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Turning German Steel Production Green: Quantifying Diffusion Scenarios for Hydrogen-Based Steelmaking and Policy Implications

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Abstract

The German steel industry is in jeopardy. Current steel production must be comprehensively transformed to achieve the emission targets imposed by the Federal Climate Change Act. A promising alternative that has increasingly gained momentum in recent years is hydrogen-based steel production. This thesis analyzes the potential of this method to transform the German steel industry. First, drivers that will decisively influence the future role of hydrogen-based steelmaking are identified. Subsequently, these drivers are linked in a quantitative model to develop explorative diffusion scenarios and to draw conclusions for policymaking. Four representative scenarios are extracted and analyzed. Large differences between the scenario outputs illustrate that the diffusion of hydrogen-based steelmaking is subject to significant uncertainties. It becomes clear that the most effective lever for promoting the attractiveness of hydrogen-based steelmaking is increasing the cost of conventional production by exposing it to CO_2 prices. However, such exposure simultaneously suggests disadvantages towards producers that are not subject to this regulation. To mitigate the emerging risk of carbon leakage effects, suitable policy measures are required.

Keywords: Green steel; Green hydrogen; Energy transition; Energy policy.

1. Introduction

"It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."[1] With these words, the Intergovernmental Panel on Climate Change introduces the first part of its Sixth Assessment Report, highlighting the impact of anthropogenic greenhouse gas emissions on the global climate to date. Accordingly, any further rise in global temperature is expected to increase the likelihood of drastic consequences such as heat waves, droughts, floods, or extreme weather events to occur.[2]

To mitigate such consequences, the Paris Agreement was adopted at the United Nations Climate Change Conference in 2015. In this agreement, the attending parties committed to limiting global warming to below 2°C compared to pre-industrial levels.[3] However, deep reductions in global greenhouse gas emissions are required to achieve this target.[4]

In response, German policymakers have updated the national climate targets of Germany and set the goal of becoming carbon-neutral by 2045.[5] These targets pose major challenges for many industries as their processes must be adapted to the new objectives. One industry that is significantly affected is the German steel production. In 2019, this industry was responsible for almost 7% of Germany's total emissions, generating nearly 25 times the emissions of national aviation.[6] Due to this relevance for the emissions balance of the whole economy, steel producers are increasingly under pressure. Current steelmaking must be thoroughly decarbonized to align it with the climate targets and ensure the long-term preservation of the industry.[7]

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[1] IPCC, 2021, p. SPM5.

[2] Cf. IPCC, 2021, pp. SPM21-SPM25.

[3] Cf. UN, 2015, Article 2.

[4] Cf. IPCC, 2021, p. SPM17.

[5] Cf. Federal Climate Change Act, Section 3.

[6] Including emissions from energy installations, cf. DEHst (2014-2021), pp. 26-27; UBA, 2022.

[7] Cf. Fischedick, Marzinkowski, Winzer, & Weigel, 2014, p. 574; Kushnir, Hansen, Vogl, & Åhman, 2020, p. 12; Müller, Herz, Reichelt, Jahn, & Michaelis, 2021, p. 2; Vogl, Åhman, & Nilsson, 2021, p. 79.

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In light of these challenges, hydrogen-based steel production has gained momentum in recent years. The basic idea behind this method is to achieve enormous emission savings by utilizing hydrogen produced through renewable energies as reduction agent.[8] Although hydrogen-based steelmaking offers great potential, its introduction is still subject to significant uncertainties. For instance, hydrogen-based steelmaking is currently limited to research and development projects beyond the stage of large-scale market readiness.[9] Furthermore, higher production costs compared to conventional production are expected.[10] Problems like these indicate that extensive political support is required to achieve a sustainable and timely transformation of the German steel industry.[11]

The motivation underlying this thesis is derived from the described problem set. The first objective is to assess the current framework for introducing hydrogen-based steel production and identify drivers that will most significantly influence its diffusion. The identified drivers will then be linked in a quantitative model to develop explorative scenarios for the diffusion of hydrogen-based steel production in Germany. Based on the developed scenarios, foreseeable developments and key interrelationships in the defined environment will subsequently be derived. From these findings, the aim is to draw conclusions for policymakers regarding targeted support of German steel production. The following research questions reflect the key objectives of this thesis:

1. Which drivers will decisively shape the diffusion of hydrogen-based steel production in Germany?
2. Based on these drivers, which key scenarios can be derived for the diffusion of hydrogen-based steel production in Germany?
3. How should policymakers act to foster the diffusion of hydrogen-based steel production in Germany sustainably?

First, a brief overview of previous modeling approaches is provided in Chapter 2 to derive the additional informative value of this thesis. Chapter 3 then analyzes the environment of the German steel industry from various perspectives to gain initial insights into the first research question and to create a qualitative foundation for the subsequent model development. The model development then takes place in Chapter 4: After describing the underlying methodology, suitable scenarios are extracted, evaluated, and discussed in the context of the research questions. The conclusion, as well as an outlook on future research potential, are provided in Chapter 5.

2. Literature Research

In this chapter, excerpts of previous research are presented in order to derive the scope of this thesis. First, studies that investigated the overall potential of hydrogen-based steel production on the technological level are considered. Secondly, approaches that provide a perspective on the potential of hydrogen-based steelmaking in a systematic application are examined. Lastly, a review of previous work regarding policy implications is provided.

At the technological level, the assessment of hydrogen-based steel production has already been part of several studies. Fischedick et al. (2014) compared alternative technologies within a techno-economic model. They concluded that hydrogen-based steelmaking, also known as hydrogen direct reduction (H-DR), will only show sufficient profitability for actual introduction between 2030 and 2040.[12] Vogl, Åhman, and Nilsson (2018) also investigated the H-DR method in terms of its competitiveness against conventional steel production and deduced that it is fundamentally associated with higher costs, which are highly dependent on specific factors. Furthermore, the authors consider the H-DR method as an option to achieve the long-term emission targets of the European Union.[13] Jacobasch et al. (2021) predicted that H-DR production will have lower production costs as well as ecological advantages over conventional production by 2050.[14]

In a systematic context, an early approach is provided by Woertler et al. (2013). The authors considered various production methods in the framework of the entire European steel industry and with respect to the European climate targets. They concluded, among others, that saving about 10% of the steel industry's 1990 emissions is the most likely scenario and will be achieved mainly by improving current processes.[15] Kushnir et al. (2020) analyzed systematic conditions within Sweden to assess the potential for a switch to hydrogen-based steelmaking. The authors characterized H-DR production as the best available option to meet Swedish climate targets but derived major barriers and the need for strong policy support.[16] Similarly, in the context of the Swedish steel industry, Toktarova et al. (2020) developed a model to analyze specific pathways to achieve deep emission reductions. These pathways differ, for example, in applied production methods and different assumptions of steel output development. The authors concluded that establishing H-DR production offers significant abatement potential but is associated with challenges due to its high electricity consumption.[17] A similar approach is provided by Arens, Worrell, Eichhammer, Hasanbeigi, and Zhang (2017) for the German steel industry. They, too, defined individual pathways to analyze the emission reduction potential until 2035. Their approach focused on the emission abatement potential of the pathways and did not consider the production costs of the individual methods. In this analysis, the authors found that the European emission targets for 2030 can only be achieved through substantial reductions in production vol-

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[8] Cf. Otto et al., 2017, p. 10.
[9] Cf. Kushnir et al., 2020, p. 2.
[10] Cf. BMWI, 2020b, p. 15.
[11] Cf. Kushnir et al., 2020, p. 12; Vogl et al., 2021, p. 79.
[12] Cf. Fischedick et al., 2014, p. 563.
[13] Cf. Vogl et al., 2018, p. 744.
[14] Cf. Jacobasch et al., 2021, p. 18.
[15] Cf. Woertler et al., 2013, p. 5.
[16] Cf. Kushnir et al., 2020, p. 12.
[17] Cf. Toktarova et al., 2020, pp. 14-15.

ume.[18]

Policy-based analyses and detailed recommendations for promoting sustainable production methods currently exist mainly at superordinate levels, such as basic materials or energy-intensive industries.[19] In the context of steel production, several studies identified the need for policy support for transforming the industry but do not offer specific approaches or recommendations.[20] More detailed results are provided by Vogl et al. (2021). The researchers analyzed different policy approaches for promoting the early market introduction phase of sustainable steel and derived potential especially in direct subsidies for steel production.[21] Furthermore, Muslemani, Liang, Kaesehage, Ascui, and Wilson (2021) investigated the potential to promote green steel and products thereof by creating separate markets. The authors concluded that policy approaches would be particularly promising if these included measures that consider potentially emerging distortions of competition across countries and sectors.[22]

Relating these results to the future of H-DR production in Germany, many ambiguities arise, which previous research has not answered. For instance, uncertainties exist about how exactly the development of production costs or other essential factors might affect the diffusion of H-DR production. Furthermore, the current policy regulations and targets suggest playing a critical role in the steel industry's future. However, its systematic implications on the German steel industry were rarely analyzed in detail. This raises questions such as to what extent the current emission targets are compatible with the steel industry in the short and long term and which specific levers could be used by policymakers to exert influence effectively. This thesis contributes to the clarification of these and other questions.

3. Analysis of the Initial Situation

This section forms the qualitative foundation for the subsequent quantitative scenario development regarding the diffusion of hydrogen-based steel production in Germany. Therefore, this chapter aims to define the initial situation and to identify the major challenges as well as the most significant drivers influencing this diffusion. These findings will then be utilized to draw a plausible picture of the current and foreseeable framework conditions as inputs for the scenario development. For this purpose, the German steel industry will first be characterized with a focus on its economic setting, followed by an analysis of the prevailing environment from various perspectives. These are divided into technological, industry-specific, and political aspects, with a particular emphasis on factors most likely to influence the adoption of more sustainable methods and especially H-DR steelmaking.

3.1. Profile of the German Steel Industry and Its Economic Environment

Generally, iron and steel production, like many other industrial sectors, is characterized by increased difficulty of decarbonization. The reasons for this can be found in the long lifetimes of production plants and corresponding infrastructure, as well as the lack of less emission-intensive alternative technologies.[23] Furthermore, the heterogeneity of industrial plants and the frequent utilization of fossil fuels as input material increasingly complicate decarbonization.[24] Additionally, the steel industry is attributed to the hard-to-abate sectors, typified by a non-electric supply of their energy requirements and difficult or even impossible electrification due to reasons like high costs or technical barriers.[25]

These complications also become evident when considering the German steel industry. In terms of emission intensity, no discernible progress has been observed in recent years, as the overall emission intensity remained relatively constant. In 2013, an average of 1.34 metric tons of carbon dioxide equivalents (tCO_2-eq) per metric ton of steel (tSteel) were generated, while in 2020, this figure had slightly risen to 1.35 tCO_2-eq/tSteel.[26] This immense intensity led to emissions of about 48.2 million metric tons (MMT) of CO_2-eq in 2020, corresponding to 6.6% of total German emissions.[27]

In Germany, steel production is a core industry with a long history. It has about 83,000 direct employees and is closely linked to other major sectors such as automotive, mechanical engineering, and construction.[28] In 2020, 35.7 MMT of steel were produced, representing an exceptional drop compared to the 39.6 MMT produced in 2019, mainly attributable to impacts caused by the Covid-19 pandemic. This decline became even more evident in the generated revenue, which dropped by over 19% between 2019 and 2020, from € 39.8 billion to € 32.1 billion.[29] However, a quick recovery from the crisis can already be observed. In 2021, the total steel production increased to about 40.1 MMT of steel, exceeding the production level of 2019.[30] In an international context, this production volume makes the German steel industry the largest in the European Union, representing a world market share of 2.1% in terms of crude steel produced in 2021.[31] A large part of this total production is accounted for by single players dominating the market. The three biggest market

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[18] Cf. Arens et al., 2017, p. 89.

[19] Cf. Nilsson et al., 2021; Sartor & Bataille, 2019; Wyns, Khandekar, Axelson, Sartor, & Neuhoff, 2019.

[20] Cf. Fan & Friedmann, 2021, p. 856; Holappa, 2020, p. 15; Weigel, Fischedick, Marzinkowski, & Winzer, 2016, p. 1074.

[21] Cf. Vogl et al., 2021, p. 78.

[22] Cf. Muslemani et al., 2021, pp. 10-11.

[23] Cf. IEA, 2021, p. 135.

[24] Cf. Bhaskar, Assadi, & Nikpey Somehsaraei, 2020, p. 1.

[25] Cf. IEA, 2019, p. 23.

[26] Including emissions from energy installations, cf. DEHst, 2014-2021; Worldsteel, 2009-2022, p. 1.

[27] Emissions of the German steel industry consisted of 16.8 MMT CO_2-eq from own energy installations and 31.4 MMT CO_2-eq from process emissions, cf. DEHst, 2014-2021, p. 28. Total German emissions in 2020 amounted to 729 MMT CO_2-eq, cf. UBA, 2022.

[28] Cf. WV Stahl, 2021b, pp. 11-12.

[29] Cf. WV Stahl, 2021b, pp. 7, 13.

[30] Cf. WV Stahl, 2022, p. 1.

[31] Cf. Worldsteel, 2009-2022.

players are thyssenkrupp, ArcelorMittal and Salzgitter AG. In 2020, these were responsible for the production of around 11.0, 6.5, and 6.0 MMT of crude steel, respectively, and thus accounted for roughly 66% of total steel production in Germany.[32]

A distinction is drawn between two types of steel: primary and secondary steel. Primary steel is produced from virgin iron ore and is usually of high quality. For this reason, it is mainly used for the production of flat steel products for application in industries such as automotive or machine building. Secondary steel is produced by recycling steel scrap, which results in inferior quality. Therefore, it is mainly employed to create long steel products for applications in construction.[33] German steel producers focus on producing high-quality primary steel, which is reflected, for example, in a consistent export surplus of steel scrap.[34] As shown in Figure 1, primary steel production thus accounts for around 70% of the total production volume, while secondary steel production accordingly accounts for around 30%.

From an economic perspective, the German steel industry is facing increasing difficulties. The consideration of key indicators regarding its economic situation highlights that these have often been mediocre or even declining in recent years. The volume of crude steel produced, and the sales revenues generated show a negative growth path between 2010 and 2019, with compound annual growth rates of -1.1% and -0.3%.[36] During the financial crisis in 2009 and the Covid-19 pandemic in 2020, the German steel industry reacted sensitively. During both, German steel production slumped sharply compared to global levels.[37]

Initial explanatory approaches for this development can be found in fundamental characteristics of the steel industry, which complicate operations. As such, the production of steel is facing high entry barriers. Furthermore, characteristics of energy-intensive industries like long investment cycles and high capital intensity discourage investors, reducing the economic attractiveness of the industry.[38] However, the most striking reason for this development is provided in the challenging market environment of the German steel industry. In many countries, enormous overcapacities exist, which seriously impair the functioning of global steel markets. In addition, protectionist measures by trading partners are weakening exports, and competition from subsidized manufacturers offering steel at significantly lower prices is increasingly distorting competition.[39] In particular, the Chinese steel industry strongly influenced global steel production in recent years and increased its world market share from 15% in 2000 to over 53% in 2019.[40]

Additionally, steel production in Europe and Germany is characterized as cost-intensive compared to other countries, which further impedes the globally competitive pricing of German steel. These pricing constraints are reflected in an analysis of global steel production costs by the Joint Research Centre of the European Commission. The authors concluded that European and thus German manufacturers are among the most expensive steel producers globally, especially in terms of raw material and labor costs.[41] As shown in Figure 1, in their entirety, these factors have caused the global market share of German steel production to drop by 1.3 percentage points since 2008, despite an increase in the global market of around 40% during the same period in terms of production volume.[42]

Thus, it can be concluded that the German steel industry finds itself in a difficult economic situation to implement and finance a large-scale transformation of current production capacities. In the context of the transformation towards hydrogen-based production, the latter in particular appears to be a major challenge: The German Steel Federation, representing the political interests of German steel producers, estimates that the transition of German primary steel production would require investments of around € 30 billion, almost as high as total industry sales in 2020, and hence derives significant burdens for steel producers.[43]

3.2. Technological Environment

In order to gain a more precise understanding of the initial situation, it is essential to consider current as well as foreseeable technological circumstances of steel production. For this purpose, an analysis of these processes is conducted, followed by the identification of promising alternatives from literature and a characterization of hydrogen-based steel production.

3.2.1. Currently Applied Production Technologies

At present, primary and secondary steel production each takes place within the framework of one dominant production method. These methods will be explained in the following.

In primary steel production, the raw materials in the form of coal and iron ore must initially be processed separately in a sintering or coking plant to obtain the intermediate products sinter and coke. Sinter consists of small lumps produced by melting the iron ore (Fe2O3). Coke (C) serves as energy source and is produced by heating coal to remove volatile fractions. These are then added to a blast furnace (BF) along with lime fluxes, which are used to control the impurity level

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[32] Cf. ArcelorMittal, 2021, p. 74; Salzgitter AG, 2021, p. 2; Thyssenkrupp, 2021, p. 68.

[33] Cf. Arens, Åhman, & Vogl, 2021, p. 4; Woertler et al., 2013, pp. 6-8.

[34] Cf. Arens et al., 2017, p. 86; WV Stahl, 2021a, p. 3.

[35] Cf. Worldsteel, 2009-2022; WV Stahl, 2022. Due to lack of data, 2019 primary/ secondary split adopted for 2020.

[36] Cf. WV Stahl, 2021b, pp. 7, 13.

[37] 2009 global/ German growth: -8%/ -29%; 2020: 0%/ -10%. Cf. Worldsteel, 2009-2022.

[38] Cf. Karakaya, Nuur, & Assbring, 2018, p. 651; Wesseling et al., 2017, p. 1311.

[39] Cf. EC, 2021b, pp. 5, 23.

[40] Cf. Worldsteel, 2009-2022.

[41] Cf. Medarac, Moya, & Somers, 2020, p. 15.

[42] Global steel production increased from 1,343 MMT in 2008 to 1,875 MMT in 2019, cf. Worldsteel, 2009-2022.

[43] Cf.WV Stahl, 2021c, p. 4.

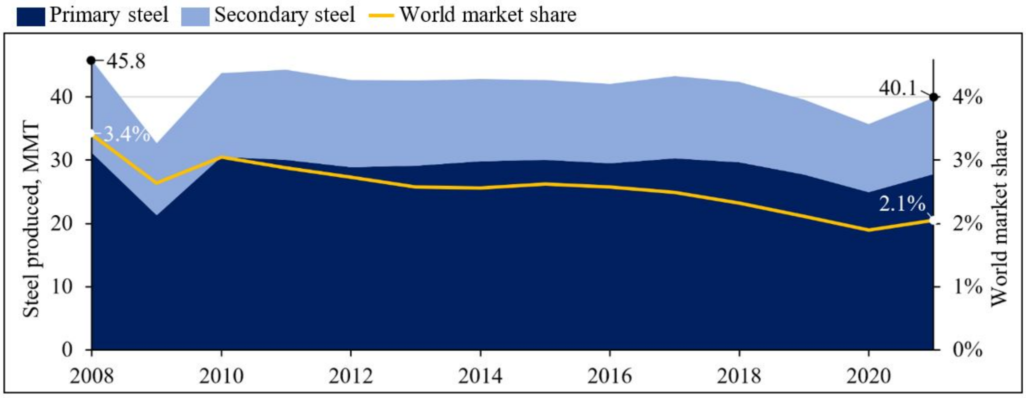

Figure 1: German steel production volume (2008-2021).[35]

and temperature. This mixture is called the burden.[44] Iron production then takes place in the BF by passing a stream of hot air, pulverized coal, and oxygen through it. Iron (Fe) is produced through the reduction of the iron ore by the coke or carbon monoxide (CO) with the simultaneous formation of carbon dioxide (CO_2), as illustrated in the following equations:[45]

$$Fe_2O_3 + \frac{3}{2}C \rightarrow 2Fe + \frac{3}{2}CO_2 \tag{1}$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \tag{2}$$

The product of this step is pig iron, which contains too much carbon resulting in increased brittleness of the material. To reduce the carbon content from around 4% to 0.25%, the liquid iron must be heated again in a basic oxygen furnace (BOF) while adding steel scrap and oxygen, a process referred to as steelmaking. The steel can then be further processed through additional steps such as casting or rolling to produce the required final product.[46] Due to the combination of a BF with a BOF present, this production route is also referred to as BF-BOF. The production steps and major material flows are summarized in Figure 2.

Secondary steel production is less complex. This process is based on recycling steel scrap, which is melted in just one step by heating it with electrical energy in an electric arc furnace (EAF). Additives such as coal and natural gas as complementary energy sources as well as lime fluxes are required. Furthermore, electrodes are consumed.[48] This production route is summarized in Figure 3.

Although the secondary production route only provides steel of limited quality, it incorporates a significant advantage in its comparatively low emission intensity. While emissions from primary production are usually reported at 1.7-1.9 tCO_2-eq/tSteel,[50] emissions from the secondary route are much lower at around 0.3-0.5 tCO_2-eq/tSteel.[51] Since only about 0.1 tCO_2-eq/tSteel of these consist of direct emissions,[52] the majority result from indirect emissions caused by the emission intensity of the respective power grid. These could thus be eliminated by decarbonizing electricity generation. The prospects for the integrated route are much worse: The theoretical minimum, determined by chemical limitations, is 1.37 tCO_2-eq/tSteel, a multiple of the already realized emissions within the recycled route.[53]

This analysis shows that primary steel production in particular is responsible for the largest part of emissions. Not only does it cause up to six times more emissions per metric ton of steel than the secondary route, but it is also utilized to produce around 70% of the total steel volume, thus causing over 90% of all emissions of German steel production.[54] As the prospects for potential emission savings are also limited, this displays a high degree of incompatibility with decarbonization efforts. For this reason, decarbonization of the steel industry by substituting BF-BOF production has been a focal topic of discussion in literature for years and will be dealt with in greater depth in the next section.

3.2.2. Alternatives for Currently Applied Production Technologies

Consensus exists that large-scale decarbonization of steel production can only be realized by comprehensively transforming current steel production.[55] However, other ap-

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[44] Cf. Bailera, Lisbona, Peña, & Romeo, 2021, p. 3; IEA, 2020, pp. 27-29.

[45] Cf. Bailera et al., 2021, pp. 3-4; Otto et al., 2017, pp. 5-6.

[46] Cf. Birat, 2020, p. 6; IEA, 2020, pp. 19, 29; Otto et al., 2017, p. 6.

[47] Own illustration based on process description above.

[48] Cf. Demus, Reichel, Schulten, Echterhof, & Pfeifer, 2016, p. 565; Otto et al., 2017, p. 7.

[49] Own illustration based on process description above.

[50] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 164; Bhaskar et al., 2020, p. 2; Germeshuizen & Blom, 2013, p. 10673; Vogl et al., 2018, p. 740; Weigel et al., 2016, p. 568.

[51] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 51; Kirschen, Badr, & Pfeifer, 2011, p. 6148; Morfeldt, Nijs, & Silveira, 2015, p. 2.

[52] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 52; Demus et al., 2016, p. 565.

[53] Cf. Schoemaker, 1995 (as qtd. in Kirschen et al., 2011, p. 6148).

[54] When considering 1.8 tCO_2-eq/tSteel for BF-BOF and 0.4 tCO_2-eq/tSteel for EAF.

[55] Cf. Fischedick et al., 2014, p. 574; Kushnir et al., 2020, p. 12; Müller et al., 2021, p. 2; Vogl et al., 2021, p. 79.

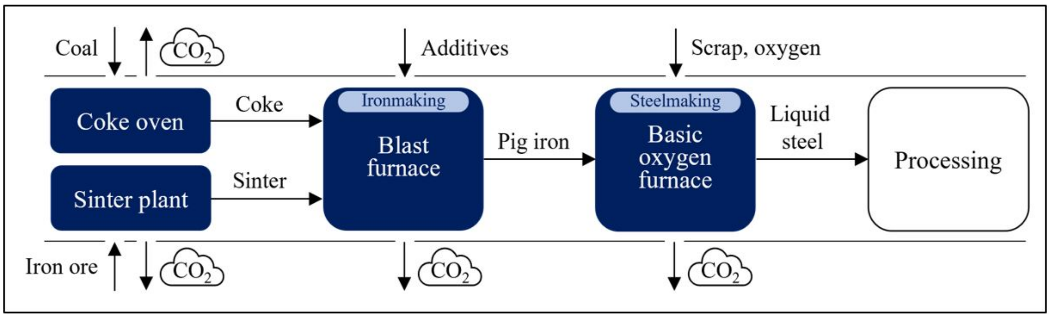

Figure 2: Primary steel production within the BF-BOF production route.[47]

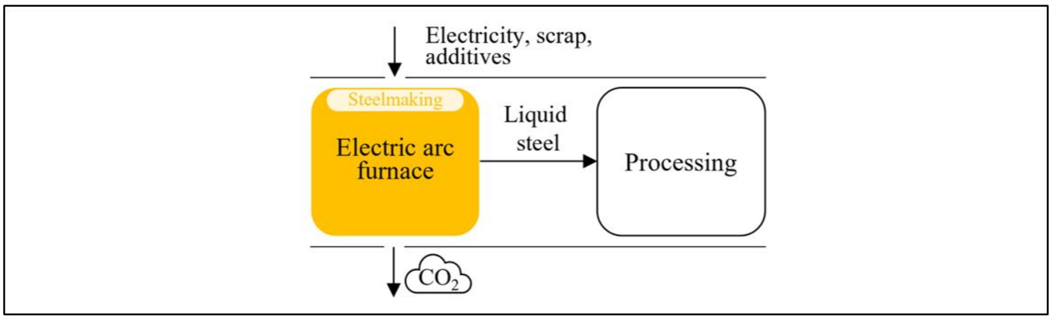

Figure 3: Secondary steel production within the EAF production route.[49]

proaches apart from hydrogen-based technologies exist, of which an overview is provided below.

A variety of studies have already investigated energy and material efficiency strategies for reducing emissions and have derived considerable potential from material efficiency strategies in particular.[56] Another area of research is the development of secondary steel production in the EAF. Pauliuk, Milford, Müller, and Allwood (2013) concluded that secondary steel production will double globally by 2050, replacing primary production as the dominant route between 2050 and 2060.[57] Xylia, Silveira, Duerinck, and Meinke-Hubeny (2018) presented similar results, predicting that the share of secondary production will be around 50% in 2050 and will become the globally dominant route by 2060.[58] Further improvements to this production route are also in prospect: Reducing direct emissions from the EAF could be realized by substituting the applied fossil fuels with biological alternatives such as biochar, which would enable an entirely carbon-neutral secondary steel production.[59]

Nevertheless, these results suggest that primary steel production will still be required in the coming decades, as Vogl et al. (2021) even conclude for the "(...) most ambitious circular economy scenarios (...)"[60] in Europe. Various studies have investigated alternatives to realize emission savings through incremental or radical technology shifts. For example, the operation of conventional BF-BOF production with additional recycling of the furnace gas or the application of carbon capture and storage (CCS) technologies were considered.[61] Similarly, the use of bioenergy as energy source could reduce total emissions by up to 20%, as concluded by Mandova et al. (2019).[62] More radical solutions are found in novel methods such as the electrolysis of iron oxide or the electrification of production within the range of various power-to-X processes.[63] As Weigel et al. (2016) determined in the course of a multi-criteria analysis and Jacobasch et al. (2021) via an economic evaluation, the direct reduction of iron ore using hydrogen as reduction agent and subsequent steel production in an EAF stands out among all alternative primary production methods.[64]

3.2.3. Hydrogen-Based Steel Production

The main distinction between the BF-BOF and H-DR methods is the substitution of carbon or carbon monoxide as reducing agents by hydrogen to yield water instead of carbon dioxide during the reduction of the iron oxide.[65] The applied hydrogen can be produced by various means, such as nuclear

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[56] Cf. Hertwich et al., 2019, p. 15; Milford, Pauliuk, Allwood, & Müller, 2013, p. 3455; Pauliuk & Heeren, 2021, p. 479.

[57] Cf. Pauliuk et al., 2013, p. 3448.

[58] Cf. Xylia et al., 2018, p. 1135.

[59] Cf. Baracchini et al., 2019, p. 79; Demus et al., 2016, p. 569; Fidalgo, Berrueco, & Millan, 2015, p. 279.

[60] Vogl et al., 2021, p. 79.

[61] Cf. Otto et al., 2017; Paltsev, Morris, Kheshgi, & Herzog, 2021; Toktarova et al., 2020.

[62] Cf. Mandova et al., 2019, p. 118.

[63] Cf. Bailera et al., 2021; Fischedick et al., 2014; Weigel et al., 2016.

[64] Cf. Jacobasch et al., 2021, p. 18; Weigel et al., 2016, p. 1074.

[65] Cf. Patisson & Mirgaux, 2020, p. 2.

energy or natural gas with or without CCS technologies.[66] However, the focus lies primarily on the use of green hydrogen, i.e., hydrogen produced by renewable energy sources, as this offers the greatest potential for emission savings. The German government has a similar view: It considers the use of green hydrogen to be the only sustainable option in the long term,[67] which is why it also constitutes the focus of this thesis.

The H-DR process runs as follows: Before actual steel production takes place, the hydrogen must be produced by electrolyzers. These split water (H_2O) into oxygen (O_2) and hydrogen (H_2). At the same time, the iron oxide must be processed into pellets in a pellet plant.[68] Iron production then takes place in a shaft furnace, to which the iron ore pellets are added and subsequently reduced, utilizing the hydrogen as reductant and electricity as energy source.[69] This step is referred to as direct reduction since the iron ore is not melted as in a BF but is solid during the process and hence forms solid iron, called direct reduced iron or sponge iron.[70] The following equation illustrates these processes:[71]

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

For the final steel production, the produced direct reduced iron must be melted in an EAF. Apart from minor differences in the energy and material flows, this step is similar to secondary steel production. Additionally, steel scrap can be added to reduce the amount of hydrogen required, which affects the quality of the final steel and could thus limit its suitability as a direct substitute for BF-BOF production.[72] In the Figure 4, the major material flows of the described production method are summarized.

The most significant advantage of H-DR production resides in the vast emission savings that can be achieved in primary steel production. Pei et al. (2020) consider the feasible emissions to be around 25 $kgCO_2$-eq/tSteel, less than 2% of BF-BOF emissions, highlighting the enormous potential savings that arise from a production switch.[74] This is only valid if the hydrogen production is entirely green. Assuming hydrogen production with electricity from the German power grid in 2020, this alone would have resulted in indirect emissions of 935 $kgCO_2$ eq/tSteel, fundamentally changing the carbon footprint of this production method.[75] These circumstances highlight a crucial challenge that will have a major impact on the establishment of hydrogen-based steel production and yet remains to be solved: the procurement of the required green hydrogen.

3.2.4. Procurement of Green Hydrogen

In principle, green hydrogen can be procured in two ways. One option is importing hydrogen from countries with large renewable production and export potential. Alternatively, it could be produced domestically.

In the case of domestic hydrogen production, the underlying electricity price turns out to be a decisive factor due to the high electricity consumption of this method. For a price range between € 20-100 per MWh, Vogl et al. (2018) concluded a cost range for H-DR production between € 361-640 per ton of steel.[76] Furthermore, the enormous electricity consumption of the H-DR method is likely to impose an even more significant constraint. In the context of total electricity consumption in Germany, producing the hydrogen required for the H-DR steel would result in enormous burdens to the electricity grid. The production of one ton of steel using the H-DR process consumes roughly 3.5 MWh. Combined with the production volume of nearly 27.98 MMT of primary steel in 2021, the application of H-DR production would amount to a total consumption of nearly 98 TWh,[77] more than 17% of Germany's gross electricity consumption.[78] This picture intensifies considerably if one only takes electricity from renewable energies into account, as would be necessary for the production of entirely green steel and as targeted by the German government: Over 41% of the electricity generated through renewable technologies in Germany in 2021 would be required to power primary steel production in its current volume.[79]

Such problems are not expected for imported hydrogen since it can be assumed that it is supplied by regions with enormous production potential for green hydrogen. Such assumptions have already been made by the German government as well. In the National Hydrogen Strategy, it concluded that "(...) the domestic generation of green hydrogen will not be sufficient to cover all new demand, which is why most of the hydrogen needed will have to be imported."[80], thus raising the necessity for corresponding supply infrastructure.

The establishment of such infrastructure is currently subject to extensive interest in literature and is still associated with many uncertainties. These relate, for example, to the source of supply, the form of transport, and its temporal availability. Brändle et al. (2020) investigated the global hydrogen export potential of different countries in terms of volume and costs by using newly built or refurbished pipelines. The

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[66] Cf. Germeshuizen & Blom, 2013, p. 10671; Toktarova, Göransson, & Johnsson, 2021, pp. 2-3.

[67] Cf. BMWI, 2020b, p. 2.

[68] Cf. Pei, Petäjäniemi, Regnell, & Wijk, 2020, p. 9; Toktarova et al., 2021, p. 3.

[69] Cf. Vogl et al., 2018, pp. 737-738.

[70] Cf. Patisson & Mirgaux, 2020, p. 2.

[71] Otto et al., 2017, p. 10.

[72] Cf. Kirschen et al., 2011, p. 6151; Vogl et al., 2018, pp. 739, 743.

[73] Own illustration based on process description above.

[74] Cf. Pei et al., 2020, p. 7.

[75] Electricity consumption: 50.1 kWh/kgH_2, H_2 consumption: 51 kg/tSteel, grid emission factor: 0.366 $kgCO_2$-eq/kWh. Cf. Brändle, Schönfisch, & Schulte, 2020; UBA, 2021, p. 9; Vogl et al., 2018, p. 739.

[76] Cf. Vogl et al., 2018, p. 744.

[77] Cf. Pei et al., 2020, p. 8; Vogl et al., 2018, p. 739; WV Stahl, 2022, p. 1.

[78] Gross electricity consumption in Germany, 2021: 565.3 TWh, cf. AGEB, 2021.

[79] Share of renewable electricity: 41.9%, cf. AGEB, 2021.

[80] BMWI, 2020a, p. 2.

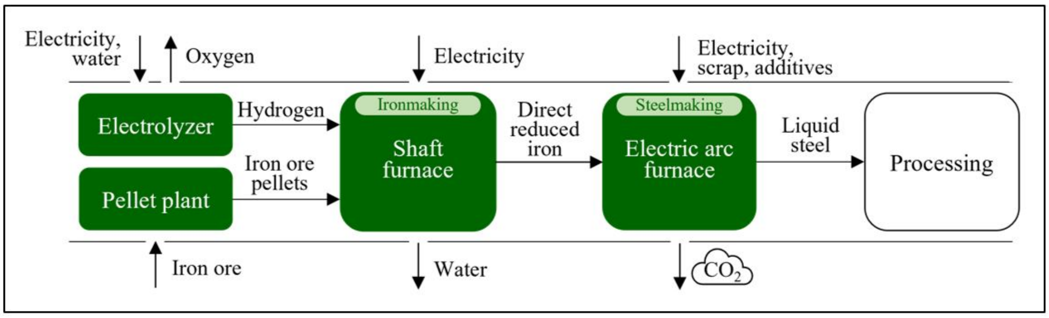

Figure 4: Primary steel production within the H-DR production route.[73]

researchers deduced that onshore wind sources from northwestern Europe or photovoltaic sources from southern Europe are well suited for exports of green hydrogen to Germany. If transport costs are low, Morocco or Algeria offer great potential, too.[81] The German federal government intends to foster such infrastructure as well as the establishment of an international market for hydrogen in the National Hydrogen Strategy, and one year after its publication reported about initial initiatives with the purpose of importing hydrogen from non-European countries.[82]

Nevertheless, concrete developments are not apparent. When, from where, and in what volume green hydrogen could be imported to Germany is therefore still subject to great uncertainty. Similarly, the costs of such imports are not yet precisely foreseeable, even though studies have identified these as a driver that will significantly determine the future cost competitiveness of H-DR steel.[83]

An initial concept for import infrastructure for hydrogen is provided by the European Hydrogen Backbone Initiative, which was jointly founded by several European gas infrastructure companies. These envision to successively expand a European pipeline network and link the first industrial regions, including parts of Germany, as early as 2030.[84]

Consequently, it can be concluded that the procurement and cost of hydrogen will play a major role in shaping the future role of H-DR production. Hydrogen procurement is subject to various limitations in this regard: While importing holds out the prospect of a fully green and low-cost option in sufficient quantities, it requires appropriate infrastructure. Domestic production may be available at an earlier stage but is expected to be more expensive and can only provide limited quantities. Thus, potential could arise from domestic production as a transitional technology until import infrastructure is available.

3.3. Internal Dynamics

This section analyzes the foreseeable developments for implementing hydrogen-based production within the steel industry. Especially the willingness of German steel producers and steel consumers to transform as well as developments thereof will be considered. The analysis of steel producers relates mainly to the three largest producers in Germany: thyssenkrupp, ArcelorMittal, and Salzgitter AG. As already outlined in Chapter 3.1, these account for the majority of total German steel production.

Fundamentally, each of the three producers has formulated the goal of entirely carbon-neutral steel production, which is equivalent to a commitment to depart from conventional BF-BOF production due to its high emission intensity. ArcelorMittal plans to become carbon-neutral by 2050, and thyssenkrupp intends to produce only climate-neutral steel by 2045.[85] Salzgitter even opts to transform its entire primary production until 2033, saving 1% of Germany's total emissions solely in the course of that. Besides introducing H-DR production, Salzgitter plans to substantially increase its secondary steel production.[86]

Considering current H-DR projects on a general level, promising pilot projects in Sweden are particularly noteworthy. There, the decarbonization of the steel industry is receiving attention, as the domestic steel industry is responsible for 10% of all emissions and thus plays an essential role in achieving the target of climate neutrality by 2045.[87] Karakaya et al. (2018) concluded that Swedish companies, governmental as well as research institutions "(. . .) strongly collaborate to drive the transition towards hydrogen-based direct reduction technology."[88] In particular, the HYBRIT project, a joint venture between Swedish companies SSAB, LKAB, and Vattenfall, is receiving broad attention. This project plans to bring green steel to market through demonstration plants starting in 2026 and to establish industrial production between 2030 and 2040 to fully produce carbon-neutral steel in 2045.[89] The H_2 Green Steel project, also based in Sweden, is even more ambitious and plans to start green steel production in 2024, aiming at producing five million tonnes per year by 2030[90] - more than the total Swedish

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[81] Cf. Brändle et al., 2020, pp. 24-25.

[82] Cf. BMWI, 2021b, pp. 1-2.

[83] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 167; Mayer, Bachner, & Steininger, 2019, p. 1520; Vogl et al., 2018, p. 744.

[84] Cf. Wang, van der Leun, Peters, & Buseman, 2020, p. 4.

[85] Cf. ArcelorMittal, 2021, p. 31; Thyssenkrupp, 2022.

[86] Cf. Salzgitter AG, 2022b.

[87] Cf. Pei et al., 2020, p. 2.

[88] Karakaya et al., 2018, p. 662.

[89] Cf. Pei et al., 2020, p. 10.

[90] Cf. H2GS, 2022.

production volume to date.[91]

Although German steel production is more than eight times larger than its Swedish counterpart,[92] comparatively small-scale projects exist. The following table provides an overview of the mentioned Swedish projects and the largest announcements for hydrogen-based iron or steel production in Germany up to date:

The observed projects, as well as the formulated emission targets, indicate a willingness of steel producers to transform their current production processes by implementing H-DR technology. Salzgitter AG and thyssenkrupp, in particular, are targeting significant production volumes within the next decade. Nevertheless, contrary to the Swedish projects, concrete commitments only account for small parts of the total production volume.

Furthermore, the role of steel consumers constitutes an essential factor. Representatives of the steel industry argue "(...) that substantial additional costs could not be borne by steel producers, as they operate on increasingly miniscule margins in a globally competitive market."[94] Because hydrogen-based production of green steel is initially most likely associated with higher costs, the willingness of steel consumers to purchase the product constitutes an essential factor for its success. In principle, German steel producers compete with international producers, as customers can freely choose between the alternatives. The decline in German steel production in recent years despite a growing global production indicates that consumers have increasingly chosen cheaper alternatives from abroad and thus preferred lower-cost options.[95]

Nonetheless, initial positive signals can already be observed. First analyses of primary steel-consuming industries point to favorable framework conditions. Rootzén and Johnsson (2016) reported that the additional cost of using green steel in the automotive industry would result in an increase of less than 0.5% in the cost of a mid-size car and thus would only moderately influence purchasing decisions.[96] This example is reinforced by Muslemani et al. (2021), who identified potential for an increased willingness to pay for green steel most likely to develop in the automotive sector.[97] Furthermore, initial procurement commitments exist from various companies that attach additional value to green steel compared to its conventional equivalent. Examples are listed in the following table:

However, these commitments are still within a somewhat limited scope, from which a comprehensive demand cannot be derived. The extent to which the added value through the green property of the steel can counteract higher associated costs on a large scale cannot be precisely determined at present. In studies of comparable thematic areas, positive indications are found that could favor such development. Exemplary, these studies have derived that consumers show an increased willingness to pay for green electricity.[99] If such effects were to be transferred to the steel market, significant opportunities for accelerating the transformation could arise.

Steel producers likewise consider the development of dedicated markets for green steel as a major opportunity. On this occasion, the German Steel Federation calls for suitable policy instruments such as quotas or setting incentives to stimulate demand.[100] The role of political support is analyzed in more detail in the next section, in which a perspective on the current policy frameworks and foreseeable developments thereof is provided.

3.4. Political Environment

Political directives to which the German steel industry is subject exist at the European and national levels. In the context of this thesis, climate policy aspects will be discussed in particular, as these are expected to significantly contribute to the development of hydrogen-based steelmaking in the coming years.

3.4.1. European Policy

In 2019, the European Commission presented the European Green Deal, a concept that envisions making the European Union climate-neutral by the year 2050. This concept also defines targets for the steel industry. It emphasizes the decarbonization of the steel industry as an essential part of total decarbonization and that new emission-free technologies are to be promoted for introduction starting in 2030. Hydrogen-based steel production is mentioned as a potential technology for such decarbonization.[101] Factors such as these set the European Union apart from other regions: Based on an analysis of the current framework conditions, Arens et al. (2021) concluded that the European Union currently offers steel producers the globally most promising environment for a transformation of steel production in the coming decades.[102]

Part of the current regulatory framework of the European Union is its Emission Trading System (EU ETS), to which steel producers are subject. Within this system, they are in principle obliged to cover their emissions by purchasing allowances. The actual exposure to this regulation is severely limited at the moment, as will be explained in the following.

Being a trade-intensive industry, European steelmaking directly competes with international competitors. For this reason, policymakers fear that the EU ETS would increase

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[91] Swedish steel production in 2019: 4.7 MMT, cf. Worldsteel, 2009-2022, p. 1.

[92] Cf. Worldsteel, 2009-2022, p. 1.

[93] Cf. ArcelorMittal, 2021, p. 43; H2GS, 2022; HYBRIT, 2021; Salzgitter AG, 2022b; Thyssenkrupp, 2021, p. 67.

[94] Muslemani et al., 2021, p. 9.

[95] As outlined in Chapter 3.1.

[96] Cf. Rootzén & Johnsson, 2016, p. 1.

[97] Cf. Muslemani et al., 2021, p. 9.

[98] Cf. Faurecia, 2021; Mercedes-Benz Group, 2021; Miele, 2021; Salzgitter AG, 2022b; Salzgitter AG, 2022a; Scania, 2021; Schaeffler, 2021; SSAB, 2022; Volvo Group, 2022.

[99] Cf. Sundt & Rehdanz, 2014, p. 16.

[100] Cf.WV Stahl, 2021c, p. 3.

[101] Cf. EC, 2019b, pp. 1-8; EC, 2020, p. 1.

[102] Cf. Arens et al., 2021, p. 8.

Table 1: Announced projects for hydrogen-based steelmaking.[93]

Country	Company	Project name	Year online	Iron/steel volume (MMT/year)
Sweden	H_2 Green Steel	H_2GS	2024	5 (by 2030)
Sweden	SSAB	HYBRIT	2026	2.7 (by 2030)
Germany	ArcelorMittal	Hamburg H_2	2023-2025	0.1 (by 2023-2025)
Germany	Salzgitter AG	SALCOS	2025	>3 (by 2033)
Germany	thyssenkrupp	tkH_2Steel	2025	3 (by 2030)

Table 2: Public commitments to purchase green steel.[98]

Company	Supplier	Year	Volume (MMT/year)
Mercedes-Benz	H_2GS	2025	N/A
Scania	H_2GS	N/A	N/A
Schaeffler	H_2GS	2025	0.1
Faurecia	SSAB	2026	N/A
Polestar	SSAB	N/A	N/A
Volvo	SSAB/ Ovako	2022	N/A
BMW	Salzgitter AG	2026	>0.5
Miele	Salzgitter AG	2021	>0.288 (low carbon instead of entirely green steel)
Volkswagen	Salzgitter AG	2025	N/A

the risk of carbon leakage. In this case, this threat refers to the relocation of steel production capacities abroad due to lower production costs, which would result in a loss of the industry from the perspective of the European Union. At the same time, emissions would still be generated elsewhere, thus counteracting climate policy efforts.[103] Therefore, the EU ETS provides industries exposed to the risk of carbon leakage with partially or entirely free emission allowances to prevent them from being disadvantaged in international competition. Steel production has been classified as such industry by the European Commission.[104] Under the provisions of the currently active Phase 4 of the EU ETS, which runs from 2021 to 2030, it is planned that steel producers will thus receive free allowances for all generated emissions.[105] Therefore, no direct cost pressure for steel producers incurred by the EU ETS regime in the next few years is apparent at the current time.

Additionally, issues related to the distribution of emissions can be observed. Although the allowances granted to steel producers are measured based on a benchmark set by the most emission-efficient producers, European steel producers have consistently received excessive free allowances since the EU ETS was launched: In 2019, the free distributions covered around 27% more emissions than were verified for steel producers in the European Union, resulting in windfall profits, which they obtain by selling the allowances.[106] Presumably, this can be attributed to lobbying activities by steel producers, through which they strategically exaggerated their vulnerability to the EU ETS in the past and thus successfully exerted influence on its design.[107]

Considering the roll-out of H-DR technology, the cost of allowances to compensate for emissions is a factor that could accelerate its competitiveness towards BF-BOF production and thus contribute significantly to its success.[108] However, to generate such an effect, the EU ETS in its current form turns out to be insufficient. Various studies argue that the EU ETS has not yet resulted in adequately high CO_2 prices to incentivize the application of more expensive low-carbon alternatives to substitute basic materials or energy-intensive technologies in general.[109] Furthermore, the high volatility of CO_2 prices covered by the EU ETS shapes the investment base of capital-intensive projects as uncertain and poorly suited for making the necessary, far-reaching investment decisions.[110]

Since the current EU ETS regulation can be assessed as rather inefficient concerning the uptake of H-DR production, alternative policy instruments have already been suggested to foster H-DR technology more effectively while still preventing carbon leakage. The European Commission presented a concrete proposal in July 2021 as part of its Fit-for-55 package.[111] The package proposes a phase-out of

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[103] Cf. Branger, Quirion, & Chevallier, 2016, pp. 109-110.

[104] Cf. EC, 2019a, p. 25.

[105] Cf. EC, 2021d, p. 221.

[106] Cf. Carbon Market Watch, 2016, p. 3; EEA, 2021.

[107] Cf. Okereke & McDaniels, 2012, p. 9.

[108] Cf. Jacobasch et al., 2021, p. 16; Vogl et al., 2018, p. 744.

[109] Cf. Sartor & Bataille, 2019, p. 5; Vogl et al., 2021, p. 81.

[110] Cf. Sartor & Bataille, 2019, p. 6; Vogl et al., 2021, p. 81.

[111] Cf. EC, 2021a; EC, 2021c, p. 12.

all free allowances between 2026 and 2035 and instead to establish a Carbon Border Adjustment Mechanism for various products. In the case of steel, such a mechanism would impose tariffs on steel imported into Europe to offset the additional allowance costs of European producers. Conversely, when European producers export their steel, they would be reimbursed for the allowance costs to ensure competitiveness in the international market. Even if this alternative seems effective in fully internalizing CO_2 costs, its introduction would be associated with considerable administrative effort: For each product concerned, extensive knowledge about its emission intensity would have to be available, and trade law disputes would be likely.[112] As this model only constitutes a proposal at the present time, a continuation of the free allowances regime for steel producers seems to be the most likely option at the European level.

3.4.2. German Policy

German policy has set climate targets that exceed European regulations. In 2021, the Federal Climate Change Act was amended, tightening the national goals. There, Germany has set the targets of reducing 65% of 1990 emissions by 2030, becoming climate-neutral by 2045, and achieving negative greenhouse gas emissions from 2050 onwards.[113] Specific emission targets were also set for all major sectors. As steel production was responsible for around 28% of all industrial emissions in 2020,[114] regulations for the industry sector are particularly relevant. Between 2010 and 2019, the industrial sector reduced its emissions by less than 3%, from 188 to 183 MMT CO_2-eq, thus contributing minimally to Germany's emissions reductions to date.[115] However, considering the update of the Federal Climate Change Act, it becomes evident that much higher emission reductions are anticipated until 2030. By then, total industrial emissions are to be reduced by more than 35% from 2019 levels to 118 MMT CO_2-eq,[116] from which a significant emission reduction pressure on German steel producers can be derived.

The significant role the German steel industry will play in the decarbonization of the overall economy has already been recognized by the German government in 2020 with a concept developed jointly with steel producers, the Steel Action Concept. In this, as well as in the National Hydrogen Strategy, the H-DR production method is considered the most promising decarbonization alternative.[117] In the Steel Action Concept, the German government signals a strong willingness to foster hydrogen-based steel production and already envisions support within the framework of other policy instruments, such as the promotion of markets for green steel, the establishment of adequate energy infrastructure and markets for hydrogen, among others. Although the Steel Action Concept includes the intention to continue the free allowances of the EU ETS in its current form, it additionally indicates an openness towards other carbon leakage prevention instruments without naming any definite plans.[118]

More specific information was published one year after the publication of the Steel Action Concept: In 2021, the Federal Ministry for Economic Affairs and Energy listed electricity price compensations, a reduction in the levy to support renewable energies, and the free allocation of allowances within the EU ETS as measures already active to support steel producers. Furthermore, an announced support package intended for the entire industrial sector could initially affect the German steel industry. From 2022 to 2024, the German government announced funding of five billion euros for promoting the application of hydrogen or to test the suitability of carbon contracts for difference (CCfD) to initiate the transformation as part of pilot projects, among others.[119]

The concept of CCfDs is regarded as an efficient instrument for the large-scale commercialization of promising industrial technologies.[120] In the given context, such a contract could consist of an agreement between the regulator, such as the German government, and steel producers to subsidize H-DR projects. For this occasion, a strike price, which is the CO_2 price the H-DR plant needs to become competitive with conventional steel production, and a period in which this strike price is guaranteed, are first agreed upon. If the actual CO_2 price is below the strike price within this period, the steel producer receives payments from the regulator for each avoided quantity of emissions. If the CO_2 price is above the strike price, the producer conversely has to make payments to the regulator.[121] To ensure the efficient formation of the strike price, CCfDs could be allocated among producers through tendering processes.[122] This policy measure entails several advantages. In addition to offsetting increased operating costs, the precisely defined conditions reduce uncertainty for producers regarding the development of CO_2 prices as well as future policy developments, resulting in better investment conditions. Furthermore, basing the payment on avoided emissions creates incentives for the project to be implemented successfully. From a regulator's perspective, opportunities arise to recoup expenditures if CO_2 prices rise above the strike price, limiting the threat of over-subsidization. A potential weakness may be found in the complexity of the design, making this instrument most suitable for large-scale projects.[123]

In conclusion, it can be noted that while ambitious emission reductions have been formulated for the industrial sector by German policymakers, a high degree of willingness to support the transformation of steel production is also evident. A combination of several instruments seems most likely

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[112] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 106.

[113] Cf. Federal Climate Change Act, Section 3.

[114] Cf. DEHSt, 2014-2021, p. 28; UBA, 2022.

[115] Cf. UBA, 2022.

[116] Cf. Federal Climate Change Act, Annex 2.

[117] Cf. BMWI, 2020b, pp. 2-7; BMWI, 2020a, p. 2.

[118] Cf. BMWI, 2020b, pp. 13-17.

[119] Cf. BMWI, 2021a, p. 2.

[120] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 110.

[121] Cf. Vogl et al., 2021, p. 84.

[122] Cf. Sartor & Bataille, 2019, p. 10.

[123] Cf. Agora Energiewende und Wuppertal Institut, 2019, pp. 110-113; Richstein, 2017, p. 16.

at present, but the use of CCfDs, the application of which has already been announced in pilot projects, should be particularly emphasized. As current measures are still far from a comprehensive commercial rollout, and concrete projects for supporting the steel industry have not yet been published, this perspective is still subject to increased uncertainty.

3.5. Summary of the Initial Situation and Identification of Major Drivers

After analyzing the current and foreseeable framework for the introduction of H-DR production from various perspectives, the key findings are summarized in this section. Firstly, the aim is to obtain initial qualitative findings on the first research question and thus to identify factors and interrelationships that are most likely to influence the diffusion of hydrogen-based steel production. Furthermore, these findings will serve as the foundation for quantitative modeling in the next step of this thesis.

A key result that emerges from the conducted multi-perspective analysis lies in the conclusion that the emission targets set by German policymakers are unlikely to be achieved with the currently applied BF-BOF production method without reducing production volume. To realize a sustainable alignment of steel production with the overall German decarbonization pathway, an urgent need to transform primary steel production can thus be derived. Although various alternatives exist for substituting the BF-BOF method, hydrogen-based direct reduction promises great potential primarily due to its exceptionally low emission intensity. Additionally, H-DR production emerges as the currently most favored technology, as it forms a pivotal role in key political concepts as well as in the corporate strategies of the largest German steel producers. Thus, it can be concluded that extensive development of the H-DR method is likely to take place, standing out from alternatives in all observed aspects.

However, one factor that could influence the scale of H-DR production is found in the future role of secondary steel production. Various studies hold out the prospect of a global expansion of the latter in the coming decades. Furthermore, first steel producers expect an expansion of their secondary production to achieve the set emission targets. As such, the prospect of an increasingly dominant role in EAF production within the German steel industry represents a plausible option.

Regarding H-DR production, several major uncertainties exist, which could significantly impact the success of this technology. Above all, the expected higher production costs result in substantial disadvantages. The German steel industry currently finds itself in a disadvantageous position to manage this burden. Whereas the steel industry, in general, provides rather unattractive investment conditions, German steel producers have been additionally exposed to tough international competition in recent years, resulting in declining production volumes and sales. Achieving competitive production costs between H-DR and BF-BOF thus represents an essential precondition for adopting the new technology and preventing the migration of steel producers due to increasing cost pressures. Two factors were identified as having the most substantial impact on future production costs: On the one hand, the costs for the required hydrogen, whose future reduction could make the H-DR more attractive, and on the other hand, costs for the compensation of generated emissions through CO_2 prices, which would primarily result in increased costs of BF-BOF production.

Regarding the procurement of hydrogen, it appears that the import of hydrogen will probably be superior to domestic production in Germany solely due to the capacity limitations of the German energy grid. However, such large-scale imports are not yet foreseeable and are subject to significant uncertainty, which may allow domestic production to act as a transitional technology in the short term.

Besides the actual development of CO_2 prices in the EU ETS market, an additional factor is found in their applicability to steel production through political regulation. The analysis of the current policy framework showed that the protection of steel production from carbon leakage has so far played a pivotal role in policy measures. The resulting distribution of free allowances does not indicate any additional cost pressure for BF-BOF production until at least 2030 and results in a lack of stimulation of the EU ETS for steel production. Nevertheless, the European Commission has already submitted alternative proposals for an early phase-out of free allowances and a simultaneous introduction of a Carbon Border Adjustment Mechanism that might play a role in the future. German policymakers are also expressing great willingness to support H-DR production. Extensive support measures such as the creation of required energy infrastructure, the promotion of green lead markets, and, above all, the establishment of CCfDs are suggested. Still, specific projects have yet to materialize. Accordingly, the future design of the political framework in terms of its type and scope is a factor that is expected to impact H-DR diffusion heavily.

Lastly, the market potential of green steel remains an open question which might lead to an acceleration of H-DR diffusion. Several companies have already made initial commitments to purchase green steel. However, it is to be clarified to what extent this will trigger a comprehensive increase in the willingness to pay on the part of consumers, leading to the establishment of separate markets that soften direct competition with conventional steel.

In summary, it can be concluded that a complex picture of the framework conditions for H-DR diffusion emerges. Various factors that are often subject to considerable uncertainty have been identified as drivers exerting a decisive influence on the future role of hydrogen-based steel making. Table 3 provides an overview of the discussed factors.

Table 3: Identified major drivers for H-DR diffusion

Dimension	Driver
Technological	Expansion of secondary production
Industry-internal	Market potential of green steel
Costs	Development of Hydrogen costs Domestic hydrogen production feasibility Import infrastructure availability Development of CO_2 prices
Political	Development of the free allowances regime Overall type and scope of policy measures

4. Scenario Development

After the prevailing framework conditions for the diffusion of H-DR steelmaking were defined in the first part of this thesis, these will now be incorporated into a quantitative model. Based on this model, the aim is to develop realistic scenarios of H-DR diffusion in Germany to identify critical relationships and gain insights for policymaking, as pointed out in the research questions. Figure 5 summarizes the developed model, followed by a description of the individual steps and the input variables employed.

4.1. Methodology

Fundamentally, the model considers the period from 2022 to 2050 and links directly to historical values underlying until 2020 or 2021, depending on availability. The limitation to 2050 is implemented since many input variables, such as the selected CO_2 prices and hydrogen costs, are only available up to this year.[125] Furthermore, the year 2050 is often the boundary for political emission and climate targets. For instance, Germany's Climate Change Act sets concrete targets up to 2045, while for the period after 2050, the only statement is that negative greenhouse gas emissions are to be realized.[126]

The model consists of three successive steps, each achieved by incorporating additional variables. The foundation is formed by a tipping point analysis, in which forecasts for the price development of the various production methods are compiled by including pivotal cost drivers. In addition to the established technologies, the costs for hydrogen-based steel production are taken into account, each for importing and domestically producing the hydrogen. Based on these cost projections, a general diffusion scenario of H-DR production as replacement for BF-BOF is then simulated. The final step provides an approach to model the impact of strict compliance with the defined annual emission budgets on actual production volumes and the loss of primary steel production.

Each scenario is subject to a policy framework, which serves as the lead indicator since it is expected to impact other input variables and the overall development most decisively. Quantitatively, the policy framework is reflected by various options for the future distribution of free allowances. Three different variations are analyzed: a continuation as currently anticipated, an early phase-out, and the complete absence of free allowances. Within the first option, it is assumed that steel producers can compensate all emissions at no cost until 2030, followed by a linear phase out until 2040. The ten-year duration of this process is derived from the European Commission's early phase-out proposal contained in the Fit-for-55 package, which estimates this period for the phase-out. This proposal further describes the second alternative considered. For the H-DR diffusion, this would entail an earlier onset of support, as it foresees a phase-out of free allowances between 2026 and 2035 and would likely be accompanied by the introduction of new policy instruments.[127] The final policy framework is the complete absence of free allowances for steel producers. This alternative is a somewhat unrealistic assumption, as such developments are not apparent at the current time. However, this variant will serve as a benchmark as it allows drawing interesting conclusions, especially on the effects of the distribution of free allowances.

4.1.1. Tipping Point Analysis

The tipping point analysis aims to model the production costs of the observed production routes per ton of steel as an aggregate of the most critical cost factors. For each scenario, the goal is to identify the tipping point - the year in which cost equality between H-DR and BF-BOF production is achieved. The analysis is undertaken in real euros with the base year 2020. Currency transformations are conducted based on historical exchange rates of the European Central Bank, and the adjustment of cost data to the underlying base year is carried out using the wholesale price index by the Federal Statistical Office.[128] A detailed list of the underlying material quantities and price inputs is provided in Appendix 1 to Appendix 4.

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[124] Own illustration.

[125] Cf. Brändle et al., 2020, p. 1; IEA, 2021, p. 329.

[126] Cf. Federal Climate Change Act, Section 3.

[127] Cf. EC, 2021a.

[128] Cf. Destatis, 2022, p. 7; ECB, 2022.

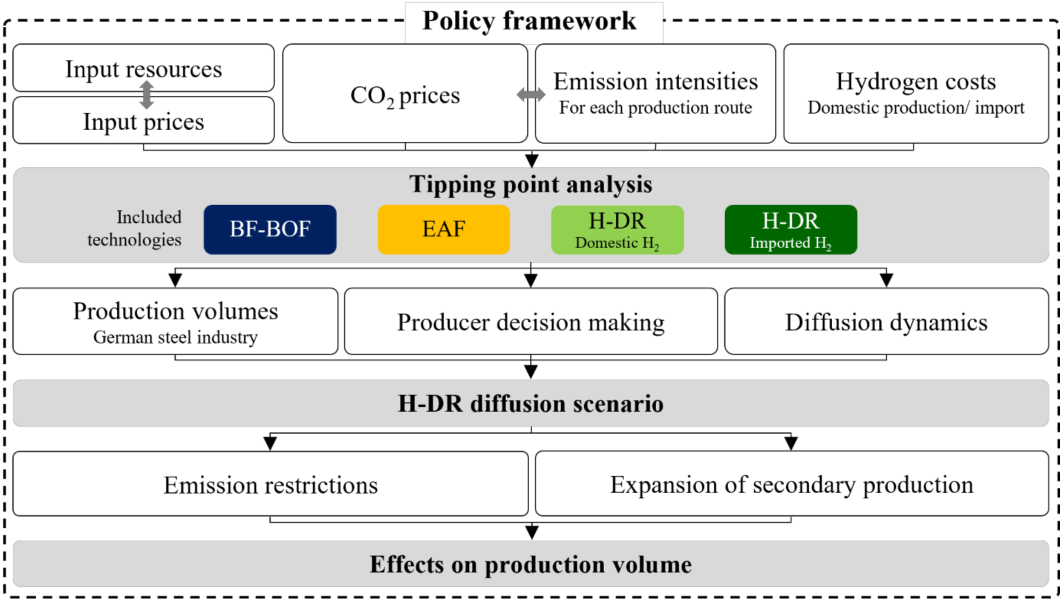

Figure 5: Methodology for modeling the diffusion of H-DR steelmaking in Germany.[124]

General Input Resources

The consumption of materials constitutes the largest part of the production costs of all methods. The specific material flows were identified through literature research as well as through comparison with assumptions of similar papers. In order to derive the material costs, these quantities are linked to cost data. Due to exceptionally high fluctuations in various raw material costs, particularly since the beginning of the Covid-19 pandemic, the prices underlying the model were extrapolated linearly over the entire observed period based on the trend of historical market prices between 2010 and 2021. A cost progression corresponding to the average of available cost data was assumed for cost factors for which extensive historical data are not available.[129]

Besides the material costs, additional cost components are taken into account. For the calculation of the capital expenditures, data of Woertler et al. (2013) is applied, as it is also underlying in the models of Fischedick et al. (2014), Toktarova et al. (2020), and Vogl et al. (2018).[130] Assumptions following the methodology of Vogl et al. (2018) are employed to determine annual capital costs: The authors assigned a lifetime of 20 years to all production facilities and applied an interest rate of 5%.[131] Furthermore, operations and maintenance costs are accounted for at 3% of capital expenditures, as introduced by Fischedick et al. (2014).[132] As indication of labor costs, the analysis of Medarac et al.(2020) is referenced. Due to lack of data availability, it is assumed that the labor costs of H-DR and BF-BOF production are equal.[133] Since no comprehensive historical data are available for steel production-specific capital and labor costs, these are assumed to remain constant.

Because the underlying CO$_2$ prices within the EU ETS and the costs for hydrogen have been identified as major drivers for the future H-DR development, these are considered in a more detailed analysis.

CO$_2$ Prices

CO$_2$ prices are expected to rise, thus having the primary effect of increasing the costs of the most emissions-intensive BF-BOF production. Since none of the observed production methods is consistently carbon-neutral, CO$_2$ prices will impact all of them accordingly, albeit less than for BF-BOF production. For specific input values of CO$_2$ prices, forecasts of the International Energy Agency (IEA) within the framework of its World Energy Model are adopted. In this model, the IEA forecasts CO$_2$ prices in different scenarios for 2030, 2040, and 2050. By linearly interpolating the years in between, these projections are included in the model as illustrated in Figure 6.

For the Net Zero Emissions by 2050 (NZE) scenario, the IEA's modeling is subject to a pathway in which the global energy sector will be carbon-neutral by 2050. In the Announced Pledges (APS) scenario, the IEA assumes that current climate commitments made by all governments worldwide will be implemented as announced. The Stated Policies (STEPS) scenario "(. . .) reflects current policy settings based

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[129] This concerns oxygen and the steel production-specific materials of fluxes and graphite electrodes.

[130] Cf. Fischedick et al., 2014, pp. 577-578; Toktarova et al., 2020, p. 16; Vogl et al., 2018, p. 741; Woertler et al., 2013, p. 22.

[131] Cf. Vogl et al., 2018, p. 739.

[132] Cf. Fischedick et al., 2014, p. 577.

[133] Cf. Medarac et al., 2020, pp. 10-12.

[134] Cf. ICAP, 2022; IEA, 2021, p. 329; own calculations. 2021 value based on interpolation, as the actual development was exceptionally volatile. All numerical values are listed in Appendix 4.

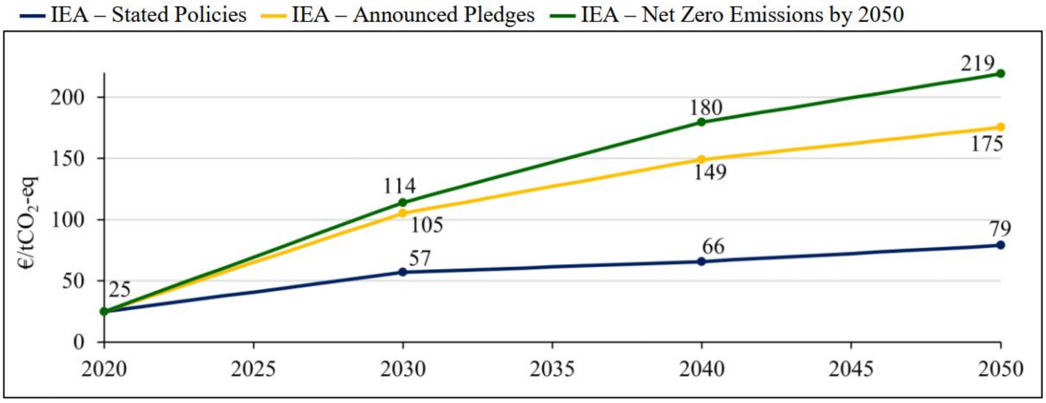

Figure 6: Underlying forecasts of CO_2 prices.[134]

on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world."[135]

Hydrogen Costs

Contrary to CO_2 prices, Hydrogen costs are expected to decline and thus increase the attractiveness of H-DR production. Factors such as economies of scale, supply infrastructures, and technological advances are anticipated to reduce the costs of green hydrogen, decreasing the costs of green steel alongside. The work of Brändle et al. (2020) is employed to model hydrogen costs. Within their study, the authors provide a detailed long-term and scenario-based forecast for the supply costs of hydrogen in more than 80 countries. Numerous techno-economic assumptions include learning curves, transport distances, and efficiency improvements, as well as capital requirements of electrolyzers.[136] The values underlying are obtained from the Tool for Costs of Hydrogen, co-published by the authors alongside the paper.[137] To preserve the import costs for sourcing in Germany, the average price of the ten most competitive hydrogen sources is applied up to 2050. Based on the data on low-cost pipeline transport of hydrogen, one data series is extracted each for optimistic and baseline assumptions.[138] Analogously, the average costs of all production options, without the influence of different transport alternatives, are considered as domestic production costs in Germany for each year until 2050 for optimistic and baseline assumptions. The optimistic data series include improved techno-economic assumptions such as underlying learning curves or electrolyzer capital costs.[139]

For the imported hydrogen, it is assumed that it was produced exclusively with renewable energies since it originates from regions with considerable production potential and offers the prospect of sufficient availability. However, the production of hydrogen in Germany is subject to the assumption that it cannot be accomplished exclusively with renewable capacities due to limitations of the German electricity grid, as already discussed in Chapter 3.2.4. For this reason, it is assumed that hydrogen can only be produced domestically with electricity from the national power grid, which results in the following modification for the domestic production costs: In addition to the hydrogen costs derived from Brändle et al. (2020), compensation costs for the indirect emissions caused by consuming electricity from the German power grid will be considered. This calculation is based on the projections of electrolyzer efficiency improvements by the IEA (2019), which is also applied by Brändle et al. (2020), and a projection of the emission intensity of the German electricity grid.[140] The German grid emission factor is assumed to linearly decline from 366 gCO_2-eq/kWh in 2020 to zero in 2045 in line with the net neutrality target in the Federal Climate Change Act, as similarly modeled, for example, by Fischedick et al. (2014).[141] The applied logic yields the hydrogen costs shown in Figure 7.

Emission Intensities

The final variable for the tipping point analysis is the emission intensity of the individual production methods. Combined with the underlying CO_2 prices, this factor directly impacts the costs of the produced steel, as long emissions are not fully covered by free allowances. Different developments are foreseeable for the individual emission intensities, as explained in the following.

Only limited potential for future reductions in its emission intensity can be identified in BF-BOF production. An indicator for such improvements is provided by the benchmarks set

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[135] IEA, 2021, p. 27.

[136] Cf. Brändle et al., 2020, pp. 7-16.

[137] The third version of the tool from March 2021 was used.

[138] The model includes the transport alternatives of retrofitted pipelines, low-cost, and high-cost pipelines, of which the low-cost pipeline was selected as intermediate option.

[139] Cf. Brändle et al., 2020, pp. 10-12.

[140] Cf. IEA, 2019, p. 44.

[141] Cf. Federal Climate Change Act, Section 3; Fischedick et al., 2014, p. 572; UBA, 2021, p. 9.

[142] Cf. Brändle et al., 2020; own calculations. For reasons of clarity, only the baseline values are visualized for domestic production. All numerical values are listed in Appendix 4.

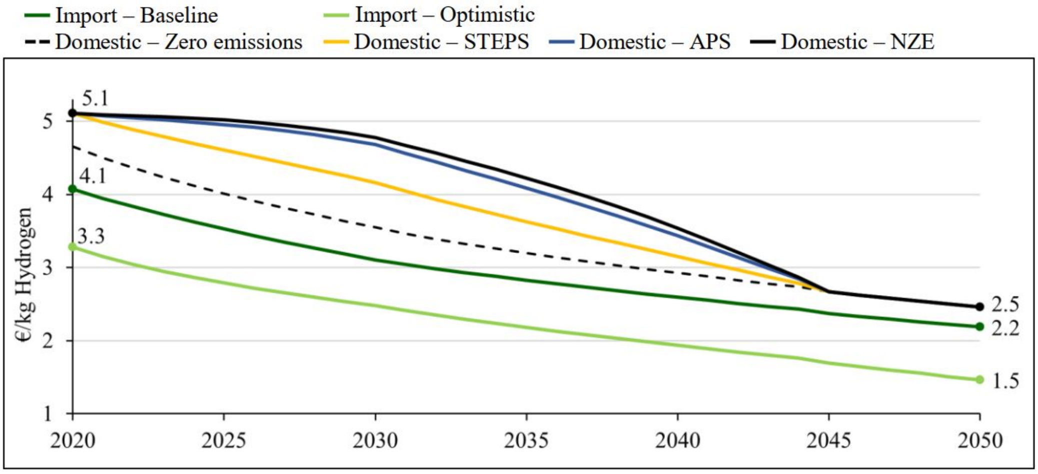

Figure 7: Underlying forecasts of hydrogen costs.[142]

by the EU ETS framework. Within the current Phase 4 of the EU ETS, an annual reduction of BF-BOF emissions by 0.2% is expected due to technological improvements.[143] This model adopts this assumption to forecast BF-BOF emissions over the observed period. Hence, a reduction of BF-BOF emissions from around 1,800 kgCO_2-eq/tSteel in 2020 to almost 1,700 kgCO_2-eq/tSteel in 2050 is underlying.

The emissions from secondary steel production in the EAF first need to be divided into an indirect and a direct component. The indirect emissions result from consuming electricity supplied by the German power grid and are thus reduced alongside the grid emission intensity from 244 kgCO_2-eq/tSteel in 2020 to zero in 2045.[144] The direct emissions result from adding fossil fuels during the melting process in the EAF. In 2020, direct emissions are assumed to be at 100 kg/tSteel.[145] However, as different studies suggest replacing fossil fuels with sustainable alternatives, future zero-emission steel production in the EAF is a reasonable prospect.[146] Therefore, it is assumed that direct emissions, alongside indirect emissions, will be reduced linearly to zero by 2045.

Since the H-DR production is also subject to a melting process in an EAF, it initially consists of the same emission dynamics as secondary production. Additionally, the H-DR method requires more electricity because the shaft furnace must be operated. Secondly, the EAF within the H-DR production consumes slightly more electricity.[147] The emission intensity of the H-DR production with imported hydrogen, which is entirely produced from renewable energy, is thus only about 149 kgCO_2-eq/tSteel higher than the emissions of secondary production in 2020. Significantly different emissions persist if the hydrogen is produced domestically with electricity from the German power grid, as assumed. Due to the high electricity consumption of the electrolyzers, additional indirect emissions of 935 kgCO_2-eq/tSteel arise at the emission intensity of the German electricity grid in 2020, worsening the climate balance of this alternative.[148] Nevertheless, this method features vast improvements under the assumptions adopted. By decarbonizing the power grid and increasing the efficiency of electrolyzers, this alternative also allows carbon-neutral steel production by 2045. Thus, the emission intensity projections can be summarized as follows in Figure 8.

4.1.2. Diffusion Scenario of Hydrogen-Based Steelmaking

As shown in the model methodology in Figure 5, the tipping point analysis serves as the foundation for the H-DR diffusion scenarios. In these scenarios, the H-DR roll-out is simulated according to plausible diffusion dynamics. A description of the underlying inputs is provided in the following.

Producer Decision Making

Even though the market potential of green steel has been identified as a significant driver of H-DR diffusion, it will not be incorporated into the underlying model for reasons of simplification. As a result, it is assumed that no separate market or additional sales potential exist for green steel, which is therefore treated equally to conventional steel. Within this model, this assumption allows producers to make primary steel production decisions based purely on costs, as the same

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[143] Cf. ICAP, 2021, p. 4.

[144] Electricity consumption: 667 kWh/tSteel, grid emission factor (2020): 0.366 kgCO_2-eq/kWh, cf. UBA, 2021, p. 9; Vogl et al., 2018, p. 740.

[145] Cf. Agora Energiewende und Wuppertal Institut, 2019, p. 52; Demus et al., 2016, p. 565.

[146] Cf. Baracchini et al., 2019, p. 79; Demus et al., 2016, p. 569; Fidalgo et al., 2015, p. 279.

[147] Shaft furnace electricity consumption: 322 kWh/tSteel, EAF with direct reduced iron: 753 kWh/tSteel (+408 kWh/tSteel compared to secondary steelmaking), cf. Toktarova et al., 2021, p.19; Vogl et al., 2018, p. 740.

[148] Electricity consumption: 50.1 kWh/kgH_2, H_2 consumption: 51 kg/tSteel, emission grid factor: 0.366 kgCO_2-eq/kWh, cf. Brändle et al., 2020; UBA, 2021, p. 9; Vogl et al., 2018, p. 739.

[149] Own calculations as described above. The initial value of BF-BOF emission intensity results from harmonizing data on emissions and production volumes, which are obtained from different sources, cf. DEHst, 2014-2021; Worldsteel, 2009-2022.

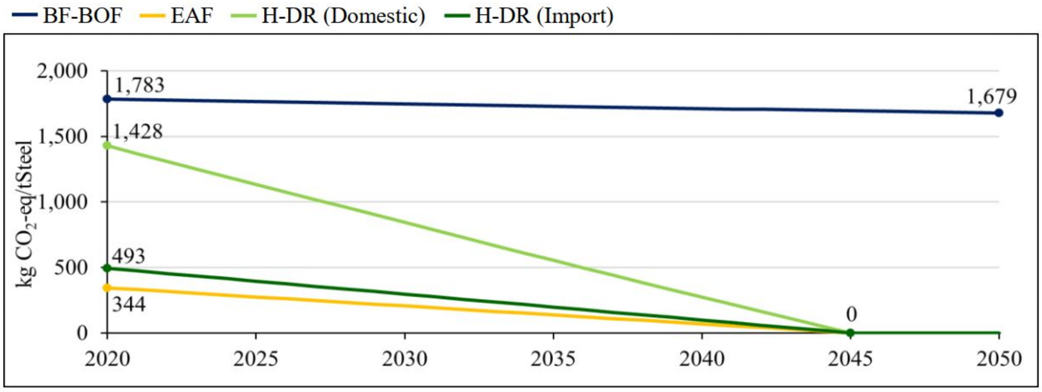

Figure 8: Forecast of emission intensities for the observed production methods.[149]

expected revenue exists for all alternatives. Furthermore, it is assumed that steel producers have perfect information on expected production costs within their planning horizon.

In addition to production costs, the planning horizon of steel producers will serve as the key input for the point in time when the phase-out of conventional steel production is initiated. For steel producers, the decision to start such a transition has far-reaching consequences, as it would entail long-term investments and affect large proportions of total production volume. Consequently, a decision of this type will influence companies' long-term success and can therefore be classified as a strategic decision.[150] The planning horizon for strategic decisions strongly varies between industries and companies. General information is provided by Paul (2015), who considers the strategic planning horizon at more than five years. Weber, Kabst, and Baum (2018) state a similar view, indicating a time horizon of typically five to ten years.[151] To acknowledge the long-term character of steel production, the upper limit of this range will serve as the base assumption of the planning horizon. Thus, the following decision rule is derived: If the expected average costs of H-DR production over the next ten years fall below the analogous costs of BF-BOF production, steel producers initiate hydrogen-based production.

Diffusion Dynamics

In his seminal book Diffusion of Innovations, Everett M. Rogers described innovations as "(...) an idea, practice, or object that is perceived as new by an individual or other unit of adoption"[152], which classifies hydrogen-based steel production as such due to its novelty for steel producers.

An integral part of Rogers' theory is that the cumulative adoption of an innovation follows an s-shaped distribution over time,[153] a proposition that has taken a dominant stance in the diffusion theory of innovation today. Such development is evident, for example, in the diffusion of wind energy, which follows an s-shaped path in many countries.[154] In the German steel industry, such patterns have been observed as well: Arens and Worrell (2014) analyzed historical diffusion dynamics and characterized the diffusion of various technologies such as basic oxygen furnaces or continuous casting machines as s-shaped.[155] Based on these findings, Arens et al. (2017) modeled the future diffusion of H-DR production in Germany with an s-shaped progression in a subsequent study.[156] This assumption is adopted in this thesis.

Different frameworks exist for modeling diffusion processes. A popular approach to model s-shaped diffusion curves can be found in the logistic function, which is described by the following equation:[157]

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}}, \tag{4}$$

where L describes the maximum value, x0 the midpoint, and k the function's slope.

To implement the diffusion dynamics according to the logistic function, L equals one in all scenarios, representing complete diffusion at the end of the respective period. However, the decisive factor is the variation of x0 and k, which define the duration until total diffusion and the adoption rate. The determination of these is described below.

Because H-DR technology is still at the beginning of its extensive global application and no historical data are available, determining a realistic diffusion period is subject to significant uncertainties. Nevertheless, to obtain plausible input values, predictable diffusion periods will serve as proxies to derive a realistic time span. A collection of these proxies is provided in the following table:

The most significant problem associated with these observations lies in a lack of representation for the German steel

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[150] Cf. Bea & Haas, 2017, p. 327.
[151] Cf. Paul, 2015, p. 165; Weber et al., 2018, p. 92.
[152] Rogers, 1983, p. 11.
[153] Cf. Rogers, 1983, pp. 242-243.
[154] Cf. Davies & Diaz-Rainey, 2011, p. 1235.
[155] Cf. Arens & Worrell, 2014, pp. 972-973.
[156] Cf. Arens et al., 2017, pp. 87-89.
[157] Cf. Sidorov et al., 2021, p. 102.
[158] Cf. ArcelorMittal, 2021, p. 43; Arens et al., 2017, p. 87; H2GS, 2022; Pei et al., 2020, p. 10; Salzgitter AG, 2022b; Thyssenkrupp, 2021, p. 67; Thyssenkrupp, 2022.

Table 4: Proxies for the diffusion period of H-DR production.[158]

Source	Location	Diffusion Period	Description
H_2 Green Steel	Sweden	6 Years (2024-2030)	H-DR introduction until large-scale availability of five million tons per year.
Salzgitter AG	Germany	8 Years (2025-2033)	H-DR introduction until the complete transformation of primary production.
HYBRIT	Sweden	15 Years (2025-2040)	Introduction of H-DR demonstration plants until the comprehensive transformation of industrial plants.
Arens et al. (2017)	Germany	20 Years	Time until total diffusion in Germany, based on historical diffusion periods of other steelmaking technologies.
thyssenkrupp	Germany	20 Years (2025-2045)	Introduction of H-DR until fully carbon-neutral steel production.
ArcelorMittal	Europe	25 Years (2025-2050)	Introduction of H-DR until the Group's steel production is completely carbon-neutral throughout Europe.

industry as a whole. For example, the data from H_2 Green Steel and Salzgitter AG only describe the transformation of a single company, which suggests a more extended period for the entire industry. In the case of thyssenkrupp and ArcelorMittal, only general company targets in the form of carbon-neutral steel production by 2045 and 2050 exist for determining the end of the diffusion period as the companies' H-DR projects lack such precise information. The most realistic specification is presumably found in HYBRIT's project plan considering a diffusion period of 15 years. This outlook describes a transformation across several companies and covers large parts of Swedish steel production. The indication of 20 years by Arens et al. (2017) might serve as a lower bound, as this figure was derived from historical technology diffusions driven purely by efficiencies. Thus, it probably does not fully reflect external factors such as potential political subsidies, emission reduction pressures, or the threat of losing production capacities. Acknowledging the significant uncertainty inherent in this factor, a diffusion period ranging between 10 and 20 years is adopted as being the most predictable at the current time.

For modeling the slope of the diffusion curve, data from Arens et al. (2017) is referred to. They concluded that 5% of H-DR diffusion is reached after three years, i.e., 15% of the total diffusion period.[159] This property is applied proportionally to all underlying diffusion curves. The resulting dynamics are illustrated in the Figure 9.

The input values compiled so far can thus be combined to generate a diffusion scenario. Within this initial projection, the total production volume and the split between primary and secondary production are kept constant at 2021 levels.

4.1.3. Potential Effects on the Production Volume

As constant production volume is assumed in the previous step, this step contains an approach to model effects on the production volume of the German steel industry. The boundary of this model is implemented by emissions budgets for German steel production over the observed period, derived from the German Climate Change Act.

In addition to the increased complexity, more detailed assumptions must be established to provide a framework for consistent modeling. The underlying logic is listed below:

- German steel producers cannot exceed the stated emission budgets;
- If total emissions exceed the emission budgets, producers must reduce their production volume accordingly;
- When forced to reduce their production volume due to emission restrictions, producers maximize their output by expanding less emission-intense secondary production, reducing BF-BOF production only;
- Once BF-BOF production volume is reduced due to emission restrictions, it is lost and cannot be recovered;
- As no separate market for green steel exists, production of it cannot develop additional markets, hence only the remaining BF-BOF capacity can be transformed into H-DR production;
- The reduction of production volumes does not affect production costs and H-DR diffusion dynamics.

Before introducing the input variables underlying this approach, it is to be noted that the presented logic will most likely not be implemented in this form in reality. Instead, it is opposed to the current policy framework, as the foreseen distribution of free allowances until at least 2030 was designed to preserve German steel production. Strict enforcement of emission budgets, at least while free allowances are still being issued, therefore does not seem logical. In the context of these circumstances, this analysis aims to examine the degree of incompatibility of German steel production with the

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[159] Cf. Arens et al., 2017, p. 87.

[160] Own calculations.

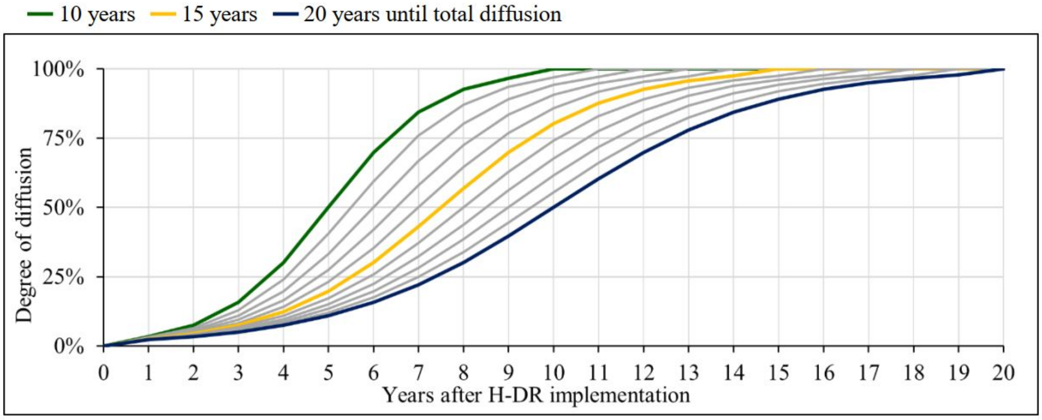

Figure 9: Underlying diffusion dynamics.[160]

applicable emission targets. The vulnerability of the steel industry to migration effects, which would result from a strict implementation of emission restrictions without further support measures, is also to be investigated.

Considering the emission budgets set by politics in the Federal Climate Change Act, it becomes apparent that these were only defined with limited granularity. Targets specific to the steel industry are not indicated, yet they have been specified for the industrial sector as a whole. As explained in Chapter 3.1, German steel production was responsible for a substantial share amounting to 28% of total industrial emissions in 2020, making a restriction by these superordinate targets reasonable. Consequently, the industrial emission budgets are applied proportionally to the emissions of the steel industry. Until 2030, specific annual limits exist. Afterward, emissions are interpolated linearly to the target of carbon neutrality in 2045. This results in the following emission budget for German steel production in the coming decades:

The production volumes are linked to the emission intensity forecasts. The product of these two factors constitutes the emissions generated and must therefore not exceed the restrictions evident in Figure 10.

The final input variable is the development of secondary steelmaking, which is expected to expand when steel producers are forced to reduce their production due to emission restrictions. This logic is based on the assumption that secondary production is likely to become more dominant in the future, as discussed in this thesis's qualitative part. For the expansion of secondary production, a framework is provided in a joint study conducted by the German Steel Institute and the Boston Consulting Group. These concluded that future European secondary production volumes will primarily be limited by the availability of the required steel scrap. Until 2050, the study predicts an annual increase in this availability of 0.9% - an assumption adopted for this model.[162]

Now that all variables have been introduced, Table 5 provides an overview of varying factors, including the values each can assume in the underlying model. Combining these variables forms the basis for extracting the final scenarios, which will be carried out in the next section.

4.2. Scenario Extraction

In principle, it would be possible to create 108 different combinations from the drivers presented in Table 5. However, it is necessary to extract individual combinations to illustrate pivotal interrelationships in the observed environment as desired. Insights from scenario planning literature are relied upon for this purpose.

Amer, Daim, and Jetter (2013) provide a comprehensive review of scenario planning literature in which they compare and discuss results from numerous studies. Thereby, the authors identified particularly two properties, which are repeatedly regarded as fundamental for the credibility of scenarios: plausibility and consistency. The plausibility criterion refers to the fact that an occurrence of scenarios should be realistic. The consistency criterion addresses the need for the combinations of individual driver values to follow a clear logic and not be contradictory.[163] Considering the number of generated scenarios, most researchers favor the development of three to five scenarios to achieve the best trade-off between manageability and insight quality.[164]

For the final scenario selection, the role of the policy framework serves as the foundation. To ensure plausibility and internal consistency, the aim is to derive coherent combinations of the other drivers based on the policy framework. Since the continuation of the current free allowances regime has been classified as the likeliest, two scenarios are created for this variant. Furthermore, one scenario each is subject to an early phase-out and the complete absence of free allowances. The four scenarios that have proven to be particularly meaningful are presented below.

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[161] Actual emission data included until 2020, cf. DEHst, 2014-2021; UBA, 2022. Values after 2020 are based on specified targets in Federal Climate Change Act, Section 3 & Annex 2.

[162] Cf. Woertler et al., 2013, pp. 33-35.

[163] Cf. Amer et al., 2013, p. 37.

[164] Cf. Amer et al., 2013, pp. 32-33.

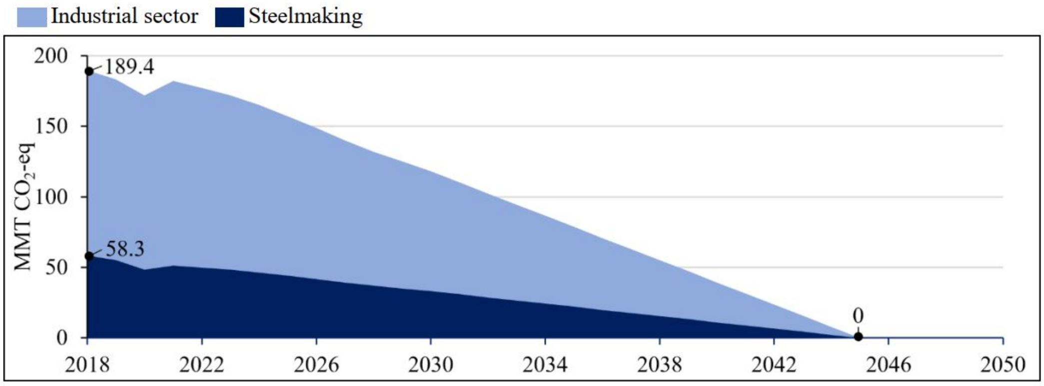

Figure 10: Emission budgets derived from the German Climate Change Act.[161]

Table 5: Summary of drivers included in the model.

Variable	Potential Values	Notes
Policy framework	▲ No free allowances ▶ Early phase-out ▼ Current policy	Lead indicator for each scenario.
CO_2 prices	▲ NZE ▶ APS ▼ STEPS	Adopted from IEA(2021).
Hydrogen source	▲ Import ▼ Domestic production	Domestic production mainly suitable as transition technology.
Hydrogen costs	▲ Optimistic ▼ Baseline	Adopted from Brändle et al.(2020).
Diffusion speed	▲ 10 years ▶ 15 years ▼ 20 years	Extracts from the derived period of 10 to 20 years.

▲ ▶ ▼ High/ medium/ low support of H-DR diffusion

4.2.1. Scenario 1: Current Policy – Downside (CP-D)

This scenario is subject to the current free allowances regime, which means that steel producers receive free allowances for all emissions until 2030, followed by a phase-out until 2040. Additionally, this scenario has the objective of reflecting foreseeable downside risks for H-DR diffusion. It is assumed that policy support measures exceeding the current measures will not be realized, resulting in a sluggish increase in CO_2 prices according to the Stated Policies Scenario by the IEA. Furthermore, no subsidies are provided for green hydrogen projects, negatively affecting their costs. Due to missing cost pressures and a lack of policy support, steel producers show little willingness to transform, resulting in slow uptake of H-DR technology.

4.2.2. Scenario 2: Current Policy – Baseline (CP-B)

This scenario likewise relies on the currently anticipated free allowance policy for steel production but draws a more positive picture of future developments. A higher willingness of politicians to support sustainable projects leads to a faster increase in CO_2 prices following the Announced Pledges forecasts of the IEA. However, measures to support green hydrogen production remain absent, leaving them unchanged compared to the first scenario. Nevertheless, steel producers face increased transformation pressure mainly due to rising emission compensation costs and implement H-DR production faster than would be the case through pure efficiency gains.

4.2.3. Scenario 3: Early Phase-Out (EPO)

Scenario 3 assumes that the current free allowances regime is modified into a phase-out between 2026 and 2035. This industry-specific measure arises from a strong willingness of policymakers to accelerate the energy transition, leading to a rapid increase in CO_2 prices as anticipated in the Net Zero Emissions By 2050 Scenario by the IEA. Green hydrogen projects are being promoted, resulting in an improved cost outlook. As this exerts intensified cost pressure on conventional steel production and simultaneously increases the attractiveness of H-DR production, steel producers show a high willingness to transform, which manifests in a short diffusion period.

4.2.4. Scenario 4: Best Case (BC)

This scenario is based on the EPO Scenario but additionally displays the consequences of an absence of free allowances over the entire observation period. Even though this assumption is somewhat unrealistic, this scenario represents the best possible case and will thus mainly serve as a benchmark.

The following table provides an overview of the specific input values for each scenario:

4.3. Results

In this chapter, the results obtained through the developed model are presented. After an excursus on the potential of domestically produced hydrogen, the analysis of the selected scenarios follows. This analysis is structured in line with the previous chapter: After considering the results obtained from the tipping point analysis, an examination of the corresponding diffusion scenarios follows. Then, effects on production volumes resulting from strict adherence to emission budgets are investigated. Nevertheless, the general informative value of the developed model must first be assessed.

The very nature of scenarios implies essential elements that must always be taken into account when analyzing results of this kind: Scenarios are not exact predictions of what the world will look like tomorrow. Instead, their purpose is to create a broad perspective on fundamental trends and uncertainties.[165] Complex aspects are ordered and woven into "(...) coherent, systematic, comprehensive, and plausible"[166] stories to map the range of potential alternatives.[167] Such a simplified structuring of complex relationships is also subject to this model and is essential to identify the key interdependencies in the underlying long-term approach. Moreover, the included input variables are exposed to high uncertainties or do not yet offer any actual data, which also must be considered. Fischedick et al. (2014) noted the consequence of such limitations during a similar approach. The researchers argued that absolute numerical values should be assumed to be less meaningful. Instead, the observable relative correlations and the comparison of different scenarios allow the most reliable conclusions to be drawn.[168] This reasoning is adopted for the results presented here.

4.3.1. Potential of Domestic Hydrogen Production

As illustrated in Table 6, all extracted scenarios assume that the hydrogen required for steel production will be imported and that domestically produced hydrogen will thus be of minor importance. Therefore, before presenting the scenario analysis results, the rationale for this selection is stated.

As already explained in Chapter 3.2.4, the domestic production of hydrogen is associated with considerable restrictions compared to hydrogen imports, which led to the conclusion that this variant could primarily draw potential as a transition technology until sufficient hydrogen import infrastructure is available. However, within the developed model, correlations became visible that seem to limit this potential and led to the exclusion of domestic production from all scenarios.

Comparing the impact of the different hydrogen sources on the cost projection of H-DR production, domestic production is associated with significantly higher costs than imports. This disadvantage is illustrated in Figure 11 for the BC Scenario: There, the additional costs of domestic hydrogen production lead to a delay of five years until cost equality to the BF-BOF is achieved. Within the underlying mechanisms, this has the consequence that domestically produced hydrogen does not offer sufficient incentives in any of the scenarios to initiate the H-DR roll-out in the critical phase until around 2030,[169] in which it could serve as a substitute for imported hydrogen. Even within the BC Scenario, where the assumption of strong policy support favors earlier hydrogen imports, implementing H-DR steelmaking using hydrogen produced in Germany is only feasible from 2030 onwards.

One significant factor influencing this development is the contradictory development of domestic hydrogen production costs compared to CO_2 prices. As illustrated in Figure 7, higher CO_2 prices lead to higher hydrogen production costs, driven by the compensation costs for the generated emissions. Thus, while high CO_2 prices in principle foster the early implementation of H-DR technology by raising the cost of conventional steel production, they simultaneously disadvantage domestic hydrogen production. Within the defined framework, it can therefore be concluded that domestic hydrogen production in Germany does not offer enough incentives to unfold its potential as a transition technology without further support.

4.3.2. Tipping Point Analysis

This section presents the results obtained from the analysis of the four extracted scenarios. First, the tipping point analysis is discussed, which considers the cost forecasts of the observed steelmaking technologies until 2050.

Figure 12 visualizes the breakdown of production costs by cost factor for each production method in 2022, representing the starting point of the projections.

This analysis shows that raw material and energy costs account for the largest part of production costs in all methods. In 2022, these two cost factors account for 56% of total costs

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[165] Cf. Schoemaker, 1995, p. 28.

[166] Coates, 2000, p. 116.

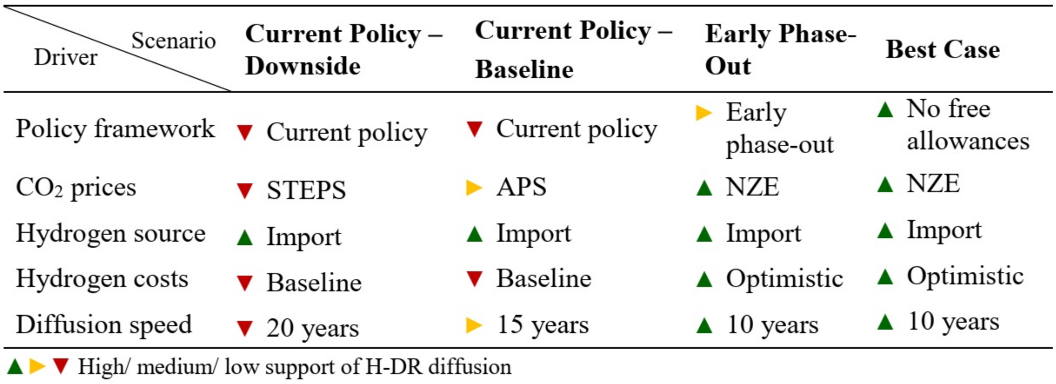
[167] Cf. Hiltunen, 2009, p. 151.

[168] Cf. Fischedick et al., 2014, p. 567.

[169] This period is derived from the plans of the European Hydrogen Backbone which include establishing initial European hydrogen infrastructure starting in 2030, cf. Wang et al., 2020, p. 4.

[170] BC scenario underlying.

Table 6: Input values underlying the selected scenarios.



Driver \ Scenario	Current Policy – Downside	Current Policy – Baseline	Early Phase-Out	Best Case
Policy framework	▼ Current policy	▼ Current policy	► Early phase-out	▲ No free allowances
CO₂ prices	▼ STEPS	► APS	▲ NZE	▲ NZE
Hydrogen source	▲ Import	▲ Import	▲ Import	▲ Import
Hydrogen costs	▼ Baseline	▼ Baseline	▲ Optimistic	▲ Optimistic
Diffusion speed	▼ 20 years	► 15 years	▲ 10 years	▲ 10 years

▲ ► ▼ High/ medium/ low support of H-DR diffusion

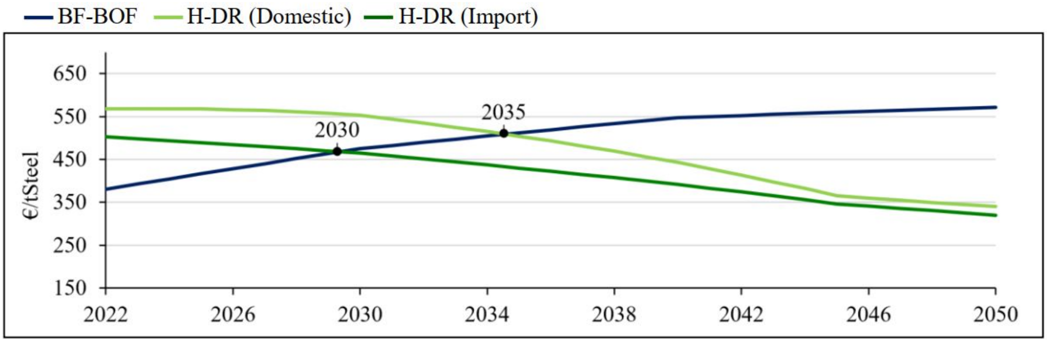


Figure 11: Impact of domestic hydrogen production on H-DR cost forecast.

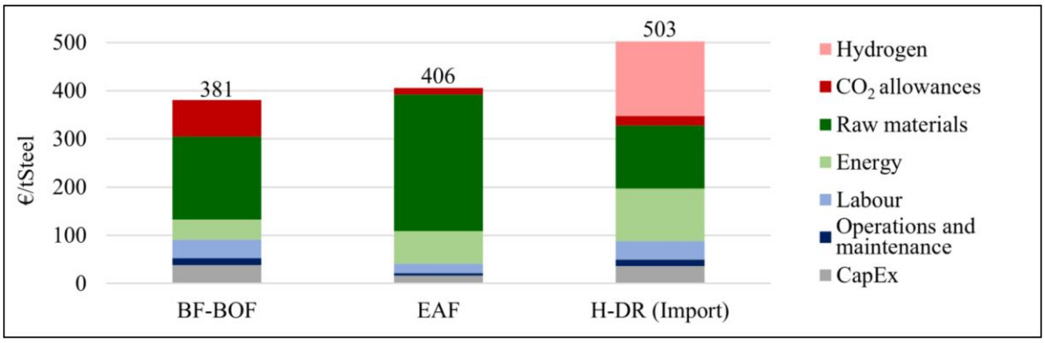


Figure 12: Production cost breakdown of the observed methods (2022).[170]

within BF-BOF production and about 87% in secondary production. The increased exposure of secondary production is caused by the high consumption of the relatively expensive steel scrap and the high electricity demand of this method. For H-DR production, this share, including hydrogen costs, is also responsible for the largest part of total costs, amounting to 78% in 2022. Since this illustration is based on the BC Scenario, the production costs already include compensation expenses for caused emissions, a factor that is not yet present in reality. However, even in this analysis, the BF-BOF method turns out to be the substantially more economical primary production method as the H-DR method causes about 32% more costs. If the costs of CO_2 allowances are disregarded, this share even rises to almost 59%, demonstrating the enormous cost differences between the two primary production methods at the beginning of the observation period.

Based on the described production costs, various combinations of CO_2 prices and hydrogen cost developments are underlying, affecting the initial cost gap differently. The resulting tipping point analysis is provided in Figure 13.

It becomes evident that mainly the costs of BF-BOF and H-DR production change significantly in all scenarios. Due to its low emission intensity and as no hydrogen is required, the changes in EAF production costs are much less pronounced.

Within the CP-D Scenario, relatively limited effects on individual production costs are evident and result in H-DR pro-

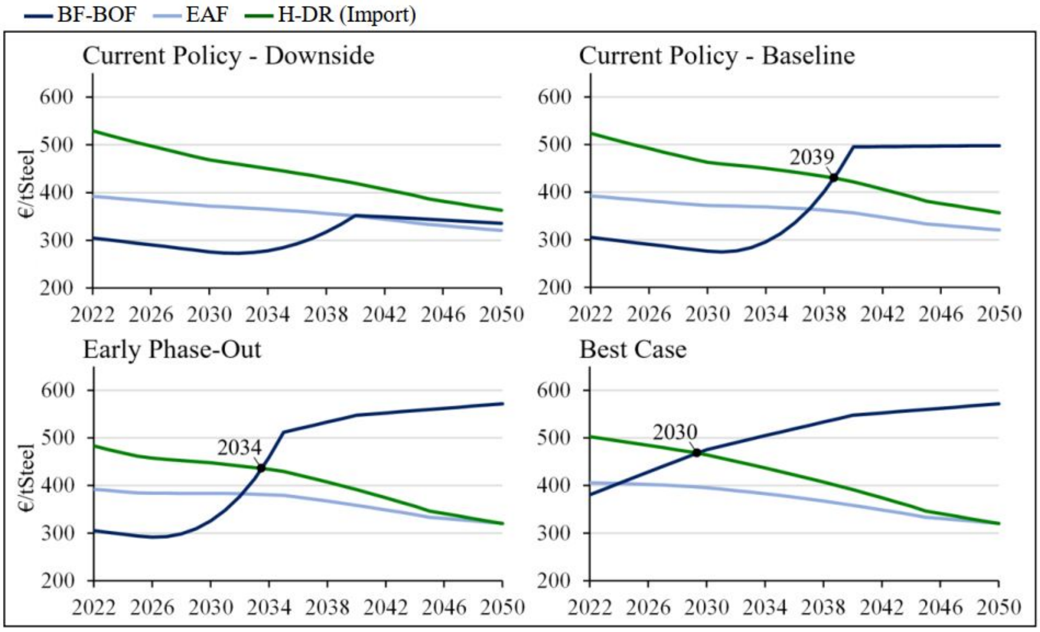


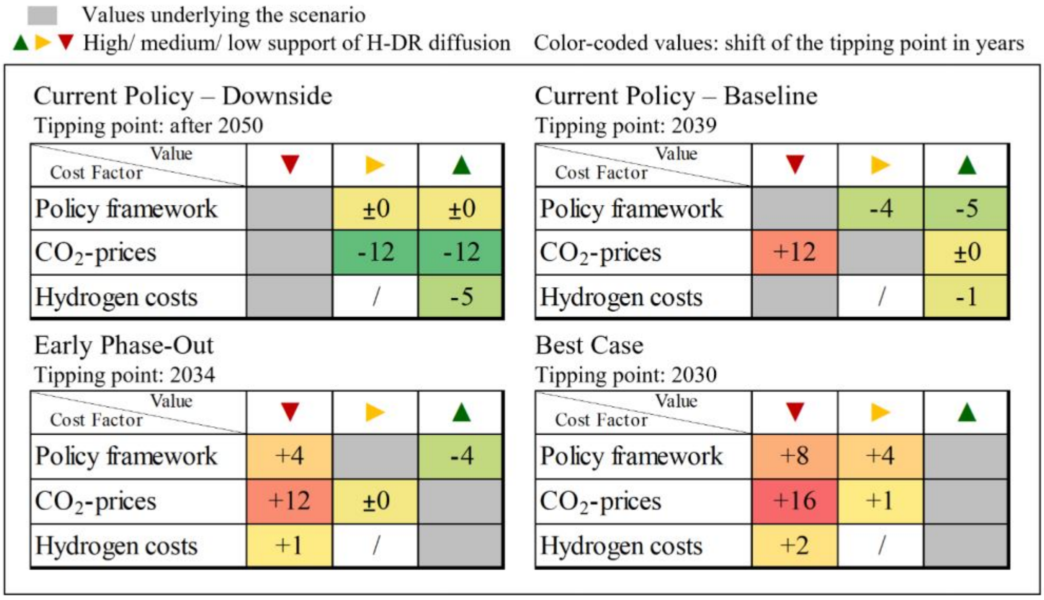
Figure 13: Tipping point analysis of the selected scenarios.

duction imposing higher costs than BF-BOF production over the entire period. Low CO_2 prices emerge as a major cause, as even the complete absence of free allowances from 2040 onwards does not result in a sufficient increase in BF-BOF costs to achieve cost advantages of H-DR production. This differs in the CP-B Scenario: A significant increase in BF BOF production costs is apparent, driven by higher CO_2 prices combined with the phase-out of free allowances. This development ultimately leads to reaching the tipping point in 2039.

Within the EPO and BC Scenario, a stronger trend in production costs emerges. Due to lower hydrogen costs and rapidly increasing CO_2 prices, the costs of the individual methods converge faster and result in cost advantages of H-DR production starting in 2034 and 2030, respectively. The significant effects caused by a phase-out of the free allowances in combination with high CO_2 prices can be observed particularly. While BF-BOF production still has the lowest costs at the beginning of the observation period, these rise sharply in the phase-out period due to their high emission intensity and thus considerably influence the timing of the tipping point. Because of their low emission intensity, EAF and H-DR production costs show only minor changes caused by the phase-out, not affecting their overall trend.

Further insights can be obtained by examining the leverage of the individual cost factors on the tipping point timing. For this purpose, each of them is modified in all scenarios under otherwise constant conditions (ceteris paribus). The alternative values of the cost factors are found within the dimensions defined for the model, summarized in Table 5. For each of these modifications, the triggered shift of the tipping point in years is recorded in Figure 14. Values indicating a change to a point whose location lies outside the period depicted in the model refer to the year 2051. Thus, the given information reads as follows: If the CP-D Scenario would be subject to the development of CO_2 prices according to the NZE instead of STEPS forecasts, the tipping point between H-DR and BF-BOF production would be reached 12 years earlier. Since the CP-D Scenario is not subject to a tipping point within the observation period until 2050, the described change would result in reaching the tipping point in 2039, i.e., 12 years before 2051.

Considering these findings, it becomes apparent that the individual cost factors exert varying degrees of influence on the timing of the tipping point. By far, the greatest leverage is found in the CO_2 prices: Especially the step between the STEPS and APS projections turns out to be impactful and results in a shift of the tipping point by at least twelve years in all scenarios. The step between the APS and the NZE forecasts is of significantly smaller importance and merely causes a shift of one year in the BC Scenario. The factor with the second-largest impact is the underlying policy framework, whose variation mostly causes a shift of four to eight years. Only in the CP-D Scenario its modification does not influence the timing of the tipping point. This lack of stimulus is caused by the factors' underlying dimensions, which only constitute different values up to 2040 since no free allowances are underlying from this point on at the latest. As the tipping point of the CP-D Scenario is far beyond 2040, changes in this factor no longer have any influence. The situation is different for the hydrogen costs: In the CP-D Scenario, a reduction would result in a shift of the tipping point to 2046. Among the other scenarios, this factor modification only results in minor changes.



▨ Values underlying the scenario

▲►▼ High/ medium/ low support of H-DR diffusion

Color-coded values: shift of the tipping point in years

Current Policy – Downside
Tipping point: after 2050

Cost Factor \ Value	▼	►	▲
Policy framework	▨	±0	±0
CO_2-prices	▨	-12	-12
Hydrogen costs	▨	/	-5

Current Policy – Baseline
Tipping point: 2039

Cost Factor \ Value	▼	►	▲
Policy framework	▨	-4	-5
CO_2-prices	+12	▨	±0
Hydrogen costs	▨	/	-1

Early Phase-Out
Tipping point: 2034

Cost Factor \ Value	▼	►	▲
Policy framework	+4	▨	-4
CO_2-prices	+12	±0	▨
Hydrogen costs	+1	/	▨

Best Case
Tipping point: 2030

Cost Factor \ Value	▼	►	▲
Policy framework	+8	+4	▨
CO_2-prices	+16	+1	▨
Hydrogen costs	+2	/	▨

Figure 14: Effects of the individual cost factors on the timing of the tipping point.

4.3.3. Diffusion Scenario of Hydrogen-Based Steelmaking

The analysis of the diffusion scenario is carried out according to key indicators, which primarily include the respective emission profiles and cost projections resulting from the different diffusion dynamics. The production volume is assumed to remain constant at the 2021 level and thus includes the production of 27.98 MMT of primary steel and 12.09 MMT of secondary steel.[171]

Figure 15 provides an overview of the diffusion scenarios of all selected scenarios.

What strikes first are the differences in the starting points of the respective H-DR rollout, which are derived from the tipping point analysis according to the underlying decision rule of producers explained in Chapter 4.1.2. While the BC Scenario would result in the initiation of H-DR production already in 2026, a substantial delay occurs in the other scenarios. However, the CP D Scenario is particularly prominent. There, the H-DR costs exceed the BF-BOF costs too much over the entire period to enable sufficient stimulus for triggering H-DR production. Given the long diffusion period of 20 years underlying the CP-D Scenario, this indicates that a comprehensive transformation will not occur until well into the second half of the century. However, a distinct shift can be identified for the CP-B Scenario. This scenario anticipates an implementation nine years after the BC Scenario. It would thus result in a complete transformation of steel production at the end of the observed period in 2050. Nevertheless, it ranks well behind the BC and EPO Scenarios, including a change in the free allowances regime and a 14 and 10 years earlier completion of the transformation.

Emissions

The emissions profile of each scenario is of fundamental importance to assess their compatibility with the emissions budgets targeted by the federal government. An overview of annual and total emissions resulting from each scenario is provided in Figure 16.

A finding that emerges from the analysis of annual emissions is that no scenario can realize the annual reduction targets of the Federal Climate Change Act in the near future. Even the EPO and BC Scenario do not foresee realizing them until 2035 and 2030. However, their trajectories reveal that H-DR production contributes to vast emission reductions after its implementation: A sharp decline in annual emissions occurs and enables significantly lower emissions than budgeted. The long-term goal of carbon neutrality by 2045 is achieved within both scenarios despite temporary budget overruns.

The analysis of the CP-D and CP-B Scenario reveals far more pessimistic emission trends. Due to the lack of H-DR introduction, the emission savings within the CP-D Scenario are exclusively based on improvements to the established production methods. This results in only a minor reduction of annual emissions by about 12%, from 53.5 to 47.0 MMT CO_2-eq between 2022 and 2050. Consequently, the emissions budgets are vastly exceeded over the entire observation period. The CP-B Scenario is also subject to exceeding the emission targets until 2049. However, the introduction of H-DR technology still facilitates a completely carbon-neutral production from 2050 onwards, five years later than targeted by policy.

Regarding the total emissions, it can be concluded that only the BC Scenario, with total emissions of about 528 MMT CO_2-eq between 2022 and 2050, can remain below the budget, which amounts to 607 MMT CO_2-eq. Although the

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[171] Cf. WV Stahl, 2022, p. 1.

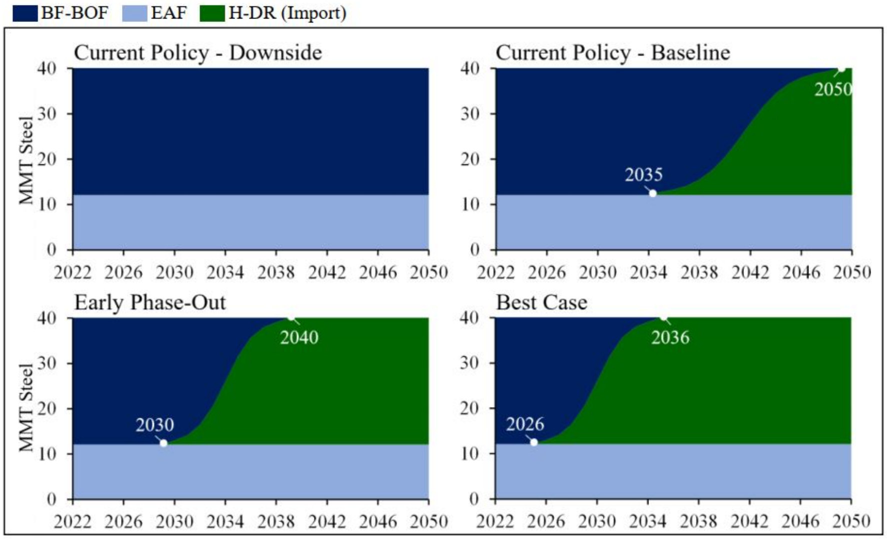

Figure 15: Diffusion dynamics of the selected scenarios.

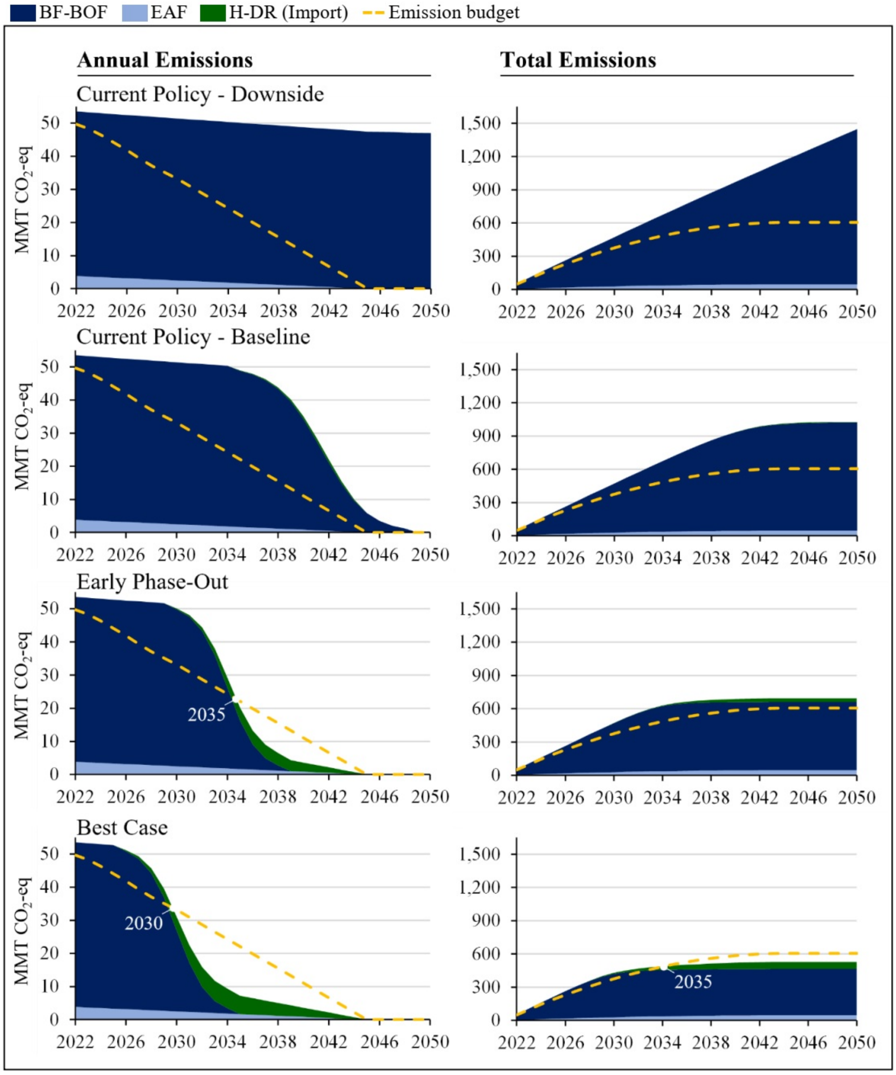

Figure 16: Annual and total emissions of the selected scenarios.

EPO Scenario undercuts annual target emissions beginning in 2035, the subsequent savings are insufficient to offset the previously generated excess emissions. With total emissions of 694 MMT CO_2-eq, it misses the budget by about 14%. Both scenarios, which include the continuation of the current free allowances regime, result in massive overruns of the budget regarding the total emissions caused. With emissions of 1,026 MMT CO_2-eq, the CP-B Scenario already exceeds the budget by 69%. Nevertheless, it raises expectations of a positive development after 2050 since the completed transformation in 2050 ensures that subsequent steel production will be emission-free. The situation is different for the CP-D Scenario: There, the total emissions of 1,447 MMT CO_2-eq exceed the budget by 138% and do not indicate any improvement, as the H-DR implementation has not yet occurred.

Production Costs

The analysis of production costs is based on calculating the average production costs in each scenario. The average costs are composed of the different production methods applied, weighted by their shares in total production volume. Additionally, the development of average costs is displayed for the case where no H-DR adoption takes place, and no allowances have to be purchased to compensate for emissions. Figure 17 provides an overview of the underlying development.

Examining the average costs shows that these are subject to a temporary increase in each scenario, followed by a reduction. It can be observed that the earlier the scenario conditions stimulate the H-DR rollout, the higher the average production costs. Averaging at 391 € /tSteel over the entire period, the BC Scenario features the highest costs reaching a maximum value of 447 € /tSteel in 2030. The EPO Scenario follows in second place and includes average costs of 358 € /tSteel. Its highest value of 432 € /tSteel is reached in 2035, the year the phase-out of free allowances is terminated. The CP-B and CP-D Scenario appear even more favorable, with average costs of 351 and 325 € /tSteel, respectively. The maximum values of 438 and 352 € /tSteel for both are found in 2040, which again is the first year purchased allowances must fully compensate for the generated emissions. The influential role of free allowances becomes evident from an overall perspective: In all scenarios involving a phase-out, an upward trend of the average costs along it is evident. Furthermore, the BC Scenario, which is not subject to any free allowances, entails significantly higher costs than the other scenarios from the very beginning.

Although CP-D Scenario turns out to be the scenario with the lowest average costs, the developments at the end of the observation period and their outlook prove to be particularly informative. After reaching their maximum average costs, all scenarios, which include transforming to H-DR production, are subject to a stronger cost reduction trend than the CP-D Scenario. The forecasts even suggest that the average costs of the BC and EPO Scenario undercut those of the CP-D Scenario in 2046, making them the least expensive variants from that point forward.

However, comparing the cost curves of the scenarios to the costs of BF-BOF production that is not subject to any emissions allowance costs, it becomes clear that the CO_2 costs burden steel production with long-lasting disadvantages in any case.[172] At an average of 285 € /tSteel, this option offers by far the lowest costs over the entire period. Furthermore, even towards the end of the observation period, only minimal convergence of the scenarios involving an H-DR transformation is evident. Conventional steel production, which is not subject to emission compensation payments, can therefore be characterized as the least expensive production alternative.

Costs of Potential Subsidies

Another interesting perspective derived from the analysis of production costs is found in the payments required to support H-DR production in each scenario. This analysis roughly follows the mechanism of a CCfD as explained in Chapter 3.4.2. The subsidy amount is defined as the difference in production costs between H-DR and BF-BOF production per ton of steel, which is then offset against the targeted H-DR production volume for each year. Thus, if H-DR costs exceed BF-BOF costs, expenses will be incurred if H-DR production is realized. Since perfect information about the course of production costs is available within this model, the subsidy amount is calculated individually for each year instead of defining a strike price over a prolonged period, as would be the case in a real setting. The BC Scenario will serve as a benchmark in the underlying case: The costs incurred to align the H-DR diffusion with the BC are calculated for each scenario. It is important to note that this calculation refers to the BF-BOF costs of the respective scenario, including costs for CO_2 allowances. Conclusions on the required subsidy volume to achieve cost parity with foreign producers, which are not subject to CO_2 prices, are not directly feasible. The respective payments are visualized in Figure 18.

In each scenario, it becomes evident that additional payments amounting to several billion euros would be required to achieve the targeted production volume. Significant differences between the individual scenarios are apparent. The EPO Scenario involves total payments of € 8.1 billion, around 20% of the German steel industry's revenue in 2019[173], spread over eight years after the H-DR introduction in 2026. The highest annual payments are required in 2031 at € 1.88 billion, and after 2034, no additional costs are generated as the H-DR production costs fall below those of BF-BOF production. A large step is evident in the CP-B Scenario, which, at costs of € 31.7 billion, results in nearly a quadruple of required funding compared to the EPO Scenario, mainly driven by higher annual payments, as shown in Figure 18. At the beginning of the H-DR introduction, the annual costs increase rapidly and reach their maximum of € 4.4 billion in 2033. A similar development is underlying the CP-D Scenario: The required annual payments also reach their maximum in 2033 at € 4.53 billion. Since, in this sce-

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[172] Represented by the dashed line in Figure 17.

[173] Revenue of the German steel industry in 2019: € 39.8 billion, cf. WV Stahl, 2021b, p. 13.

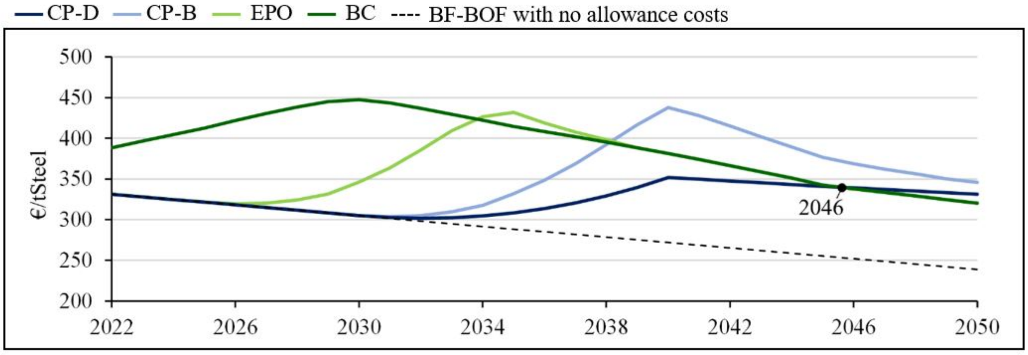

Figure 17: Average production costs of the selected scenarios.

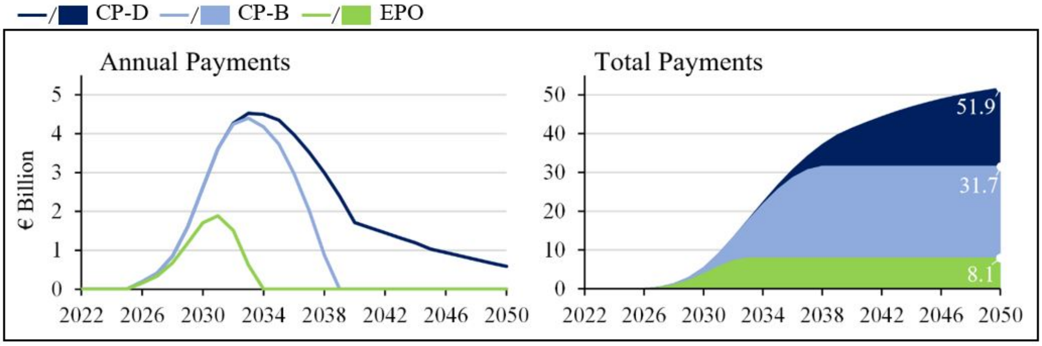

Figure 18: Required payments to achieve the diffusion of the Best Case Scenario.

nario, the H-DR costs exceed those of BF-BOF over the entire period, payments are necessary throughout all years to promote H-DR production. These amount to € 51.9 billion in total - 130% of the industry's turnover in 2020.

A relationship between the annual payments and the phase-out of the free allowances becomes apparent and is particularly evident within the CP-D Scenario. There, the end of the phase-out in 2040 abruptly causes the required annual payments to decrease at a slower rate. This deceleration illustrates that free allowances result in higher annual payments and that their phase-out contributes to rapidly reducing the required payments. This observation is confirmed when considering the primary impact of free allowances: By lowering the cost of BF-BOF compared to H-DR production, higher payments are necessary to achieve cost parity.

4.3.4. Potential Effects on the Production Volume

When evaluating the results in the previous section, it must always be taken into account that these are based on the assumption of constant production volumes and a constant split between primary and secondary production. Effects of excessive emissions or additional costs on the production volume are not reflected and therefore represent a simplification of reality. This analysis step follows an approach to evaluating potential effects on production volumes caused by strict enforcement of the imposed emission budgets. Again, the production volume of the German steel industry in 2021 serves as the starting point.

Figure 19 illustrates the evolution of production volumes for each scenario resulting from consistent adherence to the annual policy emission budgets.

Since the Federal Climate Change Act considers emission reductions not feasible with conventional production methods already for 2022, each scenario entails a reduction in primary production capacities from the beginning. Thus, steel producers also begin expanding secondary production from the start in all scenarios, limited by steel scrap availability as defined in the underlying logic.

The analysis of the CB-D Scenario again indicates that BF-BOF production is incompatible with the targeted emission reductions. There, the lack of H-DR implementation results in losing the total primary production capacity to enable achieving the emission targets. Thus, the German steel industry consists exclusively of secondary production at the end of the period and has shrunk massively overall. The loss of 27.98 MMT of primary steel is offset by an additional production of 3.59 MMT of secondary steel, reducing German steel production by 24.39 MMT to 39% of its initial size.

Within the CP-B Scenario, the introduction of H-DR allows at least parts of the primary production capacity to be transformed before becoming irreversibly depleted due to emission restrictions. Nevertheless, because of the relatively late H-DR roll-out, this scenario also entails losing most BF-BOF production. About 60% of primary steel production, corresponding to 16.73 MMT Steel, are dismantled until 2037. Considering the additional secondary steel pro-

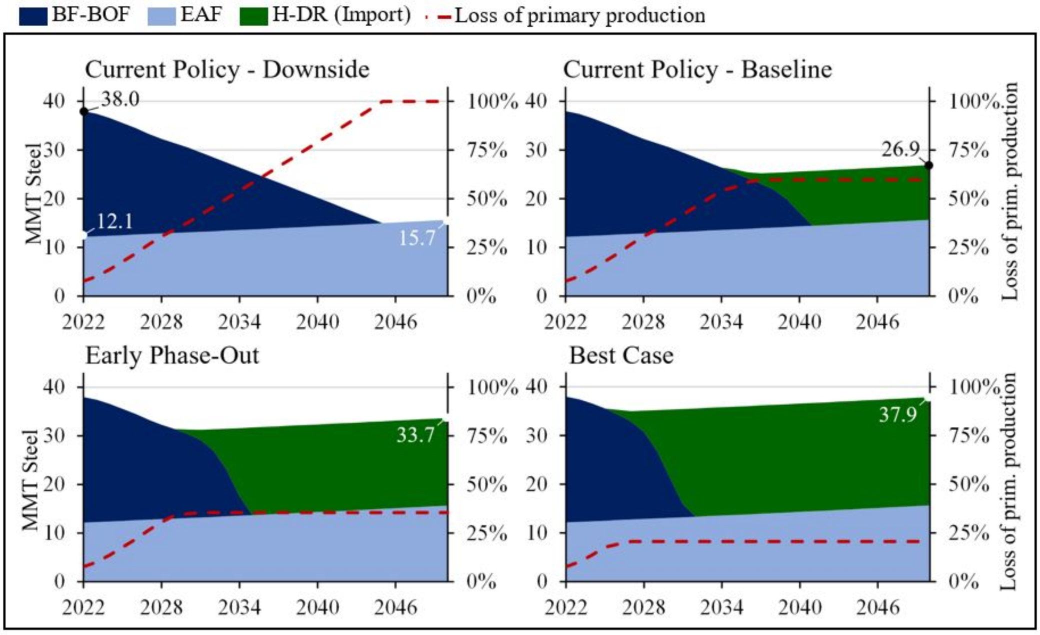

Figure 19: Effects of strict compliance with emission budgets on production volumes.

duction, which is identical in each scenario, a loss of 33% of total steel production is implied.

In the two more optimistic scenarios, the majority of primary steel production can be maintained and transformed. In the EPO Scenario, the reduction in primary production until 2031 results in losing 9.98 MMT, around 36% of its initial volume. This loss equates to a 16% reduction in total production after taking the expansion of secondary production into account. Within the BC Scenario, the required reduction until 2027 is associated with primary steel losses of 5.78 MMT, corresponding to 21% of the initial production. However, this loss can be compensated by additional secondary capacities to a large extent. As a result, the loss of total production volume adds up to 5% of its initial volume.

In summary, each scenario would be associated with a decline in overall production if annual emissions budgets were strictly enforced. Nevertheless, the severity of the triggered reduction differs greatly between the scenarios. Furthermore, the near-term emissions budgets appear to pose the greatest challenges, as these cannot be achieved in any of the scenarios, thus implying the largest output reductions.

4.3.5. Sensitivity Analysis

Since the underlying model is designed to forecast future developments, some of the contained variables are subject to considerable uncertainty. To identify the contribution of individual input values to the prevailing uncertainty and thus to better understand their role within the model, a suitable tool is found in the sensitivity analysis.[174] For this purpose, individual values are varied while holding all other constant and analyzing the impact on the model output. The sensitivity analysis will be performed from two perspectives as the model produces various outputs. First, the sensitivity towards the most significant cost factors will be tested by examining their impact on the timing of the tipping point, followed by an analysis of parameters underlying the diffusion dynamics. The foundation for the sensitivity analysis consists of the CP-B Scenario.

For H-DR production, the most significant cost factors are the costs of electricity, iron ore, and hydrogen. In 2039, the year of the tipping point in the underlying scenario, these account for about 72% of the total production costs. Accordingly, the costs of scrap, CO_2 allowances, and iron ore are the most relevant factors for BF-BOF production, accounting for 67% of total costs in 2039. Table 7 shows the results of the sensitivity analysis. The variation is applied to all cost factor values up to 2050, the color-coded figures indicate the shift of the tipping point caused by the variation.

In principle, it can be observed that the location of the tipping point is relatively robust to uncertainties in the cost factors. For example, massive changes in iron ore costs exert no influence at all, as these are subject to both production methods and cause a parallel shift of the cost curves. Electricity and steel scrap prices likewise demonstrate limited influence, although these each affect only one of the two production methods. However, the model shows increased sensitivity to hydrogen costs and especially CO_2 prices since significant shifts in the tipping point occur when these deviate. Although these two factors are already included as critical indicators in the scenario analysis and different values were

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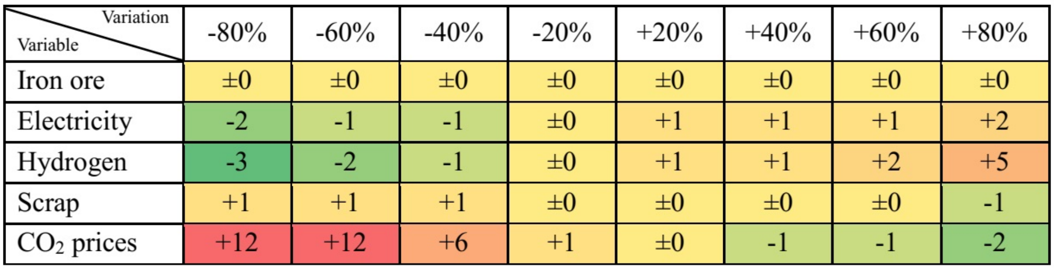
[174] Cf. Saltelli, Tarantola, Campolongo, & Ratto, 2004, p. 45.

[175] Values indicating a shift to after the observation period refer to the year 2051. CP-B Scenario underlying.

Table 7: Sensitivity analysis of major cost factors.[175]



Variation Variable	-80%	-60%	-40%	-20%	+20%	+40%	+60%	+80%
Iron ore	±0	±0	±0	±0	±0	±0	±0	±0
Electricity	-2	-1	-1	±0	+1	+1	+1	+2
Hydrogen	-3	-2	-1	±0	+1	+1	+2	+5
Scrap	+1	+1	+1	±0	±0	±0	±0	-1
CO_2 prices	+12	+12	+6	+1	±0	-1	-1	-2

Color-coded values: shift of the tipping point (2039) caused by variation in years.

considered for them, the major impact of the uncertainty underlying these factors on the model output must always be taken into account.

Considering the assumptions underlying the modeling of the H-DR diffusion, decisive input values can be found in the H-DR initiation year and diffusion speed. Since H-DR initiation is derived from the cost developments of H-DR and BF-BOF production and the planning horizon of producers, conclusions on these can simultaneously be drawn. The analysis of the diffusion rate is justified by its subjection to major uncertainties resulting from the lack of historical values or distinct proxies. The total emissions generated are applied as model output, whose change caused by the variation of the variables is observed. Table 8 presents the results of the sensitivity analysis. The variation describes the shift of the H-DR initiation or the shortening or lengthening of the time until complete diffusion is achieved in years, the colored values describe the triggered change in cumulative emissions until 2050.

A significant influence on the model output can be detected for both observed variables. However, in direct comparison, the deviations in the H-DR initiation are associated with approximately double the impact on the selected model output. If these findings are combined with those of the first step of the sensitivity analysis, this again illustrates the enormous influence that is in particular exerted by uncertainties in CO_2 prices throughout the model, which they exercise by influencing the timing of the tipping point.

4.4. Discussion

After the scenario analysis results were presented in the previous section, these will now be discussed in the research questions' context. Furthermore, potential limitations underlying the results will be considered. The discussion is structured as follows: First, observable correlations are highlighted at a general level, then the current political framework is assessed, and finally, recommendations for policymaking are derived.

4.4.1. Limitations of the Developed Model

The limitations of the proposed model are primarily found in its simplifying assumptions, which may affect the validity of the results. For instance, it was assumed for BF-BOF production to be continued only in its current form. However, additional emission savings could arise from applying BF-BOF production through modifications as a transitional solution. Examples of this can be found in applying CCS technologies or recycling the exiting gas from the blast furnace, as already considered by other papers.[177] The utilization of hydrogen produced with natural gas in the H-DR could likewise offer potential as bridging technology before green hydrogen will be extensively available.[178]

Another limitation is found in the fact that no added value is attributed to green steel compared to conventional steel. As stated in the first part of this thesis, the development of such market potential could significantly influence the future of H-DR production. If, for example, consumers express a greater willingness to pay for green steel, additional incentives for transformation could arise for steel producers beyond purely cost-based decisions as considered in the underlying approach. Thus, this limitation is identified as upside potential that might cause significant shifts in the developed scenarios.

4.4.2. General Findings

The modeling aimed to depict realistic scenarios for the diffusion of hydrogen-based steelmaking subject to various policy frameworks surrounding the German steel industry. It becomes clear that the future development of steelmaking is only vaguely foreseeable, reflected in significant differences between the individual scenarios.

For instance, the timing of the tipping point is subject to major shifts. Examining the drivers for the individual shifts leads to the conclusion that particularly the development of CO_2 prices exerts a decisive influence by increasing the costs of BF-BOF production. In contrast, H-DR cost reductions turned out insufficient for significantly increasing early H-DR attractiveness since the included hydrogen cost forecasts cause comparatively low approximations of H-DR to BF-BOF costs. Thus, at a general level, the increase in conventional steelmaking costs represents the essential prerequisite for achieving a cost advantage of hydrogen-based production.

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[176] CP-B Scenario underlying.

[177] Cf. Fischedick et al., 2014; Toktarova et al., 2020.

[178] Cf. Facchini, Mossa, Mummolo, & Vitti, 2021.

Table 8: Sensitivity analysis of major diffusion factors.[176]

Variable \ Variation	-8	-6	-4	-2	+2	+4	+6	+8
H-DR initiation	-34%	-26%	-18%	-9%	+9%	+18%	+26%	+33%
Diffusion speed	-18%	-13%	-9%	-4%	+5%	+9%	+13%	+17%

Color-coded values: change in total emissions caused by variation.

These correlations are confirmed when considering the underlying production costs of the scenarios. It was found that circumstances resulting in an early tipping point and thus an early initiation of H-DR production are simultaneously associated with increased production costs. However, it also became evident that these cost disadvantages are of temporary nature. By stimulating H-DR production, framework conditions that at first glance seem to negatively affect production costs might unlock additional cost reduction potential in the long term. This effect is mainly driven by the continuous reduction of hydrogen costs, accompanied by increasing BF-BOF costs, even occurring at low CO_2 prices, and a late phase-out of free allowances.

Nevertheless, these cost benefits of H-DR production are considerably smaller when BF-BOF production is not subject to any CO_2 allowance costs. If foreign producers are not obliged to purchase such allowances, German producers will face cost disadvantages in each scenario. Furthermore, it becomes apparent that future H-DR cost reductions can only compensate for these additional costs to a limited extent, thus indicating a long-lasting manifestation of these disadvantages. These findings reinforce the concerns about carbon leakage effects that might result in losses for the German steel industry. From a cost perspective, the influence of CO_2 prices must therefore be differentiated: On the one hand, a rapid rise and the associated increase in steel production costs lead to the earlier implementation of H-DR production. On the other hand, long-term cost disadvantages towards foreign producers would result.

A closer look at the insights of the emission forecasts reveals that the annual emission budgets are highly unlikely to be realized in the near future. Even the BC Scenario, subject to optimal conditions for an H-DR implementation, foresees compliance only from 2030 onwards. As a result, primary steel production turned out to be highly vulnerable to potential capacity reductions in case of strict compliance with the annual emission budget. Furthermore, the compensation potential of secondary production proved insufficient. In no case was the expansion of secondary production able to offset the required reduction in primary production to prevent the overall output from shrinking. A contradiction emerges from these findings: Strict enforcement of annual emission targets is incompatible with maintaining current production levels and requires one of the targets to be abandoned.

Looking beyond the exceedance of annual emissions budgets, a comprehensive transformation of primary production promises excellent opportunities to unleash enormous emissions savings and bring German steel production on track with its long-term emission targets. This potential is evident in the BC and EPO Scenarios, which both include achieving the long-term goal of carbon neutrality in 2045 despite temporarily exceeding emission budgets. The opposite occurs if current primary production is continued, as represented in the CP-D Scenario. BF-BOF production does not offer sufficient emission savings potential without reducing the production level, and thus proves to be the biggest obstacle to achieving the emission targets. Thus, the early reduction of BF-BOF capacities is identified as a prerequisite to aligning steel production with the German climate targets.

In summary, a positive picture emerges when assessing the potential of H-DR diffusion. In principle, a shift to H-DR production offers the prospect of achieving the long-term emission targets while maintaining the production volume of the German steel industry. Furthermore, such transformation raises the possibility of reaching a more favorable cost path, on which cost advantages compared to BF-BOF production could grow in the long term. However, the findings confirm the high risk of carbon leakage effects, which should not be underestimated. Exposing the steel industry to CO_2 prices would be associated with long-lasting cost disadvantages for German steel production.

4.4.3. Assessment of the Current Policy Framework

The previous section concludes that raising the cost of conventional production provides the most effective lever for increasing H-DR attractiveness at an early stage. Thus, the current policy framework is conceptually well suited to exert influence on steel production by regulating free allowances. Furthermore, the issuance of free allowances offers effective protection against cost disadvantages, as can be seen in the enormous effects of the phase-outs on production costs within the scenarios. However, potential future challenges associated with this regulation are apparent.

Since the EU ETS Regulation anticipates that the allocation of free allowances will be continuously reduced, this instrument provides only temporary support for involved emitters. In other sectors, such as aviation, loosening of the regulation has already been implemented, which suggests that steel production will also be affected at some point.[179] Thus, for German steel producers, it can be concluded that the current policy framework most likely only provides temporary protection in any case and merely delays the point in time

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[179] Cf. ICAP, 2021, pp. 3-5.

when the disadvantage against international competitors is initiated. While this might provide producers time to transform their production processes, the emerging incentives are not entirely clear. Within the purely cost-based evaluation underlying, a prolonged issuance of free allowances delays H-DR diffusion as the key leverage for its attractiveness is suspended. The resulting extension of BF-BOF production leads to significantly higher overruns of annual emissions budgets and increases the likelihood of BF-BOF lock-in due to long-term investments being made. Long-term cost disadvantages also seem likely, as the scenario analysis showed that early H-DR implementation could enable achieving a more favorable cost path in the long term.

Furthermore, it is apparent that the current policy framework conflicts with the more incentive-based support via CCfDs: The calculation of required compensation payments showed that the distribution of free allowances causes significantly higher payments. This incompatibility leads to the result that ending the issuance of free allowances would increase the efficiency of more targeted measures.

In summary, the distribution of free allowances basically meets its objective of protecting the German steel industry from cost disadvantages in international competition. However, various complications were identified within the underlying modeling. The arising key issue is that the current policy framework prolongs the economic viability of BF-BOF production and thus delays the implementation of H-DR production. As discussed in the general findings, this might create long-term cost disadvantages. Combining this with the fact that the distribution of free allowances is only temporary in any case, these disadvantages might constitute the major long term impact of the current regulation. Hence, effects counteracting the actual policy target would result. Moreover, the current policy framework proves problematic from a climate policy point of view: The longer BF-BOF production is maintained, the more the emission targets are exceeded, and the more severe the consequences for the steel industry would turn out, should the targets eventually be strictly enforced.

4.4.4. Recommended Actions for Policy Makers

It has become clear that a serious climate policy, which also aims to preserve the German steel industry, must promote the earliest possible switch in primary steelmaking. This option is the only way to meet the defined emission targets without significantly reducing the steel output. Hydrogen-based steel production turned out to offer great potential for uniting these objectives, which is why it should be part of this political endeavor.

The developed scenarios show that the range of possible developments is still extensive, which can be justified by enormous underlying uncertainties. Of the scenarios, only the BC Scenario can be classified as unrealistic since an immediate end to the free allowances regime, and the availability of imported green hydrogen from 2026 onwards are not foreseeable. Both the CP D and the CP-B Scenario involve gross violations of the emission targets and would likely result in major losses in German steel production. Especially the CP-D Scenario turns out to be entirely incompatible with climate policy aspirations, which is why its materialization should be utterly prevented. On the contrary, the EPO Scenario would be associated with many desirable developments. It meets annual emission targets from 2035 onwards and enables realizing the long-term goal of carbon neutrality by 2045 while fully maintaining German steel output. Under currently foreseeable developments, reaching the EPO Scenario can thus be considered to be a realistic target.

Key parameters that should be focused on from a political perspective can be derived from the scenario assumptions. On a general level, the earliest possible promotion of adequate import infrastructure is a fundamental prerequisite, without which extensive H-DR production in Germany would probably be impossible. Subsidizing imported hydrogen would also directly impact H-DR costs and increase its attractiveness.

However, to promote H-DR diffusion as effectively as possible, the main focus of political efforts should lie in the role of CO_2 prices. Their development plays an essential role, whereby the step from the Stated Policies (STEPS) to the Announced Pledges (APS) scenario of the IEA proved to be critical. Based on this finding, recommendations can be derived from the applied IEA scenarios. Nevertheless, these recommendations can only be made at the level of the European Union, apart from steel industry-specific aspects, as decisions taken there primarily influence the EU ETS pricing. To close the gap between STEPS and APS forecasts, the IEA describes the current measures of the European Union as insufficient and recommends the full implementation of the proposed Fit-for-55 package.[180] Besides a stronger Emission Trading System and establishing new infrastructure for alternative energy carriers, this package includes numerous other measures.[181] Thus, it illustrates the need for a high degree of climate policy commitment at the European level as an essential factor for the future of German steel production.

The second lever that policymakers can use to regulate the effect of CO_2 prices is the distribution of free allowances. The underlying analysis has clearly shown that exposing steel production to the EU ETS is highly effective in increasing H-DR attractiveness at an early stage. Therefore, the early phase-out of free allowances described in the Fit for 55 package, as it is also subject to the EPO Scenario, would be beneficial. Additionally, such phase-out would allow efficient subsidization by other measures such as CCfDs, enabling a targeted and success-oriented promotion of H-DR production. As the findings suggest that opening steel production to the EU ETS would likely lead to increased production costs, the protection currently provided by free allowances must be replaced by other measures to counteract carbon leakage effects. For this purpose, a Carbon Border Adjustment Mechanism is a reasonable solution, as it would allow exposure to

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[180] Cf. IEA, 2021, p. 170.

[181] Cf. EC, 2021c, p. 3.

the market mechanisms of the EU ETS while providing protection against international competition.

Lastly, the scenario analysis illustrates that focusing on long-term targets instead of annual emission budgets is most reasonable, as a temporary overshooting of emission budgets seems unavoidable and distracts from long-term developments. Instead, it becomes clear that once the transition to H-DR production is initiated, it offers excellent potential to align the industry with the long-term emission targets within a few years.

Summarizing the results, it emerges that the current policy framework can only temporarily fulfill its objective of protecting the costs of German steel from international competition. It does not provide distinct incentives for initiating a transformation of steel production and could even result in long-term disadvantages by delaying it. For this reason, it is recommended to adopt the initiation of H-DR production in Germany as the core policy objective, as the method offers great potential to achieve Germany's long-term emission targets while preserving the current output levels. Nevertheless, H-DR production needs extensive policy support to develop sufficient competitiveness with BF-BOF production. A vital prerequisite is establishing hydrogen import infrastructure to enable cost-competitive and large-scale H-DR steel production in Germany. However, the most effective lever for influencing the attractiveness of H-DR production proves to be the effects of CO_2 pricing on conventional steel. In addition to efforts at the European level to stimulate the increase in CO_2 prices through new climate policy measures, it is particularly recommended to terminate the free allowances regime for the steel industry. Such measures would significantly increase H-DR attractiveness and impose direct cost incentives on steel producers to abandon BF-BOF production. Furthermore, these would allow an effective application of other targeted support measures. Nevertheless, it must be acknowledged that exposing the steel industry to the EU ETS would result in significant cost disadvantages for producers. Thus, adequate measures for protection in the international market are required.

5. Conclusion and Outlook

The first research question focuses on identifying decisive drivers for the future role of hydrogen-based steelmaking in Germany. The first part of this thesis was devoted to answering this question. For this purpose, a qualitative analysis of the German steel industry's environment was carried out, through which technological, industry-internal, political, and other cost-influencing drivers were identified.

These results served to answer the second research question, which addresses the development of explorative scenarios for the diffusion of H-DR production in Germany. Within the modeling, four scenarios were extracted based on different combinations of the identified drivers: the Current Policy - Downside (CP-D), the Current Policy - Baseline (CP-B), the Early Phase Out (EPO), and the Best Case (BC) Scenario.

The analyzed scenarios differ considerably regarding observed model outputs, indicating that the future role of H-DR production is subject to significant uncertainties. While the CP-D Scenario does not provide sufficient incentives for H-DR implementation over the entire observation period, the other scenarios anticipate a comprehensive H-DR diffusion: Within the CP-B Scenario, H-DR production is implemented between 2035 and 2050, in the EPO scenario between 2030 and 2040, and in the BC Scenario between 2026 and 2036. The associated emission developments are also subject to strong deviations. The CP-D Scenario results in a massive overrun of annual emission budgets and proves to be completely incompatible with all emission targets. The CP-B Scenario likewise exceeds the annual emissions budgets until 2049 but reaches the goal of climate neutrality in 2050, five years later than required by current policy targets. The EPO and BC scenarios project annual emissions budgets to be undercut as of 2035 and 2030, thus both achieving the long-term goal of carbon neutrality by 2045. The development of CO_2 prices and the exposure of steel production to these were identified as the most effective levers for early H-DR promotion.

Major challenges arise from these findings. For instance, it seems unrealistic to achieve short-term emission targets without reducing production volumes. Furthermore, exposing steel production to CO_2 prices leads to increased production costs, suggesting disadvantages compared to producers that are not subject to this regulation.

To cope with these challenges, implications for policymaking were investigated, as was the aim of the third research question. Key recommendations are to focus on achieving long-term emission targets and stimulating the H-DR transformation. Only such transformation holds out the prospect of sufficient emission reductions while preserving the current level of industry output. To provide steel producers with distinct incentives for transformation and to enable the establishment of targeted policy measures, a shift from the current policy framework towards the earliest possible end of the free allowances regime is recommended. However, resulting cost disadvantages in the international market and the associated risk of carbon leakage effects must also be acknowledged. Thus, suitable mechanisms for its prevention must be established simultaneously.

Future research should identify and investigate the associated implications of concrete support measures such as CCfDs or Carbon Border Adjustment Mechanisms to better understand their suitability. For instance, an interesting approach could be determining the distribution of the incurred costs among the different actors and the resulting consequences. In addition, analyzing the market potential of green steel should be a core subject of future research. Practical approaches could be discussed in terms of the extent to which consumers might show an increased willingness to pay for green steel, how large the resulting markets might become, and how the creation of such markets could be promoted.

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