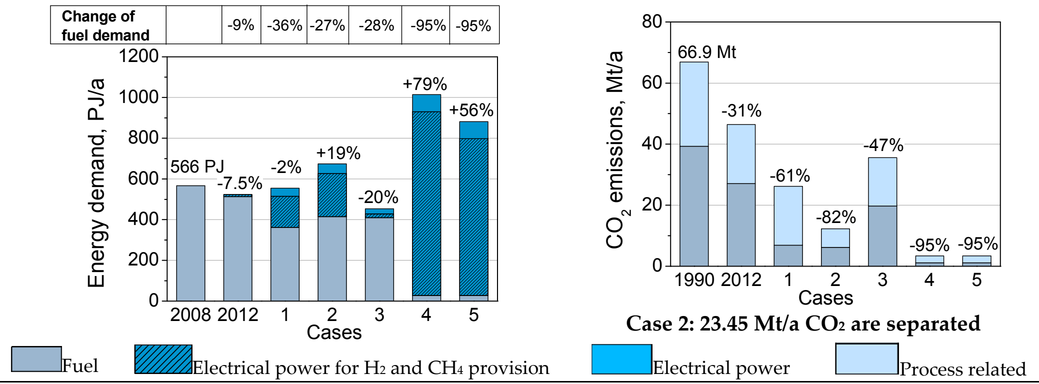
Case 5: Circored Process Wit EAF Using Hydrogen Produced by Electrolysis

From a technical point of view, Case 5 is very similar to Case 4 (see above), but as shown in Figure 9, the kind of energy used and the resulting CO_2 emission levels are very different. In Case 5, the energy demand is dominated by electrical power for hydrogen production via electrolysis (see Section 5.4.1). In spite of a reduction of fuel demand by 35% against 2008, the total energy demand is higher because of the high demand for electrical power. As a result of the relatively high CO_2 footprint of the German electricity mix, CO_2 emissions are only 1% lower than in the year 1990, but higher than in 2012.

6.4. Alternative Processes with the Integration of Renewable Power

In this section, as already suggested above, the feasibility and influence of insertion of renewable electrical power for the same cases as in Section 6.3 are investigated. At the conventional steelworks, coke is not only used as an energy carrier, but is also necessary for the correct operation of the blast furnace, because coke is also a reducing agent and responsible for the gas permeability and stability of the layers inside the furnace and cannot be easily replaced. The alternative processes are less dependent on coke, but more dependent on electrical power and a substitute fuel for COG and BG gas to ensure electricity and heat export beyond the balance limit (see Figures 7 and 9).

Although in Section 6.3 and Figure 9 natural gas is used to ensure the production of electricity, at this point synthetic natural gas is not used to substitute this part of the natural gas. The reason for this is that from an energetic point of view, it makes no sense to convert electrical power into synthetic methane and directly back into electrical power unless the synthetic methane is used as a large energy storage medium for excess power from fluctuating renewable sources (see Section 1). Since the focus of the present study is on the integrated steelworks and not on a possible energy supply system for Germany, it is assumed that the missing output of the power plant, due to the lack of BF and COG gas, is directly replaced by renewable electrical power without the detour via synthetic methane or the methanation process. However, the provision of heat is still based on gas, which is substituted by synthetic methane. The impact on energy demand and CO_2 emissions through the use of renewable electricity, either directly or via synthetic methane or hydrogen, is shown in Figure 10.



Cases

Defined integrated steelworks (see Section 6.1) with:
2008: Conventional blast furnace in 2008 for the comparison of energy demand
1990: Conventional blast furnace in 1990 for the comparison of CO_2 emissions
2012: Conventional blast furnace in 2012
1: Blast furnace with gas recirculation (see Section 5.1)
2: Blast furnace with gas recirculation and carbon capture (see Section 5.2)
3: Reduced conventional blast furnace production and 6.1 Mt/a more steel production by EAF (see Section 5.3)
4: Circored process with EAF using hydrogen produced by natural gas (see Section 5.4)
5: Circored process with EAF using hydrogen produced by electrolysis (see Section 5.4.1)

Figure 10. Energy demand and CO_2 emissions of the different cases using as much renewable electrical power as possible directly and indirectly for the provision of synthetic methane and hydrogen.

Figure 10 also shows for this case the potential to integrate renewable power. It is only possible to substitute a relatively small amount of natural gas (0.214 GJ/$t_{pig\ iron}$) by synthetic methane used in the coke oven and sinter plant. All other energy carriers are not replaceable by renewables, because they are a conversion product of the coal used and must be burned for heat and electrical power generation. Given the electricity demand for the production of synthetic methane (see also Table 1) and a production volume of 27 Mt pig iron per year, 5.8 PJ of natural gas could be replaced with 2.86 TWh of renewable electricity in the conventional process. This would lead to an increase of 0.5% of energy demand and a CO_2 reduction of only one percent (compare Figures 9 and 10).

In Cases 1–5, the integration of renewable energy technologies had a significantly higher impact on CO_2 emissions. In Cases 4 and 5, a CO_2 reduction of 95% against 1990 is achievable. However, the total energy demand increased by 79% and 56%, respectively, so higher than in the use of conventional energy sources (see Figure 9), because the provision of synthetic methane has an electrical energy demand of 1.785 MJ_{el}/MJ_{CH4}. Furthermore, at this point Case 4 does not make sense, because the necessary hydrogen is first produced via electrolysis and then converted into methane, and finally reconverted into hydrogen. This leads to a higher energy demand than in Case 5, where hydrogen is directly used. In both cases, the energy demand is almost completely covered by renewable power, and so the higher energy demand of Case 4 has no influence on CO_2 emissions, resulting in a reduction of 95% against 1990 in both cases.

Only in Case 2 does the energy demand decrease compared to the results in Section 6.3, because the direct use of renewable power instead of a substitute gas bypasses the efficiency losses of the power plant.

7. Discussion

Table 5 summarizes the different cases, with and without the integration of renewable power sources (Sections 6.3 and 6.4). Even with the conventional energy supply, a significant reduction of CO_2 is possible through the use of alternative technologies. The only exception is Case 5, which presents the Circored process that uses hydrogen produced by electrolysis. In this case, only CO_2

emissions are 1% less than those of conventional integrated steelworks in 1990, because the high electricity demand is provided by the German electricity mix. However, this case achieves the highest reduction in fuel demand, because the main share of the energy demand is supplied by electrical power. The greatest CO_2 reduction using conventional fuels is achievable by using a blast furnace with blast furnace gas recirculation and carbon capture (Case 2, −68%). However, in this case the gross reduction is lower, because 23.45 Mt_{CO2} per 27 $Mt_{pig\ iron}$ are separated, which must be further treated to prevent it from entering the atmosphere, such as by means of geological storage, even if such storage is legally limited to 4 Mt/a in Germany [47]. Nevertheless, in countries such as Germany, the separated CO_2 can be reused as a feedstock in the chemical industry [10] or for the production of synthetic methane. In all analyzed cases, the CO_2 (−80 to −95% vs. 1990) and energy reduction targets (electrical power −25% and primary energy demand −50% vs. 2008) of the German government (see Section 1) are not achievable by using conventional energy carriers. In all cases, the electrical power demand increases. Only in Case 2 (a higher share of EAF) is a relatively high reduction of CO_2 emissions and a simultaneous reduction in energy demand achievable, because steel production in the integrated steelworks decreases and the additional production in EAFs needs less energy and emitted less CO_2.

In addition, the technical effort is relatively low compared to the other alternative processes, and so the production of more steel in an EAF can lead to a significant reduction in CO_2 and energy saving in the steel industry in the short term. However, the availability of scrap is limited, so that other technologies are also necessary to achieve further CO_2 reductions.

Table 5. Changes in thermal and electrical energy demand of the conventional steelworks in 2012 and the steelworks with alternative processes against 2008, as well as the changes in terms of CO_2 emissions towards 1990, with and without the integration of renewable energies.

Case	Results with Conventional Energy Provision			Results with Integration of Renewable Energies		
	Electrical Energy Demand against 2008	Fuel Demand against 2008	CO_2 Emissions against 1990	Electrical Energy Demand against 2008	Fuel Demand against 2008	CO_2 Emissions against 1990
2012 (Conventional steelworks in 2012)	0 TWh	−8%	−30%	+3 TWh	−9%	−34%
1 (Blast furnace with gas recirculation)	+3 TWh	−10%	−46%	+54 TWh	−36%	−61%
2 (BF gas recirculation with CO_2 separation)	+6 TWh	+5%	−68%	+72 TWh	−27%	−82%
3 (Reduced conventional blast furnace production and 6.1 Mt/a more steel production by EAF)	+3 TWh	−20%	−41%	+12 TWh	−28%	−47%
4 (Direct reduction of iron ore with H_2 produced by steam reforming)	+16 TWh	+5%	−46%	+274 TWh	−95%	−95%
5 (Direct reduction of iron ore with H_2 produced by electrolysis)	+90 TWh	−35%	−1%	+237 TWh	−95%	−95%

The application of alternative technologies not only has the potential to reduce CO_2 emissions, but also opens a way to using renewable energy sources instead of coal, so that the effect of CO_2 reduction can be increased. With the integration of renewable energies, either directly by electrical power or indirectly by synthetic methane or hydrogen as a reduction agent, CO_2 emissions significantly decrease in all cases (see Table 5). Both the Circored processes (Cases 4 and 5) and the integration of a blast furnace with BF gas recirculation and CO_2 separation achieve the CO_2 reduction targets of the German government. At the same time, the fuel demand decreases by 82–95% against 2008. As already mentioned above, by using renewable power sources, Case 4 does not make sense, because the necessary hydrogen can be delivered directly by an electrolyzer without additional methanation and reforming steps, which only leads to unnecessary additional energy demand (Figure 10).

Nevertheless, the huge reduction in fuel demand leads to a strong additional demand for electrical power for heat (via synthetic methane) and hydrogen provision, which is contrary to the electrical power saving targets of the German government. Apart from this, the required renewable electrical energy demand (237 TWh) is higher than that generated (194 TWh) in Germany in 2015 [48]. This, along with the high present cost of synthetic methane and hydrogen [4], are from today's perspective a factor that makes instant implementation implausible. However, in numerous studies, such as Sternberg 2015, Robinius 2015, ETG-Task-Force 2012, DLR 2012 and Prognos AG 2012, about the future energy system in Germany, it is assumed that both the massive expansion of renewable power generation and the availability of large quantities of excess power will also lead to a reduction in costs [8,49–53]. Through the use of alternative technologies for steelmaking, future energy systems could also be supported because the released power generation capacity of the integrated steelworks could be used as backup power to ensure security of supply in a strong share of fluctuating renewable energies for power generation.

8. Conclusions and Outlook

This study demonstrates that it is possible to reduce CO_2 emissions by up to 95% through the integration of renewable electrical power into the currently coal-based steel industry by using alternative technologies. Both the possibility to integrate renewable power and CO_2 reduction is mainly achieved by an increase or complete discontinuation of coal or the resulting BF gas, which is usually burned for power and heat production in order to avoid release into the atmosphere. With less or no BF gas production, there is an opportunity to use lower-emission fossil fuels or even renewable energies for heat and electricity provision. The latter would allow the coupling of renewable electricity and the steel industry, which could also be seen as "Power-to-Steel". However, to achieve the CO_2 reduction targets of the German government in the steel industry, a major extension of renewable electrical power generation is necessary for providing the processes with energy. Thereby, a large reduction in CO_2 emissions would only be enabled by an increase in electrical power demand and a simultaneous reduction of both is not possible. Nevertheless, the mere substitution of steel production in blast furnaces with the direct reduction via hydrogen could reduce current CO_2 emissions in Germany by about 5%.

Further questions that must be resolved are, for example, how the integration of renewable energies and hydrogen into the steel-making process can be introduced, such as through a specific subsidy regime or by considering carbon pricing. Nevertheless, steel is an internationally-traded product and must therefore be cost-competitive, which necessitates concerted international action.

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Abbreviations

Abbreviations and symbols

BF-CC	Blast furnace with carbon capture
BF gas	Blast furnace gas
BF-GR	Blast furnace gas recirculation
BOF gas	Basic Oxygen Furnace gas
$CaCO_3$	Limestone
$CaMg(CO_3)_2$	Dolomite
CH_4	Methane
CO	Carbon monoxide
CO_2	carbon dioxide
COG	Coke oven gas
DR	Direct reduction
EAF	Electrical arc furnace
Fe_2O_3	Hematite
Fe_3O_4	Magnetite
H_2	Hydrogen
η	Efficiency
HBI	Hot briquetted iron
H-DR	Direct reduced iron with hydrogen as reduction agent
IEA	International Energy Agency
N_2	Nitrogen
NG	Natural gas
OHF	Open hearth furnaces
SR	Smelting reduction
ULCOS	Ultra-Low Carbon Dioxide Steelmaking
VPSA	Vacuum pressure swing adsorption

Subscripts

el	Electrical
LS	Liquid steel
S	Steel
th	Thermal

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