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Techno-economic evaluation of innovative steel production technologies

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Contents

Abstract

At current primary steel production levels, the iron and steel industry will fail to meet the 80% emission reduction target without introduction of breakthrough technologies (Wörtler et al., 2013: 19). The current research analyses the technical and economical long-term potential of innovative primary steel production technologies in Germany throughout 2100. Techno-economic models are used to simulate three innovative ore-based steelmaking routes verses the reference blast furnace route (BF-BOF). The innovative routes in focus are blast furnace with CCS[1] (BF-CCS), hydrogen direct reduction (H-DR), and iron ore electrolysis (EW). Energy and mass flows for the production of one tonne of crude steel (CS) are combined with hypothetical price, cost, and revenue data to evaluate the production routes economically, technically, and environmentally. This is a purely theoretical analysis and hence further external factors that may influence practical implementation or profitability are not considered.

Different future developments are considered by using three scenarios, representing an ambitious, a moderate, and a conservative transformation of the German energy sector. In general, looking into the future bares various uncertainties which should be reflected in a suitable manner.

According to the present scenario analysis chances are that with rising prices for coal and CO_2 allowances BF-BOF and even BF-CCS become unprofitable by mid-century. With a high share of renewable energy sources and high prices for CO_2 allowances H-DR and EW become economically attractive in the second half of the current century, when BF-based routes are long unprofitable. Energy and raw material efficiency is significantly higher for H-DR and EW, and furthermore, the 80% reduction target by 2050[2] can be achieved in the *ambitious* scenario. However, high investment costs and high dependency on electricity prices prohibit a profitable implementation before 2030-2040 without further subsidies. EW is the most energy and resource efficient production route. Since continuous electricity is needed for the continuous operation, the electricity costs are 20-40% higher than for H-DR (with high-capacity hydrogen storage units).

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[1] CCS = Carbon Capture and Storage

[2] BMU (2010: 4)

Even though hydrogen production implies efficiency losses compared to the EW route, the decoupling of hydrogen production from continuous operation of the steel plant through hydrogen storage offers the opportunity to use cheap excess electricity whenever available. This makes the H-DR economically and environmentally the most attractive route and provides a crucial contribution to stabilize the grid and to store excess energy in a 100% renewable energy system.

1 Introduction

Climate change is one of the crucial challenges for humanity. Since the pre-industrial era the concentration of greenhouse gases (GHG) in the atmosphere has risen steadily from below 300 ppm (1900) to a new record high of 400 ppm in May 2013 (Birol et al., 2013: 11). In order to maintain a chance to keep global warming below 2°C, the maximum threshold is considered to be 450 ppm and would be reached in 30 years at current emission levels (World Meteorological Organization, 2013: 2). Drastic emission reduction is necessary across the world to achieve this target. As suggested by the Intergovernmental Panel on Climate Change (IPCC) for developed countries the EU targets to reduce GHG emissions 80-95% by 2050 (Europäische Kommission, 2011: 3).

The iron and steel industry, one of the most energy-intensive industries in Germany, is expected to contribute to the climate targets and to reduce GHG emission by at least 80% by 2050 from 1990 level (BMU, 2010). In 2011 the German iron and steel industry consumed 6.2% (554 PJ)[3] of the total German end-use energy demand and caused 4% (41Mt CO_2e)[4] of the total GHG emissions.

Reducing GHG emission of the steel industry can be achieved in three areas: Steel demand reduction, increased steel recycling, and innovation in steel production technologies. Even though steel demand in some developed countries might peak within the current century, the world steel demand is expected to rise at least until the end of the 21st century (Pauliuk et al., 2013: D). A shift towards the secondary production route through recycling efficiency has a great impact on CO_2e emission. Even though higher shares may be possible in long-term, until 2050

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[3] AG Energiebilanzen e.V. (2012)

[4] Statistisches Bundesamt (2013)

only 44% of the steel demand can be covered by the secondary route (Wörtler et al., 2013). In order to achieve the 2050 reduction targets a combination of the above mentioned demand reduction measures with additional efficiency measures and innovative iron ore reduction technologies will be necessary (Milford et al., 2013).

The most common primary production route is based on the blast furnace (BF) in combination with the basic oxygen furnace (BOF), which accounted for 68% of the German steel production in 2012 (Stahlinstitut VDEh, 2013). The best available technology (BAT) benchmark in Europe for emission of the blast furnace route is at 1475kg CO_2e / t CS. Due to continuous optimization the industry is already approaching the theoretical minimum of 1371 kg CO_2e / t CS (Kirschen et al., 2011: 6148). Therefore, without demand reduction, substantial emission reduction is only possible through the implementation of new breakthrough technologies (Pardo and Moya, 2013: 127).

Research and development initiatives around the world cooperate under the 'CO_2 Breakthrough Programme'[5] and exchange information on innovative steelmaking technologies investigated in the respective national programs (e.g. ULCOS[6], AISI[7], POSCO[8], COURSE50[9], etc.). The goal is to develop breakthrough technologies "that revolutionise the way steel is made" and hold the promise of large reduction in CO_2e emission (World Steel Association, 2009: 1). Key areas of research identified are Carbon Capture and Storage (CCS) in combination with fossil fuels and hydrogen and electricity as innovative reducing agents for the reduction process. According to recent techno-economic evaluations and scenario analysis ((Wörtler et al., 2013); (Birat and Borlée); (Remus et al., 2013); (Gerspacher et al., 2011); (International Energy Agency (IEA), 2012)) the technologies with the highest long-term potential in the iron and steel industry are carbon capture and storage (CCS) in combination with a top gas recycling for the blast furnace (TGR-BF), direct reduction (DR) with electric arc furnace (EAF), and a rather immature

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[5] World Steel Association (2009)

[6] ULCOS = Ultra-Low CO_2 Steelmaking (EU)

[7] AISI = American Iron and Steel Institute with technology roadmap programme

[8] POSCO = CO_2 Breakthrough Framework (Korea)

[9] COURSE50 = CO_2 Ultimate Reduction in Steelmaking process by innovative technology for cool Earth 2050

technology with high future potential, the iron ore electrolysis also called electrowinning (EW). Since plant lifetimes are long and investments are very high, technological breakthroughs are considered a long-term option and not expected before 2020/30 (Ahman et al., 2012: 31).

The current research aims to analyse these innovative technologies from a techno-economic perspective regarding their potential for economically viable GHG emission reduction up to 2100. The main research question is:

Which innovative steelmaking technology allows substantial economically viable GHG emission reduction in the primary steel production by 2050 and beyond?

The focus goes beyond existing scenario analysis in the iron and steel industry. Not only is the timely perspective much longer, but also are the technologies assessed very innovative technologies, that have not been evaluated by other techno-economic scenario studies so far. Emission effects due to decreasing steel demand or increased scrap recycling are not included in the current calculation.

2 Background and rationale

This section starts with the approach of the present research and background information on steel production processes. Theoretical considerations regarding the methods applied and the selection of evaluation parameters lay the foundation for the following sections.

2.1 Technology screening and selection of production routes

The current research starts with a screening of steel production technologies. Conventional as well as innovative technologies are assessed along the following aspects based on available literature information[10] (see Figure 2-1).

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[10] Hasan (2011); Birat (2010); Gerspacher et al. (2011); Remus et al. (2013); Wörtler et al. (2013); Pardo et al. (2012); Midrex Technologies ; Arens et al. (2012); Stahlinstitut VDEh (2013); Worrell et al. (2008: 10); Lindroos (2009: 21); Fruehan (2009); Nitsch et al. (2010: 77); Ahman et al. (2012: 31); Croezen and Korteland (2010); Neelis and Patel (2006)

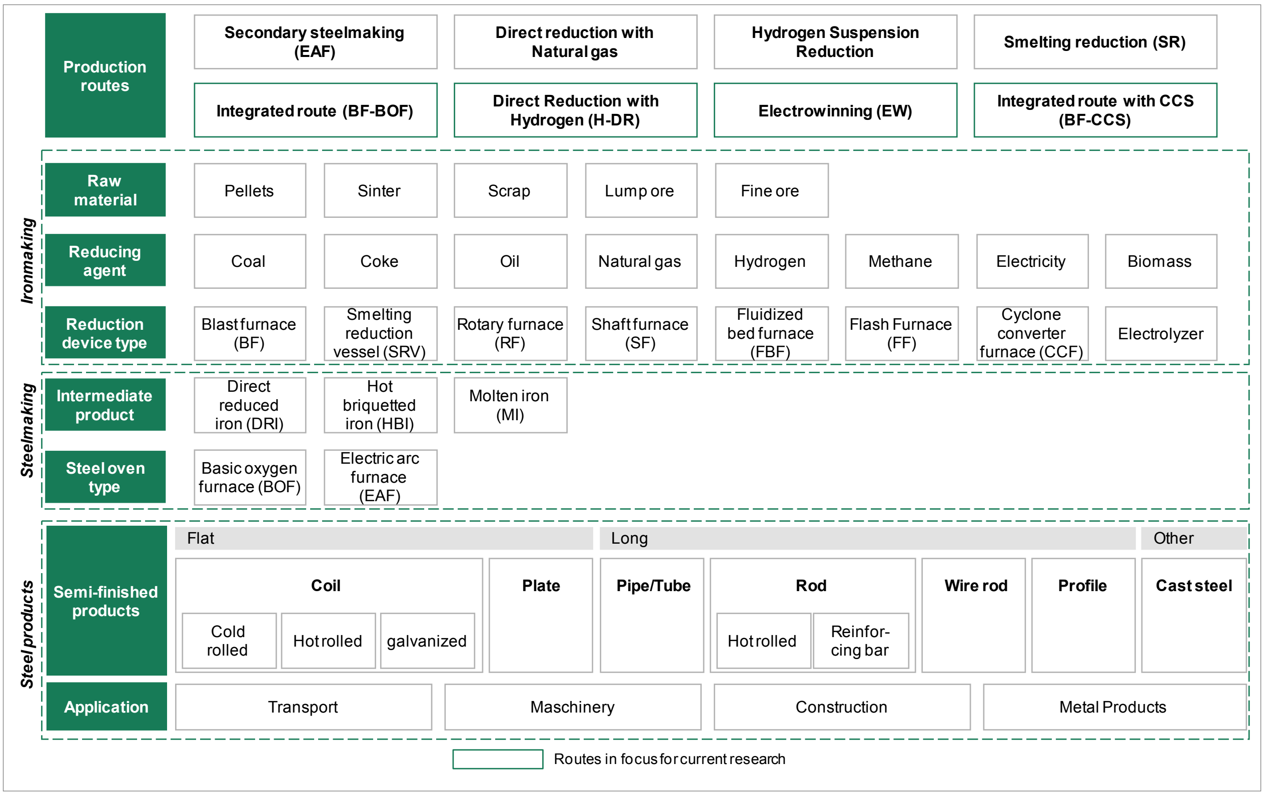

Figure 2-1: Spectrum of steel production routes

For each technology the following information is gathered additionally:

- Energy demand
- GHG emission (including indirect emission)
- Maturity level of technical development
- Advantages and disadvantages of production route
- Necessary external preconditions

Narrowing down the number of technologies to be assessed in more detail, four production routes are selected. First, as reference case the most established route, the integrated route (blast furnace followed by basic oxygen furnace), is selected. As second route the combination of the integrated route with carbon capture and storage (CCS) is chosen as intermediate option based on existing infrastructure. CCS technology is considered to have a high relevance for energy intensive industries like the iron and steel industry (BMU, 2010: 19). For the purpose of the current research with a long-term outlook for the iron and steel industry additionally the innovative technologies with the highest future potential are selected, being Hydrogen Direct

Reduction (H-DR) and Electrowinning (EW) as third and fourth route. In summary the four steel production routes in focus are:

1) Integrated route (BF-BOF)
2) Integrated route with CCS (BF-CCS)
3) Hydrogen Direct Reduction (H-DR)
4) Electrowinning (EW)

1) Integrated route (BF-BOF)

Iron ore is reduced in the blast furnace to molten iron which is subsequently refined to crude steel (CS) in the basic oxygen furnace. The BF reducing agent coke is produced on-site using metallurgic coal. Before entering the BF iron ore is agglomerated to sinter allowing the reducing gas to stream through the burden. The utilisation of coke for the reduction step in the BF creates waste gas with large amounts of CO_2.

2) Integrated route with CCS (BF-CCS)

This route is based on the regular BF-BOF route as described above. The BF is equipped with top gas recycling (TGR) and carbon capture and storage (CCS). After capturing the BF gas most of its CO_2 content is removed via pressure swing absorption (PSA), compressed, and transported to an underground storage site. The remaining CO-rich BF gas is re-circulated into the blast furnace for further burning. All technologies used in this route are already technically available. The unresolved questions regarding storage technique and storage site impede an early market entry of this route before 2020 (EUROFER, 2013: 42).

3) Hydrogen Direct Reduction (H-DR)

Direct reduction is a solid-state reduction process for iron ore with a reducing gas (typically natural gas), already in operation since the 1970s (Wörtler et al., 2013: 8). In the current study hydrogen is used as innovative reducing gas in a fluidized bed reactor which minimizes sticking of the iron ore particles during reduction and allows the direct use of fine ore instead of pellets (Circored technology[11]) (XU and CANG, 2010: 5). Since the direct reduction does not allow the separation from gangue only ores with high iron and low gangue content can be used

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[11] First and only Circored plant in Trinidad in operation since 1996 Nuber et al. 2006

(EUROFER, 2013: 34). Subsequently, the solid hot briquetted iron (HBI) is fed into an EAF together with scrap for steel production. With 100% renewable hydrogen production this route can be virtually free of CO_2e emission. In the EUROFER report "A steel roadmap for a low carbon Europe 2050" this technology is appraised to have the maximum CO_2 saving potential but market entry is not expected before 2030 (EUROFER, 2013: 50).

4) Electrowinning (EW)

The electrolysis of iron ore is a rather immature technology with proven results only in laboratory scale (Yuan and Haarberg, 2008) but still without industrial scale pilot plants. With electricity as reducing agent the future potential of this technology in an electricity-dominated world is significant. In the current research, electrolysis of iron ore in an alkaline solution at 110°C and subsequent refining in an EAF is simulated. Depending on the electricity mix used for electrolysis this route is potentially carbon free. Market entry is not expected before 2040 (EUROFER, 2013: 42).

As basis for in depth assessment four models are developed in section 3, that simulate the effect of different future scenarios on the performance of the above mentioned production routes.

2.2 Evaluation methodology

Based on the international standard of material flow cost accounting (Deutsches Institut für Normung, 2011), mass and energy flows are simulated for each process step of the four alternative steelmaking routes. Technical parameters (mass-, energy-intensity, efficiency, etc.) are taken from relevant literature[12]. For a complete techno-economic assessment hypothetical future price, cost and revenue data are investigated (see Table 3-1) and added to the technical models. The production of one tonne of crude steel is simulated with either process route in a simplified system without consideration of external factors like competition, barriers for market entry, existing infrastructure, etc. These theoretical simulations describe potential development trajectories towards climate-neutral primary steelmaking and do not conclude on the probability of any development.

[12] Wörtler et al. (2013), Worrell et al. (2008), Schwaiger (1996); Spath et al. (1999), Weißbach et al. (2013), Morgan Stanley Research Global (2013), Ahman et al. (2012), Birat and Borlée , Pardo and Moya (2013), Germeshuizen and Blom (2013)

2.3 Evaluation parameters

Basis for comparison in the present research are the following simulated parameters:

Economic

5) Revenues
6) Operating expenses
7) EBIT (Earnings before interest and tax)
8) NPV (Net present value)

Environmental

9) GHG Emissions
10) Energy consumption
11) Raw material efficiency

Especially the combined assessment of NPV, as key indicator for profitability, and the specific GHG emission indicate the suitability of the assessed routes for future requirements. The types of raw materials and energy sources used provide important information on the future system compatibility.

In the next section the models used as basis for the evaluation are defined in detail.

3 System definition

In this section three alternative future scenarios are depicted, that lead to three different sets of model assumptions. Additionally system boundaries, technical and economical parameters, and common conventions for the simulation models are defined to provide a transparent basis for the simulation results.

3.1 Future scenarios

For the model assumptions that have a high time-dependency and that are very relevant for the simulation results, it is common to use scenarios to cover a wide spectrum of future developments (Zeiss and Valentin, 2011). Scenarios are hypothetical but very precise and consistent description of future situations, including the transition path from the present to the future state (Lechtenböhmer, 2008: 12). In the current research three different scenarios for the transition of the German energy landscape ("Energiewende") are depicted as hypothetical projections.

Ambitious scenario

In the *ambitious* scenario the "Energiewende" is realized faster and more consequent than expected. The emission reduction target of 80% by 2050[13] is expected to be reached in 2040 already. The very high proportion of renewable energy sources is balanced with large-scale underground hydrogen storages. Hydrogen can be produced from cheap renewable peak electricity and plays an increasingly important role in industrial processes and in the transport sector, leading to the necessary infrastructure construction. Past 2040 electricity prices fall below present price levels and past 2050 CO_2-free electricity is available in the national grid. CO_2 allowance prices rise fast due to internationally binding emission reduction targets and an international trading scheme causing CO_2-intensive processes to be less profitable.

Moderate scenario

In the *moderate* scenario the transition of the energy sector is realized consequently at the pace expected by the national milestone plan (BMU, 2010)[14]. A high proportion of renewable energy sources cause times of oversupply with very cheap peak-electricity prices. CO_2 prices rise moderately through a consistent national trading system without many exceptions. Fossil fuel power plants guarantee grid stability in combination with innovative smart meters and smart grids. Electro-mechanical technologies dominate the transport sector past 2050.

Conservative scenario

The *conservative* scenario assumes the ongoing transition activities to continue, without extraordinary efforts to overcome the current difficulties regarding offshore wind and public pressure against rising energy prices. Consequently the 80% emission reduction target is postponed until 2070, slowing down the roll-out of renewable energies and strengthening the medium-term importance of fossil fuels. CO_2 prices only rise slowly since no internationally binding targets are passed. Lower proportions of renewable energies do not necessitate large-

[13] BMU (2010: 4)

[14] 80% emission reduction by 2050 compared to 1990 levels

scale storage units. The nuclear phase-out is nevertheless realized by 2022. This scenario is the only one deemed possible by stakeholders of the iron and steel industry[15].

In line with these scenarios projections over the investigation period are developed for the most important model assumptions (Table 3-1 and additional details in Appendix A). These are either assumptions that have strong timely variation or very significant impact on the simulation results. The values in Table 3-1 are based on several renowned scenario studies of the German energy transition[16]. The applicability to the iron and steel industry is discussed with industry experts[17].
After having derived the main model assumptions additional information regarding system boundaries, technical parameters, and conventions are given in the next subsection.

[15] Klaus Kesseler (2014)

[16] Nitsch et al. (2012), Nitsch et al. (2012), Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU) (2011), Pardo and Moya (2013)

[17] Klaus Kesseler, ThyssenKrupp Steel Europe AG; Nicole Voigt, The Boston Consulting Group

Assumptions	Price metal. coke	Price iron ore	Price CO_2 allowances	Price natural gas	RE fraction	Price Electricity fossil	Price electricity RE	Price peak electricity	CO_2 emission electricity	Price scrap	Price hot rolled coil
Year \ Unit	EUR_{2010} / t	EUR_{2010} / t	EUR_{2010} / t	EUR_{2010} / GJ	%	EUR_{2010}/MWh	EUR_{2010}/MWh	EUR_{2010} /MWh	EUR_{2010} / GJ	kg/MWh	EUR_{2010} / t
Ambitious Scenario											
2010	170	106	14	5,8	17%	62	157	50	546	255	631
2020	200	114	27	8,1	38%	93	87	38	410	287	680
2030	235	123	45	10,5	59%	118	62	25	273	324	733
2040	277	133	60	12,7	80%	136	48	13	137	365	790
2050	326	143	75	14,9	100%	157	40	0	0	411	851
2060	351	143	100	18,7	100%	197	40	0	0	391	851
2070	378	143	100	23,5	100%	247	40	0	0	372	851
2080	408	143	100	29,5	100%	310	40	0	0	354	851
2090	439	143	100	37,0	100%	389	40	0	0	336	851
2100	473	143	100	46,4	100%	489	40	0	0	320	851
Moderate Scenario											
2010	170	106	14	5,8	17%	62	157	50	546	255	631
2020	200	114	23	7,0	35%	81	93	42	455	287	680
2030	235	123	34	8,3	50%	88	68	33	364	324	733
2040	277	133	45	9,6	65%	97	55	25	273	365	790
2050	326	143	57	10,6	80%	106	46	17	182	411	851
2060	351	143	80	12,3	95%	122	40	8	91	411	851
2070	378	143	100	14,3	100%	140	40	0	0	411	851
2080	408	143	100	16,6	100%	161	40	0	0	411	851
2090	439	143	100	19,2	100%	185	40	0	0	411	851
2100	473	143	100	22,3	100%	212	40	0	0	411	851
Conservative Scenario											
2010	170	106	14	5,8	17%	62	157	50	546	255	631
2020	200	114	20	6,1	28%	66	96	44	478	275	680
2030	235	123	26	6,6	38%	70	73	38	410	296	733
2040	277	133	36	7,3	49%	74	59	31	341	319	790
2050	326	143	45	8,1	59%	78	51	25	273	344	851
2060	351	143	60	8,8	70%	82	45	19	205	371	851
2070	378	143	80	9,5	80%	86	40	13	137	399	851
2080	408	143	100	10,3	91%	91	40	6	68	430	851
2090	439	143	100	11,1	100%	95	40	0	0	464	851
2100	473	143	100	12,1	100%	100	40	0	0	500	851
Source	(Pardo and Moya, 2013: 119)	(Pardo and Moya, 2013)	(Nitsch et al., 2012: 51)	(Nitsch et al., 2012: 51)	(BMU, 2010) (Böhme et al., 2011)	(Nitsch et al., 2012) +€10; (Statista GmbH)	(Nitsch et al., 2012: 167)+ €10; (Statista GmbH)	(Nitsch et al., 2012: 23) (Schinko et al., 2014)	(Icha, 2013)	(Pardo and Moya, 2013)	(Statistisches Bundesamt, 2012)

Table 3-1: Model assumptions according to scenario predictions (Additional justification see Appendix A)

3.2 Model description

The four steel production models include the iron and steel production process steps as well as the preparation of the input materials (sintering, coking, grinding, etc.). To compare routes with different reducing agents also the upstream value chain of the reducing agent is included, starting from the source (mining of coal, RE electricity generation, hydrogen production). Further processing of crude steel is not included in the system boundaries since these process steps are similar regardless of the production route (Germeshuizen and Blom, 2013: 10680). For the BF-CCS route only the carbon sequestration and capture steps are inside the boundaries. Energy demand and infrastructure for the carbon storage is not considered. The schematic diagram in Figure 3-1 visualizes the system boundaries.

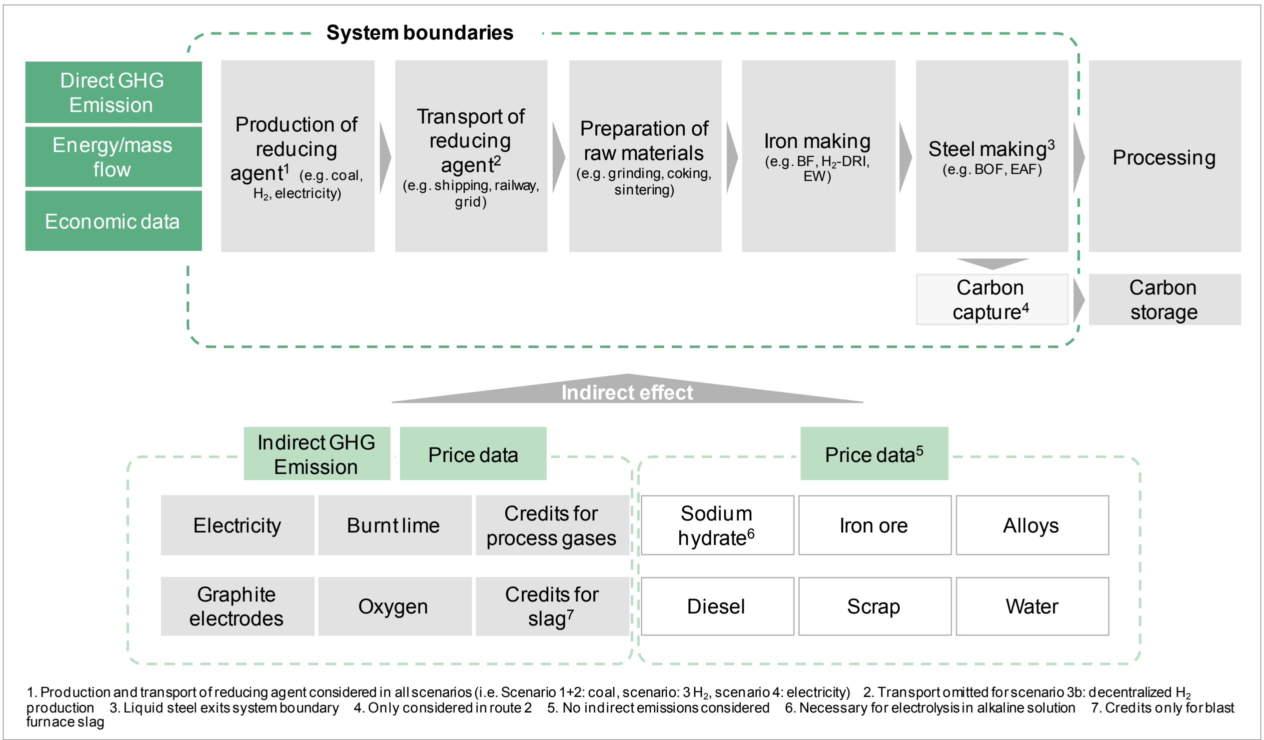

Figure 3-1: System boundaries of steelmaking models (Illustration based on Wörtler et al., 2013)

For the process steps inside the system boundaries all material and energy flows as well as all direct GHG emissions are considered. Many input materials already carry a certain burden of 'up-stream' GHG emissions from their production. To keep the models realistic the most significant indirect effects are included. The indirect emission from the production of electricity, lime, graphite electrodes, and oxygen are included in the total emission of the model. For process gases that are commonly used for electricity generation and for blast furnace slag, which can substitute clinker in the cement industry, emission credits are allocated to the relevant process steps. For other input materials according to Figure 3-1 no indirect emissions are considered. To ensure the comparability of the models the following conventions are applied rigorously throughout all four models:

- Credits for waste gases are accounted only with the balance to the average emission factor of the grid[18]
- Credits for slag are only considered for the blast furnace based production routes (BF-BOF and BF-CCS)
- 100% of GHG emission is compensated by CO_2 allowances (to guarantee a common basis for economic comparison)
- GHG emission is allocated to the process steps where it leaves the system boundaries (polluter principle)
- Waste products are used internally whenever possible (see self sufficiency assumption Wörtler et al., 2013: 13)
- All input materials are bought at assumed market price (Table 3-1, Table-A 1 – Table-A 5)
- Lower heating value is used for all energy calculations
- All monetary values are real values to the base year 2010
- Same sales price for hot rolled coil is assumed for all production routes
- Not available technical assumptions were taken from similar technologies in operation, together with an uncertainty factor (e.g. CAPEX assumption in Table-A 5)

In addition to the main assumptions in Table 3-1 a variety of technical parameters are included in the models (see Appendix Table-A 1 – Table-A 5). To reduce the complexity these technical parameters are kept constant over the investigation period (*ceteris paribus* assumption). Therefore, no incremental improvements, e.g. through efficiency gains, are included. For mature technologies and long investment cycles this is an acceptable simplification.
Before presenting the simulation results the following subsection discusses the limitations of the used numerical models.

3.3 Model limitations

In modelling there is inevitably a trade-off between reproducing reality and maintaining a simplicity that allows identification of dependencies. The models in this research are not accurate

[18] Based on Ecofys (2009: 14) but with average emission factor instead of natural gas emission factor

simulations of specific plants. The lack of real data and the focus on a long-term technology outlook calls for a simplified modelling approach with hypothetical plants and assumptions that are nevertheless thoroughly investigated and representative for the iron and steel industry. The absolute results of the models are less meaningful because the long-term assumption basis has high uncertainties. The relative comparison of results between the different production routes though, is very relevant for the technology evaluation. Comparable to (Germeshuizen and Blom, 2013) also the current results cannot be generalized since the model represents a hypothetical plant.

4 Results

Without a decline in world steel demand, emission reduction targets for the iron and steel industry will not be met without technological breakthrough (Wörtler et al., 2013). In this section the results of the techno-economic assessment of alternative primary steelmaking routes are presented.

Subsection 4.1 starts with mass and energy balances for the four respective routes. Time-dependent simulation results for each route are subsequently presented in subsection 4.2, with an overall technology comparison in subsection 4.3. Finally in subsection 4.4 the results of a sensitivity analysis to validate the robustness of the model to changing input factors in the future are presented.

4.1 Mass and energy balance

The technical characteristics of the models are not time dependent (see section 3.2). Therefore calculated energy and mass balances are valid throughout the investigation period. In Figure 4-1 the energy and raw material demand for one tonne of crude steel is compared between all four production routes. For detailed simulation results please refer to Figure-A 1 in the appendix.

The BF-BOF route is by far the most energy intensive route (model 1). The combination with TGR and CCS technology consumes additional electricity but reduces the coal/coke demand by about 20%. The total energy demand of model 2 is about 15% lower than for model 1, which is remarkable since in most cases CCS application causes a higher energy demand (EUROFER, 2013: 42). Typical for the direct reduction (H-DR) process is the significantly lower energy demand (model 3). Even including energy losses through hydrogen production via electrolysis the total demand is still 40% lower than for the BF-BOF route. For the hydrogen production large amounts of electricity are necessary, which need to be produced carbon-free if CO_2 emission reduction is to be achieved (approx. 3% of Germany's electricity demand would be needed to substitute a 5 Mt/a BF-route with H-DR)[19]. Since no transformation step is needed for the EW route (model 4) this is the most energy efficient route with 9.3 GJ / t CS. The energy demand is entirely covered by electricity which drives the routes unprofitable during times of high electricity prices. With continuous production of 8640h[20] per year only 22% of the electricity demand can be covered by cheap and renewable peak electricity. Apart from an insignificant amount of carbon as aggregate (less than 0.1% of carbon content in steel)[21], no further fossil fuels are used in the routes described by model 3 and 4. The GHG emissions are caused indirectly by the consumed grid electricity and fluxes.

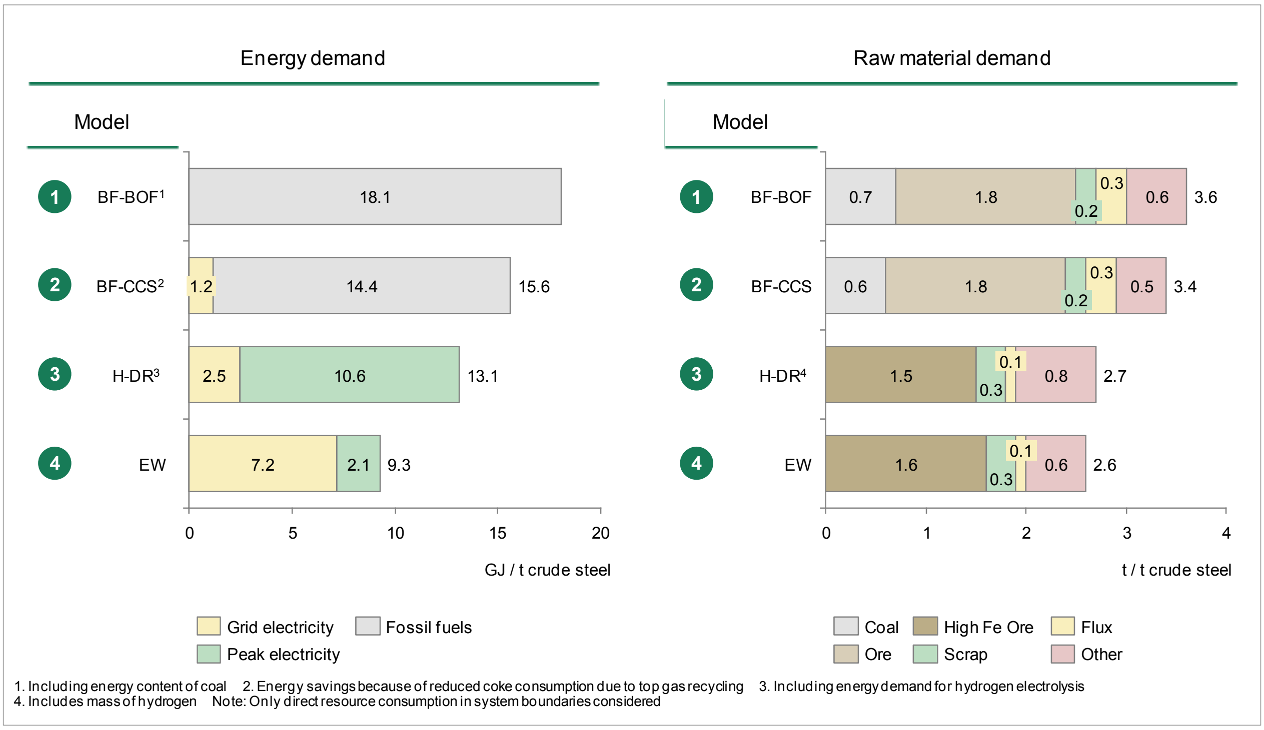

Figure 4-1: Comparison of mass and energy balances based on simulation results for 1 tonne of crude steel

[19] Klaus Kesseler (2014)

[20] Remus et al. (2013)

[21] Klaus Kesseler (2014)

The cumulative raw material demand in metric tonnes differs significantly between the coal-based routes (model 1 and 2) and the electricity based routes (model 3 and 4). In the BF-CCS route 200 kg of coal and fluxes are omitted but additional electricity for the TGR and carbon sequestration is needed. For the hydrogen production in model 3 and the sodium hydroxide solution in model 4 about 700 kg of water is necessary and included under 'Other' in Figure 4-1. The iron ore demand for model 3 and 4 is lower because fine ore and concentrates with high iron content are used. Overall the lowest raw material demand is simulated for the electrowinning route, where massless electricity is used as energy source and reducing agent. The substitution of coal as reducing agent by hydrogen or electricity eliminates the largest source of CO_2e emission. About one tonne of CO_2e emission solely for the iron ore reduction step can be omitted by a virtually carbon free reduction, if 'green' electricity is available (see Figure-A 1).

4.2 Economical analysis

In this section the simulated economic performance based on the three future scenarios is compared. The four routes are compared separately for each scenario. As indicators for the economic performance the revenue, the operating expenses (OPEX), and the earnings before interest and taxes (EBIT) are plotted for the investigation period. The time frame before a technology is realistically market-ready is displayed faintly and is not considered for the comparison.

Conservative scenario

The *conservative* scenario is the most favourable one for the conventional route (BF-BOF). Even though 100% of the CO_2e emission has to be compensated, the relatively low prices for CO_2 allowances, fossil based electricity, and scrap in the first decades of the investigation period maintain a positive EBIT until 2030 (see Figure 4-2). In combination with TGR and CCS even until 2050 (BF-CCS). In long-term, rising prices for fossil fuels, scrap and carbon allowances make both BF-based routes unprofitable unless subsidies or significantly higher sales prices for steel become reality. With a small share of RE sources towards the beginning of the investigation period no cheap peak electricity is available for hydrogen production or iron ore electrolysis. Therefore the two routes with alternative reducing agents (H-DR and EW) are highly unprofitable until 2040 even if technological marketability would be accomplished earlier. Past 2040 H-DR has lower OPEX than BF-BOF due to decreasing peak electricity cost at times of renewable electricity oversupply. The selective consumption of renewable peak electricity for excess hydrogen production and storage provides H-DR with an electricity price advantage and makes it the most profitable steel production route in the second half of the current century, even outperforming the more energy efficient EW route.

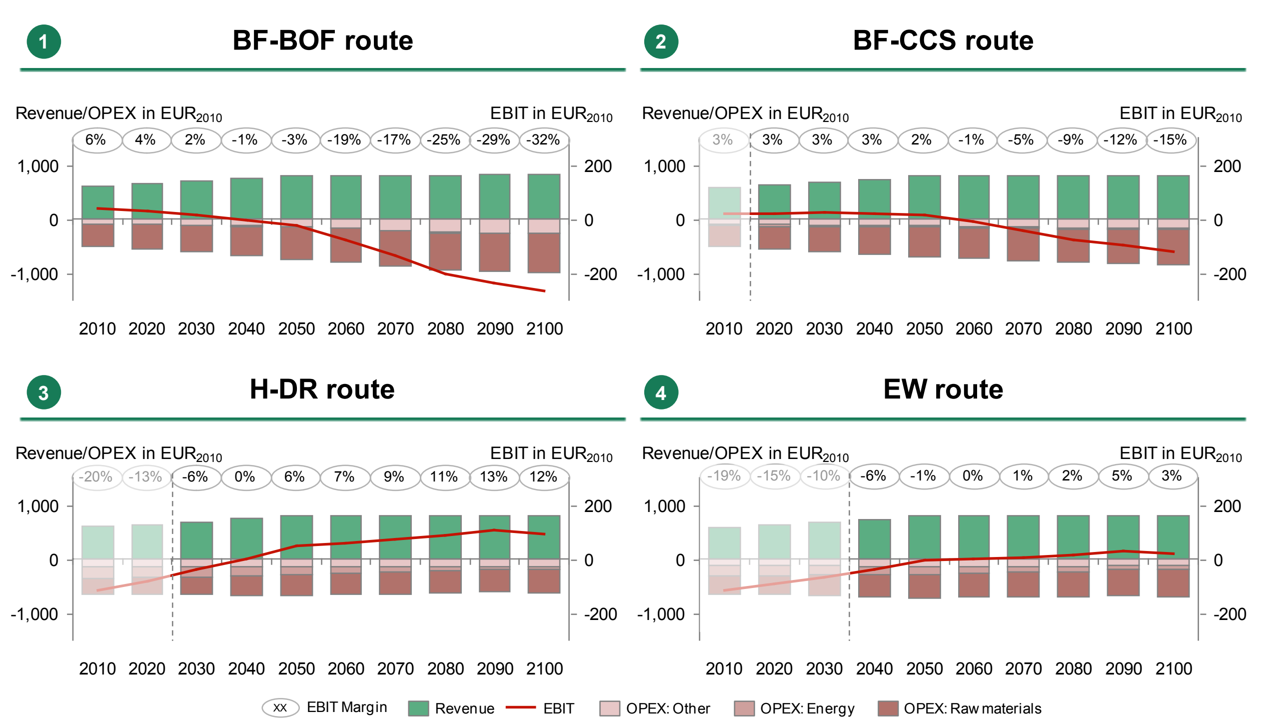

Figure 4-2: Economical comparison in the *conservative* scenario

Moderate scenario

The faster transformation of the energy sector causes electricity prices to rise faster and higher between 2020 and 2030 before falling faster than within the *conservative* scenario. The faster price increase for carbon allowances and steel scrap causes the BF-BOF and the BF-CCS route to become unprofitable about 10 years earlier than in the *conservative* scenario due to higher production costs. The more severe interim electricity price increase impedes an early market entry for the H-DR and EW route. For H-DR past 2050 the long-term profitability is higher and with two-digit EBIT margins past 2080 comparable to the most profitable times of the conventional steel production route. Lower grid electricity prices and lower scrap prices past 2040 compared to the *conservative* scenario provoke the EW route to become profitable past 2060. The electricity price advantage through higher share of RE for H-DR remains.

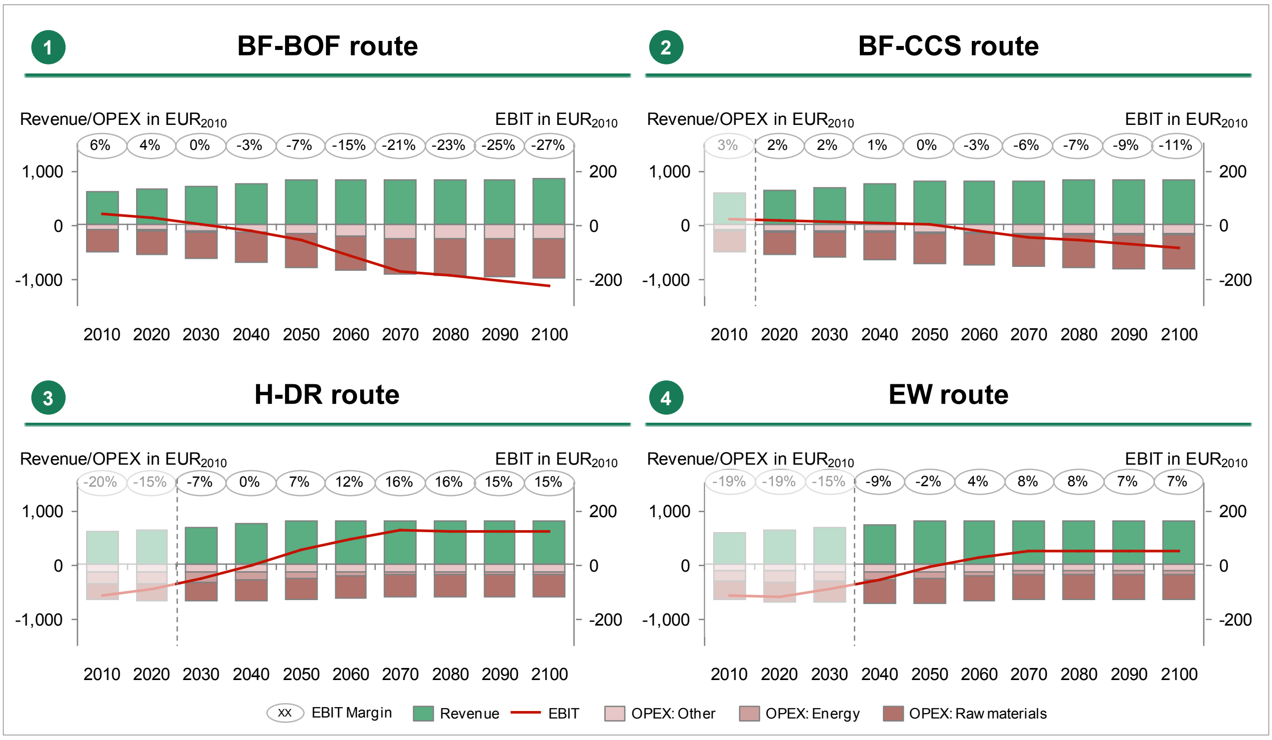

Figure 4-3: Economical comparison in the *moderate* scenario

Ambitious scenario

In the *ambitious* scenario the accelerated energy transformation leads to an even higher electricity price peak in 2020 with lower price levels than 2010 already in 2040. The high share of RE sources (100%) in 2050 provides virtually free peak electricity at times of oversupply, favouring the electricity-based production routes. H-DR which uses 80% peak electricity becomes profitable already shortly past 2030 due to the energy cost advantage (see Figure 4-4). EW, which is the most sensitive route to electricity price changes, cannot be operated economically before 2050 when electricity prices drop to their lower limit at € 40 / MWh. The BF-based routes are struck by quickly rising prices for CO_2 allowances. The BF-BOF route already suffers from OPEX levels above € 650 / t CS (break-even) by 2030, ten years earlier than during the *conservative* scenario. The BF-CCS route, which is less prone to scenario changes than the conventional route, remains with a revenue-cost balance close to zero throughout the investigation period. With subsidies for this technological option the BF-CCS route could be a viable intermediate technology for the gap after BF-BOF phase-out and before market entry of breakthrough technologies (see section 5).

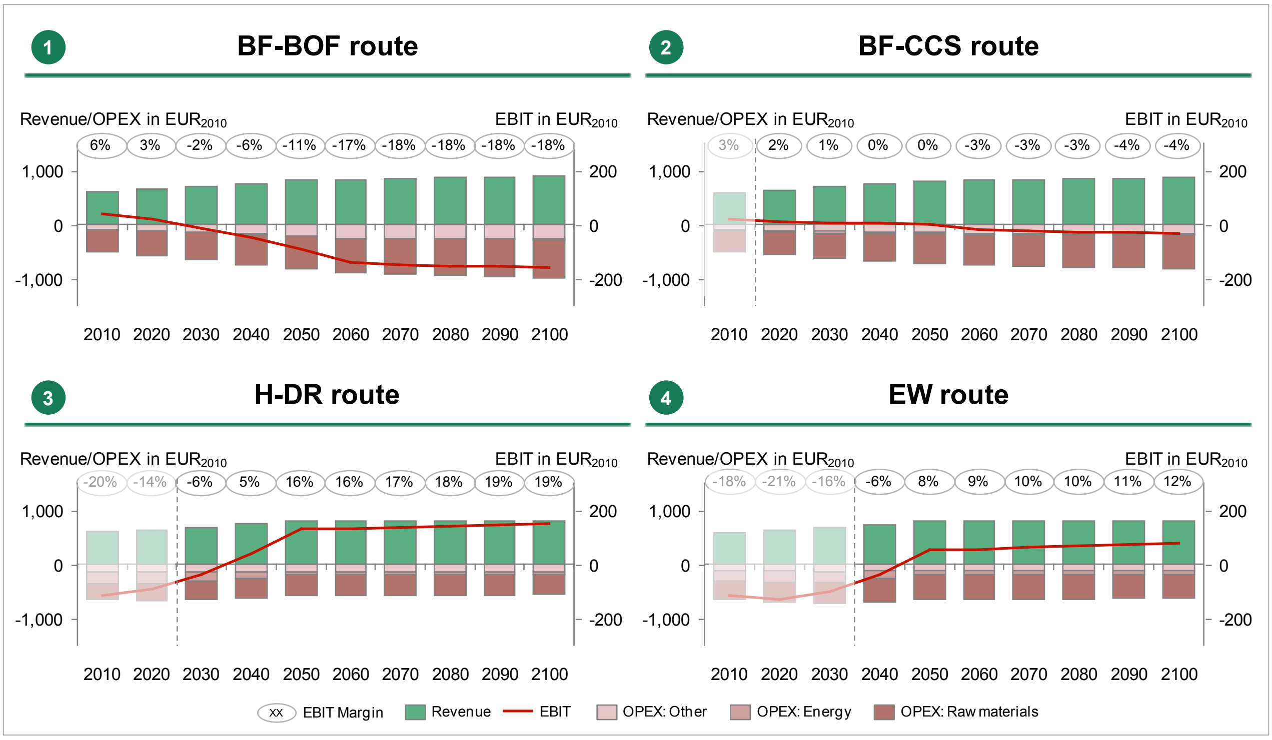

Figure 4-4: Economical comparison in the *ambitious* scenario

4.3 Technology comparison

NPV comparison

NPV is one of the key indicators for economical investment decisions in the selection of alternative investment options like new production facilities based on different technology options. The direct comparison of the simulated NPVs for the four discussed alternative steelmaking routes reveals technological turning points. Even though absolute NPV levels might include an offset due to uncertainties in future development, the relative comparison shows the economical future potential of the production routes. In Figure 4-5 the simulated NPV projections are plotted for the different routes during the *moderate* scenario case. BF-BOF as incumbent route starts out to be the most attractive technology option. The hypothetical assumption to completely offset all CO_2e emissions results in a NPV that turns negative already before 2020. In direct comparison to the other routes the NPV of BF-BOF is significantly higher and thus it is obvious why this option has been the most popular production route until today. Even including the full cost of emitted CO_2, at price levels below € 30 / t CO_2e, BF-BOF is the most profitable new plant investment choice until 2020 (until 2030 in *conservative* scenario). Starting from 2030 onwards (in *ambitious* scenario from 2020) the combination with TGR and CCS becomes more attractive. In 2040 mainly due to high CO_2 price pressure and cheap peak electricity the new construction of a H-DR plant is technically marketable and economically the most profitable investment choice (in the *ambitious* scenario even several years earlier). Under present electricity supply assumptions, with higher electricity prices for EW, H-DR remains the most attractive route throughout the current century; even without taking hydrogen synergies with other sectors into account (see section 5).

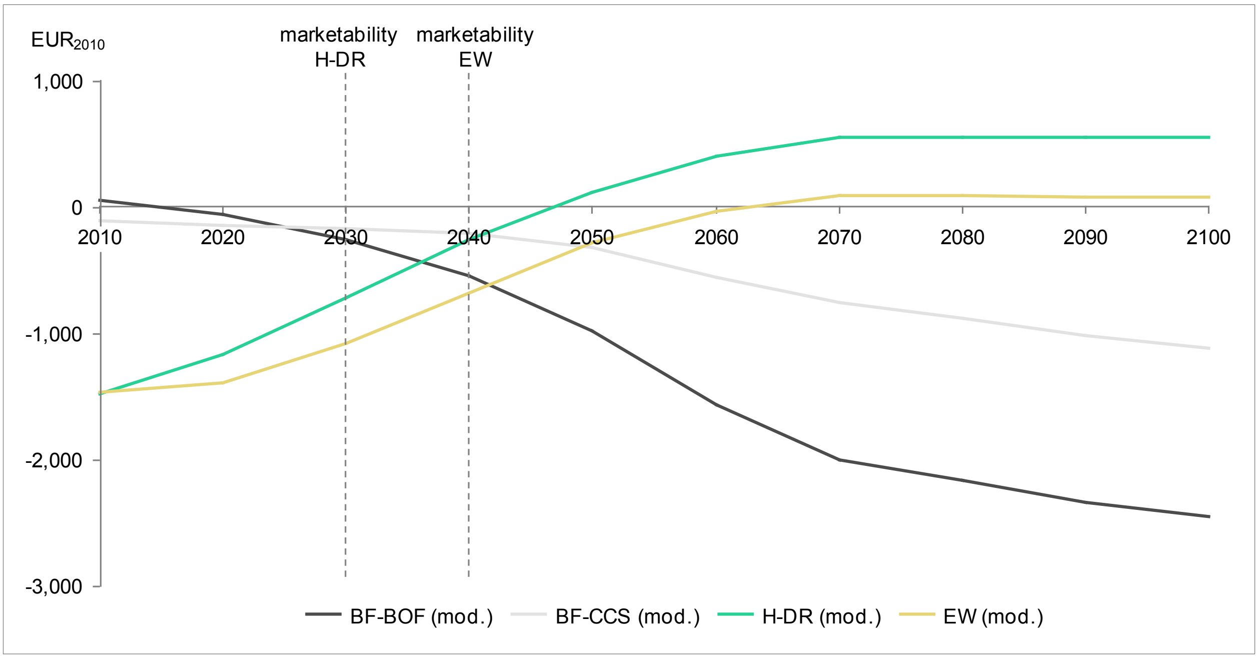

Figure 4-5: Technology comparison: NPV in *moderate* scenario

CO_2 comparison

Since no technical improvement within the production routes is simulated during the investigation period the CO_2 emission reduction either results from substitution of coal or from a smaller emission factor during electricity generation, which is not controlled by the steel plant operator. In Figure 4-7 the projection of the specific CO_2e emission for the production of one tonne of CS is shown for all four production routes. The *moderate* scenario is plotted in bold, *conservative* and *ambitious* scenarios are displayed by dotted lines, representing the three different development options for each production route. The BF-BOF route is the only route with rising net CO_2e emissions due to diminishing credits for electricity production from waste gases compared to a decreasing grid emission factor. BF-CCS route with relatively constant CO_2e emission of around 800 kg CO_2e / t CO_2 could already reduce emission levels compared to BF-BOF by about 50%. A reduction of 80% is impossible to achieve without breakthrough technologies that use alternative reducing agents.

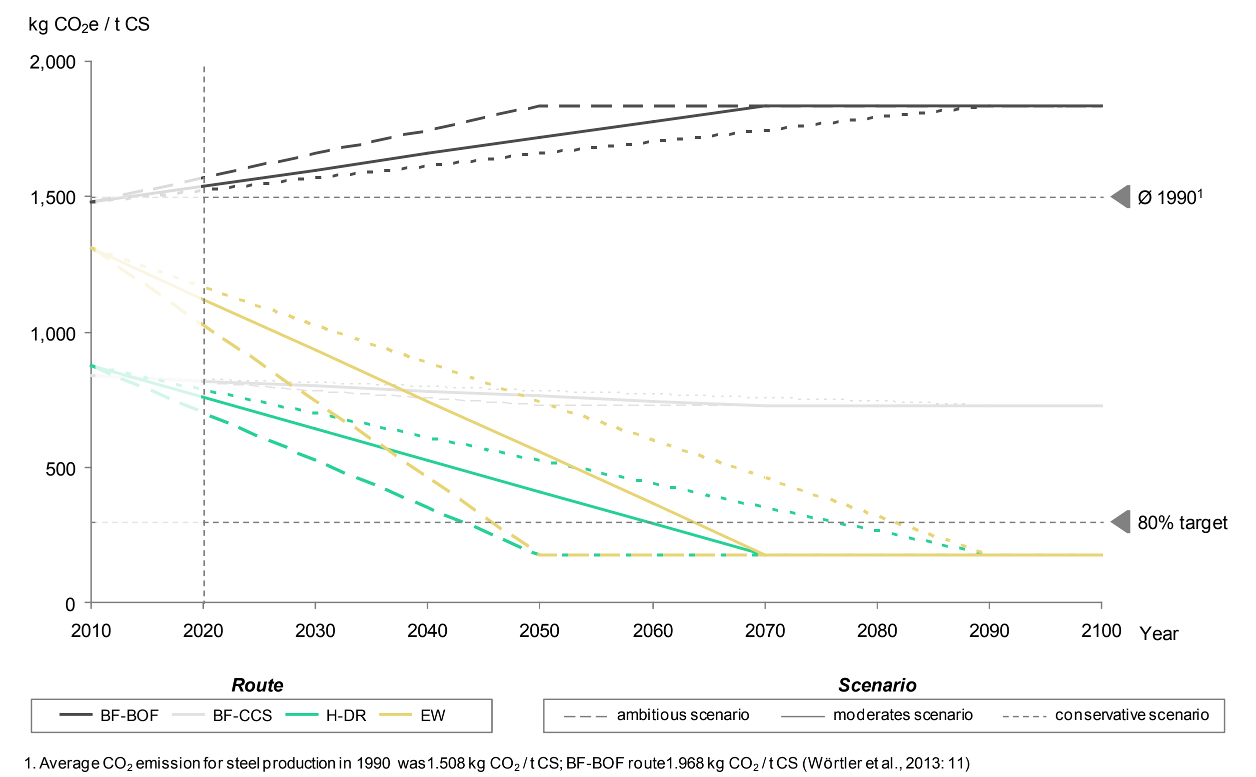

Figure 4-6: Technology comparison: CO_2e emission in all three scenarios

The EW route uses electricity directly as reducing agent. Depending on the type of electricity generation CO_2e emission can be almost as high as for the BF-BOF routes for example if the grid emission factor (EF) is at 2010 levels (455 kg CO_2e / MWh). For carbon free electricity produced by 100% RE sources the specific CO_2e emission of the EW route is at 180 kg and stems from coal utilisation as aggregate in the EAF steelmaking step to attain the desired carbon content of the final steel product. The same dependency on the CO_2e EF can be seen for the H-DR route, with the exception that, by assumption, 80% of the consumed electricity is 100% renewable peak electricity without a CO_2 burden ("Rucksack"). Hence, even with higher grid EF the H-DR route can be very carbon lean. The timing of the CO_2e emission reduction for the two breakthrough routes depends on the transformation speed of the energy sector. For the *ambitious* scenario the

80% emission reduction target can be reached in time before 2050. In all other scenarios the target is not met even with the use of breakthrough technologies. In these cases additional material efficiency and demand reduction measures would be necessary to comply with emission targets.

4.4 Sensitivity analysis

Modelling future developments bares a high number of uncertainties. Sensitivity analyses help to estimate the impact that variation in the model assumptions have on the simulation results and hence improves the understanding of the model validity (Zopounidis and Pardalos, 2010: 158). During the sensitivity analyses one key assumption is varied and all other assumptions are kept constant. As convention for all following sensitivity analyses, assumptions that are not varied use their value of year 2050 in the *moderate* scenario. The sensitivity can change slightly if another base year and scenario is selected and hence other absolute values are simulated. Relative trends in comparison between the respective sensitivities remain similar. In the following, three sensitivity analyses are presented for assumptions that have a high degree of uncertainty and a crucial impact on the simulation results.

CO_2 price

The price for CO_2 allowances does not solely depend on classical supply and demand balances but is influenced strongly by political decisions regarding implementation of an international trading scheme. In the case of the iron and steel industry with large amounts of CO_2e emission the production cost depend significantly on the degree of enforcement and the price for CO_2 allowances. Enforcement of carbon offset is assumed to be 100% for all models in this study. The impact of variation in carbon price levels on the profitability of the respective routes is displayed in Figure 4-7 for the market situation in the *moderate* scenario in 2050 and in the *ambitious* scenario in 2030 which marks a turning point in technology breakthrough. The EBIT as direct indicator for the profitability of a production route is affected negatively by increasing CO_2 prices in all cases (negative slope for all routes in Figure 4-7). The BF-BOF route is most sensitive to high CO_2 prices because the highest volume of CO_2e is emitted per tonne of steel produced. The high share of renewable electricity for the H-DR route causes this route to be least sensitive to CO_2 prices and hence receives a relative advantage in case of rising prices for carbon allowances. Past 2050 H-DR is the most profitable production route regardless of CO_2

prices. Even without the obligation to pay for CO_2 emission (price level 0 € / t CO_2) the profitability of the BF-based routes shrinks drastically in the second half of the current century due to increasing cost of coal and natural gas. In 2050 *moderate* scenario the grid electricity still contains a 180 kg / MWh CO_2 "Rucksack" causing the EW route to be less profitable than BF-BOF and BF-CCS for low and medium CO_2 price levels. In 2030, when H-DR is expected to reach technical maturity, for the CO_2 price level in the *ambitious* scenario (€ 45 / t CO_2) H-DR is still not competitive with the conventional routes. In case of a high CO_2 price level of € 70 / t CO_2 H-DR would match profitability of the BF-BOF route already in 2030 closing the gap towards a technological breakthrough in time to reach 2050 reduction targets. On the other hand (EUROFER, 2013: 46) estimates that at a price of € 25 / t CO_2 the steel industry would be pushed to reduce production and abandon market share to foreign competitors.

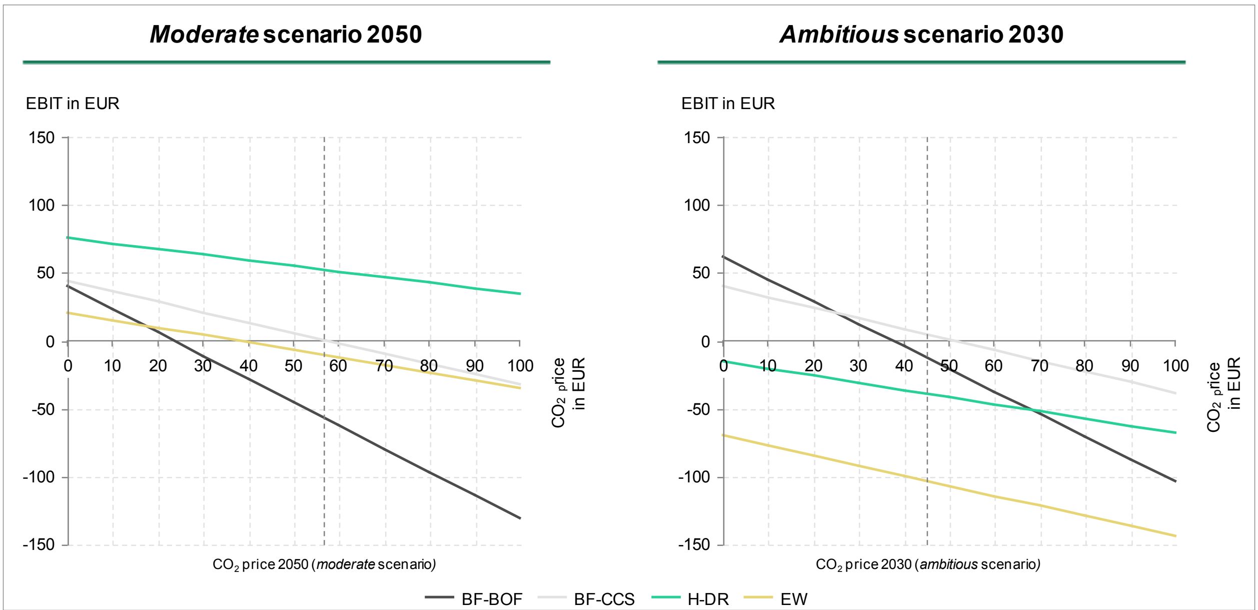

Figure 4-7: Sensitivity analysis: CO_2 price for *moderate* scenario 2050 and *ambitious* scenario 2030

Emission factor grid

The emission factor (EF) of the German electricity grid is the average CO_2e emission for generation of one MWh of electricity. Every electricity consumer causes this indirect emission. The emission factor cannot be influenced directly but results from developments in the mix of energy sources and the technological efficiency during electricity generation. For the present models the EF is assumed to decline linearly from 2010 levels (550 kg / MWh) to 0 when electricity is produced from 100% renewable sources. Analysing the sensitivity of the models against a variation of the assumed emission factor shows the results in Figure 4-8.

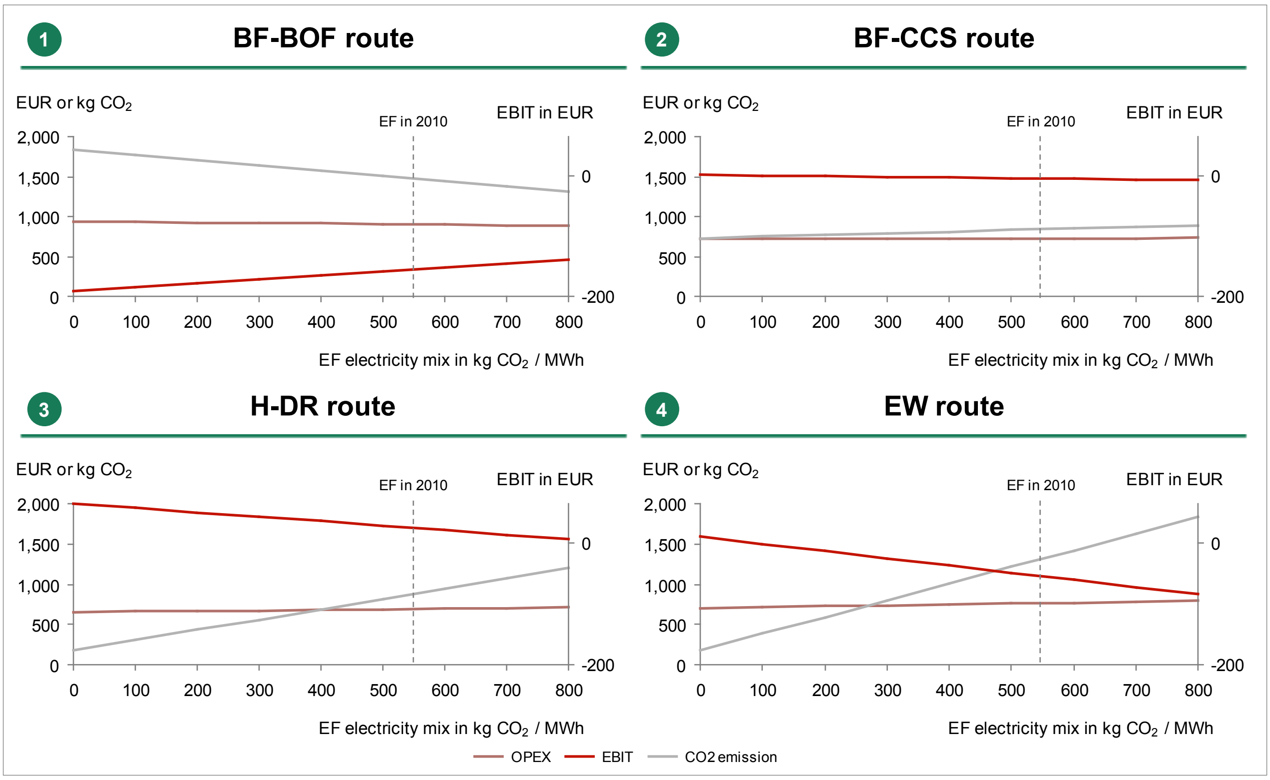

Figure 4-8: Sensitivity analysis: EF electricity mix

OPEX and CO_2e emission are plotted on the left axis, the corresponding EBIT on the right axis. Similar to the characteristics of the CO_2 emission comparison in section 4.3 the BF-BOF route shows an opposite sensitivity trend to the other routes. This is again caused by emission credits for waste gases that depend on the difference to the grid emission factor. A higher grid EF causes less credits and therefore higher OPEX through higher cost for CO_2 allowances. For all other routes that are net electricity consumers, increasing grid EF causes higher indirect CO_2e emission and hence higher OPEX leading to a reduction in the profitability. With the highest electricity demand EW is the most sensitive route to the grid EF which can only become profitable if electricity is produced almost entirely by RE sources in the future. With EF close to zero H-DR and EW both achieve an emission reduction of 90% compared to average 1990 levels. Already today (for EF smaller 550 kg CO_2e / MWh) H-DR is the most carbon lean production route making BF-CSS as intermediate technology unnecessary from an environmental point of view. At emission factors below 300 kg CO_2e / MWh also EW is able to produce steel less carbon intensive than BF-CCS.

Sensitivity CAPEX

Variations in the CAPEX assumptions for the alternative routes have most impact in the NPV projections. With CAPEX values as displayed in Table-A 2 through Table-A 5 the earliest point in time when H-DR offers a more profitable investment choice than BF-BOF in the *moderate* scenario is in 2040 (see section 4.3). At the point of technological marketability of the H-DR route[22] in 2030, NPV is still considerably lower than for the conventional routes. A CAPEX of € 465 / t capacity (reduction of almost 50%) would be necessary for the H-DR to become as economically attractive as BF-BOF already in 2030. In the *ambitious* scenario a CAPEX reduction of only 10% would be sufficient to make H-DR more attractive than BF-BOF already in 2030 at the time of technical availability eliminating the need of an intermediate production route. A 10% CAPEX cost decrease for the H-DR technology seems realistic if further research efforts are promoted throughout 2030.

After having presented the techno-economic performance of the four alternative steelmaking routes in detail, the next sections aims to discuss the results and to draw conclusions to answer the research question from section 1.

5 Discussion and conclusion

In this section the applicability and limitation of the alternative steelmaking routes are discussed and conclusions regarding their future potential for the steel industry are drawn. An outlook identifies further research potential that will add to the reliability of the current conclusions.

Technology potential

Steelmaking is a highly sophisticated industrial process that has developed its current route over centuries adapting to changing raw materials, technologies, consumer requirements, and market constrains. A high degree of integration with the energy sector and sensitive dependencies to a

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[22] EUROFER (2013: 42)

variety of input factors make the prediction of future developments in steelmaking highly challenging especially in light of a major energy transformation to come.
From a purely environmental perspective various facts point towards a radical technology change towards the most material and energy efficient route with only marginal CO_2 emission – the EW route. This is especially true if the energy transformation follows the *ambitious* scenario development towards a ‘green’ electricity-dominated system.

Adding economic considerations to the picture and assuming price developments for input materials and cost for GHG emission changes the picture. Economical viability and efficient emission reduction have to be taken into account. The present research highlights the importance of the two breakthrough technologies H-DR and EW which have not been assessed in most techno-economic scenario studies due to shorter investigation periods and the immature technical development. Both routes show a great potential to allow economically viable emission reduction in line with climate targets and to substitute the conventional routes within the next 50 years. H-DR would be favoured in case synergies with hydrogen infrastructure and production exist with other sectors. EW can only contribute to emission reduction in a renewable electricity based system.
Mainly due to increasing cost of fossil fuels and the politically driven decisions for an energy transformation the current profitability of the incumbent BF-BOF route will diminish within the current century. The *conservative* scenario which assumes a rather slow energy transformation and a deferral of climate targets predicts the coal based production routes (BF-BOF and BF-CCS) to remain the preferred choice for a new plant investment throughout 2040 – 2050. The *ambitious* scenario on the other extreme, which assumes an accelerated energy transformation and high shares of RE sources in the next decades, predicts the breakthrough technologies H-DR and EW to outperform the coal based routes already in 2030 – 2040. Past 2050 even without prices for CO_2 allowance BF-BOF and BF-CCS cannot compete with H-DR and EW. This is due to the expected price increase of fossil fuels and a significant decrease in electricity prices through the merit order effect of RE sources. The relevant question is which timing and technology choice can be expected during the transition.
In the *conservative* scenario, starting between 2020 and 2030, new plants will use TGR and CCS technologies to produce steel according to the BF-CCS route. From 2040 onwards the most attractive choice for a new plant is the H-DR route, which remains the preferred primary route

throughout the end of the present investigation period (2100). In the *moderate* scenario the technology switch happens about 5 years earlier. In the *ambitious* scenario CCS technology is applied from 2020 onward, H-DR already before 2040. Due to the low electricity prices also EW is a viable alternative whenever no synergies with the hydrogen production and storage are expected.

As shown in section 4.4 higher CO_2 prices (€ 70 / t CO2) or a 10% lower CAPEX in 2030 could avoid the tendency to use CCS as intermediate technology with necessary infrastructure investments only for a rather short competitive period before more economical and less carbon-intensive technologies are available.

Overall it can be concluded that the 80% emission reduction target for the iron and steel industry in 2050 is very challenging to achieve and can only be achieved with early implementation of breakthrough technologies accompanied by very stringent international political climate measures and preferably additional material efficiency measures.

Implications

The current research illustrates the importance of technological innovation in the iron- and steel industry. Steel producers are recommended to invest into the development of innovative technologies like H-DR or EW to reach industrial maturity by 2030 - 2040. Explicit technology strategies should be developed to ensure future competitiveness in a fast changing environment. Policy makers are recommended to provide a consistent and secure climate policy for the industry. Once targets are clearly set a substantial research and development support as well as international knowledge exchange programs would be necessary to facilitate the necessary innovation. Regarding the interdependencies of the steel production with developments in other sectors binding roadmaps regarding CCS utilization, hydrogen infrastructure, and renewable energy rollout are recommended and would allow the industry to develop future strategies.

Limitations

All derived results have to be put into perspective considering the lack of real data from plants in operation and proven data for the two innovative routes that have not been field tested in industrial scale yet. The prediction of future developments always bares a high degree of uncertainty especially for long investigation periods like in the present research. Using three scenarios for different developments of future assumptions broadens the spectrum of possible

results but does not guarantee to predict the most probable future development. As stated by (EUROFER, 2013: 52) *"from today's perspective it is not possible to predict which technology is most likely to emerge"*.
The current scenario analysis assumes a very simplified world reducing complexity by neglecting external factors like path dependencies through existing infrastructure, national and international competition in the iron and steel industry, and carbon-leakage. For the innovative routes with partly immature technologies there is a significant risk that marketability for industrial scale application is never achieved. As highlighted by (Allwood and Cullen, 2012: 145) it is not necessarily the best technology which gains the highest market share. The application of certain technologies depends on the system context. The strong interdependencies of the iron and steel industry with other sectors in- and outside Germany as well as the risk of unilateral discrimination of the German steel industry has to be taken into account to receive a more realistic and well rounded assessment of future steelmaking technologies.

Outlook
As discussed in the previous section the present results are just a small excerpt of the wide variety of factors that have to be taken into account to provide an exhaustive evaluation of innovative steelmaking technologies. In the next step a multi criteria analysis (MCA) is planned, which includes numerous criteria from the areas *technology*, *society & politics*, *economics*, *safety,* and *ecology* (see Table-A 6). The criteria are valued based on quantitative or qualitative data that originates from the presented techno-economic models, literature review, or expert judgement. In order to integrate the unique perspectives of different stakeholder groups different sets of weighting factors are used for the MCA. The weighting factors are determined in various discussions with experts from NGO's, politics and steel producers.

6 Appendix

A. Scenario assumptions

The justifications of the scenario assumptions from Table 3-1 are presented as follows.

Price metallurgical coal

Especially the predictions of the coal price vary widely in literature. (Kirchner and Matthes, 2009) expects a price increase of 3.4% p.a. until 2050, due to increased procurement costs and taxes. (Nitsch et al., 2012: 3) predicts an annual price increase between 1.4% and 2.8%. Since the worldwide coal supply will last at least for another 150 years (International Energy Agency (IEA), 2010: 207) a dramatic price increase due to shortage is not expected for the current research. Metallurgical coal is a special coal which does not follow the normal price variation for hard coal, but correlates closely with the worldwide production volume of iron and steel. Independently of the steel production in Germany, the steel production worldwide is expected to grow at least until 2050 (Neelis and Patel, 2006: 71–74). Assuming no carbon-free production technology to gain significant market shares before 2050, also the metallurgical coal demand is expected to rise. (Pardo and Moya, 2013: 119) predicts a compound annual growth rate (CAGR) from the 2010 price level of metallurgical coal (€ 170 / t) of 1.64%. In the current research this CAGR is used until 2050. Past 2050 a reduced annual growth of 0.75% is used because a demand reduction is expected mainly due to the market entry of carbon-free steel production technologies (Neelis and Patel, 2006: 74). Since the development of the metallurgical coal price does not depend on the transformation of the German energy system, the same price trajectory is used for all three scenarios.

Price iron ore

In the past 50 years the iron ore price grew by 2.56% per year (Babies et al., 2011: 137). Recent scenario studies of the iron and steel industry predict a price increase of 1.2% CAGR until 2050 (Pardo and Moya, 2013: 119). In mid-term experts expect an oversupply of iron ore by 2020 because steel production grows slower than ore mining (Lelong et al., 2014: 24). Since the iron ore price does not depend on the energy transformation and all production routes use very similar amounts of iron ore feedstock, the price projections for all scenarios is the same with a very moderate CAGR of 0.75%.

Price CO_2 Allowances

The CO_2 price development is very difficult to predict since it does not solely depend on supply and demand dynamics but also heavily on political decisions. Due to the planned exit from nuclear power production in Germany by 2022 and increased CO_2 emission price levels are expected to rise significantly (Schlesinger et al., 2011: 14). Despite current exceptions for energy intensive industries, like the iron and steel industry, the current research assumes that all CO_2 emission has to be offset by an equivalent amount of CO_2 allowances. Like this all primary production routes in focus of the current research can be compared economically. Starting from a price level of € 14 / t CO_2 in 2010, in the *ambitious* scenario a very strong price increase of 4.2% p.a. is assumes based on „price path A - high“ from (Nitsch et al., 2012: 51). For the *moderate* and *conservative* scenarios price paths “B – moderate” and “C – low” with CAGR of 3.5% and 2.9% from (Nitsch et al., 2012: 51) are applied. The mentioned growth rates are extrapolated past 2050 until a max. price level of € 100 / t CO_2 is reached.

Price natural gas

The natural gas price, like prices for other fossil fuels, will rise continuously due to increasing production costs and growing demand in developing countries. Like for the CO_2 price the three projections from (Nitsch et al., 2012: 51) are used again. For the *ambitious* scenario the price path A with a CAGR of 2.3%, in the *moderate* scenario the path B with a CAGR of 1.5%, and in the *conservative* scenario the path C with a CAGR of 0.8% is used. The impact of the natural gas price on the simulation results is rather small since it makes up less than 1% of the OPEX for the BF-based routes.

RE fraction of gross electricity consumption

The share of RE in the German energy mix depends on a multitude of external factors. Some scenario studies even calculate the energy mix as a simulation result (Nitsch et al., 2012), (Schlesinger et al., 2011). In the current research the simulation focus is on the steel production routes and therefore it is assumed that the RE fraction in the *moderate* scenario develops according to the targets of the German federal government (BMU, 2010: 4). That is 80% RE share by 2050. In the *ambitious* scenario the 80% share is reached already in 2040 and in the *conservative* scenario by 2070. The development is assumed to be linear for the entire investigation period.

Price electricity

The electricity price depends on the production cost of electricity in fossil fuel plants and from renewable energy sources, weighted by the specific distribution. Especially in the beginning of the investigation period, due to high investments and low utilization, RE sources are much more expensive than large scale fossil fuel plants. Through very low fix cost (merit order effect) and further learning effects of the immature renewable technologies on one hand and steadily rising prices for fossil fuel feedstock on the other hand, the price developments of RE and fossil energy are opposite. The average electricity price is derived as a weighted average of both sources depending on the RE fraction.

The price projections for the fossil fuel based electricity are taken from (Nitsch et al., 2010: 167) with a 12% surcharge for the grid utilization (Bundesnetzagentur, 2010: 24). The price projection for the renewable electricity starts with an initial value for 2010 of € 140 / MWh (Nitsch et al., 2010: 167), plus the 12% surcharge and then evolves like a typical learning curve23. The long-run marginal cost for renewable electricity of € 40 / MWh are reached in 2050 (ambitious scenario), 2060 (moderate scenario) or respective 2070 (conservative scenario).

Price peak electricity

Peak electricity refers to excess electricity at times of oversupply (e.g. strong wind, high sun intensity), that is usually sold at very low prices to maintain grid stability. The higher the RE share, the more volatile is the electricity production and more peaks have to be compensated by variable pricing. In the current research the development of the peak electricity price is assumed to start with the minimal production cost of wind power (€ 50 / MWh) [24] and decreases until peak electricity is free when 100% RE sources are used.

CO_2 emission factor

The emission factor (EF) of the German electricity mix evolves dependent on the RE fraction. Like for the peak electricity price, a linear development of the current value until electricity is generated 100% by RE and the EF is 0, is assumed. The 2010 value is 546 kg / MWh according to (Icha, 2013: 2). In the *ambitious* scenario an EF of 0 is reached by 2050. In the *moderate* and *conservative* scenario this point is reached by 2070, 2080 respectively.

Price scrap

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[23] Learning curve with typical exponential trend $f(x)=ax^{-b}$, with a=157

[24] Nitsch et al. (2010: 23)

Scrap recycling is an energy and emission efficient alternative to primary steel making. Therefore scrap price is usually twice as high as unreduced iron ore. In the *conservative* scenario this price difference is maintained, i.e. the scrap price evolves with the same CAGR as iron ore (0.75% p.a.). In the *moderate* scenario, where higher CO_2 prices favour the secondary steel production, scrap prices rise faster until 2050 (CAGR of 1.2%[25]). Past 2050 the market entry of carbon free production technologies like H-DR or EW damps the scrap demand and a constant price level until 2100 is assumed. In the *ambitious* scenario the same effect is expected more intensely. Hence the scrap price is expected to decrease past 2050 by -0.5% per year.

Price hot rolled coil

To simulate revenues the most basic product of the steel production routes is chosen – the hot rolled coil (HRC). With the assumption that one tone of crude steel leads to 910 kg HRC, the production cost can be compared with a revenue dimension. Expecting the industry to pass on iron ore prices, the 0.75% CAGR of the iron ore price is also applied to the sales price of HRC until 2050 and stays constant afterwards. The starting price in 2010 is assumed to be € 631 / t HRC (Statistisches Bundesamt, 2012: 77). The same price developments are assumed for all three scenarios.

B. Constant model assumptions

Table-A 1: Common assumptions for all routes

Parameter	Value	Unit	Comment	Source
Discount rate	10	%	Weighted Average Cost of Capital (WACC)	(Wörtler et al., 2013)
Inflation	3	%		(Wörtler et al., 2013)
Investment period	20	years		(Wörtler et al., 2013) (Europäische Kommission, 2010)
Labor cost	38	EUR / t crude steel	Corresponds to 9% of OPEX from BF route (Wörtler et al., 2013)	(Klaus Kesseler, 2014)
Price Water	1,5	EUR / m³		(Ramming, 2003)
Price Oxygen	66	EUR / t		(Pardo and Moya, 2013) (Steelonthenet.com)
Price diesel	28	EUR / GJ		(OECD, 2010)

[25] Pardo and Moya (2013: 119)

Price fluxes	27	EUR / t	Average price from lime € 20 / t and limestone € 100 / t in ratio 10:1	(Pardo and Moya, 2013)
Price ferroalloys	1.777	EUR / t	Same amount and price for all routes	(Pardo and Moya, 2013)
Material loss crude steel to end product hot rolled coil	9	%		(Birat et al., 2008)
Maintenance cost	3	%	of CAPEX	(Voigt and Schmidt, 2014)
Other cost (fix and overhead)	10	%	of revenue	(Klaus Kesseler, 2014)
Tax	25	%	of EBIT	(Europäische Kommission, 2010) (Klaus Kesseler, 2014)
CO_2 "Rucksack" oxygen	239	kg / t O2		(Voigt and Schmidt, 2014)
CO_2 "Rucksack" fluxes	1.150	kg / t flux		(Voigt and Schmidt, 2014)

Table-A 2: Assumptions for BF-BOF model

Parameter	Value	Unit	Comment	Source
CAPEX	442	EUR / t Capacity	'greenfield'	(Wörtler et al., 2013)
Sales price BF-slag	16	EUR / t		(Pardo and Moya, 2013)
Sales price process gases	90	%	of natural gas price	(Klaus Kesseler, 2014)
Sales price electricity	90	%	of purchase price for industrial customers	Own assumption

Table-A 3: Assumptions for BF-CCS model

Parameter	Value	Unit	Comment	Source
CAPEX	566	EUR / t Capacity	'greenfield'	(Wörtler et al., 2013)
Additional assumptions according to Table-A 2				

Table-A 4: Assumptions for H-DR model

Parameter	Value	Unit	Comment	Source
CAPEX	874	EUR / t Capacity	CAPEX DRI-EAF €414 / t additional € 450 / t for H2 electrolyser (€ 650 / kWel [212]) and ca. € 10 / t CS for hydrogen underground storage (capacity for 14 days with CAPEX € 0,09 / kWh [212])	(Wörtler et al., 2013) (Smolinka et al., 2011) (Nitsch et al., 2010) (Töpler and Lehmann, 2014) approved by (Klaus Kesseler, 2014)
Surcharge for peak electricity transport	12	%	12% are charged by net provider for transport of RE electricity to plant	(Bundesnetzagentur, 2010)
Share of peak electricity for hydrogen electrolyzer	80	%	80% of electricity demand are covered by cheap peak electricity; 20% by average grid electricity mix	Own assumption
Sales price oxygen	60	%	of purchase price	Own assumption
Labor cost increase compared to BF-BOF route	40	%	Lower capacity of H-DR plant cause higher specific labor costs	(Klaus Kesseler, 2014)
Surcharge for iron ore	10	%	Price surcharge for high quality iron ore with min. 68% Fe-content needed for H-DR route	(Klaus Kesseler, 2014)

Table-A 5: Assumptions for EW model

Parameter	Value	Unit	Comment	Source
CAPEX	639	EUR / t Capacity	EAF: € 184 [107], EW: € 340 (Assumption: CAPEX EW = CAPEX H2 electrolyzer [212] +100%) (Wörtler et al., 2013)	Wörtler 2013 #107} (Smolinka et al., 2011) (Töpler and Lehmann, 2014)
Share of peak electricity for hydrogen electrolyzer	25	%	25% of electricity demand are covered by cheap peak electricity	Own assumption
Sales sodium hydroxide	60	%	of purchase price	Own assumption
Additional assumptions according to table Table-A 4				

C. Additional simulation results

	Production and transport of reducing agent (e.g. coal, H_2, electricity)	**Preparation of raw materials** (e.g. grinding, coking, sintering)	**Iron making** (e.g. BF, H_2-DRI, EW)	**Steel making**[3] (e.g. BOF, EAF)	**Total** (flows into system boundaries)
1 **BF-BOF**	**Energy**: 44 MJ **Ore**: - **Coal** : 712 kg **Other:** **CO_2**: 2 kg	**Energy**: - (all internal) **Ore:** 1254 kg **Coal**: - **Other:** 642 kg **CO_2**: 498 kg	**Energy**: 162 MJ **Ore**: 523 kg **Coal**: - **Other:** 124 kg **CO_2**: 1051 kg	**Energy**: 390 MJ **Scrap:** 190 kg **Coal**: - **Other:** 165 kg **CO_2**: 167 kg	**Energy**: 596 MJ **Ore:** 1967 kg **Coal**: 712 **Other:** 930 kg **CO_2**: 1718 kg
2 **BF-CCS**	**Energy**: 34 MJ **Ore**: - **Coal** : 552 kg **Other:** - **CO_2**: 1 kg	**Energy**: 140 MJ **Ore:** 1254 kg **Coal**: - **Other:** 582 kg **CO_2**: 345 kg	**Energy**: 1057 MJ **Ore**: 523 kg **Coal**: - **Other:** 124 kg **CO_2**: 224 kg	**Energy**: 520 MJ **Scrap:** 190 kg **Coal**: - **Other:** 182 kg **CO_2**: 193 kg	**Energy**: 2117 MJ **Ore:** 1967 kg **Coal**: 552 **Other:** 182 kg **CO_2**: 763 kg
3 **H-DR**	**Energy**: 10603 MJ **Ore:** - **Other**: 707 kg **CO_2:** 107 kg	**Energy**: - **Ore:** - **Other**: - **CO_2:** -	**Energy**: 439 MJ **Ore**: 1453 kg **Other:** - **CO_2:** 22 kg	**Energy**: 2028 MJ **Scrap**: 325 kg **Other**: 114 kg **CO_2:** 280 kg	**Energy**: 13070 MJ **Ore:** 1778 kg **Other:** 821 kg **CO_2**: 339 kg
4 **EW**	**Energy**: - **Ore:** - **Other**: - **CO_2:** -	**Energy**: - **Ore:** - **Other**: - **CO_2:** -	**Energy**: 7235 MJ **Ore:** 1658 kg **Other:** 545 kg **CO_2:** 275 kg	**Energy**: 2028 MJ **Scrap:** 325 kg **Other:** 114 kg **CO_2:** 280 kg	**Energy**: 9263 MJ **Ore:** 1983 kg **Other:** 709 kg **CO_2**: 555 kg

Note: CO_2 emissions for *moderate* scenario in 2050

Figure-A 1: Detailed mass and energy balance from simulation results

D. Multi criteria analysis

Table-A 6: Criteria catalogue for multi criteria analysis

Criteria groups	Sub criteria
Technology	
1	System compatibility
2	Innovative potential
Society & Politics	
3	Compability with social objectives
4	Contribution to regional value creation
5	Intensity of implementation
Economics	
6	Profitability
7	Strategic advantage
Safety	
8	Vulnerability
9	Safety risks
Ecology	
10	GHG emission
11	Other environmental impact
12	Energy efficiency

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