

# Prospective Assessment of Hydrogen-Based Steel Making in Germany considering Demand Response, Economic and Environmental aspects

An Environmental Modelling Master Thesis by  
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“But need alone is not enough to set power free: there must be knowledge.” — Ursula K. Le Guin, *A Wizard of Earthsea*

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# 1 Introduction

Steel industry is a major carbon dioxide emitter, as it accounts for 9% of the global, and 4% of Germany's total greenhouse gas emissions (Fischedick et al. 2014; Nuss and Eckelman 2014; Wang et al. 2021). In the 2020s, the steel industry is at a cross-road as around 70% of the world's coal-based blast furnace capacity will reach the end of its operating lifetime before 2030 (Agora 2021). The upcoming refurbishments and reinvestments are an optimal opportunity for decarbonisation of steel production and electrifying it to meet the German climate goals of climate neutrality at 2045 (Federal Office of Justice 2019). This massive electrification of steel production processes is enabled through utilising hydrogen from water electrolysis for direct reduction of iron and producing afterwards steel in electric arc furnaces (EAF). The added demand of the additional electrified steel making sector can put more pressure on the energy transition and be a part of solving its problems at the same time.

In Germany 2024 54.4% of electricity was already produced by renewables (UBA 2025). However a large share of processes in industry, transport and heat generation are still running on fossils, reducing the share of renewables at general primary energy carriers to 20%. Many of these processes are going to be electrified in the future requiring further additional renewable generation capacities. The issue is that energy systems reliant on significant proportions of renewable technologies require consistent, efficient, and sustainable control of generation fluctuations to maintain the grid. Two main management strategies are consumption flexibility, also called demand response (DR) and deployment of storage systems (IEA 2023b). An electrified steel sector in Germany provides opportunities for both, as the incorporation of electrolysis and melting processes in steel production offers flexibility potential and allows produced hydrogen to be stored in gas caverns for later use and re-electrification. Therefore this thesis is assessing the potential of hydrogen based steel production to contribute to the balancing of fluctuating renewable energy generation integrating flexible loads and storage systems.

Multiple technologies and possibilities are available in other sectors to manage flexibility and storage demand (Apata 2023; Bakare et al. 2023), raising the question why should the steel sector make the effort. Especially residential decentralised DR behaviour for heat provision and vehicle loading is discussed to have a significantly higher capacity and stabilising effect (Gils 2014). This issue has been extensively explored; yet, the effectiveness of methods for a decentralised rollout remains ambiguous, resulting in inconsistent outcomes (Shabha et al. 2023). The application of DR in industrial settings exhibits several deficiencies, which will be elaborated further in the thesis. Nevertheless, given that the industrial sector accounted for 41% of electricity consumption in Germany in 2023 (UBA auf Basis AGEBA 2024), the substantial electricity usage indicates significant technical DR potential, appealing due to rapid implementation and cost efficiency. Consequently, its potential need more sector- and process-specific study (Heitkoetter et al. 2021; Stanelyte et al. 2022). Addressing the potential of direct reduction (DR) in future hydrogen-based steel production involves not only technical aspects but also necessitates an examination of sector- and region-specific future developments in global trading strategies and interactions,

allowing for a concentration on individual technologies or production processes. For this study, northern Germany is used as a case study since it has substantial offshore wind capacities but lacks the capacity to handle fluctuating generation and is in the process of decarbonising a steel industry in Bremen, which has the potential for future flexibility. To find an ideal transition pathway, several actor viewpoints must be considered determining not only techno-economic barriers.

To determine DR potentials in hydrogen-based steel manufacturing, this thesis identifies and resolves research issues by first providing an overview of the current state of research in the topic. Relevant research areas include energy transition and demand response (Section 2.1), steel industry transformation (Section 2.2), and sustainability research as a lens for problem assessment (Section 2.3). Section 2.4 presents pertinent research gaps and objectives, emphasising the study's background and contributions.

Section 3 explains the various methods and materials used in this investigation. Section 3.1 presents scenarios for producing hydrogen-based steel in northern Germany using wind electricity. These scenarios are modelled in a mixed integer linear programming (MILP) optimisation to evaluate economic, operational, and grid stabilising factors (Section 3.2). In addition, the manufacturing life cycle is modelled for a prospective life cycle assessment (Section 3.3) to evaluate environmental implications. The purpose of these methods is to evaluate essential information for managing sustainable development at the intersection of the power and steel production systems. An information system for sustainable development is therefore generated in Section 3.4.

Section 4 presents the outcomes for each approach individually. The discussion in Section 5 summarises the findings and examines their implications, limitations, and uncertainties.

## **2 Current State of Research**

The energy system and steel industry are critical parts within a sustainable development, providing essential resources and materials. However while being critical parts, transformation within themselves is needed at the same time, changing not only production practice but their own structure and how they are organised. Additionally to individual challenges, the interfaces and interaction of both sectors become more significant for efficient system functioning. This intersection forms the primary focus of this thesis. In order to provide a comprehensive foundation for the analysis, this section will examine the developments unfolding in each of these sectors and describe the system level perspective from which transition in electricity and steel sector is approached and researched in this thesis.

### **2.1 Electricity System Transformation and Demand Response**

The "Energiewende", the energy transition, is supposed to be Germany's path to a secure, environmentally friendly and economically successful future. The federal Climate Action Act sets the

goal to deplete green house gas emissions in 2045 (Federal Office of Justice 2019). This requires massive capacity expansion of renewables, instalment of storage systems to manage fluctuating generation as well as a changeover of production pathways and adapting consumption.

In order to achieve these ambitious goals, it is crucial to consider the role of markets organising and facilitating the energy transition. Because market design is founded on policy decisions, it is critical to consider not only technical and economic potentials but to look at problems from a variety of perspectives including policy maker objectives.

To effectively facilitate the transformation of energy system, a reform of market design is indispensable ensuring an efficient integration of renewable energy sources into the grid (IEA 2025). The energy transition will lower the total cost of power generation; nevertheless, grid charges and other incidental costs are projected to increase with increasing effort to ensure resilient supply and enhanced grid expansion (Cevik and Ninomiya 2023).

The transition affects not only generation technologies, prices and their behaviour, but also how the market is built, who participates in it, and how the actors communicate. With fluctuating renewables the importance of balancing measures rises, which are summarised in the term ancillary services (Cozzolino and Bella 2024). The services aggregate several measures such as congestion management, frequency and voltage control, oscillation damping, loss compensation and black start capabilities. Currently especially grid congestion management and frequency balancing demand for new market mechanism and implementation of new modes of communication as in Germany congestion costs tripled from 2019 to 2022 due to higher wind availability and high oil and gas prices (Bundesnetzagentur and Bundeskartellamt 2019; Bundesnetzagentur and Bundeskartellamt 2023), reducing just slowly till 2025 (Bundesnetzagentur and Bundeskartellamt 2025). A grid management system that is based on real-time pricing and DR mechanisms can allocate resources and manage peak periods and reduce stress on the transmission infrastructure (Vardakas et al. 2015). Current market design with time-independent prices, taxation and grid charge structure hinders the implementation by decreasing the incentives to adopt (Blaschke 2022). However as storage technologies can offer similar services and significantly decrease in their prices they are in competition with DR measures (Müller and Brunner 2015). The downside of storage technologies are costs and impacts of additionally required materials and rare metals and the losses in the storage process (Al Shaqsi et al. 2020).

According to IEA (2023b), DR plays a crucial role in providing short-duration flexibility and in their Net-Zero Scenario they project DR capacities provided globally in 2030 to be 275 GW from buildings, 50 GW from transport sector, 25 GW from industry and 150 GW from hydrogen production (IEA 2021; IEA 2023a). These capacities are realised by different methods for adapting loads as described by Macedo et al. (2015):

- a Peak clipping: Reduce peak demand through direct load control, shutdowns, or distributed generation.
- b Valley filling: Encourage off-peak consumption through incentives like discounts to increase non-peak periods and reduce average prices.
- c Strategic conservation: Reduce seasonal energy consumption by increasing efficiency and reducing waste through technological changes and incentives.
- d Strategic load growth: Control seasonal energy consumption growth using intelligent systems, efficient equipment, and competitive energy sources.
- e Load shifting: Shift peak period loads to off-peak periods without changing total consumption, possible with distributed generation.
- f Flexible load shape: Implement integrated planning between utilities and consumers to model loads, limit power usage at certain times, and install load-limiting devices.

It becomes evident that various DR strategies operate on different time scales between seconds and years. DR contribution to long-duration flexibility is expected to be significantly lower (IEA 2023b). However, when combined with long-term energy storage solutions, DR's services can be extended to longer timescales, enhancing its overall flexibility potential. This underscores the need for a comprehensive understanding of the strengths and limitations of different DR strategies and technologies, as well as their interactions with other flexibility options. As DR works best in interplay with energy storage systems an optimal selection and management of the available options is essential for achieving an efficient energy system especially with increasing flexibility requirements (Koolen et al. 2023). DR can be offered by several electricity consumers, either more centralised in flexibilisation of large loads in energy intensive industrial processes, or decentralised through managing multiple smaller loads like air conditioning, ventilation, heat pumps, or charging of electric vehicles (Bauknecht et al. 2024). Bakare et al. (2023) lists residential, commercial, industrial, and transportation sectors as capable of providing DR behaviour, each with unique challenges. Due to its high and rising electricity consumption this work focuses on assessing DR potential in the industrial sector, namely the steel industry.

## **2.2 Steel Industry Transformation**

In Germany steel industry with a turnover of around 50.6 billion euros and 90,000 employed people 2023 (Wirtschaftsvereinigung Stahl 2023) is within a large transformation process. A quick decarbonisation and electrification of steel production has far reaching potentials, decreasing environmental impacts throughout the entire production chain in Germany. Steel serves as a critical material in the manufacturing of numerous products, including construction materials, automotive parts, machinery, and consumer goods (Bender et al. 2008). However German steel industry turnover and employment has decreased in the last years in light of this transformation and other factors, mostly referred to be high electricity prices and grid charges, as well as missing political

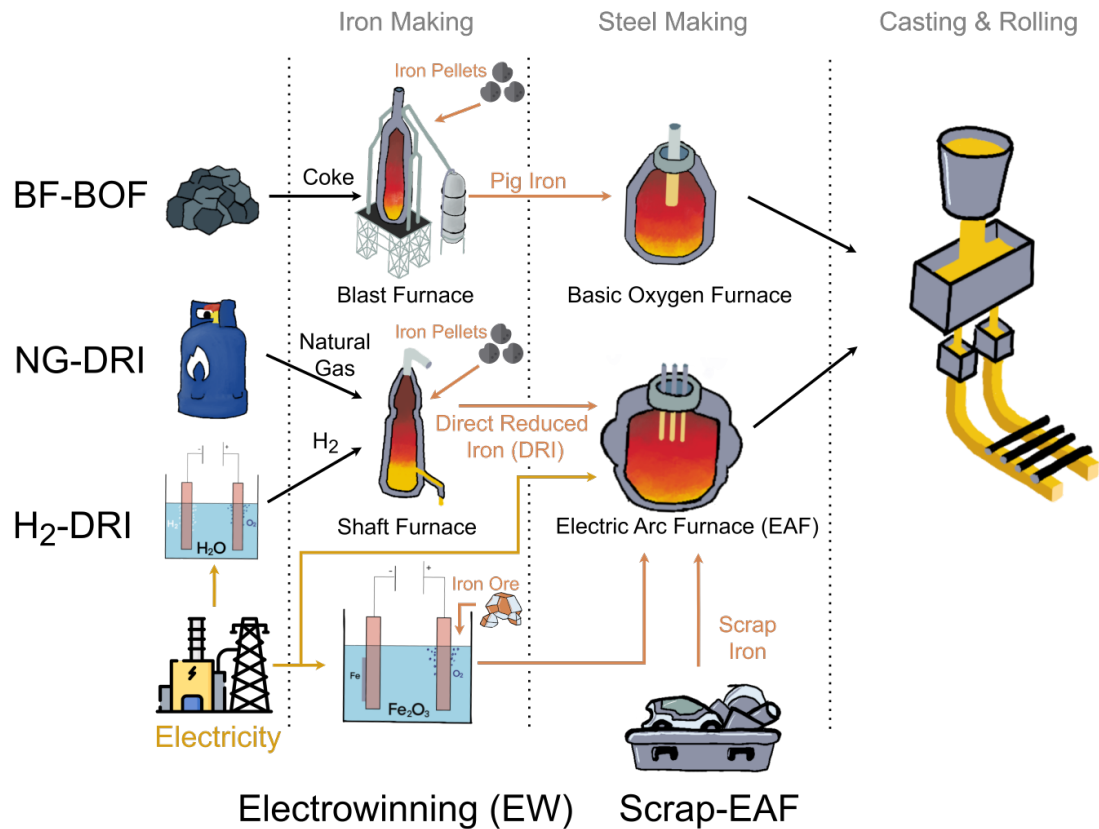


Figure 1: Contemporary and prospective Steel Production Methods, including Production Facilities, Energy Carriers, and Iron Sources

guidance and subsidies (Wirtschaftsvereinigung Stahl 2023). This highlights the strong connections of the steel and energy sector, and the demand for a strategy, which enables the actors to manage this transformation successfully.

The transformation in the steel sector alters not just the fuels utilised but also the entire production processes. Figure 1 illustrates the pathways currently employed and those anticipated for future use. These routes have multiple steps which can be roughly divided in three units: iron making unit, which is either producing pig iron or direct reduced iron (DRI); steel making unit, which is melting the iron in an electric arc furnaces (EAF) and producing liquid steel; and the finishing unit where the steel is cast and rolled into the desired form.

In Germany the largest share of produced steel with 70% is currently coming from the Blast Furnace - Basic Oxygen Furnace route (BF-BOF) (World Steel Association 2024b). The first step of this route is processing mined and sintered or pelletised iron ore to pig iron in a blast furnace. For steel making pig iron is molten in a Basic Oxygen Furnace into crude steel, which is processed further by casting and rolling practices. This route has especially high CO<sub>2</sub> emissions with the global average of 2.33 tons CO<sub>2</sub> per ton of cast steel, compared to 0.67 tons of Scrap-EAF and 1.36 tons of DRI-EAF production routes (World Steel Association 2024a). The large emissions are the result of the use of coal or coke as energy supply and chemical reactant. Implementing

post-combustion carbon capture and storage to BF-BOF can cut emissions by as much as 60% (IEAGHG et al. 2013), but this is not sufficient to meet the long-term climate goals and still depends on fossil fuels, which are depleting.

The second most utilised steel production route is secondary, or recycled steel accounting for 30% of German steel. Scrap steel is melted in EAF through high electric currents. Decarbonisation of this route can be reached with higher shares of renewable electricity in the supplied mix. However recycling rate is already high as it surpassed 80% in 2017 (IRENA 2020). Nevertheless if the steel demand is higher as available recyclable steel, decarbonisation of primary steel production is still essential.

The furthest developed primary steel production route with potential independency on fossil energy sources is utilising hydrogen based direct reduced iron ( $H_2$ -DRI) and making it into steel in an EAF. As natural gas and coal gas can also be utilised in this process route, direct reduction of pelletised iron ore is a production practice already applied in industrial scale worldwide. Especially India and Iran have large DRI production capacities (World Steel Association 2024b) using coal gas. Changing the gas source to natural gas (NG-DRI) can reduce the process related specific emissions to 0.82 tons  $CO_2$  per ton of cast steel, whereas utilisation  $H_2$ -DRI can result in 0.042 tons  $CO_2$  per ton of cast steel (Hölling et al. 2021). A small fraction of process related emissions can not be prevented as the steel making process requires injection of foaming coal for increasing the carbon content in steel. For independence of fossil fuels charcoal can replace fossil coal at this step.

By processing mined iron ore directly rather than using treated pellets, electrowinning (EW) technology offers a more direct method of producing iron while preserving the same steel-making procedure as an EAF. Iron ore is dissolved in a solvent and the iron is separated from other materials by electrolysis. While EW is deployed already in aluminium production (Haraldsson and Johansson 2018), for steel it is considered a prospective potential technology and only realised in laboratory scope. Further technological maturity is required to fully realise its benefits (Tokushige et al. 2022) of higher efficiencies and lower capital as well as operational expenditure compared to  $H_2$ -DRI (Humbert et al. 2024).

Today only carbon capture and storage technology and hydrogen based direct reduction offer carbon neutral steel production (IEA 2020) with EW requiring further development. Until EW reaching an industry deployable readiness level,  $H_2$ -DRI route is the only technology enabling steel production independent of depleting fossil resources. With  $H_2$ -DRI being the mainly proposed production route of primary green steel a large question remains uncertain in German steel industry: How much hydrogen and direct reduced iron is imported from other countries like Morocco or Australia? Morocco can produce hydrogen based on photovoltaic in larger quantity (Lopez et al. 2023) and Australia as the biggest iron ore exporter today (World Steel Association 2024a) is largely investing in green iron infrastructure (Wang et al. 2023; Department of Industry Science and Resources 2025). This question has also high implications for the German electricity system because the production of hydrogen through electrolysis requires large amounts of renewable electricity. If a

substantial portion of hydrogen is produced in Germany, the demand of electricity will rise, necessitating accelerated deployment of renewable energy sources and grid expansion. At the same time electrolysis plants with a high flexibility and potential of demand response in combination with H<sub>2</sub> storage tanks are an important part in maintaining grid stability and reducing congestion. If hydrogen or DRI is mainly imported, this would leave only EAF steel making production step in Germany and ancillary services need to be realised through other measures. At the same time Germany's reliance on international energy markets and supply chains will grow, potentially exposing the system to price volatility, geopolitical risks, and challenges in meeting sustainability criteria for imported hydrogen as well as grid balancing technology.

EAFs, which are already in use and electrified in the steel making phase, are employed as available potential for load shedding on balancing markets for extreme events, with an estimated potential of 931 MW in Germany (Gils 2014). However, strategic conservation or load growth techniques, particularly flexible capacity utilisation of EAFs, are not used, and understanding of the DR potential of future routes is limited. Research on industrial DR potential in Germany is scarce because implementation in industry faces multiple barriers. Scharnhorst et al. (2024, p. 11) identified as largest impediments: "(i) the lack of profitability, (ii) the fear of reduced product quality, (iii) multiple aspects regarding personnel planning ranging from additional expenditures to consolidation with the labour union, (iv) an overall missing acceptance and (v) the technical interdependencies with upstream and downstream processes". These barriers in addition to current policy and market frameworks make an increase of DR in the steel industry really difficult and need to be addressed, as DR offers low losses and high resource efficiency from system level perspective and future developments and policies will enhance DR viability further (Weng 2019).

## **2.3 Sustainability as Multi-Level and Dynamic Process**

To meet contemporary global challenges such as climate change, biodiversity loss, depleted resources and those to come, coordinated action across various societal sectors is essential. Under the concept of sustainability, a broad range of research has sought to provide theoretical frameworks and practical guidance for such long-term, systemic transformations (Lang et al. 2014). This thesis is assessing specific aspects of the transformation in electricity and steel sector but requires a framework to analyse and discuss the meaning of the results. Therefore it uses sustainability as a conceptual and methodological approach to evaluate systems with respect to their contribution to sustainable development and transition (Ness et al. 2007). At first this requires to determine what is meant by the term sustainability and later how contributions to a sustainable development theoretically can be assessed and measured.

The diverging understanding of sustainability continues to challenge standardised assessment practices. While the triple bottom line approach (Elkington 1997) remains widely used for its simplicity, categorising the effect of measures into environmental, economic, and social dimensions,

it fails to capture the complexity and interconnectivity of transforming systems (Wexler 2009; Srivastava et al. 2022). Therefore this work applies a systems thinking approach, understanding sustainability as a property emerging from the dynamic interactions of system components. This concept is summarised by Meadows (2009, p. 85) in the following words:

”Resilience, self-organization, and hierarchy are three of the reasons dynamic systems can work so well. Promoting or managing for these properties of a system can improve its ability to function well over the long term - to be sustainable.”

To render a more detailed definition of resilience, self-organisation and hierarchy would be interesting but surpass the requirements of this thesis. However this citation shows the demand for understanding the analysed systems, in this case steel industry as embedded in, dependent on and interacting with higher level systems such as the energy infrastructure, natural ecosystems, and economic structures.

When sustainability or contributions to a sustainable development is assessed Lindfors et al. (2025) argues for an integration with sustainability transitions research, criticising predominant narrow, technology-centric applications in sustainability assessment and its practices. The latter, which is more strongly rooted in the social sciences, emphasises the dynamics of systemic change and the role of societal actors. A mutual relationship between the two approaches can be beneficial as assessment of transitioning systems gains deeper integration of stakeholders and how their capacities and capabilities could be increased, while sustainability transition studies benefit from the quantitative proof of its theories. Therefore a comprehensive assessment should account for multiple stakeholder perspectives across system levels (Mathur et al. 2008). While theoretical approaches to stakeholder identification and categorisation are well-developed (Silva et al. 2019), their integration into practical sustainability assessments remains limited (Lodhia and Martin 2014; Gadenne et al. 2012).

To structure the analysis of dynamic interrelations and stakeholder perspectives in the researched transition processes, this thesis draws on the Multi-Level Perspective developed by Geels and Schot (2007). The multi-level perspective provides a dynamic but structured analytical framework for understanding technological transformation processes, integrating systems thinking with actor-based perspectives. This socio-technical perspective on transformation provides a robust understanding of the interconnections among system levels, which will be the focus of my thesis. The multi-level perspective distinguishes three levels: First the Niche Level as the sites of innovation and experimentation. Second the Regime Level aggregating the dominant structures, institutions, and infrastructures that maintain the status quo. The last and highest level is the Landscape depicting exogenous macro-trends like climate change or shifting geopolitical paradigms putting pressure on the regime and opening up windows for change.

This thesis views the electrical system as the central regime-level system undergoing a transformation. This system requires transformation due to pressures from the landscape level, as climate change is increasing its impacts, while fossil resources, the primary energy source, are diminish-

ing. The steel industry is adopting innovative technologies at a niche level, incorporating hydrogen based steel manufacturing practices, through the installation of electrolyzers, hydrogen storage systems, and fuel cells. However innovation can also be attained through the plant's scheduling of production to accommodate demand response.

To assess the performance of available options indicators are used to measure and aggregate information. Indicators are essential to understand the world and to make decisions which options to choose. Bossel (1999) describes how an indicator's purpose defines and narrows down what is looked at and what information is used in the decision making process. For sustainable development the UN (1993) emphasises the necessity of having the appropriate information for decision-makers, when determining next steps for systems and their sustainable development. Meadows (1998) emphasises both, the necessity and difficulty of using indicators for managing sustainable development. She highlights the inherent challenge of simplifying complex systems, while advocating for the use of comprehensive information systems integrating multiple indicators into sorted and hierarchical structures. Therefore in this thesis multi-level perspective helps to organise such an information system and provides guidance to select relevant indicators for respective stakeholders in Section 3.4.

## **2.4 Research Gaps and Objectives**

As described in the sections above there is a need for a comprehensive assessment of the possible deployment scenarios of hydrogen based steel production practices through the lens of sustainable development. To narrow the research field on a more focussed area this thesis applies hydrogen based steel production scenarios in a German context and assesses potential of demand response and economic and environmental impacts.

Hölling et al. (2021) developed multiple hydrogen based steel production plant setups and assessed costs for German hydrogen based steel production sites, while Lopez et al. (2023) evaluated the costs and resulting steel prices for different import and trading scenarios for the prospective German steel industry. However these regional specific assessments were leaving out the impacts of demand response and bidirectional interaction of steel production with the energy system. By deeply integrating DR into future steel production scenarios and examining its effects, research can assist to build interactions between the steel and energy sectors.

DR in a H<sub>2</sub>-DRI production plant is enabled by several units with multiple techniques. The largest potential show the electrolyzers of the reduction unit as they offer a flexible load shape and large capacities. Boldrini et al. (2022) explored the demand response potential of various setups of hydrogen-based steel manufacturing plants. Boldrini et al. (2024) also considered the future energy system implications of highly variable pricing. However the assessment of the demand response potential was solely focussed on economic gains from varying energy prices and addi-

tionally missing out steel making, respectively EAF as a production step able to conduct demand response. Fraizzoli et al. (2020) modelled flexible EAF usage in a mixed integer linear program (MILP) however did not integrate that into a hydrogen based steel production site. Boldrini et al. (2024) emphasises the need to "quantify the DR potential of EAFs within the context of future power systems". Therefore this thesis tries to depict flexible EAF capacity utilisation within prospective integrated hydrogen based steel production sites and assess the DR potential.

As Scharnhorst et al. (2024) identified deploying DR in industrial applications is not only questions on the profitability, but also operational issues impacting workforce planning, product quality and upstream and downstream processes are hindering DR in steel production. Research on operational complexity including all these aspects was not found. This thesis incorporates elements of operational planning into the evaluation of future steel production and seeks to determine the operational complexity of various steel production scenarios.

In the steelmaking unit of hydrogen-based steel production, particularly the EAF, DR can be achieved by adjusting the beginning time of single batches for load shifting. This can be supplemented by utilising different shares of the steel making unit, which is enabled by adjusting production conditions (Castro et al. 2020), such as varying the furnace filling degree (Dock et al. 2021), leaving a residual amount of molten steel and slag from a previous batch in the furnace (Taji Eshkaftaki et al. 2024), or conducting fast or slow melting practices (Weng 2019). This enables more flexible load shapes of processes in the steel making unit and their application for DR and stabilising services. According to Bakare et al. (2023) industrial sector applications have the largest limiting factors in applying DR practices due to missing data on load behaviour and time dependencies inside production processes. Therefore this work investigates the utilisation of available data on load profiles and production processes in future hydrogen based steel production and analyses its DR potential for the energy system. This flexibilisation of production can influence not only energy pricing for production but also assist grid operators in balancing the variable nature of renewable energies at the grid level. Gao et al. (2023) developed therefore a method to assess the potential to stabilise the grid of DR by measuring the ability of a technology to match a given load profile. For hydrogen based steel production DR potential was assessed as described above for economic indicators but not for this methodology on grid stability level. Therefore this research assesses the potential to provide stability and tries to determine optimal production scenarios

With the perspective of sustainable development and as electricity and steel production systems are integrated in environmental systems, impacts on the environment are also important to evaluate. When assessing the environmental impacts of hydrogen based steel production most found research focussed on the comparison of NG-DRI and H<sub>2</sub>-DRI production routes (Hu et al. 2025), some even assessed the impacts prospectively with implemented future scenarios (Weckenborg et al. 2024; Nurdiawati et al. 2025; Azimi and van der Spek 2025). However detailed assessment of possible scenarios and uncertainty on how H<sub>2</sub>-DRI production would be organised and which technology would be utilised at what regions was not conducted so far. For assessing the effects

of different technologies and production steps Taji Eshkaftaki et al. (2024) conducted a contribution analysis of a hydrogen based steel production plant. Nevertheless it was carried out for the production in Iran and based on Photovoltaic as primary energy source, so research for the German context and electricity and steel systems is missing.

Additionally research on prospective hydrogen based steel production did not include the integration of future steel production practice into the background and thereby leaving out the effect green steel production would have on the production system to produce itself. Given how much steel and other metals are used in steel manufacturing facilities, particularly in steel production facilities that are powered by renewable energy, this is noteworthy and interesting to include.

Therefore this research is aimed to address the shown knowledge gaps in environmental impact assessment of hydrogen based steel production by conducting a comprehensive assessment of the environmental impacts, taking into account the integration of future steel production practices into the background system itself. Additionally this work is expanded by considering a broader range of hydrogen based steel production scenarios, including storage technology and demand response practice to model the interaction with the energy system as well as import strategies.

To summarise, this thesis examines hydrogen based steel production scenarios and how they can contribute to a sustainable development in steel and energy sector. The performance is evaluated across several aspects of a sustainable development from a multi-level perspective of important actors. As these indicators are assessed through different methods and perspectives two research questions separate the assessment of production process scheduling and environmental assessment. The first research question focusses on the technical assessment of steel plant scenarios and the effect DR operation can have on electricity cost, operational complexity and grid stabilising potential. The second question focusses on the prospectiveness of the scenarios and is interested in the environmental effects this future possibilities to produce hydrogen based steel will have:

1. *To what extent can hydrogen-based steel production plant scenarios in Germany influence economic performance, operational complexity and grid stability through demand response?*
2. *How will hydrogen-based steel production plant scenarios impact the environment prospectively?*

## **2.5 Thesis Structure**

The thesis structure is designed to provide a nuanced understanding of the relations between the researched aspects of hydrogen based steel production in the transformation processes and sector coupling between electricity and steel production systems, ultimately contributing to a sustainable development. This is achieved by integrating operational and economic aspects of DR, as well as electricity grid stability and environmental aspects into the assessment of steel plants. Figure 2 shows how the research context and developed research objectives are approached in the following sections. This thesis adopts a multi-level perspective, combining dynamic understanding and assessment of systems in a sustainability transition process through two primary research

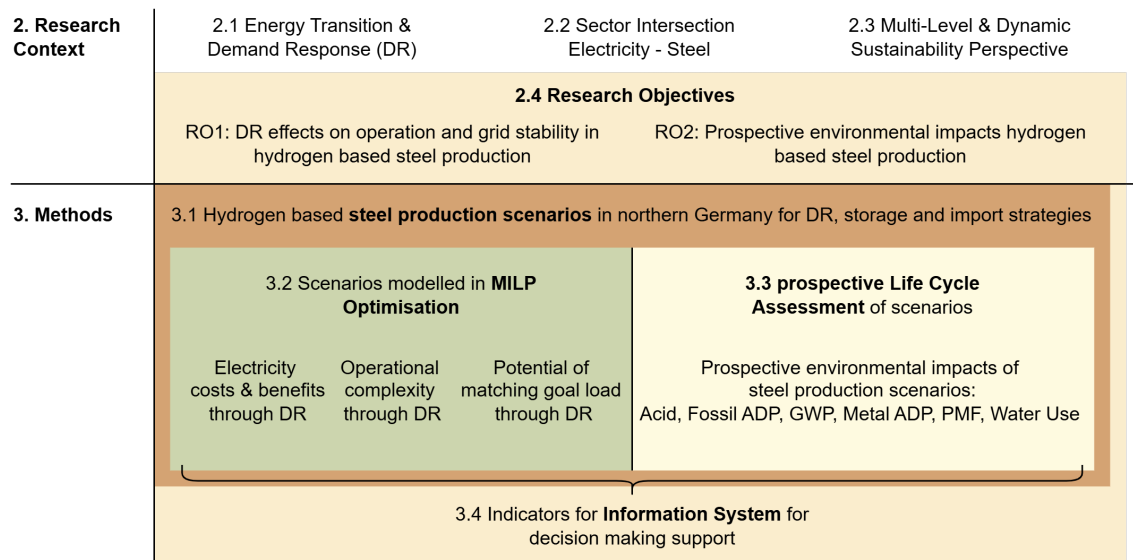


Figure 2: Visualised methodological structure explaining the research context, research objectives and the methodological parts for assessing the objectives through the lens of an information system for sustainable development of hydrogen base steel production scenarios; Acid = Acidification, ADP = Abiotic Depletion Potential, GWP = Global Warming Potential, PMF = Particulate Matter Formation

objectives. The first objective focussing on effects of DR, is addressed using a MILP optimisation that simulates processes within a hydrogen-based steel production plant. In contrast, the second objective is evaluated via a prospective Life Cycle Assessment methodology, measuring environmental impacts from 2023 to 2050 across the three distinct steel plant scenarios. These scenarios represent different strategies for maximising renewable energy usage in steel production through DR, storage, or importing DRI from abroad. The results of both research objectives and methods are aggregated into a comprehensive information system that covers various levels and aspects of sustainable development. This comprehensive approach enables a holistic assessment of the situations, as shown in Section 4. Section 5 contextualises the findings, acknowledges limits and assumptions, and provides recommendations based on the outcomes.

## 3 Methods

### 3.1 Steel Plant Scenarios

In order to constitute possible pathways of transformation towards a hydrogen based steel industry sector, this study employs a case study approach. It develops three exemplary scenarios of hydrogen based steel production plants located in Bremen with a high potential for renewable energy integration. The scenarios try to integrate current discussions from steel and energy industry considering the future transformation and how to manage it. To develop a perspective for sustainable development these three scenarios are assessed for their performance in several relevant indicators which are developed and described in Section 3.4.

A research project by ArcelorMittal Hamburg GmbH, named "Wind Steel from Northern Germany", investigated eight hydrogen based steel production plant setups that primarily rely on offshore wind electricity (Hölling et al. 2021). Two variants of this study were chosen for more detailed examination in this study, providing detailed data on steel plant setups for the scenarios: "Variante 2", which presents a steel production scenario with high flexibility and DR utilisation, and "Variante 3.2", which balances fluctuating electricity generation through DR electrolysis in combination with a large hydrogen storage system. These two scenarios rely on 100% renewable electricity supply and depict two strategies to handle the fluctuating renewable electricity generation in the future, either by high DR with small storages or building large storage solutions which enable constant operation and high capacity utilisation rates. The scenarios are supplemented by a third, deduced scenario that omits hydrogen reduction facilities in Bremen's facilities and imports H<sub>2</sub>-DRI from Australia as the globally largest iron exporter. As energy demand is reduced this means also less renewables need to be integrated in the region. However as the reduced wind park does not provide sufficient power for long enough this scenario requires a backup source of electricity which is in this case the electricity grid. At the same time water electrolysis can not be used as a regional DR option. The scenarios are explained in the following paragraphs, detailing their respective system configurations, energy sources, and operational strategies.

Table 1: Installed Equipment Capacities, Demand Response Potential and Grid Exchange behaviour in Bremen of Steel Plant Scenarios

|                             |                        | DR<br>Steel Making | Constant<br>Steel Making | H <sub>2</sub> -DRI<br>Import |
|-----------------------------|------------------------|--------------------|--------------------------|-------------------------------|
| Offshore Wind Park Capacity |                        | 852 MW             | 828 MW                   | 288 MW                        |
| Reduction<br>Unit           | Rated Power            | 501 MW             | 500 MW                   | -                             |
|                             | Minimum Power          | 100 MW             | 100 MW                   | -                             |
|                             | Maximum Power          | 555 MW             | 563 MW                   | -                             |
| Hydrogen Tank Capacity      |                        | 0.4 GWh            | 24 GWh                   | -                             |
| Fuel Cell Capacity          |                        | -                  | 171 MW                   | -                             |
| Steel Making<br>Unit        | Battery Capacity       | 7.5 MWh            | -                        | 7.5 MWh                       |
|                             | Max hourly rated Power | 108 MW             | 80 MW                    | 108 MW                        |
|                             | Min hourly rated Power | 65 MW              | -                        | 65 MW                         |
| Rolling hourly Rated Power  |                        | 69 MW              | 54 MW                    | 69 MW                         |
| Grid Exchange               |                        | Feed-In only       | Feed-In only             | Bi-Directional                |

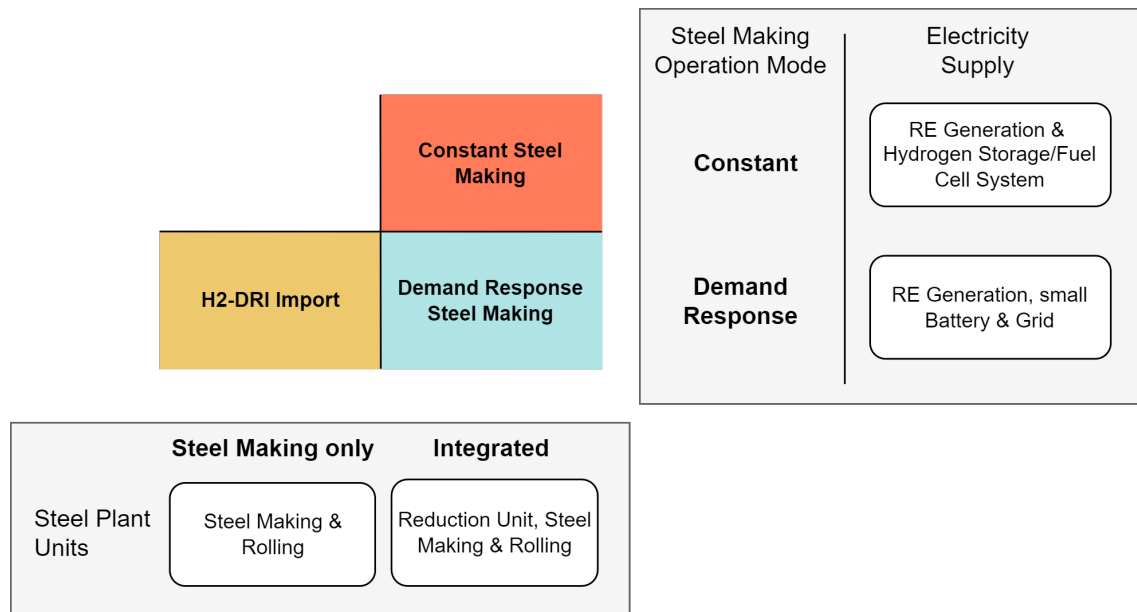


Figure 3: Characteristics of Steel Plant Scenarios

Steel plants can be segregated into three parts: the reduction unit producing direct reduced iron by utilising hydrogen from integrated electrolyzers; the steel making unit, melting iron in an EAF, a ladle oven and equipment to cast it in slabs or billets; and a rolling unit for finishing the produced steel into end use products. In hydrogen based steel production practice all these equipments are powered by electricity and can be used for DR measures. The most flexible equipment are electrolyzers, making the reduction unit the main factor of DR potential in steel plants, which can be seen in the large difference of minimum and maximum utilisable power in Table 1. The steel making unit is less flexible as it not only has less utilisation flexibility but it also melts steel in batches. When a batch is started it can not be stopped without major energy losses and runs for usually 40 minutes. However it can start batches with varying capacity utilisation degrees resulting in different load patterns, which are described with the model input data in Section 3.2.1.1. As also depicted in Figure 3 each steel plant scenario bears its own setup of equipment, units and operation behaviour:

**Demand Response Steel Making:** This steel plant scenario has the largest wind park and totally relies on its provided power. It has a large capacity steel making unit and uses flexible levels of capacity utilisation in electric arc furnaces, or the steel making unit in total as DR potential. Additionally to that flexibility it allows DR utilisation of electrolyzers in the reduction unit. Residual electricity is fed into the grid to make profits. To buffer large load jumps when turning the EAF on or off a 7.5 MWh lithium iron phosphate battery is installed. For storing the hydrogen within the production process a small hydrogen tank is installed. This scenario was developed by Hölling et al. (2021) as "Variante 2".

**Constant Steel Making:** In this steel plant scenario, a slightly smaller though still substantial wind park supplies the necessary energy. To manage the variability in provided wind power, a

large hydrogen storage tank and a fuel cell system are installed. These components store surplus hydrogen during periods of high wind generation and convert it back into electricity when wind availability is low. This setup allows the wind park, steel making and rolling unit to reduce the installed capacity and get rid of the requirement to run steel making unit flexible and enable a constant production schedule. However reduction unit and electrolyzers can still be operated flexible as well as the timing and batch scheduling in the steel making unit. Importantly, the plant remains energy self-sufficient, feeding excess electricity into the grid to generate profits but drawing no electricity from the grid. This scenario was developed by Hölling et al. (2021) as "Variante 3.2".

**H<sub>2</sub>-DRI Import:** In this steel plant scenario hydrogen based direct reduced iron is imported from the largest iron exporting port in Australia "Port Hedgeland" to Bremen. The transport is done by ship and the distance is 28,136 km. Flexibility of electrolyzers is therefore not available for DR in Germany. This regionally installed equipment is basically that of *Demand Response Steel Making* scenario without a reduction unit and solely evaluating the effect of flexible steel making capacity utilisation as it could also be executed in today scrap-EAF production. However to buffer large load jumps when turning the EAF on or off a 7.5 MWh lithium iron phosphate battery is installed. A small wind park supplies electricity for the plant and residual electricity is fed into the grid. However, this configuration introduces a new requirement as electricity must be drawn from the grid to meet the remaining energy needs of the steel making process. This requirement arises as the connected offshore wind park does not generate enough electricity to reliably power the entire plant for the required amount of time steps to produce 1Mt of steel. While technically possible, scaling the wind park to meet peak demand, this would result in over-sizing the park tremendously and an inefficient use of installed capacity. Therefore, the grid as an additional energy source is added to ensure sufficient uninterrupted operation. This reflects current practices in conventional EAF-based steel recycling plants and gives a glimpse how flexible steel plants would behave relying on the electricity grid market as electricity drawn from the grid is subject to market prices.

### 3.2 Mixed Integer Linear Optimisation of Steel Plant Scenarios

Harjunkski et al. (2014) rates MILP as most capable tool for modelling integrated production processes. A MILP model of a steel plant works by first gathering data on production processes, energy consumption, and resource availability. The model then uses this data to formulate a mathematical representation of the plant's operations, including constraints such as equipment capacity, material availability, and maintenance requirements. To determine the most efficient production plan an optimisation algorithm is applied to this model, taking into account factors like energy costs, load behaviour and production rates. Multiple researchers already implemented metal production processes for the analysis of DR measures in the process (Ramin et al. 2018; Fraizzoli et al. 2020; Boldrini et al. 2022; Boldrini et al. 2024; Zhao et al. 2024) showing its ability to assess flexibility potentials of metal batch production. Therefore this method is selected to assess the first research objective.

In this study steel plant scenarios are modelled in a MILP optimisation model developed in pyomo (Bynum et al. 2021; Hart et al. 2011). The following subsections describe first the methodological setup including required data, taken assumptions as well as the objective and constraining functions of the model. The second subsection depicts how steel plant scenarios are modelled and assessed for performance evaluation.

### 3.2.1 Setup of MILP Optimisation Model

#### 3.2.1.1 Input Data

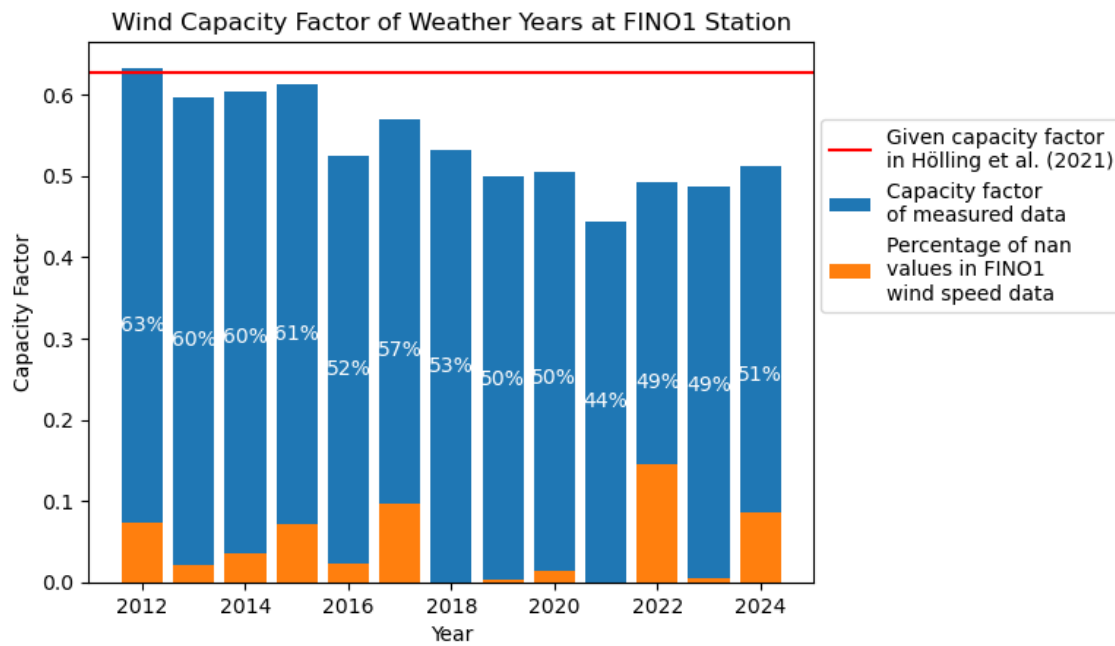


Figure 4: Capacity Factors of Wind Generation Profiles from FINO1 and ERA5 data filling measurement gaps in 2012 to 2024

The most important input for the model is the time series of renewable wind generation of the modelled time period. This data was generated as described by Hölling et al. (2021) in the development of steel plant scenarios. Wind speed data at height 102 m, temperature and air pressure data at 101 m was obtained from FINO1 offshore research platform<sup>1</sup>. Data gaps larger than one hour were filled by wind speed data at 100 m of the global atmospheric reanalysis ERA5 (C3S 2023). This data, in combination with a power curve for a Haliade X-12MW wind power plant depicted in Figure 26 in the appendix, was used to calculate a generation profile of a scenario specific wind park with the python module windpowerlib (Haas et al. 2024). The steel plant scenarios were originally developed by Hölling et al. (2021) with a wind generation capacity factor of 62.8%. Given this value, 2012 data was selected for model calculation, as it is the only year that offers the required threshold for wind energy production to support 1 million tons of steel. The

<sup>1</sup>This data was collected and made freely available by the BSH's marine environmental monitoring network (MARNET), the RAVE project ([www.rave-offshore.de](http://www.rave-offshore.de)), the FINO project ([www.fino-offshore.de](http://www.fino-offshore.de)) and the BSH's co-operation partners.

estimated capacity factors of offshore wind power plants in the vicinity of the FINO1 platform from 2012 to 2024 are shown in Figure 4. It indicates that 2012 is the sole year exceeding the projected capacity factor of the underlying model. The wind park generation profile is referred to in the model with the parameter  $G_t$ .

Profits from feeding in and selling residual electricity must be calculated using electricity pricing data. The Agorameter (Agora Energiewende 2023) provided hourly day-ahead prices for the year 2012. In the model, time-dependent electricity prices are represented by the parameter  $p_t^\epsilon$ . Steel plants must manufacture 1,000,000 tonnes of steel annually, as specified by the parameter  $m^{total}$ . Technical information on the plant, its equipment, and electricity consumption patterns are gathered from Hölling et al. (2021) and Dock et al. (2021). The values of all parameters for each steel plant scenario are depicted in Table 11 in the Appendix. In the *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* scenarios, three rates of capacity utilisation are provided to adjust the load profile of EAF batch production. For *Constant Steel Making*, this is offered for one rate of capacity utilisation because steel making in this scenario is constant. Different capacity utilisation is achieved as described in Section 2.4 by varying filling degree of the EAF, leaving residual molten steel or slag, or conducting fast or slow melting practice. To evaluate the research gap of lacking EAF flexibilisation in each scenario, the steel manufacturing unit  $u$  has a virtual equipment  $v \in V_u$  for each capacity utilisation rate. (Liu et al. 2022) created virtual equipments, which represent various equipment settings. Each virtual equipment has its own load profile, denoted by the symbol  $L_{u,v,z}^{STM}$ , where  $z$  is one of the time steps  $Z_{u,v}$  in a batch. Load profiles of these virtual equipments are depicted in Figure 5 and result for 100% utilisation in 107 MW hourly rated power, for 80% utilisation in 86 MW, 60% utilisation 65 MW and for the constant profile in 80 MW rated power. The load profile of *Constant Steel Making* scenario shows a direct load jump as EAF is turned on or off, between base load and maximum load. Load profiles of the other two scenarios show a linear increase or decrease of power demand on turn on and -off as the 7.5 MWh battery buffers the load jumps.

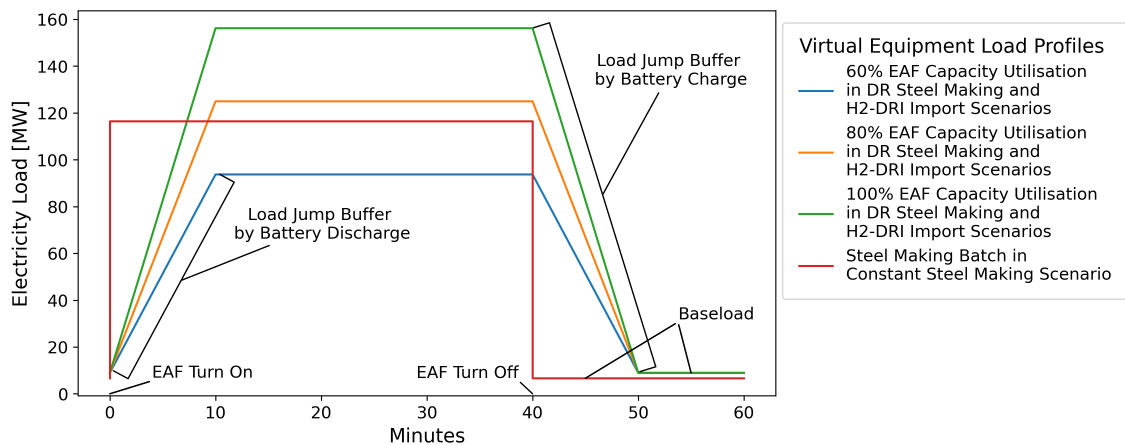


Figure 5: Electric Load Profiles for Batch Production of Virtual Equipments in Steel Making Unit in three Steel Plant Scenarios

### 3.2.1.2 Assumptions

While the linear model provides a simplified representation of the steel plant's operations, it relies on several assumptions that need to be considered. One assumption is that energy consumption of all equipments in the reduction unit additional to electrolyser, such as shaft furnace, conveyor belts and heating is aggregated into one flexible energy demand, even if in reality the consumption of the equipment like shaft furnace and conveyor belts would be more constant. This results in slightly unrealistic load profile of the reduction unit and additional losses due to electrolyser efficiency. But as these inflexible equipments are contributing under 10% of total energy demand for generating DRI, this effect is omitted to keep the model simple.

Another assumption of this model is that DRI is removed from storage once per batch, with no continuous addition of DRI material to the EAF. While this simplification neglects the reality of continuous material inflow, it reduces the number of constraints without information loss as the focus of this model lies on electric profiles and only total amounts of required materials. At the same time DRI storage capacity is assumed to be unlimited, as calculating the required capacity is interesting for further steel plant planning.

A quite big assumption compared to a real steel production plant is the omission of detailed modelling the process of compressing hydrogen to pressures above 30 bar. This would only influences the *Constant Steel Making Scenario* as it employs a large hydrogen storage with up to 300 bar and hydrogen compression at this pressure can take up to 15% of required energy for electrolysis. This energy is included in the assumed energy demand per H<sub>2</sub> unit but as compression can also be operated in a matter of DR this potential therefore is left out of the model.

As data sources on flexibility behaviour of EAFs, steel making unit and also rolling unit equipment are limited, assumptions about virtual equipment behaviour had to be made. The load profile of steel making processes are assumed for a fixed 10-minute resolution time period. In reality, the load of an EAF and also rolling units fluctuates more due to the nature of sequential process steps and achieving the assumed load profiles would require additional technical equipment to smooth out spikes in a matter of minutes or seconds. Another simplification in energy consumption is the exclusion of temperature management in the steel making unit, omitting differences of required loads between utilising hot DRI directly from reduction unit and cold DRI from imports or stored DRI. Nonetheless, the behaviour of loads in flexible steel making processes and the utilisation of hot DRI require further scientific investigation, and additional primary data sources must be accessible for their integration in this model.

In the economic structure of the model, grid charges are not included, neither for electricity consumed directly from the wind park nor for power drawn from the grid. Although an initial attempt was made to incorporate the current German grid charge system, which includes both energy-based and power-based components, this significantly increased the model's computational time.

Furthermore, the integration of potential future reforms to grid charges, such as transitioning from static power charges to more flexible, renewable generation-based pricing, posed additional uncertainties. Another unresolved issue was to what extent electricity consumed directly from the wind park would be subject to grid fees. Given that the primary aim of the model is to analyse flexibility behaviour rather than to simulate a fully detailed and realistic environment, grid charges and other electricity pricing elements such as taxes were intentionally excluded from the final setup.

### 3.2.1.3 Objective Functions

Input data is used for the initial parameters for the MILP optimisation. However the model is brought to life by the variables introduced in the following equation system. As variables and its sets are described mutually with the equations, an comprehensive and complete overview all symbols can be found in the Table of Symbols at Section 7. All sets can be found in Table 7, a list of parameters in 8, and the overview of variables is divided in decision variables in Table 9 and derived variables in Table 10.

The most prominent equation is the objective function, which is being optimised. For this model two distinct optimisation objectives are implemented describing each one way to operate the steel plant and representing a perspective and indicator area described later in Section 3.4. The first perspective is describing steel plant operator's and the second electricity grid operator's objectives. The objective is either maximising profits and optimising the financial returns from feeding electricity back into the grid from operator perspective, or fitting power consumption to a given profile by minimising deviations from it for measuring the stability potential from grid operator perspective.

#### Maximising Profits

This objective aims for reaching the best economic performance on the participation on the day ahead electricity market and providing stability through offering electricity feed in, in times of high demand and using high amounts of power in times of high electricity availability. The objective combines the profits of selling residual electricity from the wind park for the day ahead market price  $M_t^{sell}$  at each time step  $t$  and costs of buying electricity from the day ahead market  $M_t^{buy}$  if electricity at time step  $t$  is not sufficient to produce enough steel and the scenario allows to draw electricity from the grid. A important modelling assumption is that neither grid charges nor taxes are included, only the day-ahead market prices are considered. This simplification isolates the effect of price-driven operational flexibility on economic outcomes without the added complexity of regulatory cost structures. Additionally, it is important to highlight that in instances of negative electricity prices, purchasing electricity can result in financial gain, whereas selling excess electricity generates costs, adding a strategic dimension to grid interactions under volatile markets.

$$\max \sum_{t \in T} M_t^{sell} - M_t^{buy} \quad (1)$$

### Minimising Deviation from a given Goal Load

In essence this objective pushes the model to smooth the input of electricity from renewable sources into the grid with the help of DR through flexible steel production. Electrolysers, EAF and their accompanying load profiles are operated flexibly in order to balance the fluctuating energy generation profiles from renewables. This is achieved by minimising the mean deviation of actual power exchange from a given load profile. For simplicity the given profile is supposed to be the mean power exchange between grid and steel plant to promote a stable use of the electricity grid. This objectives tries to evaluate the general ability of a steel plant operator to shape the electricity load profile into a prescribed form, which does not necessarily need to be a stable baseload profile but could be any shape. Mean deviation is calculated by the absolute of difference between each value of a vector and its goal value, divided by the number of values in the vector. As a linear optimisation can not calculate absolute values, the deviation from goal load is separated into two variables, one describing the distance above the goal load  $D_t^{above}$  and one below the goal load  $D_t^{below}$  for each time step  $t$ . These derived variables are calculated in equation 27. Therefore the objective function is represented as:

$$\min \frac{\sum_{t \in T} D_t^{above} + D_t^{below}}{T^{end}} \quad (2)$$

Each steel plant scenario is evaluated for both objectives. Aspects of the evaluation are not only the optimal objective value but also mean profit generated from feeding electricity into the grid under each of the optimisation objectives, providing a comprehensive understanding of the financial implications of the different operational modes. Additionally the dynamics of steel production including analysing the pattern of electrolyser and steel making with a focus on length and frequency of breaks between EAF batches and the rates of capacity utilisation over time. The study also evaluates the stabilising effect steel plant flexibility can have on the electricity grid. This is analysed by the mean deviation from the goal load but also the standard deviation of this deviation and its variance.

#### 3.2.1.4 Constraints

This section will examine the linear model's constraints, where several new variables are established. Here it is important to distinguish between decision and derived variables. Where decision variables are those that can be controlled and derived variables are those that result from applying decision variables. The constraints section is organised around the distinct units within a steel plant. This unit-wise structure ensures that aspects of reduction, hydrogen storage, fuel cell, steel making and rolling are considered separately. For the general steel plant control and consistency of the model, constraints on total steel production, electrical power management, and economic viability are also added:

## 1. Constraints of Reduction Unit and Hydrogen Storage

If modelled steel production plant includes a reduction unit to produce iron sponges via hydrogen direct reduction the following constraints must be met:

### (a) Maximum load of reduction unit

The reduction unit, especially the water electrolyzers (WEL) are consuming varying electricity loads for producing hydrogen over time, represented by the decision variable  $L_t^{WEL}$ . The maximum power usage is given by a parameter for the installed capacity of the unit  $C^{WEL,max}$ . In the MILP optimisation problem, power demand of the reduction unit is a semi-continuous variable, as it is either zero or between the range of installed capacity and minimum power  $C^{WEL,min}$ . As the optimisation tool used for this problem is not able to map semi-continuous variables this is realised through implementing an additional binary decision variable  $\Lambda_t^{WEL}$  depicting if the reduction unit is turned on or not.

$$L_t^{WEL} \leq C^{WEL,max} \cdot \Lambda_t^{WEL} \quad \forall t \in T \quad (3)$$

### (b) Minimum load of the reduction unit

The reduction unit of the plant needs a minimum power which is given by the parameter  $C^{WEL,min}$ . If the reduction unit is turned off  $\Lambda_t^{WEL}$  equals zero as well as the load  $L_t^{WEL}$ .

$$L_t^{WEL} \geq C^{WEL,min} \cdot \Lambda_t^{WEL} \quad \forall t \in T \quad (4)$$

### (c) Flow of produced hydrogen

Hydrogen produced by the electrolyzers can either be directly used for DRI production, or be stored in a tank for later use in reduction or fuel cell. In the process electrolyser loose a certain amount of consumed energy given by parameter  $\eta^{WEL}$ , whereas the parameter  $\Delta t$  is important for the conversion from power in MW to energy in MWh, representing the amount of an hour passed in one time step. Produced hydrogen it is separated by two decision variables in a hydrogen flow directly utilised in DRI production  $Q_t^{H_2 \rightarrow DRI}$  and one for storage  $Q_t^{H_2 \leftrightarrow tank}$ . Hydrogen can also flow out of the storage for DRI production in times of low electrolyser utilisation with a negative  $Q_t^{H_2 \leftrightarrow tank}$ .

$$L_t^{WEL} \cdot \eta^{WEL} \cdot \Delta t = Q_t^{H_2 \rightarrow DRI} + Q_t^{H_2 \leftrightarrow tank} \quad \forall t \in T \quad (5)$$

### (d) Maximum utilisation of reduction unit

The reduction unit has the capacity to process at maximum utilisation the amount of hydrogen which is produced by the electrolyzers at max utilisation within one hour.

$$Q_t^{H_2 \rightarrow DRI} \leq C^{WEL,max} \eta^{WEL} \cdot \Delta t \quad \forall t \in T \quad (6)$$

### (e) Content of DRI storage

In the shaft furnace of the reduction unit, hydrogen from electrolyzers and possibly hydrogen from storage at time step  $t$   $Q_t^{H_2 \rightarrow DRI}$  reduces iron ore to iron sponges, or so

called direct reduced iron. This DRI is stored in a corresponding storage, which content at time step  $t$  is described by  $S_t^{DRI}$ . The storage is initialised with an amount of DRI already stored, given by the parameter  $S_{init}^{DRI}$ , which is zero in all scenarios. The reduction process requires  $Q^{H_2 \rightarrow DRI}$  units of hydrogen for production of one unit DRI and storing it. This is a given parameter and not to mix up with the time dependent decision variable  $Q_t^{H_2 \rightarrow DRI}$ . Together with scrap steel, DRI is used in the later process of steel making, this means storage content is reduced by the given parameter for required quantity of DRI  $Q_{u,v}^{DRI \rightarrow STM}$  for a starting batch process of steel making virtual equipment  $v$  of steel making unit  $u$ . The binary decision variable  $\Lambda_{u,v,t}^{STM}$  describes if steel making virtual equipment was turned on at time step  $t$ . The content of the DRI storage is constrained and calculated through the following two equations:

$$S_0^{DRI} = S_{init}^{DRI} + Q_0^{H_2 \rightarrow DRI} \cdot Q^{H_2 \rightarrow DRI} - \sum_{u \in U} \sum_{v \in V_u} \Lambda_{u,v,0}^{STM} \cdot Q_{u,v}^{DRI \rightarrow STM} \quad (7)$$

$$S_t^{DRI} = S_{t-1}^{DRI} + Q_t^{H_2 \rightarrow DRI} \cdot Q^{H_2 \rightarrow DRI} - \sum_{u \in U} \sum_{v \in V_u} \Lambda_{u,v,t}^{STM} \cdot Q_{u,v}^{DRI \rightarrow STM} \quad \forall t \in T \cup t > 0 \quad (8)$$

(f) Content of hydrogen storage tank

The hydrogen tank with the given nominal capacity of  $S_t^{H_2}$  is filled at the start of the model with an initial filling share between 0 and 100% given by the parameter  $S_{init}^{H_2}$ . The content of the tank is influenced by hydrogen flow  $Q_t^{H_2 \leftrightarrow tank}$  adding overproduced hydrogen from electrolyzers not directly required for direct reduction, or taking out hydrogen for direct reduction in times of low electrolyser utilisation. Also the fuel cell can reduce the hydrogen tank content by generating electricity  $G_t^{FC}$  with an efficiency of  $\eta^{FC}$ , whereby  $G_t^{FC}$  is a decision variable.

$$S_0^{H_2} = C^{S^{H_2}} \cdot S_{init}^{H_2} + Q_0^{H_2 \leftrightarrow tank} - \frac{G_0^{FC} \cdot \Delta t}{\eta^{FC}} \quad (9)$$

$$S_t^{H_2} = S_{t-1}^{H_2} + Q_t^{H_2 \leftrightarrow tank} - \frac{G_t^{FC} \cdot \Delta t}{\eta^{FC}} \quad \forall t \in T \cup t > 0 \quad (10)$$

(g) Range of hydrogen tank content

The content in the hydrogen tank can not surpass the given nominal capacity  $C^{H_2}$  or fall below 0.

$$0 \leq S_t^{H_2} \leq C^{S^{H_2}} \quad \forall t \in T \quad (11)$$

## 2. Constraint of Fuel Cell

The only constraint of the fuel cell power generation  $G_t^{FC}$  decision variable is, that it can not surpass its installed capacity  $C^{FC}$  at each time step  $t$ :

$$G_t^{FC} \leq C^{FC} \quad \forall t \in T \quad (12)$$

### 3. Constraints of Steel Making Unit

#### (a) Operating one equipment at a time for a given duration

Every steel making unit  $u \in U$  in the plant is separated into several virtual equipments. One steel making unit consists of an electric arc furnace, ladle oven and continuous casting equipment. Each virtual equipment  $v \in V_u$  represents a capacity utilisation rate, resulting in diverging load profiles and outputs of one production batch. If virtual equipment  $v$  is turned on, which is decided by variable  $\Lambda_{u,v,t}^{STM}$ , it runs for a given duration parameter  $\Delta T_{u,v}^{STM}$ . For this duration the derived binary variable  $\mu_{u,v,t}^{STM}$  has an entry of 1 at the corresponding time steps and  $\mu_{u,t}^{STM}$  if any virtual equipment in steel making unit  $u$  are running. As long as one equipment is running, every other virtual equipment of the corresponding steel making unit  $u$  can not work, therefore:

$$\mu_{u,v,t}^{STM} = \sum_{\max(0, t - \Delta T_{u,v}^{STM} + 1)}^t \Lambda_{u,v,t}^{STM} \quad \forall u, v, t \in U, V_u, T \quad (13)$$

$$\mu_{u,t}^{STM} = \sum_{v \in V_u} \mu_{u,v,t}^{STM} \quad \forall u, t \in U, T \quad (14)$$

$$\mu_{u,t}^{STM} \leq 1 \quad \forall u, t \in U, T \quad (15)$$

#### (b) Constraint of batch starting time

The final batch must be initiated at a time step which ensures it and its rolling unit are still completed before the last time step of  $T$ .

$$t \cdot \Lambda_{u,v,t}^{STM} \leq T^{total} - T_{u,v}^{STM} - T_u^{ROL} + 1 \quad \forall u, v, t \in U, V_u, T \quad (16)$$

#### (c) Constraint of minimum downtime after batch production

Each steel making unit  $u \in U$  has a minimum downtime  $T_u^{pause}$  that must elapse after a batch has been produced. After this downtime a next batch in one of the virtual equipment  $v \in V$  of the equipment  $u$  can be started. This is depicted by the following constraints:

$$\Lambda_{u,v,t}^{STM} \cdot T_u^{pause} \leq T_u^{pause} - \sum_{t_1=1}^{\min(t, T_u^{pause})} \mu_{u,t-t_1-1}^{STM} \quad \forall u, v, t \in U, V_u, T \quad (17)$$

#### (d) Constraint of steel making unit load

$L_{u,t}^{STM}$  depicts the load profile of steel making unit  $u$  at time step  $t$ . It summarises the load profiles of each virtual equipment  $v \in V_u$  and the corresponding batches. The load profile of a single batch in  $v$  is given by the parameter  $L_{u,v,z}^{STM}$ , where  $z$  is a time step within a single batch.

$$L_{u,t}^{STM} = \sum_{v \in V_u} \sum_{z=1}^{\min(\Delta T_{u,v}^{STM}, t)} \Lambda_{u,v,t-z+1}^{STM} \cdot L_{u,v,z}^{STM} \quad \forall u, t \in U, T \quad (18)$$

#### (e) Content of intermediate steel making products storage

When a batch of virtual equipment  $v$  of steel making unit  $u$  is finished after given  $T_{u,v}^{STM}$

time steps a certain amount of steel slabs or billets is produced. This output amount is given in weight by the parameter  $O_{u,v}^{STM}$ . After a finished batch, this is added to the storage variable of intermediate steel products  $S_{u,v,t}^{STM}$ . This intermediate products are directly processed further in the rolling unit but in this model the storage content is only reduced when the rolling batch is finished after the duration of a rolling process parameter  $T_u^{ROL}$ . This leads to a decrease in storage content equivalent to the output created in the batch that initiated the rolling process. This method of modelling intermediate product storage does not accurately reflect the reality of a steel making facility. Rolling is not directly contingent upon steel making operations, and storage is not specific to any unit or virtual equipment as represented in this model. However implementing intermediate steel products as a conversion step between DRI and rolled steel facilitates an interface for incorporation of more realistic models of rolling operations in the future.

$$S_{u,v,t}^{STM} = \begin{cases} 0 & t < T_{u,v}^{STM} \\ S_{u,v,t-1}^{STM} + \Lambda_{u,v,t-T_{u,v}^{STM}}^{STM} \cdot O_{u,v}^{STM} & t < T_{u,v}^{STM} + T_u^{ROL} \\ S_{u,v,t-1}^{STM} + \Lambda_{u,v,t-T_{u,v}^{STM}}^{STM} \cdot O_{u,v}^{STM} - \Lambda_{u,v,t-T_{u,v}^{STM}-T_u^{ROL}}^{STM} \cdot O_{u,v}^{STM} & t < T_{u,v}^{STM} + T_u^{ROL} \end{cases} \quad \forall u, v, t \in U, V_u, T \quad (19)$$

#### 4. Constraints of Rolling Equipment

After a batch in a virtual equipment  $v$  of steel making unit  $u$  is finished, produced steel has to be rolled in the final form. In this model rolling happens directly after the steel making and this process is not object of a decision variable but directly dependent on the decision if a virtual equipment was turned on. The process of rolling starts immediately when steel making is done, after  $T_{u,v}^{STM}$  time steps. A rolling process takes the amount of  $T_u^{ROL}$  parameter time steps. If at time step  $t$  a rolling process is running and consuming electricity the derived and binary variable  $\mu_{u,t}^{ROL}$  equals one, if it is off it equals 0. Load consumption of the rolling unit is described by derived variable  $L_{u,t}^{ROL}$  per time step  $t$  and is then constantly consuming the amount of power as the installed capacity. As described above this method of modelling rolling does not accurately reflect the reality of a rolling facility. Rolling is not directly contingent upon steel making operations. For this model however the focus is on reduction and steel making unit.

$$\mu_{u,t}^{ROL} = \sum_{v \in V_u} \sum_{t_1 = T_{u,v}^{STM}}^{\min(t, T_{u,v}^{STM} + T_u^{ROL})} \Lambda_{u,v,t-t_1-1}^{STM} \quad \forall u, t \in U, T \quad (20)$$

$$L_{u,t}^{ROL} = \mu_{u,t}^{ROL} \cdot L_u^{ROL} \quad \forall u, t \in U, T \quad (21)$$

#### 5. Constraints of Steel Production

As a rolling unit process is running, finished steel is added to the amount of produced steel of the unit  $S_{u,t}^{steel}$ . While this process steel intermediate products are lost with an efficiency

of  $\eta_u^{ROL}$ . At the end of the modelled time period sum of produced steel must be larger than a given production goal parameter  $m^{total}$ . This results in the following two constraints.

$$S_{u,t}^{steel} = \begin{cases} 0 & t = 0 \\ S_{u,t-1}^{steel} + \sum_{v \in V_u} S_{u,v,t}^{STM} \cdot \eta_u^{ROL} / T_u^{ROL} & t > 0 \end{cases} \quad u, t \in U, T \quad (22)$$

$$m^{total} \leq \sum_{u \in U} S_{u,T_{end}}^{steel} \quad (23)$$

## 6. Constraints of Electrical Power Management

The goal of this optimisation model is to map flexibility potential of electrical load profiles in a green steel production plant. Electrical power in a modelled plant is constrained by the following:

### (a) Energy Balance

Electrical power is generated by renewables  $G_t$ , the fuel cell  $G_t^{FC}$  or if the scenario includes this can be drawn from the power grid  $P_t^{buy}$ . The power is consumed by electrolyzers  $L_t^{WEL}$ , each steel making unit  $L_{u,t}^{STM}$  and rolling units  $L_{u,t}^{ROL}$ . Residual power is fed into the power grid  $P_t^{sell}$ . All these sum up to zero.

$$0 = G_t + G_t^{FC} + P_t^{buy} - L_t^{WEL} - \sum_{u \in U} (L_{u,t}^{STM} + L_{u,t}^{ROL}) - P_t^{sell} \quad \forall t \in T \quad (24)$$

### (b) Power Exchange between Grid and Plant

The power exchange between the plant and the grid  $P_t$  is the balance of the decision variable for power bought from grid  $P_t^{buy}$  and sold to the grid  $P_t^{sell}$  at time step  $t$ . If power is fed into the grid  $P_t$  is positive, if drawn from the grid it is negative. In scenarios where power can not be drawn from the grid, exchange only includes sold power.

$$P_t = P_t^{sell} - P_t^{buy} \quad \forall t \in T \quad (25)$$

### (c) Mean of Power Exchange

As the mean of the power exchange serves as the goal load in models using the objective to maximise profits, it is calculated by the following constraint. The calculated value for the profit maximising objective then is used as an externally given parameter goal load in models minimising deviation from goal load.

$$\bar{P} = \frac{\sum_{t \in T} P_t}{T^{total}} \quad (26)$$

### (d) Constraint of splitting power exchange to calculated absolute values

The mean deviation in the objective for fitting power consumption is calculated by the absolute of difference between each value of a vector and its goal value. As a linear optimisation can not calculate absolute values, the power exchange is separated into the values above its mean and below its mean. This means  $D_t^{above}$  and  $D_t^{below}$  depict the distance between actual power exchange  $P_t$  at time step  $t$  and the given parameter

of goal load  $P^{goal}$ . Models with the objective to maximise profits, mean of the power exchange calculated in Equation 26 serves as the goal load. The derived variables are calculated through the following equation:

$$D_t^{above} - D_t^{below} = P_t - P^{goal} \quad \forall t \in T \quad (27)$$

## 7. Constraints of Economics

The green steel production plant can make economic profits or losses by selling and buying electricity at the day ahead market. These are constrained by the following equations.

### (a) Electricity Market Profits

Selling electrical energy at the electricity market at time step  $t$  yields profit based on the given price profile  $p_t^\epsilon$  per energy unit and the amount of sold electricity  $P_t^{sell}$  at time step  $t$ . The sold energy content is calculated by the electrical power sold  $P_t^{sell}$  at time step  $t$  and the length of the time step in relation to an hour  $\Delta t$ .

$$M_t^{sell} = P_t^{sell} \cdot \Delta t \cdot p_t^\epsilon \quad (28)$$

### (b) Electrical Market Costs

Buying electrical energy at the electricity market at time step  $t$  cost  $p_t^\epsilon$  per bought energy unit  $P_t^{buy}$ .

$$M_t^{buy} = P_t^{buy} \cdot \Delta t \cdot p_t^\epsilon \quad (29)$$

## 3.2.2 Assessment of MILP Optimisation

The MILP optimisation in this work is formulated using the Pyomo modelling language (Bynum et al. 2021) and represents the operational behaviour of a steel plant under various flexibility scenarios. The model is solved using the Gurobi optimiser (Gurobi Optimization, LLC 2024), enabling efficient computation even with high temporal resolution over the period of a year. The full model code is publicly available for transparency and reproducibility with the equation system and analysis methods at the following repository: <https://github.com/gom-lewil/demand-response-h2-steel-plant>.

For each steel plant scenario described in Section 3.1 a parametrised model is developed. Each model is evaluated for both objectives, maximising profit and minimising the deviation from a given goal load. The model optimises the operation schedule over a one year period in a resolution of 10 minute steps and focusses on electric loads of equipment and material flows within the steel plant as well as profits by selling residual electricity, or losses from buying required electricity. Each optimisation algorithm runs for a maximum of seven days and the optimal solution calculated in that time is selected.

Aspects of the evaluation are the dynamics of steel production over the whole modelled year including analysing the pattern of reduction unit, steel making and rolling unit consumption. Also

EAF capacity utilisation, power exchange and profits and losses for selling and buying electricity are analysed over the whole year. Assessing steel plant downtimes to understand the factors inducing such downtimes is of considerable importance. These dependencies dictate the efficacy of operations management in anticipating and adapting to new conditions. In addition, the total amount of electricity drawn from and supplied back into the grid can be evaluated to gain insight into operational efficiency and the extent of renewable energy integration.

The ability to match electricity consumption to time-dependent prices can be assessed by calculating the mean profit per sold MWh while feeding electricity into the grid. Done for each of the optimisation objectives, this provides a comprehensive understanding of the financial implications of the different operational modes and plant setups.

Furthermore, this study assesses the stabilising effect steel plant flexibility can have on the energy system. This is examined using the mean deviation from the given goal load, as well as the standard deviation and variance of this deviation, to assess how effectively the goal value can be met.

These factors are thoroughly evaluated by analysing the outcomes of the MILP optimisations and later aggregated in a comparative framework across the three scenarios within an information system.

### **3.3 Prospective Life Cycle Assessment of Steel Plant Scenarios**

Life cycle assessment (LCA), or life cycle analysis, is a methodology for evaluating the impacts linked to all stages of the life of a commercial product, process, or service (Ilgin and Gupta 2010). For example, in the context of a produced product, environmental consequences are evaluated from raw material extraction and processing, through the product's manufacturing, distribution, and utilisation, to the recycling or ultimate disposal of the materials comprising it.

A large share of life cycle assessment studies are determining environmental impacts of technology as it currently is, or retrospectively how it was produced. However, the increasing interest on sustainability and environmental evaluation of future technologies and scenarios has led to the development of prospective Life Cycle Assessment (pLCA) methodologies. These methods enable the evaluation of potential future environmental impacts associated with emerging technologies in future production systems (Arvidsson et al. 2018). This section describes why this methodology was selected and its subsections, how it is conducted for future steel production. Herein it is important to distinguish between two key systems:

- Background system, which refers to the broader economic, social, and environmental context in which the product or process operates. It encompasses the entire web of activities, processes, and systems that are connected to the foreground production, as well as use and end-of-life of the product (Mendoza Beltran et al. 2020). Within the background system future energy and steel production scenarios as well as technological developments are incorporated to model a prospective production system.

- Foreground system, which describe the specific assessed production process, in this case the steel plant scenarios with varying setups of technologies, which were already described as *Demand Response Steel Making*, *Constant Steel Making* and *H<sub>2</sub>-DRI Import*.

This study employs ISO 14044 (2006), a global standard for LCA, to construct the foreground system. This standard defines four steps to conduct a LCA: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment and result interpretation. This LCA framework is used to assess the inputs, outputs, and potential environmental impacts associated for each steel plant scenario. As steel production relies on many production processes which can not be modelled all in detail this analysis employs ecoinvent, the largest source for background data LCIs (Wernet et al. 2016). A more detailed description of the conducted methodological steps of the foreground system are described in Section 3.3.2.1 as well as the used data in Section 3.3.2.2 To accommodate the prospective nature of this analysis, a superstructure approach (Steubing and De Koning 2021) is used to generate prospective ecoinvent background systems for the proposed years and integrate background scenarios into the existing background system. This is done by PREMISE which integrates and aligns processes in a standardised way. The data- and workflow is depicted in Figure 6 and described in further detail in the following Section 3.3.1.

### 3.3.1 Setup of Background System

For construction of a prospective setting and background data the python library premise 1.7.1 (Sacchi et al. 2022) manages scenario data and its integration into existing ecoinvent background system. Figure 6 displays the required data and how it is implemented. Integrated IAM and external scenario data together with new LCI data construct new activities and market aggregations. These markets are managed in the configuration yaml file and replace existing markets in ecoinvent with the parametrised, prospective scenario data. All together premise generates a new version of ecoinvent, which is utilised through brightway and the activity browser for environmental impact assessment which is explained in Section 3.3.2.3.

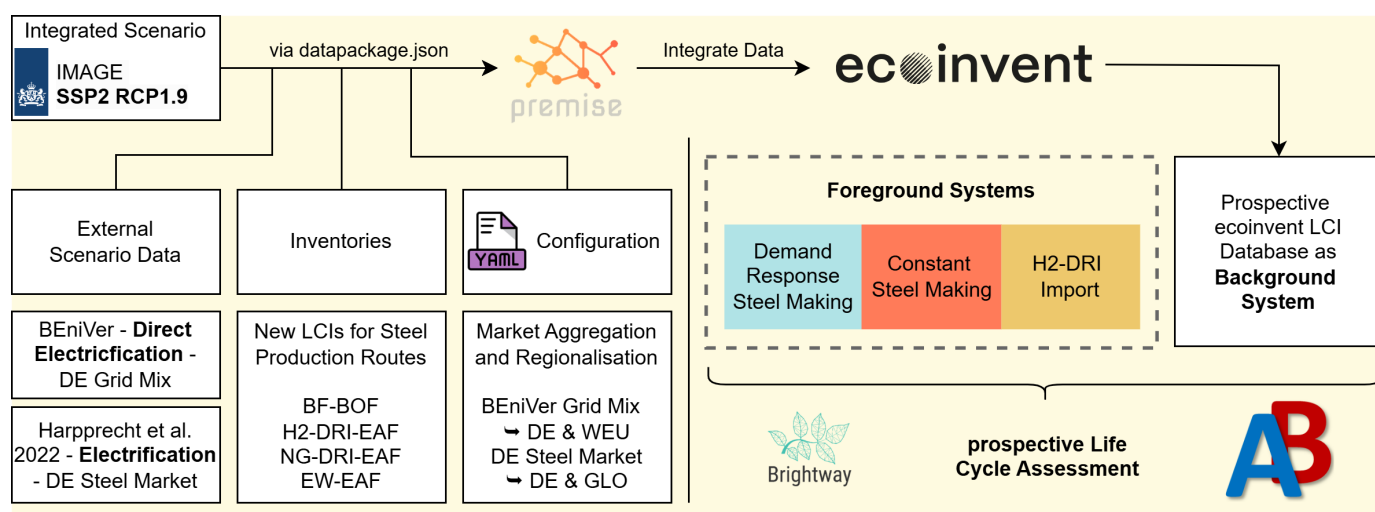


Figure 6: Data- and Workflow for prospective Life Cycle Assessment with used Tools

To assess the environmental impacts of steel plants and steel production in Northern Germany in future conditions three background scenarios are included. The first scenario depicts global system changes described by IMAGE IAM of Shared Socio-economic Pathway (SSP) scenario, capturing shifts in global production conditions and chains. As this integrated scenario does not integrate green primary steel production practices and does not depict adequate projections for steel and electricity sector in the German context, two additional external scenarios are integrated. On the one hand a German electricity mix scenario, which describes technology composition for the German electricity system (Aigner et al. 2023) and on the other hand a German steel production scenario, which includes new pathways for steel production and revised pathway production shares for Germany (Harpprecht et al. 2022).

Global background system changes are adapted via the IMAGE SSP2 RCP 1.9 scenario (Stehfest et al. 2014), which is already integrated in premise. The SSP2 "Middle of the Road" scenario is characterised by continuation of current trends accompanied by moderate global population growth, uneven development between countries, and slow progress toward achieving sustainable development goals (Riahi et al. 2017). Modifications of the SSP are influencing the electricity mix, technological efficiencies and steel production pathway shares in ecoinvent for the 27 regions IMAGE IAM models global developments<sup>2</sup>. This is done for four years of the SSP scenarios: 2023, 2030, 2040 and 2050. Steel production in ecoinvent however only models BF-BOF and Scrap EAF pathways and in rare cases coal based direct reduction. CO<sub>2</sub>-Eq emission reductions are achieved by increasing shares of secondary steel production. This raises numerous questions outlined by Haupt et al. (2023), with the primary concern being whether the necessary quantity of recyclable material is available and not locked in use. To potentially reduce emissions in primary production, prospective technologies such as hydrogen-based direct reduction must be implemented, which is done by the following scenario.

These new steel production routes are integrated through the German steel production background scenario derived from Harpprecht et al. (2022), who formulated three decarbonisation scenarios aiming at replacing fossil fuel-based furnaces and shifting to primarily electricity-based steel production in Germany by 2050. The scenarios simulate the decarbonisation of current blast furnaces in Germany by carbon capture technology, natural gas substitution, or hydrogen-based direct reduction and electro winning. The "Electrification" scenario was chosen for this study as it aligns with the narrative of SSP2 RCP1.9 and corresponding production volumes are described in Figure 7 and Table 13 in the Appendix. The material flows within the respective steel production were also depicted in detail in Figure 1.

Life cycle inventories for NG-DRI-EAF, H<sub>2</sub>-DRI-EAF, and EW-EAF steel production methods from Harpprecht et al. (2025a) are incorporated into a prospective version of ecoinvent, based on the

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<sup>2</sup>As scenario specific changes are applied over a large variety of regions, changes within the two sectors electricity and steel are difficult to depict in this thesis. For further investigation into changes I recommend the [interactive dashboard](#) of premise. Last visited on: 08th June 2025

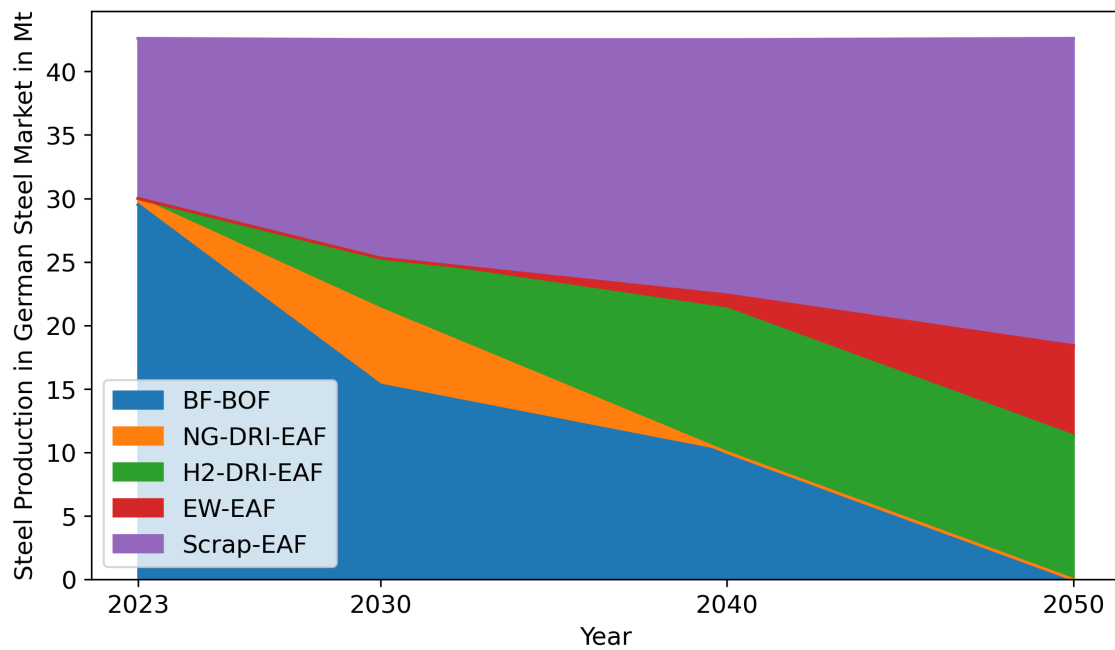


Figure 7: Steel Production Pathway Shares in German Steel Production of "Electrification Scenario" by Harpprecht et al. (2022). Exact values shown in Table 13 in the Appendix.

relevant market shares<sup>3</sup>. The H2-DRI-EAF production route applied in Germany with the background scenario grid mix from Figure 8 as energy supply, is not only used in the background but also later in the pLCA as a comparative case to the foreground steel production scenarios. This scenario substitutes both the German market and the global steel market to guarantee uniform implementation of the anticipated steel market within the background system. This is because the German market is not applied to items of the background system that are not specified to be in the regional context, despite their operations in this case being situated in Germany.

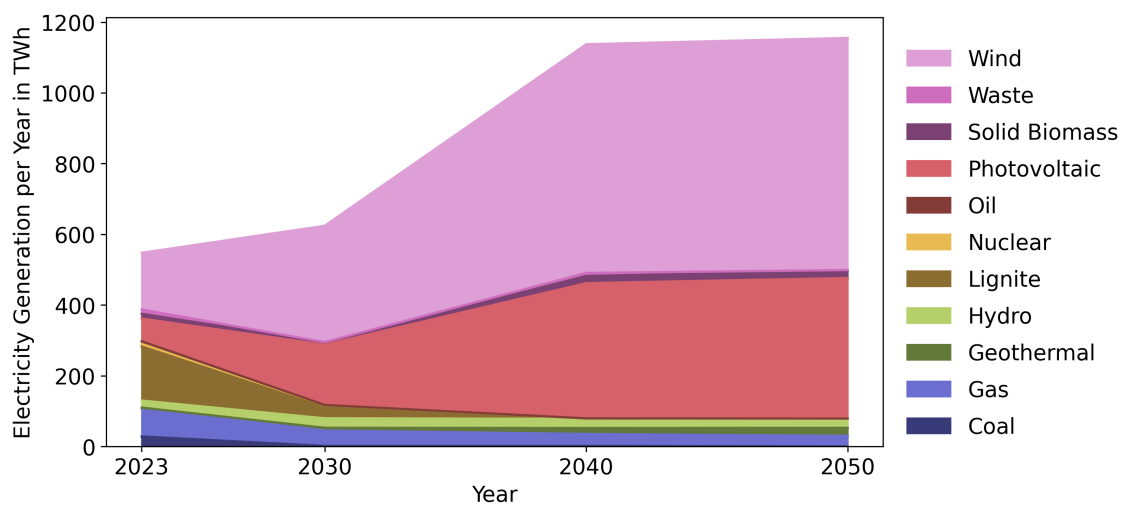


Figure 8: Power Generation Technology Shares in German Electricity Mix of "Direct Electrification" Scenario in "BEniVer" (Aigner et al. 2023). Exact values shown in Table 12 in the Appendix.

<sup>3</sup>The LCI data for the production routes can be found in this zenodo repository (Harpprecht et al. 2025b)

The use of "Direct Electrification" German electricity mix scenario replaces for the same reason as described above the Western European (WEU) electricity mix scenario from IMAGE SSP2 for Germany, ensuring that German conditions are taken into account. In Figure 8 or Table 12 in the Appendix generation technology shares for the scenario are described in detail. Main developments are the nuclear phase out in 2024, drastic reductions in coal based generation and increments in PV and wind capacities. As all utilised technologies are already included in theecoinvent background system no new LCIs need to be integrated.

### **3.3.2 Life Cycle Assessment**

#### **3.3.2.1 Goal and Scope**

This study aims to provide decision support for selecting steel plant scenarios and how to integrate them into the electricity system. In addition to the optimisation, focusing on operational and economic aspects, the pLCA estimates environmental impacts of the steel plant scenarios and its production in future surroundings. The intended audience includes policy makers, steel plant operators and grid operators, as well as a scientific audience. The functional unit of this study is one kilogram of hot rolled steel, produced in the steel plant scenarios introduced in Section 3.1 with a 20-year lifetime. Additionally to these three scenarios two reference cases of steel production are evaluated to provide context for the steel plant scenario results. First comparison case is steel production as conducted in current, coal based BF-BOF production route. The second reference case assesses H<sub>2</sub>-DRI-based steel production that relies entirely on electricity drawn from the German grid, thereby reflecting the environmental impacts associated with the projected electricity grid mix. These benchmarks serve to contrast the performance of the optimised local production scenarios against more conventional or broadly representative steel production pathways. This allows for comparison of environmental impacts between different steel plant scenarios with the effects from background scenarios from 2023 to 2050.

To evaluate the differences between steel plant scenarios in detail, the share of each installed equipment to the total environmental impact is analysed within a contribution analysis. This analysis focusses on the installed infrastructure and utilises the functional unit of the required installations of one steel production plant for 1 Mt of steel per year. This contribution analysis therefore excludes impacts from mining and other materials, like limestone required for the production process as well as emissions in the production processes itself as these are similar for each scenario.

The scope of this pLCA is cradle-to-gate, which means production processes up to the point of leaving the gate from the steel production plant are considered. Use and disposal phase of the produced steel are not reflected due to large usage variety with low impact and high recycling rate of steel. The system boundaries for each steel plant scenario are shown in Figure 9 to Figure 11. Within the dashed border the foreground system is described with deployed equipments and their respective capacities. Capacities printed in bold indicate a flexible use of this unit, however as the

assessment focusses on the installation the maximum value is used in the LCIs. The materials required for the construction of the units in the foreground system are mapped in the background system. In the contribution analysis the material flows within the production process are not evaluated, so the arrows depicting these material flows are not included in the system boundaries.

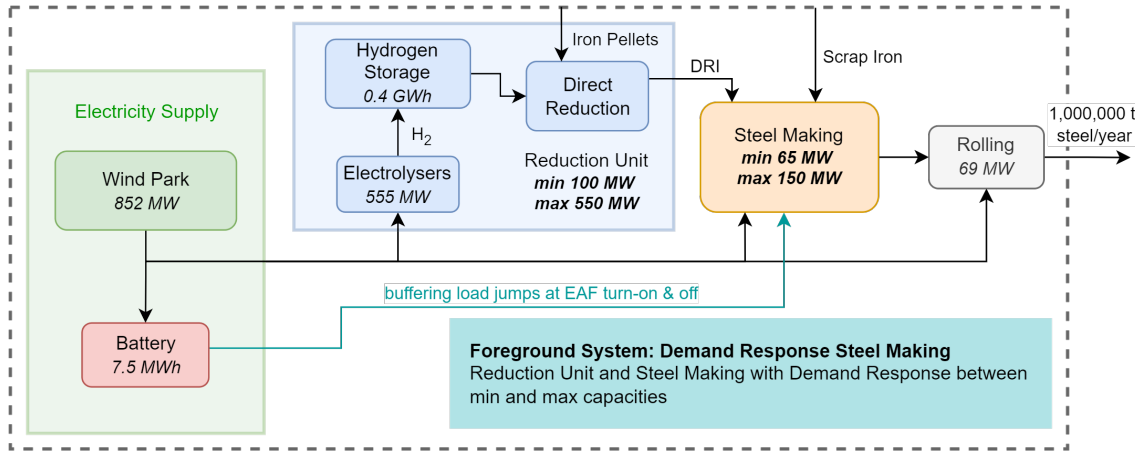


Figure 9: Foreground System Boundaries, Resource and Energy Flow Chart of *Demand Response Steel Making* Steel Plant Scenario with Unit Installation Capacities from Hölling et al. (2021)

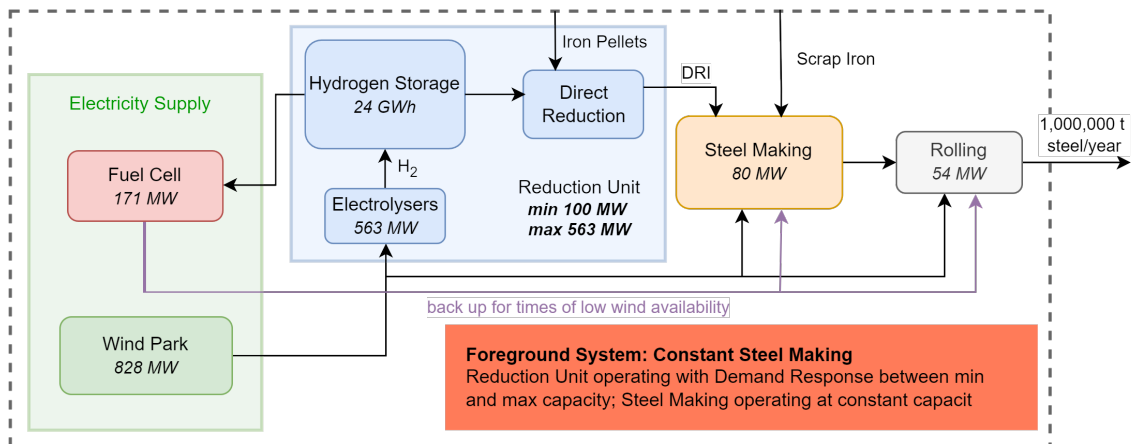


Figure 10: Foreground System Boundaries, Resource and Energy Flow Chart of *Constant Steel Making* Steel Plant Scenario with Unit Installation Capacities from Hölling et al. (2021)

As the cut-off approach for aggregation is utilised the selected version of ecoinvent 3.9.1 has the fundamental principle that the initial manufacturing of materials is consistently assigned to the primary product. When a commodity is recycled or reused, the original product is not effected in form of impact reduction for supplying recyclable resources. The impacts of secondary materials, like recycled steel solely reflect the processes of recycling procedures itself. This indicates that scrap-EAF steel solely reflects the effects of its own collection, steelmaking, and rolling processes, excluding those of primary steel, which may be coming from from coal-based BF-BOF methods during its initial utilisation.

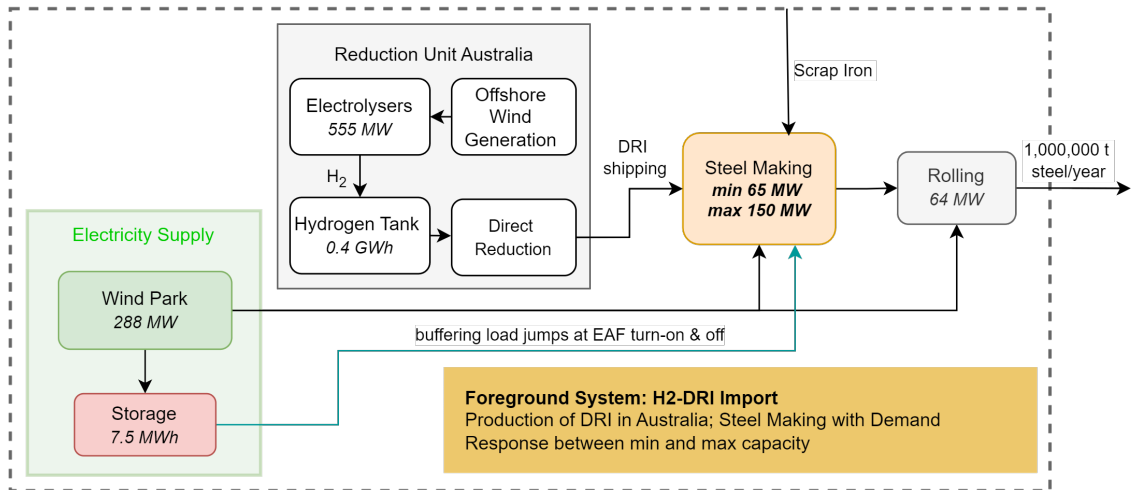


Figure 11: Foreground System Boundaries, Resource and Energy Flow Chart of  $H_2$ -DRI Import Steel Plant Scenario with Unit Installation Capacities from Hölling et al. (2021)

Covering environmental indicators to evaluate and compare steel production in context of future developments this study assesses six impact categories which are calculated by methods of Environment Footprint (EF) version 3.1 (Damiani et al. 2022). These six indicators are selected to depict steel plant scenario impacts on climate change, depletion of metal and fossil resources, health impediment by particulate matter and influences on natural habitat conditions.

- Acidification from air, water, and soil emissions primarily from sulphur compounds of combustion processes in electricity generation, heating, and transport
- Abiotic depletion potential (ADP) of fossil fuels, describing the exhaustion of non-renewable fossil energy resources and deprivation for future generations
- Global warming potential (GWP), measuring the increase in the average global temperature resulting from greenhouse gas emissions
- ADP of metal and mineral resources, indicating the depletion of non-renewable metal resources and deprivation for future generations
- Particulate matter formation (PMF) as an indicator for the impact on human health caused by PM emissions and its precursors as sulphur and nitrogen oxides
- Water use, measuring the depletion of available water for human activities and ecosystem integrity

In selection of LCI data several requirements need to be considered. Most importantly timeliness of data, as technologies like batteries or fuel cells and electrolyser are in a rapid development. Additionally, upcoming developments such as the incorporation of novel fibres in wind turbines may be taken into account. Secondly the geographical coverage for modelled system has to be included. This requires a focus on European production, with a particular emphasis on Germany if possible. However, German production also relies on products from other countries, which necessitates inclusion of world market conditions, e.g. high reliance on Chinese battery production.

Thirdly data requirement of technological coverage is considered. The study assesses large, industrial scale application of technologies as a fuel cell or electrolyser. The employed data should reflect on the corresponding scale in size and specific selected technology. And last LCI data is primarily sourced from scientific sources that openly share their developed life cycle inventories. Direct input from industry is preferred, where it is available. However the representativeness of the data needs to be assessed through qualitative research with comparable studies. Due to timely limitation and missing data, data requirements on precision, completeness, uncertainty and reproducibility are not covered in this study.

### 3.3.2.2 Life Cycle Inventories

A LCI provides a list of required material, emissions and waste flows associated with each product in the steel plant scenario. It represents the basis data for conducting a LCA. An overview of the selected technologies within steel plant scenarios and the source of their inventory can be found in Table 2. LCI data not used from proprietary LCI database ecoinvent is listed in the appendix Section B. The following paragraphs introduce and justify the selection of technology and corresponding inventories for steel plant scenarios.

Table 2: Overview of activities in modelled Life Cycle Inventories of steel plant scenarios

\* - Unit in Australia; RoW = Rest of World location parameter in ecoinvent; DE = Germany location parameter

| Activity                   | Source                                 | Technology             | Lifetime in years      | Steel Plant Scenarios |                  |                            |
|----------------------------|----------------------------------------|------------------------|------------------------|-----------------------|------------------|----------------------------|
|                            |                                        |                        |                        | DR STM                | Constant STM     | H <sub>2</sub> -DRI Import |
| Offshore Wind Turbine (DE) | Benitez et al. (2024)                  | 9.5 MW Turbines        | 20                     | 852 MW                | 828 MW           | 288 MW                     |
| Offshore Wind Energy (RoW) | ecoinvent                              | 1-3 MW Turbines        |                        |                       |                  | *2.5 TWh/a                 |
| Water Electrolyser         | Gerloff (2021)                         | Solid Oxide            | Balance of Plant Stack | 20<br>7.5             | 555 MW<br>563 MW | *555 MW                    |
| Hydrogen Tank              | Agostini et al. (2018)                 | Type III 350 bar       | 30                     | 0.4 GWh               | 24 GWh           | *0.4 GWh                   |
| Fuel Cell                  | Bicer and Khalid (2020)                | Solid Oxide            | Balance of Plant Stack | 20<br>20              | 0 MW<br>171 MW   | 0 MW                       |
| Battery                    | Han et al. (2023)<br>Li et al. (2024b) | Lithium Iron Phosphate | BMS & Container Cells  | 20<br>5               | 7.5 MWh<br>0 MWh | 7.5 MWh                    |
| Reduction Unit             | ecoinvent                              |                        | 50                     | 501 MW                | 500 MW           | 0 MW                       |
| Steel Making Unit          | ecoinvent                              |                        | 50                     | 108 MW                | 80 MW            | 108 MW                     |
| Rolling Unit               | ecoinvent                              |                        | 50                     | 69 MW                 | 54 MW            | 69 MW                      |

**Offshore Wind Park** The offshore wind park is a critical component of the steel plant scenarios, providing the main source of electricity to power production in a steel plant scenario. As wind turbine technology is rapidly evolving and increasing in power and size, Benitez et al. (2024) developed a reference turbine inventory adaptable to plant size and power and prospective changes in fibre technology with the initial power of 9.5MW described in Table 14. Additionally inventories of wind park infrastructure such as 33kV medium voltage transmission line (Table 21), 245 kV high voltage transmission line to shore (Table 22), as well as a substation (Table 20) and transport of turbines are modelled and applied to the steel plant scenarios. Wind turbine parts have a lifetime of 20-25, transmission grid and substation 40 years. As the researched lifetime of the whole plant is 20 years, the environmental impact saving effects of longer lifetime are not accounted for.

**Water Electrolysis** The water electrolysis units are the largest electricity consuming unit in H<sub>2</sub> direct reduction steel production. They are generating hydrogen for the reduction of iron ore, or electricity generation in a fuel cell in *Constant Steel Making* scenario. This study employs LCI data from Gerloff (2021) concerning the stack (Table 23) and balance of plant (Table 24) for a one megawatt solid oxide water electrolyser (SOEC). This technology is selected as best suited for the application in steel production scenarios due to high efficiencies, low costs and low material requirements (Guo et al. 2024) which can be further improved through utilisation of waste heat from other production processes Hu et al. (2022). However the high temperature conditions require additional heat management efforts as well as reduce stack lifetime.

**Hydrogen Tank** Hydrogen can be stored using a variety of technologies, and the choice of storage method is crucial for ensuring efficient production flow and compliance with safety regulations. In this study, a large hydrogen tank is utilised as a backup energy source for the fuel cell system within the *Constant Steel Making* scenario and a small tank in other scenarios for production flow. The selected storage technology is a Type III tank, as it meets the pressure requirements defined by Hölling et al. (2021). Considering the size of the storage in *Constant Steel Making* scenario also a salt cavern could also be used as a storage, however as the scenarios so far are located in Bremen without the required caver capacity, metal tanks were used. The usage of salt caverns would required additional pipelines from nearby locations, or moving the steel plant location. Type III tanks consist of an internal metallic liner encased in a thick composite material layer, which provides structural integrity and effectively prevents hydrogen leakage (Magliano et al. 2024). LCI data on Type III tanks remains scarce, as most LCA studies on hydrogen storage focus on automotive applications, which predominantly use Type IV tanks. Agostini et al. (2018) developed an LCI for small Type III tanks for auxiliary power units with a maximum hydrogen capacity of 22 litres. For modelling of a larger hydrogen storage tank it is scaled to a 1750-litre capacity storage with an assumed material reduction factor of 50% per stored litre (Table 25). While this assumption is conservative since storage volume scales much faster than surface area, it accounts for additional tubing and wiring necessary in the extensive hydrogen storage capacity required in *Constant Steel Making* scenario, which requires a total storage volume of 30,000,000 litres.

**Fuel Cell** In the *Constant Steel Making* scenario, a fuel cell system is implemented to provide backup electricity generation during periods of low wind availability. The selection of solid oxide fuel cell (SOFC) technology is based on its compatibility with hydrogen generated in SOEC (Li et al. 2024a) and its suitability for integration into a hybrid heat management system (Malik et al. 2021). The LCI for the fuel cell system is based on data provided by Bicer and Khalid (2020) for a 250 kW fuel cell and includes a detailed differentiation between the fuel cell stack (Table 26) and system installation (Table 27). In the study a fuel cell stack is projected to have a lifetime of five years under continuous operation for 8,000 hours per year. Since the fuel cell in the steel plant scenario operates only as a backup system with a maximum of 1,000 hours per year, its lifetime in this study expected to exceed the 20-year observation period.

**Battery** In *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* steel plant scenarios a 7.5 MWh battery buffers power load jumps from turning EAFs on or off over a ten minute period. Lithium iron phosphate batteries was selected as fitting technology due to its long lifecycle and security benefits (Chen et al. 2024; Yudhistira et al. 2022). This study implements LCIs from on battery management systems (Table 29) and a container (Table 28) from Han et al. (2023) as well as and cell components (Table 30) by Li et al. (2024b) for a grid scale battery storage system (Table 31). Due to its intensive use with up to 24 cycles per day in steel plant scenarios, the cells have a projected lifespan of just 5 years, whereas the battery management system and container are assumed to operate 20 years.

**Steel Plant** LCIs of reduction unit, steel making unit, and rolling mill represent the resource and product requirements for constructing buildings and equipment in the steel plant scenarios. The data for the LCIs is sourced from ecoinvent and adjusted to correspond to a production volume of 1 Mt of steel per year. The inventories are developed by Althaus and Classen (2005) and used in a large number of life cycle assessments as a background system for steel production. As the installed capacity varies across different steel plant scenarios, the required materials scale linearly. The lifetime of these facilities is assumed to be 50 years.

For each steel plant scenarios an LCI is compiled with the technologies used in the scenario with corresponding size and lifetime. These are displayed in Table 32 for *Demand Response Steel Making*, in Table 33 for *Constant Steel Making* and Table 34 for *H<sub>2</sub>-DRI Import* scenario in the Appendix.

### 3.3.2.3 Life Cycle Impact Assessment

For the assessment of environmental impacts of the modelled Life Cycle this study employs Brightway 2 (Mutel 2017), a widely-used LCA software. Brightway offers with the activity browser an interface capable of integrating the developed superstructure of the background system for assessing environmental impacts within all modelled prospective production conditions.

This impact assessment is conducted within the activity browser for the functional unit of one kilogram of steel for each steel plant scenario and the six impact categories defined in the Goal and Scope, as well as for each of the prospective modelled years. It aggregates all required materials and emissions within the production process.

The same is done for the latter, as a second functional unit is defined for a contribution analysis, as described in the Goal and Scope. Nevertheless, this necessitates the consolidation of activities within the LCIs, which are intended to be considered a single contribution to the analysis. This is performed for the activities associated with the production processes of each piece of equipment included in the steel plant scenarios. When comparing the contributions of production units to impact categories, the environmental impacts can be compared in terms of their total or relative contribution. The appropriate approach in order to observe the actual impact and compare the differences between the scenarios is to compare the total consequences.

The code and LCI data used for this is available in this [DLR internal Gitlab repository](#) as it includes proprietary LCI data.

### **3.4 Indicator Selection for Information System**

The evaluated research objectives are examined from the perspective of a multi-level and dynamic sustainability understanding, aiming to enhance sustainable development in the transitioning energy and steel production systems. This section draws on the understanding of sustainability outlined in Section 2.3, and develops an Information System that integrates already introduced indicators into stakeholder perspectives to aggregate pertinent data for decision-making supporting sustainable development.

To assess the possible contribution to sustainability development of future steel production scenarios in Germany, multiple indicators are required. These indicators can be aggregated in areas covering different aspects, or levels of the system which is assessed. This study considers three stakeholder perspectives representing each a level of the multi-level perspective and organises them into an information system which can help to determine pathways of sustainable development. These developed indicators, summarised in Table 3 are evaluated for each hydrogen based steel production scenario and compared to discuss the performance of each scenario as well as their trade-offs.

Steel Plant Operators as Niche actors developing and realising innovative solutions, Grid Operators within the Regime maintaining functioning of the electricity grid, and environmentally oriented Analysts & Policy Makers from the Landscape perspective researching and managing higher level developments. These perspectives were derived through a non-participatory process, where assumptions were made based on the literature review in Section 2. To capture the concerns and priorities of each stakeholder, overarching indicator areas are developed and assessed through

Table 3: Levels, Stakeholder, Areas and Indicators of the Information System for Assessment of Hydrogen based Steel Production Scenarios

| Level     | Stakeholder                            | Indicator Area                    | Indicators                                                                                                                                                                        |
|-----------|----------------------------------------|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Niche     | Steel Plant Operator                   | Economic performance              | Mean price for selling & buying electricity<br>Total electricity usage of production process                                                                                      |
|           |                                        | Operational complexity            | Amount and length of steel plant downtimes                                                                                                                                        |
| Regime    | Electricity Grid Operator              | DR Potential to match goal load   | Deviation from goal load (mean, standard deviation and variance)                                                                                                                  |
| Landscape | Environmental Analysts & Policy Makers | Prospective environmental impacts | Acidification<br>Fossil Energy Abiotic Depletion Potential<br>Global Warming Potential<br>Metal Resource Abiotic Depletion Potential<br>Particulate Matter Formation<br>Water Use |

multiple indicators, incorporating the key rationales and challenges associated with their perspective on the transition process. The development of these minimal amount of indicators is only a brief effort, as the scope of this research emphasises the evaluation of these indicators rather than an in-depth evaluation of each stakeholder's complex needs and interests.

For the Steel Plant Operators the economic gains of their steel plants is the driving factor of operation. An economic analysis on the capital investment and broad operation costs for steel production scenarios was already conducted by Hölling et al. (2021). The analysis of possible economic savings and respectively profits through flexibilisation of electricity demand was missing. To assess the extent of economic savings as formulated in the first research objective this study applies the approach used by Boldrini et al. (2022) and Boldrini et al. (2024) for demand response electrolyser and batch scheduling steel making. These studies are focussing on evaluating possible cost saving of flexible steel production scenarios when buying electricity at the day ahead electricity market. However this study evaluates the demand response effects by using 100% renewables by integrating a wind parks as a part of the steel production. As a result, this analysis compares the mean selling price per energy unit to determine how well each steel mill scenario utilises its DR potential. At the same time, the energy necessary to make one tonne of steel is used as a comparison to assess potential energy losses from storage or inefficient operation management, which would result also in higher costs.

As DR in industry and therefore also steel sector is not only hindered by concerns about profitability but also operation planning as shown by Scharnhorst et al. (2024) this analysis also includes the assessment of operational complexity in form of analysing the times in which a steel plant is shut down completely. Amount and length of shutdown times can serve as an indicator of operational complexity, as the complete shutdown of the plant entails a complex procedure involving numerous planning challenges related to temperature regulation, material flow, product quality and workforce management.

One of the biggest tasks of grid operators in the energy transition is to ensure stabilisation of fluctuations in the electricity grid. Therefore the indicator from the regime perspective focusses on the ability of hydrogen based steel production to stabilise power variability within renewable electricity generation. How this ability can be measured and modelled is described in Section 2.4 and 3.2. When an offshore wind park is considered as an integral component of a steel production plant, it can serve a dual purpose: meeting the energy demands of the production process while also supplying excess energy to the grid. In this context, the feed-in from the steel plant can be optimised to match a specific load level or profile. To evaluate the flexibility of the steel plant's feed in profile in conforming to a desired shape, the mean deviation between the actual load and the target load can be calculated, along with its standard deviation and variance. Because these measures provide an estimate of the ability to alter variable output to satisfy the specified load attributes, they are used to compare the scenarios.

Analysts and policymakers were selected representing the environmental perspective, as they, next to other factors also assessed here, prioritise the mitigation of global climate change, environmental degradation, and biodiversity loss and approach these issues from a global perspective. Therefore evaluated indicators capture the comprehensive environmental footprint of steel production over its production and on a global scale. Given the anticipated transformations in the production system, the assessment considers six potential environmental impacts under various future scenarios, enabling a forward-looking evaluation of its performance. The respective impacts of interest are global warming potential, fossil as well as metal resource depletion, but also water use, acidification of the environment and emission of particulate matter. These impact categories cover a relevant spectrum of environmental issues for future production systems and are compared for the whole production process of hydrogen based steel.

It is essential to acknowledge that the input information for the assessment of these indicators is often associated with uncertainties and difficulties in comparability. There would be several methods to assess uncertainty in the conducted methods (Jung et al. 2014; Charitopoulos and Dua 2017) and enable comparison of diverse indicators (Wątróbski et al. 2019). However, due to time constraints a comprehensive uncertainty and sensitivity analysis are not conducted. Instead, this work applies a reduced framework for indicator development, assessment, and comparison without weighting them against each other but organising them in an information system which can be used in decision making processes and enhance currently applied information systems.

## 4 Results

### 4.1 MILP Optimisation

For a variety of decision variables and indicators the MILP optimisation produces high-resolution time series. This includes power consumption of steel plant units, storage levels, production rates, and market interactions. A total of 52,704 time steps for each scenario and objective function represent the optimal found operation schedule over a full calendar year with a temporal resolution of 10-minute intervals. The model deploys dynamic behaviour of flexible industrial processes and their interaction with changing renewable energy supply and electricity market prices. The significant amount of output data calls for aggregation and focused visualisation to draw significant insights. But to understand how the MILP optimisation works, this section introduces the optimisation results using a high-resolution plot of one day and for one week of steel plant operation to show model dynamics. For higher-level analysis, the time series output data is sorted by renewable generation and displayed with this duration curve for the entire year. Visualisations in section 4.1.1 highlight trends, use patterns, and overall system behaviour, providing a clear picture of how the optimisation framework balances energy availability, production targets, energy prices, and flexibility restrictions. Section 4.1.2 summarises key variables pertinent to evaluating how the objectives of profit maximisation and goal load matching can be achieved in the scenarios. To demonstrate outcomes in steel plant management, its complexity, and the correlation with input variables such as wind energy production and power tariffs Section 4.1.3 does an analysis of downtime and the storage systems.

To understand the structure and operation of the model, Figure 12 illustrates the fully resolved results for a single day: Monday, March 19<sup>th</sup> in 2012 00:00 to 24:00. This example demonstrates how the model behaves when electricity prices spike with the objective of maximising profit. The first subplot shows the renewable wind generation in green, which is an external input, along with calculated power consumption of the units within the steel plant. The reduction unit, powered by flexible electrolyzers (light blue), generally compensates for fluctuations in wind generation to maintain power balance. However, brief mismatches occur when renewable output is at maximum and the steel making unit (dark blue) is in a pause between batches and battery is already fully charged. This leads to short intervals of curtailed energy.

Between 17:00 and 20:00, electricity market prices exceed 60 €/MWh, as indicated in the economics subplot at the bottom. During this period, the model opts to shut down the electrolyzers and even steel making and rolling units, capitalising on the high market price to sell electricity. This strategic feed-in results in significant deviations from the goal load, which is the mean power exchange over the whole year, as shown in the fourth subplot. Since this profit maximising scenario does not penalise load deviation, such high deviations occur. In this downtime interval consequently no new steel is produced and the cumulative steel production curve in first subplot (black) enters a plateau phase.

As indicated in the second subplot, only 100% and no partial capacity utilisation of the steel mak-

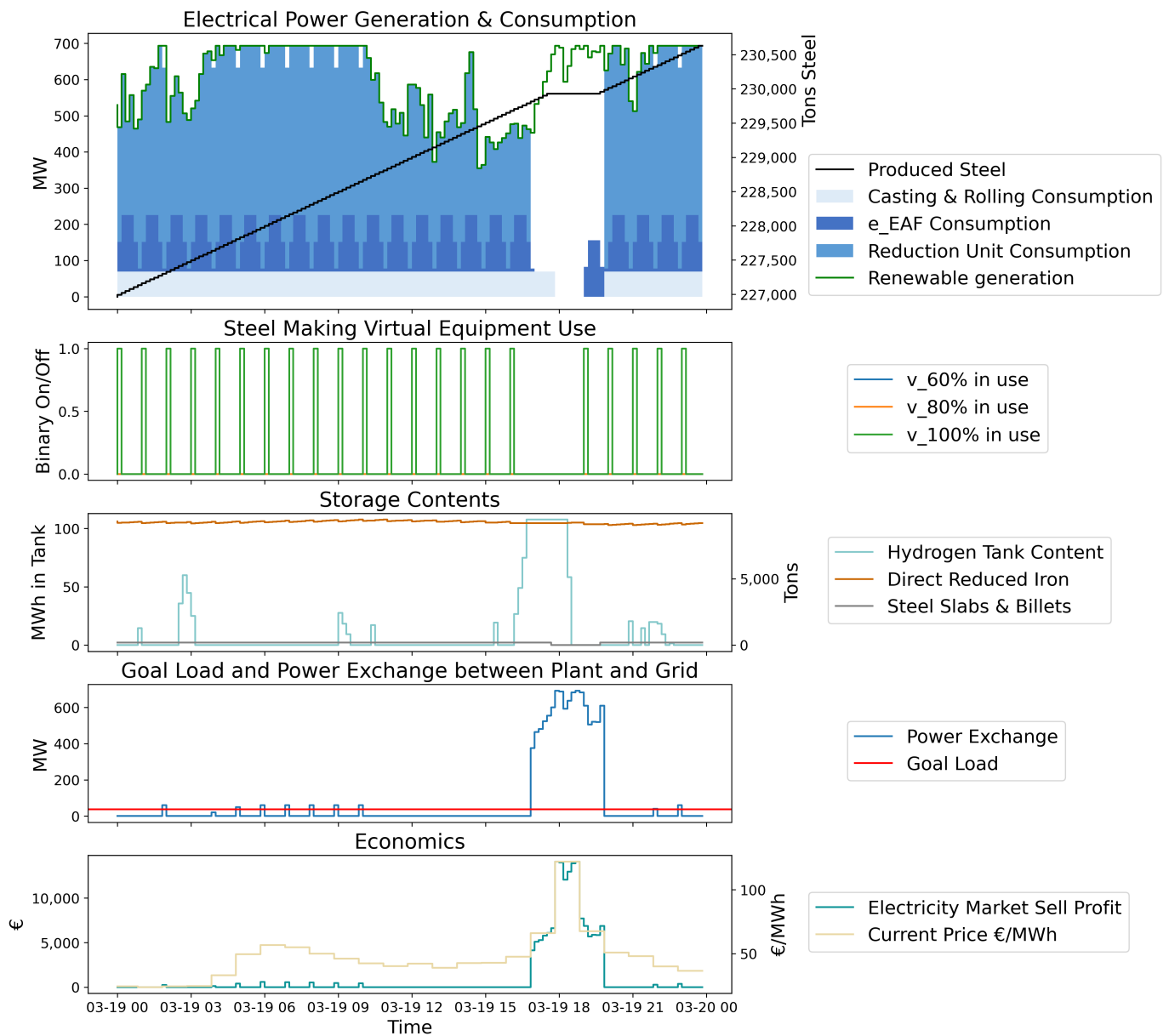


Figure 12: Ten-minute resolution Optimisation Results Monday 19th March 2012 of *Demand Response Steel Making* Steel Plant Scenario with the Objective of maximising Profit

ing unit is employed. The third subplot illustrates how hydrogen storage is strategically managed: content increases ahead of shutdown periods and is later used to produce smaller amounts of DRI, which is stored temporarily. Meanwhile, steel slabs & billets serve as intermediate storage for immediate downstream use in the rolling process.

To observe longer-term trends, Figure 13 presents the same scenario aggregated to hourly means for the week of March 19th to March 25th. Due to the aggregation method the hourly summarised EAF profile appears as a steady load (in this case 107 MW), smoothing out the respective load profiles with 10-minute interruptions and load in- or decreases. However the production downtime due to high prices on Monday the 19<sup>th</sup> March can still be observed clearly as well as a similar but shorter event on Tuesday. On Wednesday, March 21st, wind generation drops to near zero and

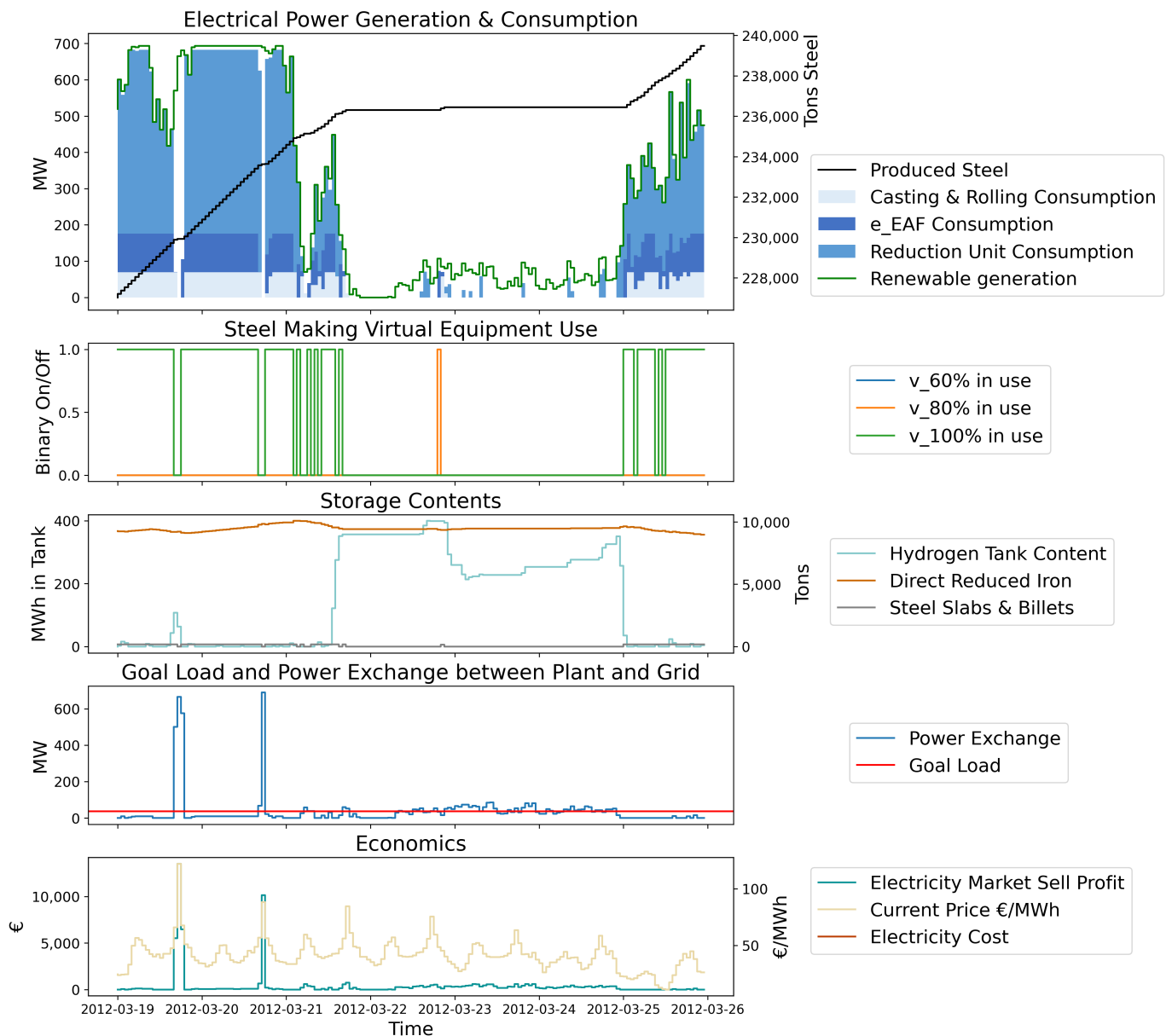


Figure 13: One-hour resolution Optimisation Results for Monday 19th till Sunday 25th March 2012 of *Demand Response Steel Making* Steel Plant Scenario with the Objective of Maximising Profit

remains low until Sunday. During this period, the plant operates only intermittently and utilises lower capacities through virtual equipments to align with limited renewable availability. The model staggers the operation of the steel making and rolling unit and avoids overlapping power demands of both units. Electrolysers are used minimally and intermittently, producing hydrogen for storage when enough renewable power, above the minimum operation capacity parameter, briefly becomes available. Over this time the hydrogen tank stays quite full with one event of significant usage for DRI production after the an 80% utilisation steel making batch. At Saturday 25<sup>th</sup> March the tank empties for another increase of DRI storage before the plant is going back to continuous production as can be seen by the increasing amount of produced steel and equipment loads in the first subplot.

#### 4.1.1 Steel Plant Scenario Model Results Hourly Sorted

In the following visualisations data is aggregated to hourly resolution and sorted by external renewable power generation as in duration curves to reveal key trends over the whole optimisation period of one year. Figure 14 illustrates the annual performance of the *Demand Response Steel Making* scenario under a profit-maximising objective. The results show a highly dynamic operational pattern where equipment use and power flows adapt to external renewable generation and electricity market signals.

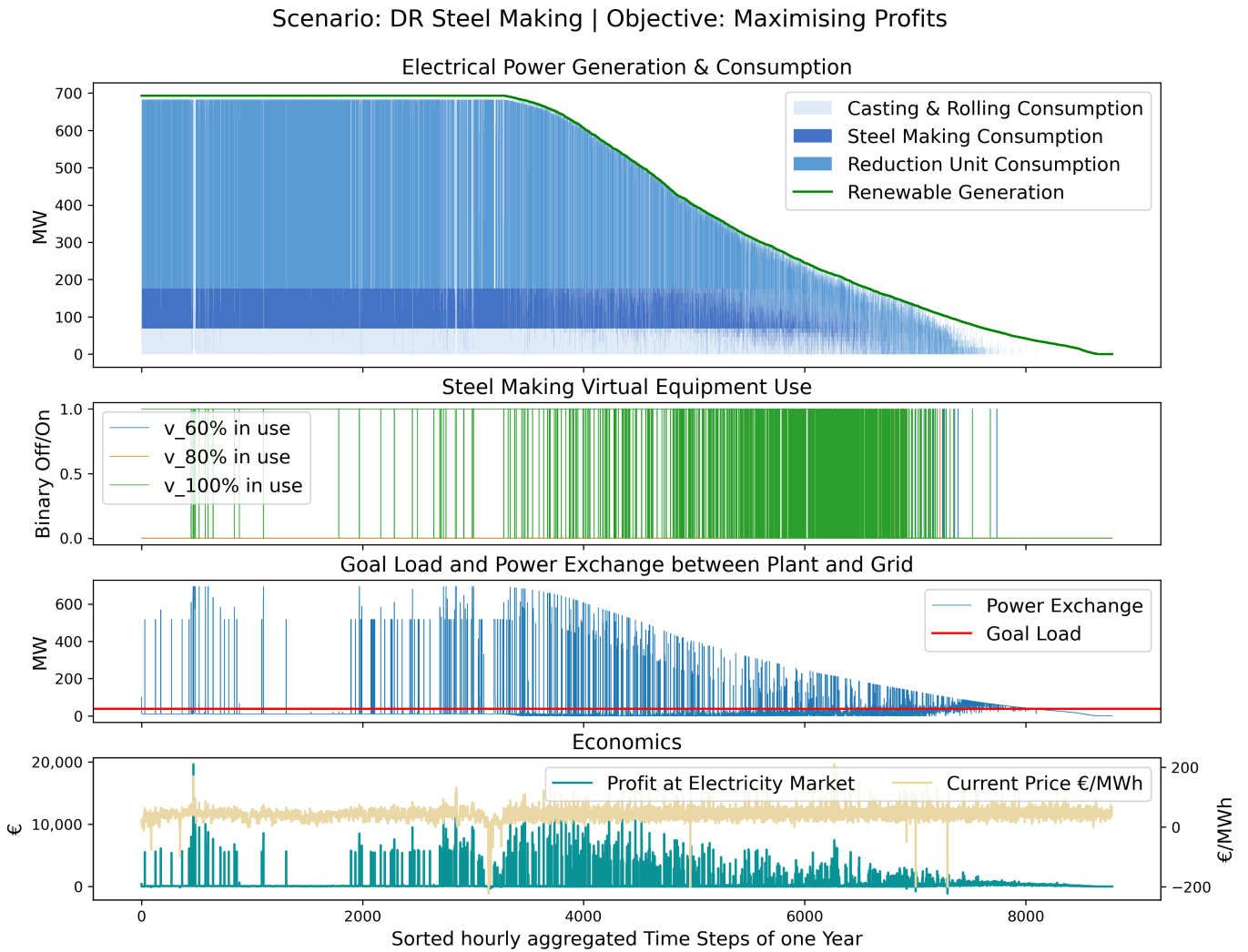


Figure 14: Sorted hourly Generation, Consumption, Virtual Equipment Use, Power Exchange and Economic Data for one year for the *Demand Response Steel Making* Steel Plant Scenario with the Objective of maximising Profits

The reduction unit, in particular, demonstrates significant operational flexibility. During periods of high wind generation, it operates either at full capacity or not at all. This pattern allows the system to feed in excess power when electricity prices are high, generating profit through market sales. Steel making and rolling unit mostly continue operating at these times utilising DRI from storage. At times of reduced renewable generation, the reduction unit scales down its operation to match

available supply and keeps shutting down entirely during price peaks. In this times of reduced renewable power generation steel making unit also exhibits adaptive behaviour. It runs more or less continuously during high renewable availability, as seen in the left part of the second subplot with a few periods of turned off steel making unit. However, as renewable generation drops, the unit begins to cycle more frequently, switching between active and inactive states. This frequent switching is visualised as dense green patterns in the virtual equipment use plot, indicating on-off transitions. Occasionally at times of really low generation, batches are processed at reduced capacities (e.g., 80% or 60%), although these are relatively rare. Economic results indicate that the highest profits are achieved during periods of moderate to high wind generation. With dropping wind generation, steel making and rolling unit are increasingly turned off also to increase electricity feed in at times of high costs. Dynamic operation of all three units enables the plant to make high profits while maintaining production requirements.

To evaluate the *Constant Steel Making* scenario with the objective of maximising profits behaviour throughout the year, Figure 15 presents the results of the optimisation aggregated hourly and sorted. In this scenario, the steel making and rolling processes operate nearly continuously as long as sufficient renewable power is available with only one steel making unit downtime at times of maximum wind generation. The reduction unit is only shut down during a price peak in December, when sufficient DRI is stored and there is no immediate need to refill the hydrogen tank. When wind generation becomes insufficient, the plant either shuts down its activity or activates the fuel cell to generate electricity from stored hydrogen, ensuring continued operation of the steel making and rolling unit.

The second subplot confirms this constant operation except for rare gaps when the entire plant is offline. These interruptions happen nearly only at times of minimal wind generation. Constant utilisation pattern is in contrast with the more flexible operation seen in the *Demand Response Steel Making* scenario. Since this scenario permits only virtual equipment representing 100% capacity utilisation and does not allow partial operation of the steel making unit, it is the only virtual equipment visualised in the subplot.

Power exchange with the grid remains low for most of the time, as the system is designed to directly consume all generated power. Occasional small feed-ins occur during peak wind or price periods. But from an economic perspective, the profits are modest. Unlike *Demand Response Steel Making* scenario, this setup seems not able to capitalise on high spot market prices by selling excess electricity as much.

The *H<sub>2</sub>-DRI Import* scenario, shown in Figure 16, differs fundamentally from the other two setups due to its possibility to draw electricity from the grid and absence of an internal hydrogen production system. This decouples the steel plant's operation from local renewable generation. Here, the steel making unit operates independently from the wind generation profile, with load levels often exceeding the available renewable power. The plant tends to run without interruptions only during periods of extremely low electricity prices (notably at hour 3,000), reflecting a cost-optimised strategy. Outside these windows, the steel making unit cycles on and off frequently, as shown in

### Scenario: Constant Steel Making | Objective: Maximising Profits

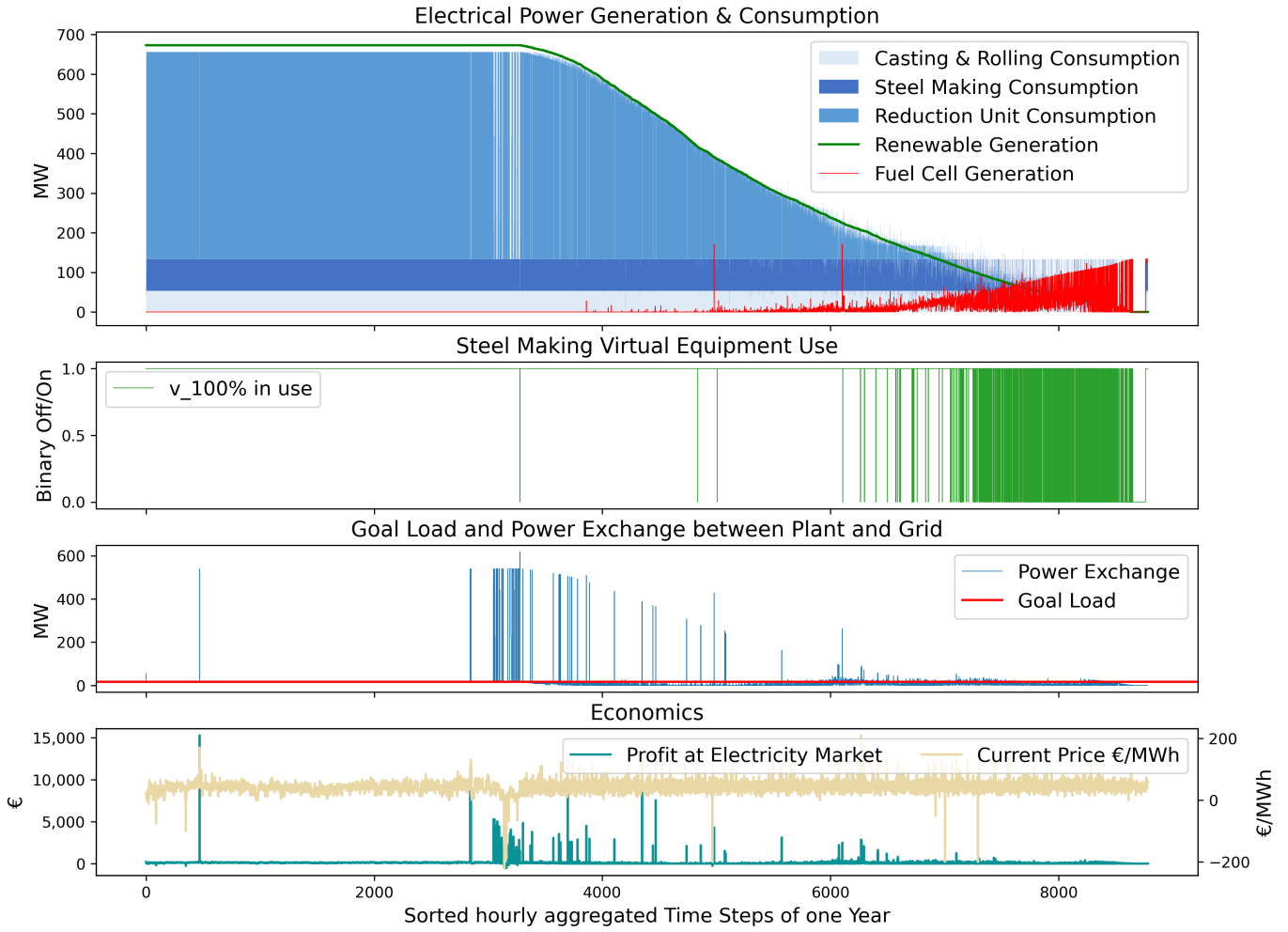


Figure 15: Sorted hourly Generation, Consumption, Virtual Equipment Use, Power Exchange and Economic Data for one year for the *Constant Steel Making* Steel Plant Scenario with the Objective of maximising Profits

the second subplot. This also shows that nearly only the virtual equipment utilising 100% capacity of the steel making unit is used. Unlike in other scenarios, the power exchange with the grid fluctuates sharply throughout the entire year. When the plant is shut down, maximum feed-in from the renewable park occurs. When the steel making and rolling units are operating, a main share of power is consumed internally. This is evidenced by the constant use of the possible bandwidth of feed in, or reliance on the grid. The absence of a reduction unit means that no additional load helps stabilise or absorb surplus power during idle periods in the steel making process and load profile. Consequently, large portions of the wind generation are fed into the grid unused. This can be seen by the large gap between wind generation and consumption in the first subplot at times of high generation. When power is drawn from the grid, depicted by a negative power exchange, the cost of purchasing electricity is shown in red in the economic subplot. During periods of negative market prices, these costs can be positive income; however, instances of negative prices in times of low enough wind generation to substantially draw electricity from the grid are rare.

### Scenario: H<sub>2</sub>-DRI Import | Objective: Maximising Profits

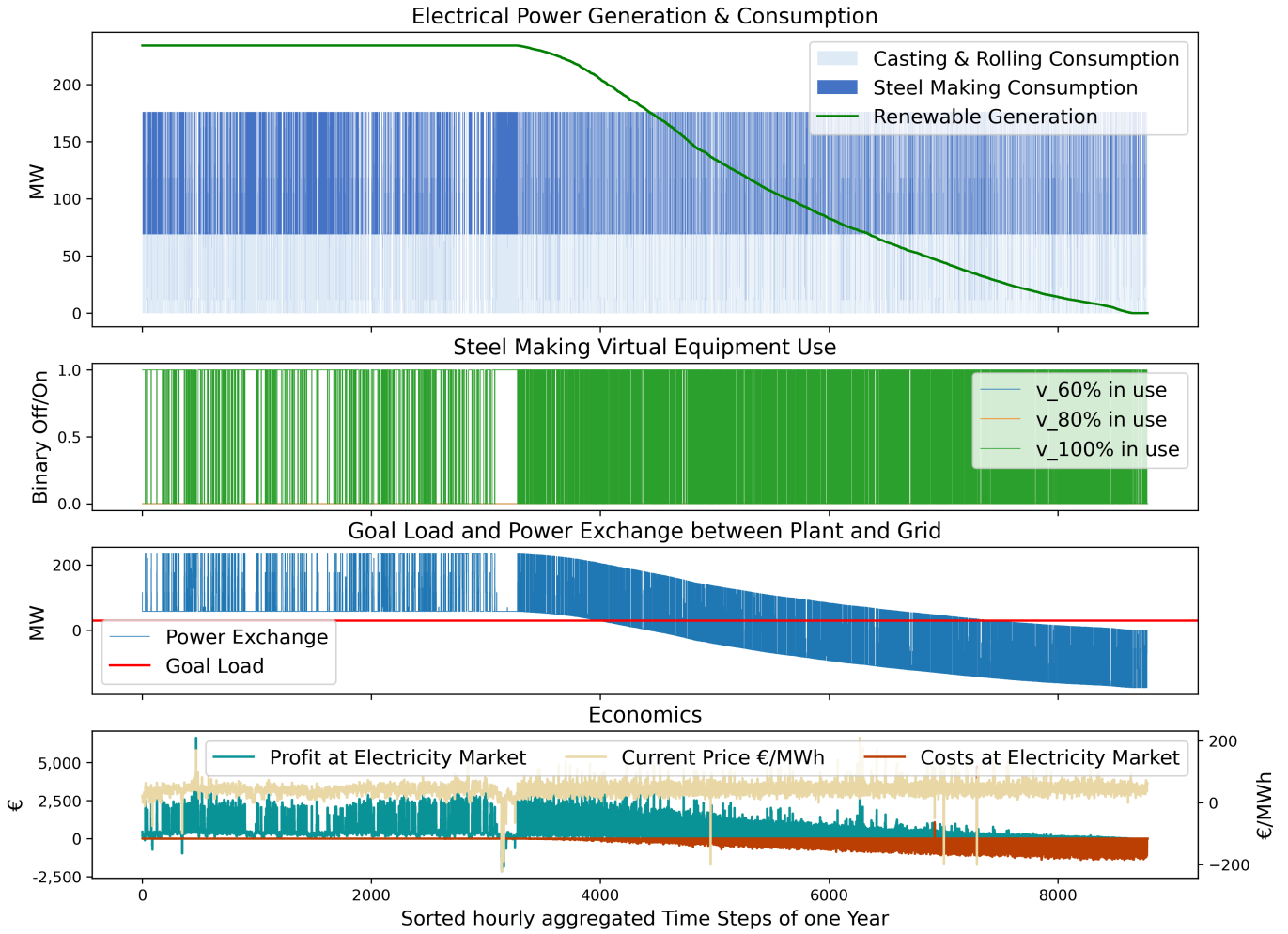


Figure 16: Sorted hourly Generation, Consumption, Virtual Equipment Use, Power Exchange and Economic Data for one year for the *H<sub>2</sub>-DRI Import* Steel Plant Scenario with the Objective of maximising Profits

Figure 17 illustrates the annual time series data for the *Demand Response Steel Making* scenario when the objective is to minimise deviation from a predefined goal load. The key difference compared to profit-driven scenarios is the consistent gap between power consumption and renewable generation, which reflects the plant's intent to maintain a constant and predictable grid feed-in. This behaviour is mainly enabled by the flexible operation of the reduction unit and its electrolyzers. The steel making and rolling units generally run continuously during periods of high wind availability. However, as wind generation decreases, these units are switched on and off more frequently, and utilisation of 80% and 60% virtual equipment increases. The minimum operational capacity in the reduction unit (100 MW) results in notable deviations from the goal load at very low renewable generation. The flexibility of the reduction unit is missing at these times and either all electricity is consumed or high amounts are fed into the grid. As the objective is not economic optimisation, market profits are marginal and due to the constant feed in profit structure matches current prices, therefore the yellow and the petrol line often overlap in the last subplot.

### Scenario: DR Steel Making | Objective: Minimise Goal Load Deviation

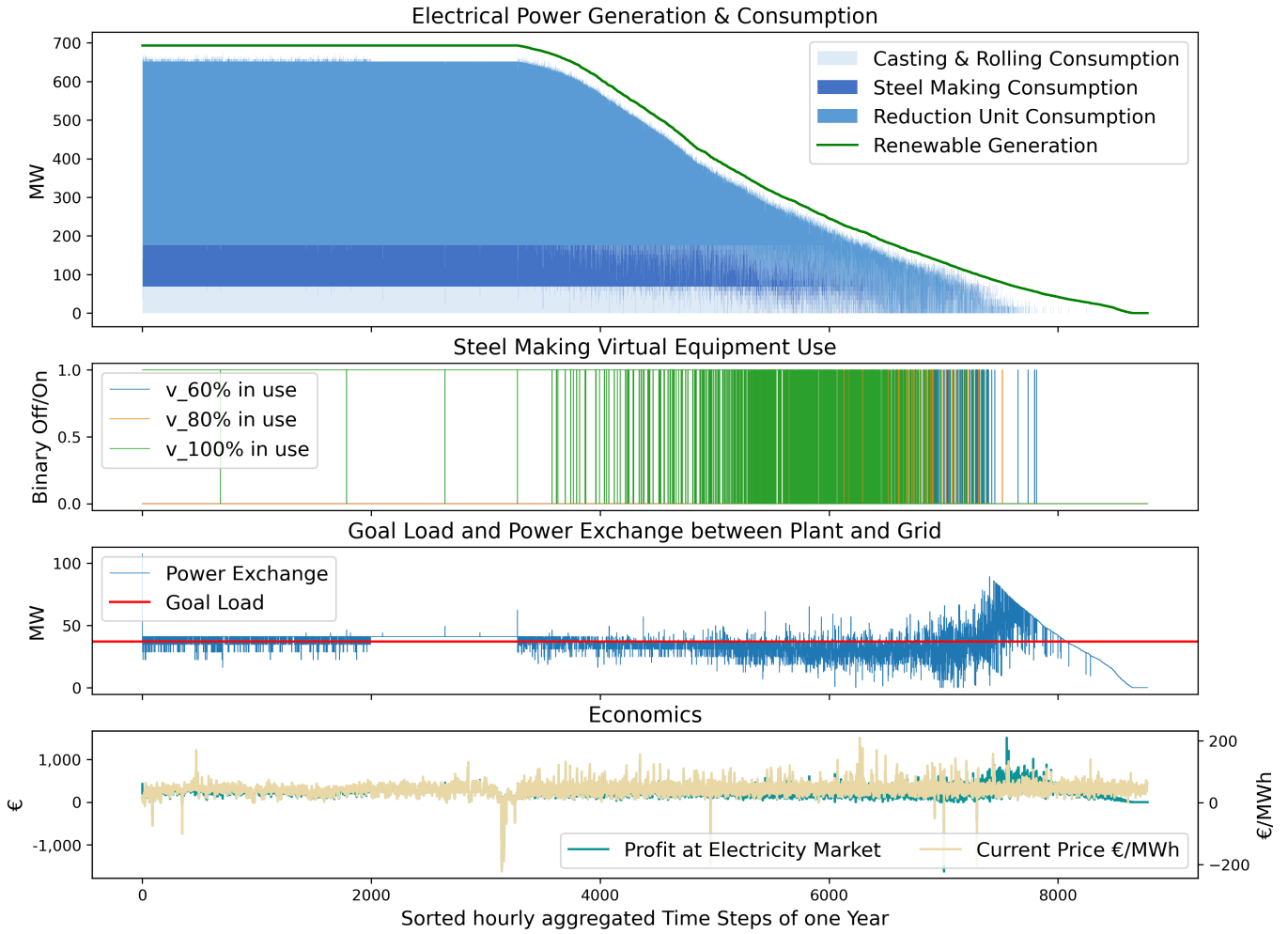


Figure 17: Sorted hourly Generation, Consumption, Virtual Equipment Use, Power Exchange and Economic Data for one year for the *Demand Response Steel Making* Steel Plant Scenario with the Objective of minimising Deviation from Goal Load

The *Constant Steel Making* scenario in Figure 18 appears to consistently meet the goal load during periods of maximum wind generation, but this is due to hourly data aggregation. When the data is examined at a 10-minute resolution, it becomes clear that during pauses in the steelmaking process, electricity exchange exceeds the goal load by approximately 20 MW, whereas during active production phases, all available energy is consumed internally, resulting in no grid exchange and a deviation from the goal load. The average of these fluctuations gives the illusion of consistently matching the goal load. In two instances a square profile can be observed and it seems the load deviates from the goal load the whole time. However this is also an artifact of hourly aggregation. In this periods within the one hour time steps, either in the first case the reduction unit is not operating at full capacity during idle EAF time steps, or in the second the fuel cell supplements electricity during an EAF batch, so it is matching the goal load during that period. These mechanisms, however, only function when the hydrogen is not required for later use. When wind generation decreases, the system must use nearly all available power for operations, limiting its ability to reliably match the goal load compared to the *Demand Response Steel Making* scenario.

### Scenario: Constant Steel Making | Objective: Minimise Goal Load Deviation

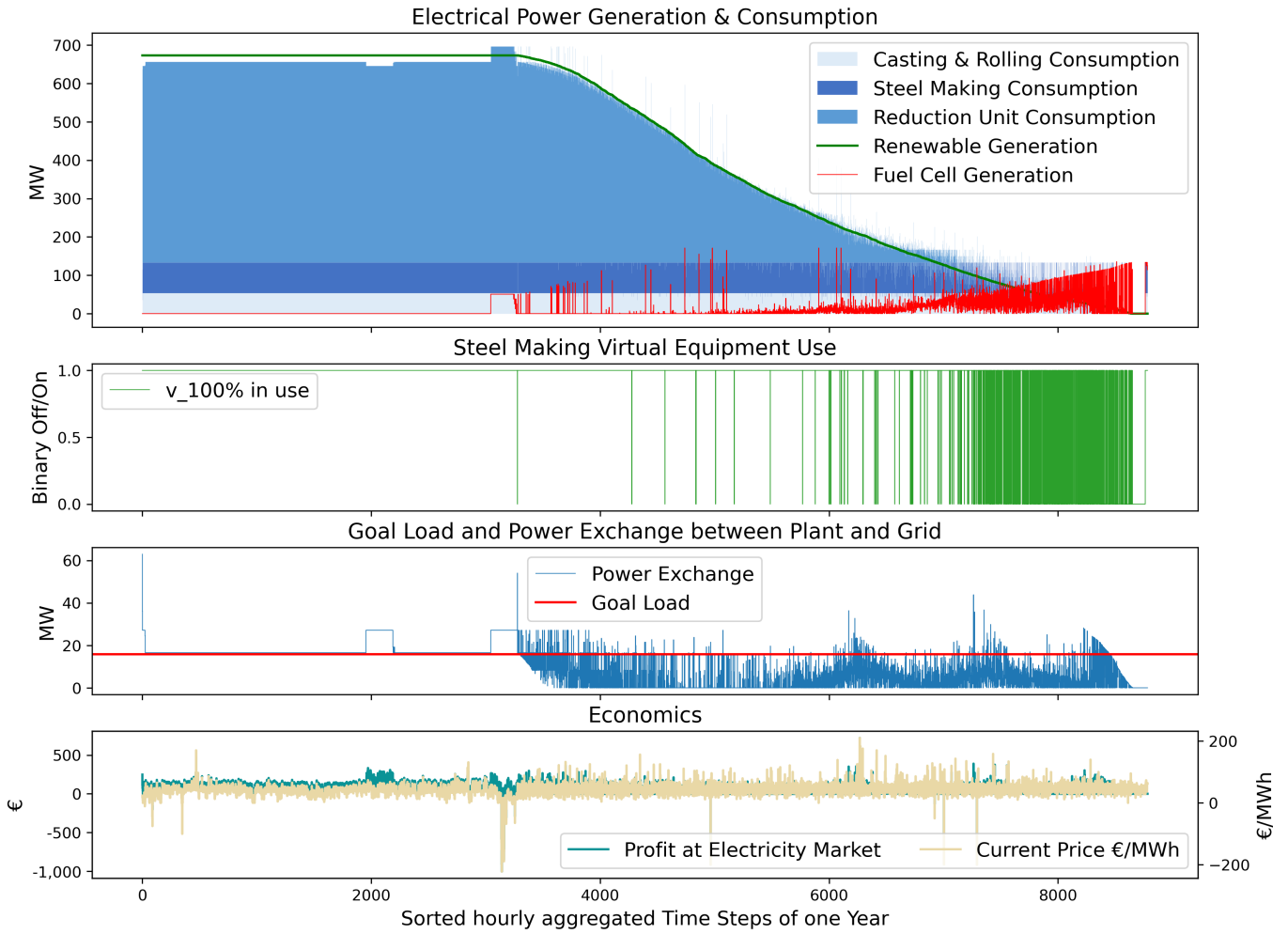


Figure 18: Annual hourly Generation, Virtual Equipment Use, Power Exchange and Economic Data for *Constant Steel Making* Steel Plant Scenario with the Objective of Minimising Deviation from Goal Load

Figure 19 presents the *H<sub>2</sub>-DRI Import* scenario under the same objective. In contrast to its profit-optimised version, this scenario matches more the wind generation profile and relies less on grid electricity to meet operational demands. Steel production batches are scheduled at times of renewable power generation and remains almost constant while renewable power generation stays above the plant's rated load (176 MW). When generation falls below this threshold, grid electricity supports the facility and the steel making unit shows more downtimes. Virtual equipment use appears to apply only maximum and minimum capacity utilisation, no 80%. As wind power decreases, 60% capacity utilisation batches are used, initially with rolling unit and then more intensively in an alternating mode, as shown by the intensifying blue bars at the end of the second subplot. This scenario accomplishes a significantly more stabilised power exchange with the grid than its profit-oriented counterpart, thereby preventing the bouncing of power exchange across the entire bandwidth of -200 MW to +200 MW. Nevertheless, the target load's deviation continues to rise when power is drawn from the grid during periods of low wind generation.

### Scenario: H<sub>2</sub>-DRI Import | Objective: Minimise Goal Load Deviation

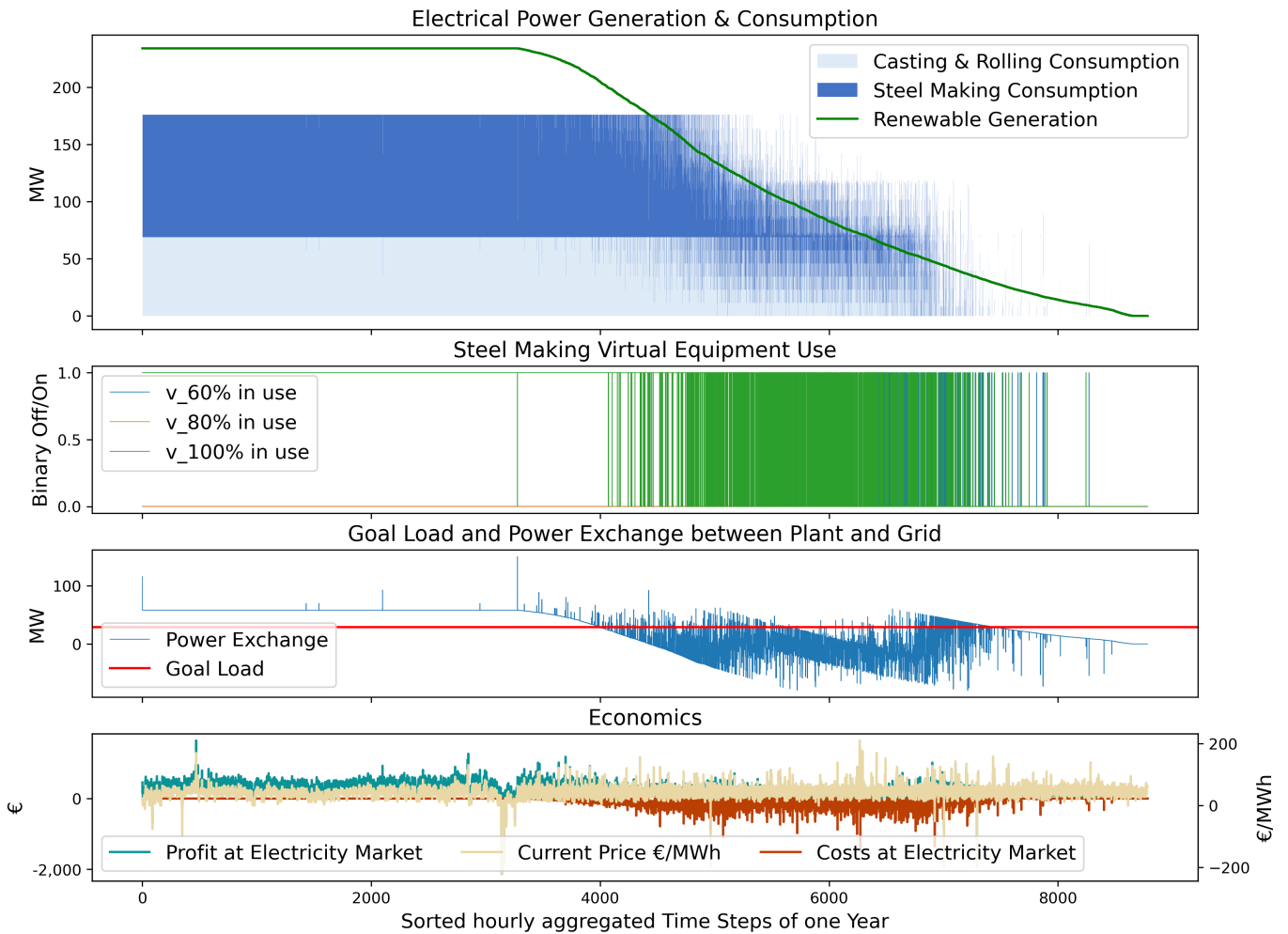


Figure 19: Sorted hourly Generation, Consumption, Virtual Equipment Use, Power Exchange and Economic Data for one year for the *H<sub>2</sub>-DRI Import* Steel Plant Scenario with the Objective of minimising Deviation from Goal Load

#### 4.1.2 Objective Function Results

To show how well scenarios achieved the given objectives Table 4 summarises key outcome metrics from the MILP optimisation for each steel plant scenario and objective function. These metrics include model quality through MIP gap, energy efficiency, electricity market interaction, and load matching performance.

The MIP gap value indicates the deviation between the best-known solution and the optimal bound of a model. All values are acceptably low below 1% except for the *Constant Steel Making* scenario reaches 2.43% and 1.15%. This likely results from high computational demands caused by the need to fully consume all available energy, leaving little room for optimisation leeway.

Electricity market results show strong variation. When maximising profit, the *Demand Response*

*Steel Making* scenario achieves the highest mean electricity selling price of 63 €/MWh, benefiting from its operational flexibility. In contrast, the *Constant Steel Making* scenario sells electricity for only 41 €/MWh, while the *H<sub>2</sub>-DRI Import* model is positioning itself in the middle. When minimising deviation from the goal load, price differences narrow and selling prices align with the market average price, since electricity exchange timing becomes subordinated to matching the target load. The energy consumption per ton of steel is highest for the *Constant Steel Making* scenario due to energy losses in its storage system, particularly the fuel cell converting hydrogen back into electricity. The *H<sub>2</sub>-DRI Import* scenario shows the lowest energy consumption, but this figure excludes reduction unit operation and associated hydrogen production, which lies outside the system boundary.

Table 4: MILP Optimisation Results reflecting Objective Performance for each Objective and Steel Plant Scenario

| Objective<br><br>Steel Plant Scenario |         | Maximise Profit |              |                            | Minimise Deviation of Goal Load |              |                            |
|---------------------------------------|---------|-----------------|--------------|----------------------------|---------------------------------|--------------|----------------------------|
|                                       |         | DR STM          | Constant STM | H <sub>2</sub> -DRI Import | DR STM                          | Constant STM | H <sub>2</sub> -DRI Import |
| MIP Gap                               | %       | 0.03            | 2.43         | 0.02                       | 0.53                            | 1.15         | 0.07                       |
| Mean Profit Selling Electricity       | € / MWh | 63              | 41           | 50                         | 42                              | 39.3         | 40.6                       |
| Mean Cost Buying Electricity          | € / MWh | x               | x            | 37                         | x                               | x            | 45                         |
| Energy per Unit Steel                 | MWh / t | 3.53            | 3.60         | 1.05                       | 3.54                            | 3.66         | 1.06                       |
| Mean Deviation from Goal Load         | MW      | 53              | 24           | 94.66                      | 11.3                            | 17           | 41                         |
| Standard Deviation                    | MW      | 92              | 52           | 72                         | 9                               | 8            | 35                         |
| Variance                              |         | 8472            | 2736         | 5250                       | 211                             | 68           | 1277                       |

Energy efficiency is calculated by total amount consumed divided by produced amount of steel. The results show that *H<sub>2</sub>-DRI Import* has lowest energy consumption as reduction unit is outside of the modelled system boundaries. When comparing the used energy per produced unit of steel, it is also essential to consider the iron making process requires in the other two scenarios 2.48 MWh/t. Adding this levels out the differences between this and the *Demand Response Steel Making* scenario for both objectives. *Constant Steel Making scenario* consistently consumes most energy due to losses in the storage process, which is highest for the objective of minimising deviation.

The ability to follow a predefined goal load also varies drastically. The *H<sub>2</sub>-DRI Import* scenario performs worst with a mean deviation of 41 MW and also highest standard deviation and variance. Its limited flexibility and lack of reduction unit complicate adaptation to changing conditions. The *Demand Response Steel Making* scenario again performs best with achieving lowest mean deviation of only 11.3 MW and a small minimal spread ( $\sigma = 9$  MW and variance = 211). The *Constant Steel Making* scenario, despite its stable operation, shows a higher mean deviation (17 MW) but lower variance of 68, indicating a consistent but moderate mismatch with the target load.

Among all the evaluated configurations, the *Demand Response Steel Making* scenario demonstrates highest performance across both objectives. It effectively utilises its inherent flexibility, achieving the highest electricity market revenues when optimising for profit and the best load matching behaviour when deviation minimisation is prioritised. Additionally, while the *H<sub>2</sub>-DRI Import* scenario appears more energy-efficient in raw terms, this is largely due to changed system boundaries omitting the energy demands of DRI production and transportation.

To have a deeper look into the reasons for the differences of objective performance Figure 20 presents a detailed view of power exchange between plant and grid as a function of renewable wind generation for all steel plant scenarios and objectives. Each data point corresponds to one time step in the modelled period and is coloured based on the corresponding electricity price at this step. A striking feature of the plot is the presence of distinct linear patterns for each scenario. These patterns represent different operational configurations of the plant with diverging sets of active units and load levels of the virtual equipment profiles.

Starting with the *Demand Response Steel Making* scenario optimised for profit maximisation, five discrete levels of power exchange can be observed as renewable generation increases. The lowest constant line at zero MW exchange shows time steps when the plant consumes available wind power entirely. The series of four upward-sloping lines depict increasing feed-in levels, each corresponding to a specific configuration of active units. For example, the bottom first line reflects periods where the steel making unit operates at maximum load and reduction unit is fully turned off for generating feed in profits. The subsequent lines represent combinations of steel making load behaviour involving battery charge or discharge, or partial shutdowns of the steel making or rolling units. The uppermost line visualises full feed-in with all units off. The colour of the lines represents the electricity price at each time step, visually illustrating how well the scheduling can fit feed in event to electricity prices. This illustrates the scenario's great flexibility potential, as it efficiently matches electricity use and production with price signals as well as renewable energy availability. At high generation levels, another small upward sloping pattern emerges above the zero line, reflecting the steel making unit's 20-minute EAF pauses. During these intervals, the reduction unit operates at full capacity, the battery is fully charged, and the remaining power cannot be consumed, resulting in a small excess feed-in.

Interestingly, the reduction unit in this scenario exhibits limited operational flexibility: it operates

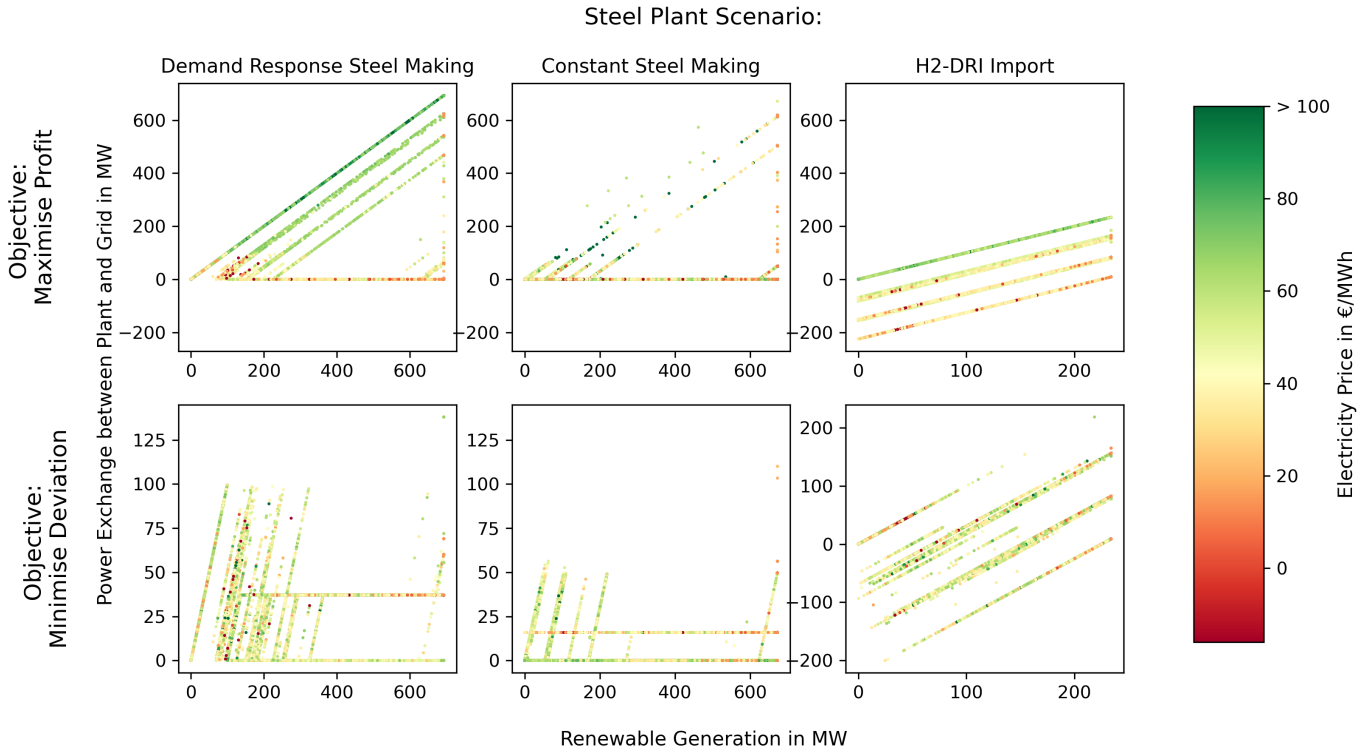


Figure 20: Power Exchange in Relation to Renewable Generation with the current Electricity Price indicated by colour. A positive exchange means a feed-in into the grid and sale of electricity, a negative exchange means drawing electricity from the grid

either at max or min capacity, or is completely turned off. Only at times of peak renewable generation does the reduction unit show partial load behaviour, represented by the barely visible, also broken vertical line at the end of the graph.

In the *Constant Steel Making* scenario, a similar structural pattern appears, but with much fewer feed in events at higher wind availability. Most visible and continuous is the base line representing full power consumption of the plant. This scenario also begins with four distinct upward-sloping lines similar to the first, but due to fewer feed-in events and differing load behaviour of the steel making unit, two lines end early. Unlike the previous scenario, the colour distinction of the lines is less, indicating a weaker alignment between high feed-in and high electricity prices. This suggests the scenario is less effective at utilising its flexibility to match production with optimal price conditions. However this scenario manages to consume the entire available power at times of low prices. A notable characteristic, however, is the rare occurrence of feed-in exceeding wind generation, which points to electricity being produced from stored hydrogen via fuel cells and sold during high-price periods—a unique flexibility feature of this setup.

For the *H<sub>2</sub>-DRI Import* scenario, the constant line at zero MW exchange is absent due to the lack of a reduction unit, which prevents full power consumption. Only the four upward sloping lines are visible, each corresponding to different combinations of steel making or rolling unit states and time steps within the virtual equipment load profiles. The lines also reach negative exchanges

indicating extraction of electricity from the grid. Here the colour distinction between the lines is also clear, indicating an effective management of the available flexibility.

For scenarios with a reduction unit, the objective function significantly changes the structure of the graph. For *Demand Response Steel Making* the use of virtual equipment becomes more frequent, particularly at low generation levels. As described above this adds new configurations and in this case new lines. Another addition to the plot is a new constant line indicating the matching of feed in with the given goal load. This scenario similar to the *Constant Steel Making* scenario manages to match goal load especially at times of medium to maximum wind generation. However in these times steel plant can also totally consume available power resulting in the a line at the bottom of the graph. High deviation from the goal load mostly occur in times of reduced wind generation when steel making unit is running and the flexibility of reduction unit can not balance the distance to goal load as the available power falls below minimum capacity of the unit. These high deviation at times of low wind generation are complemented by a minimal amount of high deviation at times of maximum wind generation, representing events in the steel making unit load profile, when EAF is turned off and steel making unit consumes only its base load. At those times reduction unit is running at maximum but the available capacity is not sufficient the increase power consumption and match level of required feed in. What becomes evident when comparing the lower left and centre sub-figures is the disparity in goal load matching indicators between the two scenarios as depicted above in Table 4. Although the *Demand Response Steel Making* scenario more reliably achieves the target load due to a smaller mean deviation, the departure from the zero line, when all generated power is utilised, is greater than that in the *Constant Steel Making* scenario. This illustrates the outcome of different values of given goal loads and explains the a reduced variance of deviation for the latter situation.

When discussing the bottom right sub-figure, it is vital to emphasise the distinct y-axis scales. This is due to the negative exchange rate when electricity is pulled from the grid. The missing second baseline clearly indicates that this scenario is unable to continuously match the goal load. This pattern is an attempt to coordinate the electrical feed-in with the goal load in order to stabilise power exchange. As a result of the missing reduction unit, this scenario relies on optimal conditions to reduce deviation to zero.

Most evident result from this analysis is the strong dependence of load behaviour on the installed units and equipments influencing the electricity consumption pattern. Especially the fluctuation within steel making load profile has a significant influence on the deviation in combination with maximum available reduction unit capacity.

### 4.1.3 Operation Management of Steel Plant Scenarios

This analysis focuses on key variables relevant to steel plant management, its complexity and the relationship with input parameters such as wind generation and electricity prices. One particularly significant operational event is the complete shutdown of the steel plant, characterised by zero load across all units. Such full downtimes are drastic events and occur across multiple consecutive time steps. Downtimes are induced by either low wind availability or high electricity prices incentivising selling unused electricity instead of producing steel. The amount and duration of these events serves as an indicator of their severity and the complexity to operate the steel plant with this operation mode.

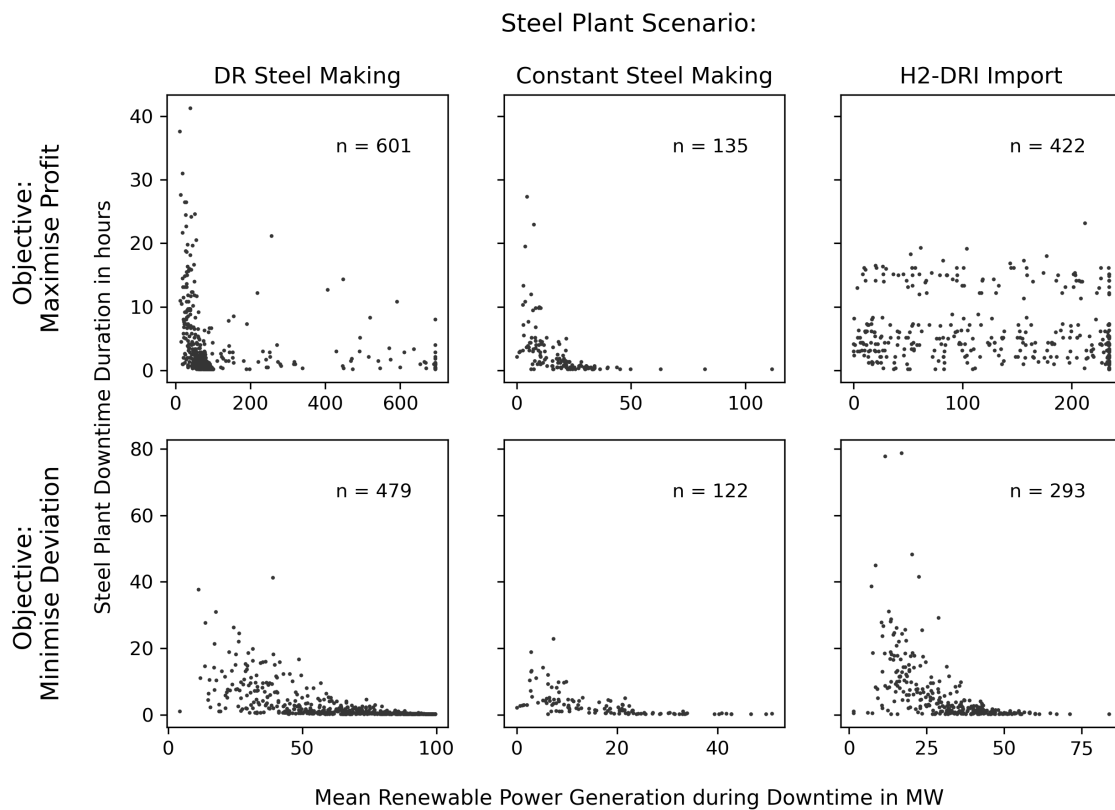


Figure 21: Distribution of Steel Plant Downtimes Duration in relation to the Renewable Power Generation during the Downtime

Figure 21 presents, for each steel plant scenario and optimisation objective, individual data points representing a period of steel plant downtime. Each point captures the average renewable generation during the downtime event and its corresponding duration.

The *Demand Response Steel Making* scenario exhibits the highest number and lengths of downtimes, while the *Constant Steel Making* scenario shows the fewest. Within each scenario, the number of downtimes is lower with the objective of minimising deviation from a predefined target load. This happens as the model is incentivised to run longer and use its flexibility potential while for maximising profits it shuts down.

In the Demand Response scenario optimised for profit, many short downtime events occur during

periods of low wind availability, typically between 0 MW and 100 MW. But there is also a significant amount of downtimes during times of higher generation. With increasing wind generation downtime duration decreases but stays quite high with a maximum duration of 9 hours, even when wind generation is at its peak. The longest downtimes above 40 hours are observed when wind availability is very low, highlighting a strong link between resource scarcity and plant shutdown. A similar pattern emerges for the *Constant Steel Making* scenario, where long downtimes also align with low wind conditions. In this case, no downtimes occur when wind generation exceeds roughly 100 MW, and most events take place when average wind generation drops below 50 MW. However the amount and also the duration of downtimes in this scenario is significantly lower. The *H<sub>2</sub>-DRI Import* scenario also displays downtime events at high wind outputs up to 230 MW. But the duration of these downtimes does not exhibit a clear relationship with wind availability. This is expected, as the ability to draw electricity from the grid offers the scenario independence of the renewable generation.

When minimising deviation from a goal load all scenarios show broadly similar behaviour. Downtime events only occur when wind generation falls below a certain threshold with quickly increasing duration for reduced generation. This is even now the case for *H<sub>2</sub>-DRI Import* scenario which is also exhibiting the longest downtimes of 80 hours but the main amount of downtimes is really short and takes place at mean wind generation between 50 and 25 MW. In the *Demand Response Steel Making* scenario, downtimes occur when generation falls below 100 MW, most frequently at wind levels between 50 MW and 100 MW. Whereas in the *Constant Steel Making* scenario thresholds are significantly lower with downtimes only scheduled in times of mean renewable generation below 50 MW.

Overall, the analysis highlights the critical influence of renewable generation availability on the frequency and duration of plant downtimes. Periods of low wind availability consistently lead to more frequent and longer shutdowns. This stresses the operational challenges of integrating variable renewable energy into continuous industrial processes. Even the plant with a large storage system requires downtimes, however for shorter time and less frequent.

To complement the previous analysis, the influence of electricity prices on plant downtime is analysed in Figure 22. Overall, no strong relation between electricity price and downtime duration is observed. The distribution of electricity prices during downtimes largely reflects the general distribution of prices throughout the year, with most events occurring around the mean price of approximately 50 €/MWh. Consequently, the majority of downtimes, including the longest ones occur at times when electricity prices are average.

An exception is found in the *H<sub>2</sub>-DRI Import* scenario under the objective of profit maximisation. Here, downtimes begin to appear only when electricity prices exceed roughly 50 €/MWh, and the longest downtimes occur during periods of even higher prices above 75€/MWh. This behaviour likely reflects the scenario's ability to draw electricity from the grid, allowing more flexibility to strategically schedule downtimes during economically beneficial periods.

In contrast, the *Demand Response Steel Making* and *Constant Steel Making* scenarios show

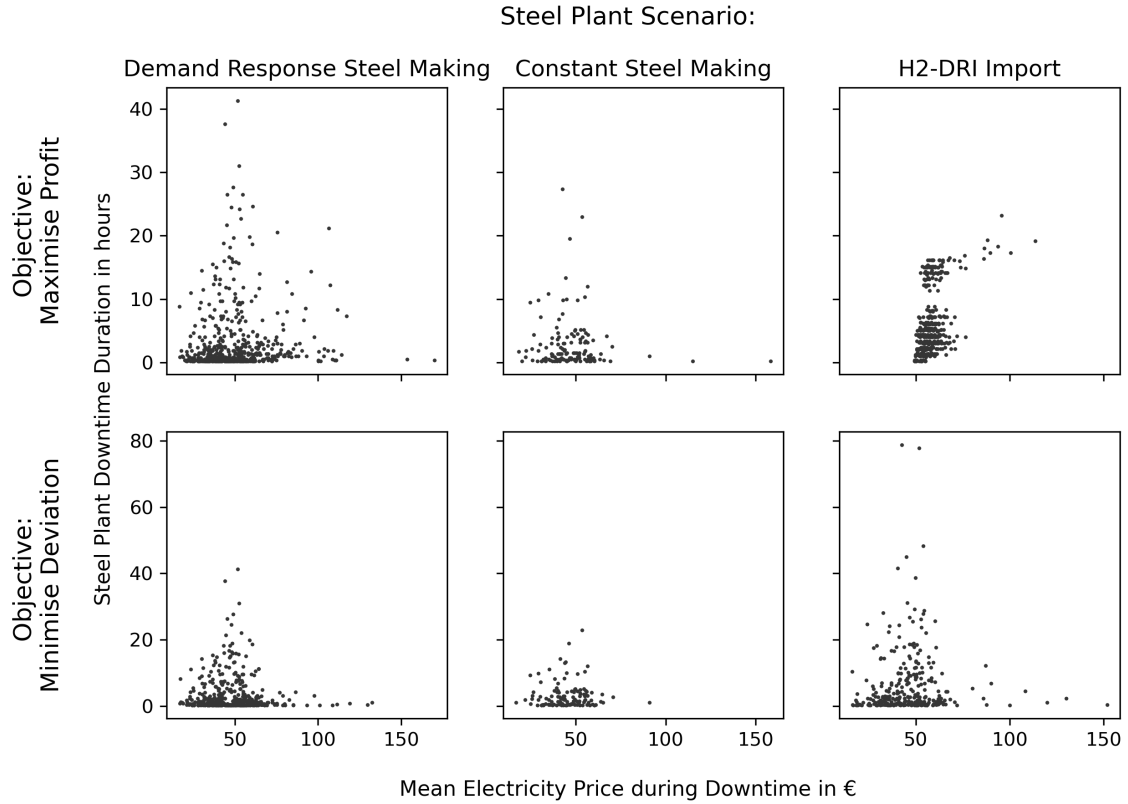


Figure 22: Distribution of Steel Plant Downtimes Duration in relation to the Electricity Price during the Downtime

limited ability to shift downtimes in response to price signals. Nonetheless, some level of responsiveness is shown, especially in the *Demand Response Steel Making* scenario optimised for profit. In this scenario a limited amount of longer downtimes are observed during periods of high electricity prices around 100 €/MWh, unlike the corresponding model focused on minimising deviation from the goal load, where such behaviour is nearly absent. This suggests that while price responsiveness is more constrained in these scenarios, limited optimisation of downtimes for economic benefit is still feasible.

Table 5 summarises the utilisation of units along with their operational and downtime periods to illustrate the correlation between reduction and the downtimes of steel making units. This is conducted to provide context regarding their average used capacities and overall plant downtime between the scenarios and objectives. Considering reduction unit behaviour, its mean power consumption is higher in the *Constant Steel Making* scenario than in the Demand Response variant. This difference is mainly due to the larger installed capacity of the reduction unit and the additional hydrogen needed for electricity generation via the fuel cell. Despite these differences, total runtime for the reduction unit remains similar between both scenarios under the profit-maximising objective. However, when minimising deviation from the target load, the reduction unit in *Demand Response Steel Making* scenario operates for a longer duration. This is because the flexibility of the electrolyser is primarily utilised to stabilise the load profile rather than being shut down for profits during peak price periods.

Table 5: MILP optimisation Unit Utilisation and Downtimes for each Objective and Steel Plant Scenario

|                            |    | Maximise Profit |              |                            | Minimise Deviation of Goal Load |              |                            |
|----------------------------|----|-----------------|--------------|----------------------------|---------------------------------|--------------|----------------------------|
|                            |    | DR STM          | Constant STM | H <sub>2</sub> -DRI Import | DR STM                          | Constant STM | H <sub>2</sub> -DRI Import |
| Mean Power Reduction Unit  | MW | 395             | 420          | x                          | 363                             | 414          | x                          |
| Runtime Reduction Unit     | h  | 6,275           | 6,217        | x                          | 6,862                           | 6,479        | x                          |
| 60% turnons                |    | 11              | x            | 2                          | 75                              | x            | 243                        |
| 80% turnons                |    | 17              | x            | 0                          | 89                              | x            | 3                          |
| 100% turnons               |    | 5,940           | 8,000        | 5,959                      | 5,844                           | 8,000        | 5,841                      |
| Runtime Steel Making Unit  | h  | 5,968           | 8,000        | 5,961                      | 6,008                           | 8,000        | 6,058                      |
| Amounts of Total Downtimes |    | 602             | 135          | 422                        | 479                             | 122          | 293                        |
| Total Downtime             | h  | 1,860           | 382          | 2,460                      | 1,420                           | 377          | 1,878                      |

For the steel making unit the constant operation is clearly visible in the *Constant Steel Making* scenario, where it runs continuously at full capacity, both in terms of power and duration. This reflects the limited operational flexibility inherent in the setup. In contrast, the *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* scenarios demonstrate more dynamic operational behaviour. The differences between the two optimisation objectives are particularly noticeable in these configurations. When minimising load deviation, steel making flexibility, meaning virtual equipment is used more frequently, especially during periods of low wind availability. While *Demand Response Steel Making* deploys 80 and 60% capacity for similar amount of times, *H<sub>2</sub>-DRI Import* scenario predominantly uses 60% steel making capacity utilisation. As a result of steel making flexibility usage, the runtime of the steel making unit increases while its mean power consumption decreases slightly. Nonetheless, the impact remains moderate, as the majority of batches are still processed in maximum capacity virtual equipments.

Overall, the *H<sub>2</sub>-DRI Import* scenario experiences the longest total downtime, as it does not include an internal reduction unit and is therefore more exposed to external energy constraints. Conversely, the *Constant Steel Making* scenario shows significantly shortest downtimes due to its inflexible and continuous operation. Notably, all steel plant configurations demonstrate longer runtimes when the objective is to minimise load deviation.

Another important operational result is the use of storage systems over the course of the year, specifically the storage of DRI and hydrogen, as well as the flexibility reflected in monthly steel production. Figure 23 illustrates the mean monthly storage content and steel production for each scenario. The *H<sub>2</sub>-DRI Import* Scenario does not require hydrogen storage, and DRI storage is not modelled, as DRI is assumed to be supplied externally and always available. As a result, hydrogen tank and DRI storage content remain zero for this scenario.

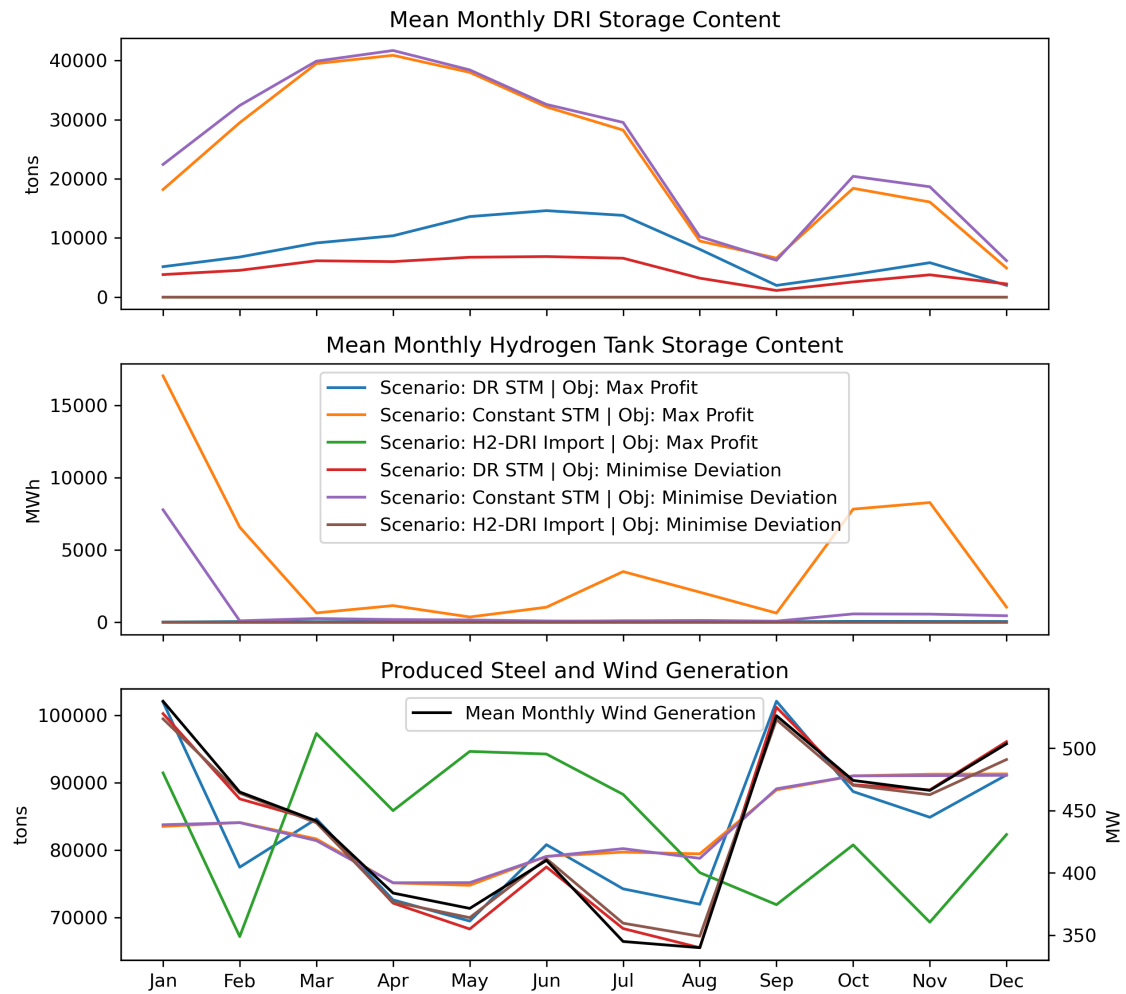


Figure 23: Monthly mean Storage Content and Steel Production for each Steel Plant Scenario and Objective

For the *Constant Steel Making* scenario, a full hydrogen tank is assumed at the model's start to ensure operational feasibility. This allows for significant DRI production early in the year, with storage peaking around April and remaining high until July. DRI levels then drop sharply, nearly depleting by September, before being replenished in October and November and completely emptied in December. This pattern is nearly identical for both optimisation objectives. Notably only one larger strategic seasonal hydrogen storage event occurs in this scenario when the tank is filled to approximately 10 GWh in October and then fully emptied by December.

In contrast, the *Demand Response Steel Making* scenario operates without large hydrogen tanks

or fuel cells and relies exclusively on DRI storage, which cannot regenerate electricity but still acts as a seasonal buffer. Here DRI storage follows a similar seasonal trend to Constant Steel Making, with accumulation over spring and summer and depletion in August and September due to lower renewable availability. However, the scenario optimised for minimising goal load deviation only fills DRI storage to roughly half the level compared to the profit-maximising run. By the end of the year, both *Demand Response Steel Making* and *Constant Steel Making* scenarios minimising goal load deviation still retain significant DRI volumes of 3,250 tons and 7,430 tons respectively. This overproduction is produced as the flexibility potential of the reduction unit is required for load balancing even though produced hydrogen or DRI is not required. This highlights the potential of reduction units to serve for load balancing or as an energy storage by converting flexible electricity input into stored iron sponge, which holds about 3.3 MWh of embedded electricity per ton and is later used in steel making unit during times of lower power generation.

Steel production patterns vary across scenarios. *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* scenarios demonstrate high monthly flexibility adjusting production close to the pattern of available renewable electricity. Conversely, the *Constant Steel Making* scenario maintains a more stable production rate. Most scenarios exhibit increased production in the first quarter from January to March and fourth quarter September to December, in response to better energy conditions. The exception is the *H<sub>2</sub>-DRI Import* scenario with profit maximisation, which shifts production toward the summer months. This deviation results from its stronger dependence on grid electricity pricing, allowing for strategic production when market conditions are favourable rather than following renewable generation patterns.

## 4.2 Prospective Life Cycle Assessment

This pLCA assesses the environmental impact of switching to hydrogen-based steel manufacturing for each steel plant scenario and two comparison cases. The analysis examines the effects of producing 1kg of low-alloyed, hot-rolled steel in 2023, 2030, 2040 and 2050. Impacts are compared to the existing BF-BOF steel production pathway and H<sub>2</sub>-DRI-EAF production, using background electricity grid mix scenario. To investigate differences between steel plant setups, scenario-specific infrastructure construction is investigated in a contribution analysis.

The *Demand Response Steel Making* (light blue) and *Constant Steel Making* (red) scenarios consistently exhibit the lowest environmental impacts across the majority of indicators and years evaluated, as shown in Figure 24. Differences between these two are minimal, suggesting that both steel production scenarios are comparably environmentally friendly under prospective system assumptions. With future implications and background scenarios the environmental impacts in both cases are reducing constantly, however not significantly. However in 2050, these scenarios reflect significant reductions in Global Warming Potential (GWP), Acidification, Fossil Energy Source Depletion and Water Use compared to the current BF-BOF benchmark. Only Metal Resource De-

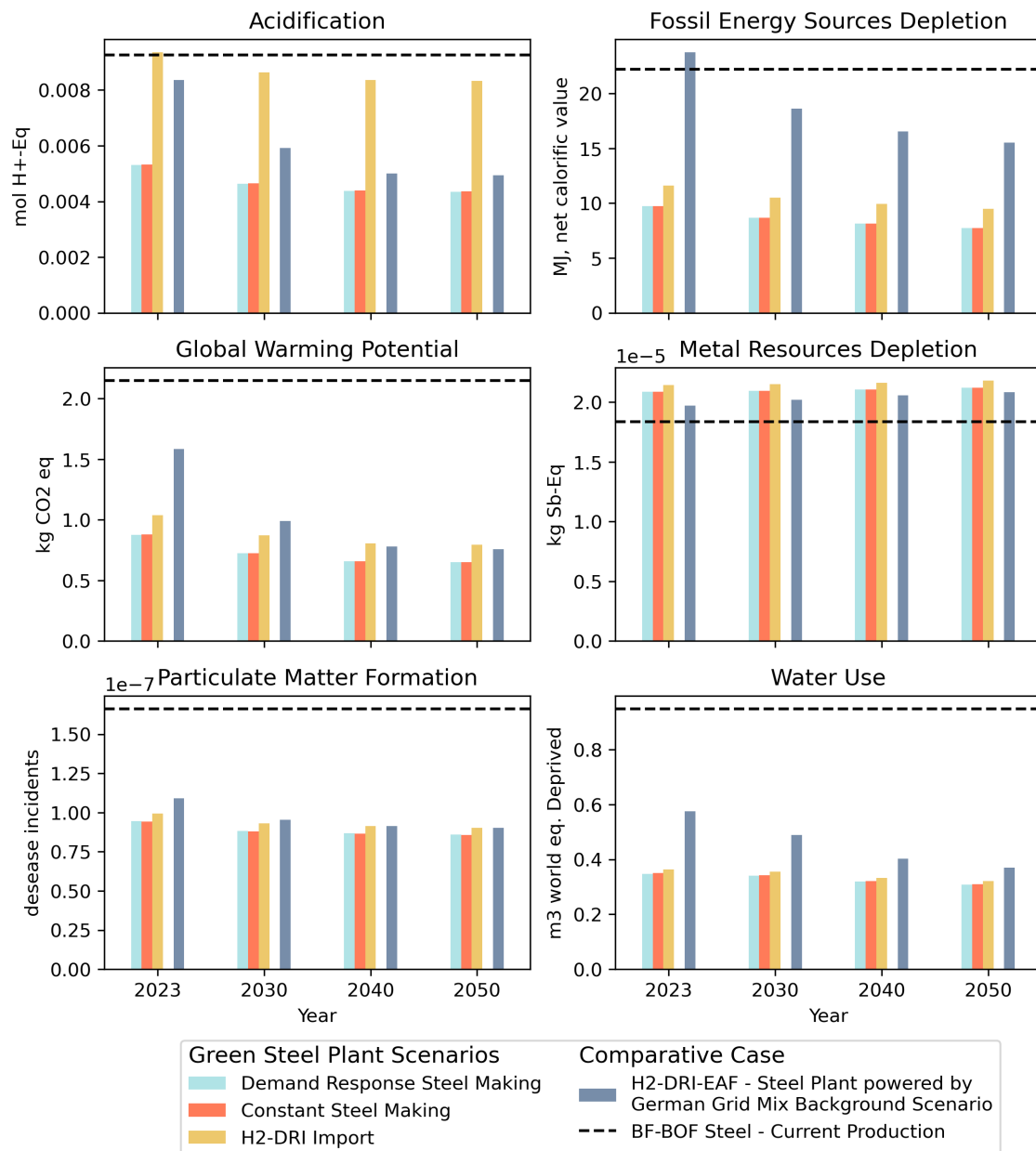


Figure 24: Prospective Environmental Impacts of 1 kilogram produced steel product for each Steel Plant Scenario and Steel Production based on prospective German Electricity Mix in comparison to current coal-based Steel Production

pletion is higher compared to the BF-BOF impacts and also not changing in future, even rising minimally as the transition away from fossil fuels necessitates the installation of metal-intensive infrastructure for renewable electricity generation.

The *H<sub>2</sub>-DRI Import* scenario (yellow) consistently exhibits higher environmental impacts compared to both integrated steel plant scenarios. The most prominent discrepancy is seen in Acidification, where it nearly shows doubled impacts and where its values approach or match the current coal-based steel production level in 2023, decreasing and moving away with the prospective scenarios. Slightly elevated impacts compared to the other steel plant scenarios are also evident in Fossil Energy Source Depletion and GWP, indicating a less favourable environmental performance despite being hydrogen-based. This is likely due to the reliance on the long transport by ship from Australia to Bremen.

While the developed hydrogen-based steel plant scenarios show relatively stable environmental impacts across the prospective years, larger variations are observed in the comparative case *H2-Steel – German Grid Mix* (dark blue). Hydrogen based steel production totally relying on electricity from German Grid Mix demonstrates high environmental burden. Especially in early years like 2023 use of fossil fuels in the national electricity mix is causing high environmental impacts. Notably, Fossil Energy Source Depletion in 2023 significantly surpasses the GWP of *Demand Response Steel Making* and *Constant Steel Making* and even exceeds the impacts of current coal based production. However these large gaps mostly diminish over time, reflecting electricity grid decarbonisation in the background scenarios between 2023 and 2050.

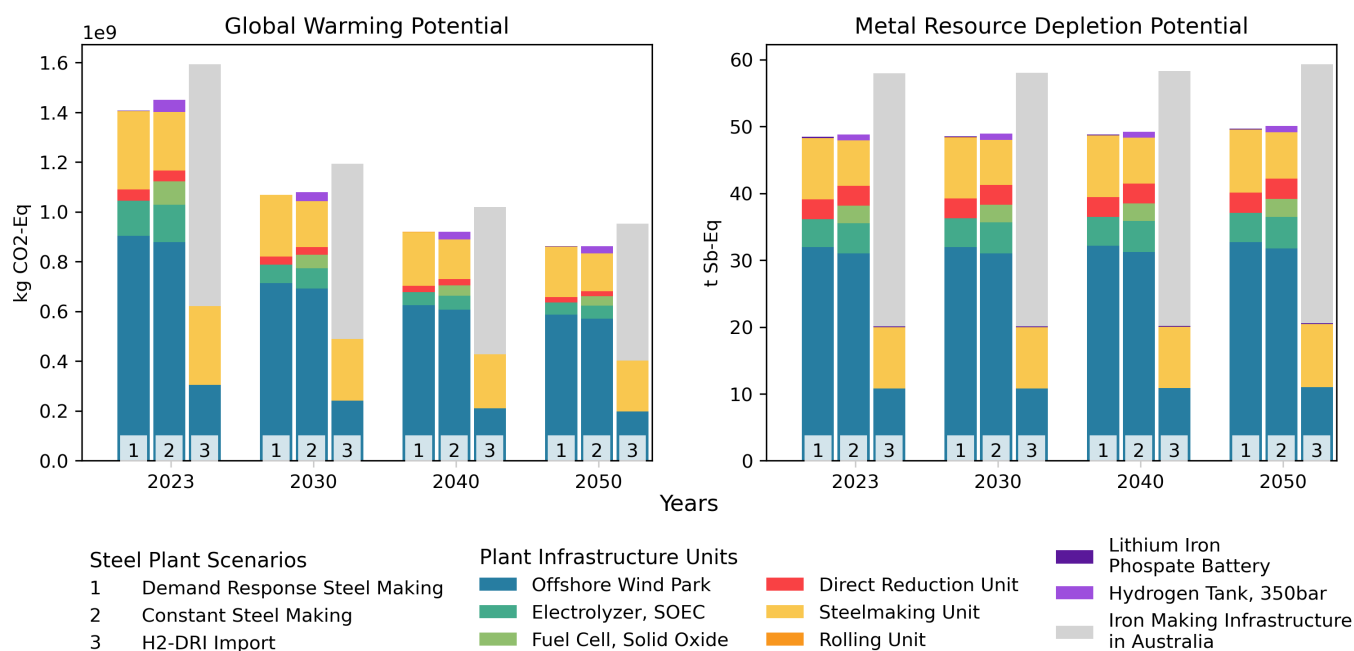


Figure 25: Contribution Analysis of Prospective Environmental Impacts of Green Steel Plant Infrastructure Construction and Comparison between Steel Plant Scenarios

To assess the differences between the three steel plant scenarios reflecting in varying steel plant installations Figure 25 depicts a contribution analysis of the infrastructure included in the steel plant. Only GWP and Metal Resource Depletion Potential is assessed as other indicators show similar behaviour as GWP. Metal Resource Depletion Potential shows a different development while being of special interest in the comparison of the different technological setups of steel plant scenarios and their respective use of rare metals.

Across all scenarios, the wind park (dark blue) is identified as having the largest impact on both GWP and Metal Depletion, driven by the need to construct up to 71 wind plants, along with their associated cables and transformation infrastructure. The steel making unit (yellow), equipped with an EAF, consistently ranks as the second-largest contributor to these impacts across all scenarios. The third largest contributor, the electrolysis (petrol) unit shows a notable reduction in its GWP impact over time, eventually reaching comparable levels with the following units. Furthermore, the fuel cell (green) and direct reduction unit (red), as well as the hydrogen tank (purple) in the *Constant Steel Making* Scenario, exhibit similar levels of impact. In the *Demand Response Steel Making* Scenario the hydrogen tank's influence is negligible and thus not depicted. Meanwhile, the rolling unit (orange) has a minimal effect on GWP and Metal Depletion across all scenarios, with impacts too small to be visibly represented in the graph.

In the system boundaries only components constructed in Germany are differentiated, meaning that infrastructure for producing H<sub>2</sub>-DRI abroad in Australia, is aggregated into one activity. If only infrastructure installed in Germany would be considered the *H<sub>2</sub>-DRI Import* scenario shows the lowest infrastructure-related environmental impacts, as it comprises fewer system components and requires a smaller wind park due to lower overall energy demand. However with the inclusion of installed Australian infrastructure this scenario clearly surpasses the other two cases in both impact categories for each prospective year.

When comparing the other two scenarios of integrated steel plants, the *Constant Steel Making* scenario generally exhibits slightly higher impacts than the *Demand Response* scenario. While *Constant Steel Making* scenario benefits from reduced installation requirements, such as a smaller wind park and a scaled-down steel making unit, these savings are offset by the additionally required infrastructure, particularly the installation of a large fuel cell system and hydrogen storage tank. However for GWP the differences replenish over time with future scenario implications and disproportionate reduction of electrolyser and fuel cell impacts.

The two comparative cases, BF-BOF and H<sub>2</sub>-Steel – German Grid Mix are excluded from the contribution analysis of infrastructure installations, as they represent average production pathways that aggregate various production practices. In such aggregated scenarios, it becomes challenging to accurately identify and attribute specific infrastructure elements to individual processes. Consequently, isolating the environmental impacts of its infrastructure components is not feasible within the scope of these models.

### 4.3 Aggregated Results for Information System

The evaluation of the steel plant scenarios using the indicators from the developed information system is based on the combined outcomes from the MILP optimisation and pLCA, as illustrated in Table 6. The best, medium, and worst effective scenarios are identified from the assessed options. In some instances, not all position are chosen due to the similarity in performance.

Economic performance of each scenario is assessed based on the outcomes from the runs aimed at profit optimisation, emphasising the average cost of electricity when bought and the average price when sold, as initially delineated in Table 4. However as mean cost of buying electricity is only applied to the *H<sub>2</sub>-DRI Import* scenario, the mean profit for selling is taken into account, resulting in clear differences between the scenarios with 63, 50, and 41 €/MWh.

When comparing the used energy per produced unit of steel, it is also essential to consider that the *H<sub>2</sub>-DRI Import* scenario omits the required energy content for reduction of iron ore in the iron-making process, which affects the comparison. As this process requires 2.48 MWh/t, adding this value to the results leads to a comparison where *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* come to similar results of 3.52 MWh/t, and *Constant Steel Making* is valued as medium performance as it has worse but not strongly differing results in comparison with 2.63 MWh/t.

Operational complexity results are described for each scenario in detail above in Section 4.1.3. The amount and length of downtimes as an indicator of operational complexity show a clear trade-off between economic performance and operational complexity. *Demand Response Steel Making* employs flexibility to regularly shut down the plant and generate high profits through dispatched electricity, which results in complex operation management. Conversely, *Constant Steel Making* is able to operate continuously due to the availability of storage, however which increases energy consumption and minimises available dispatchable electricity for profit maximisation. The *H<sub>2</sub>-DRI Import* scenario occupies the middle ground, as the steel making unit oscillates between on and off on a regular basis.

In terms of DR potential, the *Demand Response Steel Making* scenario performs best, with the lowest mean deviation from the goal load, as shown in Table 4 for the objective of minimising the deviation. Although the standard deviations and variance of *Constant Steel Making* are lower, its an artifact of varying goal loads and its mean deviation is significantly higher, leading it to be ranked as medium performance. In contrast, the *H<sub>2</sub>-DRI Import* scenario performs worst in all three values, resulting in the worst evaluation result in this area.

The pLCA results are evaluated for 1 kg of produced steel, with the changes over the years aggregated into the mean over the modelled time span from 2023 to 2050, as depicted in Figure 24. This includes all emissions in the production process of 1 kg of steel. When comparing the scenarios, *Demand Response Steel Making* and *Constant Steel Making* have similar impacts and are mostly the best-performing scenarios. the only exception is metal depletion potential, where

Table 6: Comparison of Steel Plant Scenarios for Results from MILP optimisation and prospective Life Cycle Assessment in the structure of developed Information System for Sustainable Development

| Area                              | Indicator                                                        | DR STM | Const STM | H <sub>2</sub> -DRI Import |
|-----------------------------------|------------------------------------------------------------------|--------|-----------|----------------------------|
| Economic performance              | Mean price for selling & buying electricity                      | best   | worst     | medium                     |
|                                   | Total electricity usage of production process                    | best   | medium    | best                       |
| Operational complexity            | Amount and length of steel plant downtimes                       | worst  | best      | medium                     |
| DR Potential to match goal load   | Deviation from goal load (mean, standard deviation and variance) | best   | medium    | worst                      |
| Prospective environmental impacts | Acidification                                                    | best   | best      | worst                      |
|                                   | Fossil Energy Abiotic Depletion Potential                        | best   | best      | medium                     |
|                                   | Global Warming Potential                                         | best   | best      | medium                     |
|                                   | Metal Resource Abiotic Depletion Potential                       | worst  | worst     | worst                      |
|                                   | Particulate Matter Formation                                     | best   | best      | medium                     |
|                                   | Water Use                                                        | best   | best      | best                       |

both are part of the group with worst results when compared to comparative cases, such as current coal-based steel production and grid-based H<sub>2</sub>-DRI production. The *H<sub>2</sub>-DRI Import* scenario has higher environmental impacts across all categories. This is due to the outsourced iron-making process in a region with lower offshore wind capacity factors, as well as the additional shipment of DRI from Australia to Germany. The smallest differences can be observed in Water Use and Metal Depletion Potential, resulting in a similar ranking of all three scenarios for these categories. In contrast to the other impact categories, acidification potential exceeds even existing coal-based production as current shipping has a significant impact on ocean acidification. Therefore this category is ranked as the worst-performing scenario in the impact category.

In summary, among the three steel factory scenarios, *Demand Response Steel Making* appears to be the best performing. *Constant Steel manufacturing* offers reduced complexity but performs worse in DR potentials, making it the second best. The *H<sub>2</sub>-DRI Import* scenario seems to have the lowest performance, due to its significant environmental impacts and lack of flexibility. However, how indications are weighted within the entire information system depends on the viewpoint and requires further discussion.

## 5 Discussion

This discussion sets out to contextualise the findings presented in this thesis, situating them within the broader landscape of current research, industry developments, and existing limitations. With a focus on the steel plant scenarios, this section will delve into the implications of the results obtained from the MILP optimisation, the pLCA, and ultimately, the aggregated outcomes of the information system for sustainable development. The discussion will be structured to follow the thesis's framework, ensuring a comprehensive examination of the interplay between techno-economic and environmental aspects. Furthermore, this section will explore the trade-offs and synergies that emerge from the analysis, providing insights into the complex relationships between different factors influencing the sustainability of steel production. Based on these findings, a recommendation for future developments in the steel industry will be presented. Additionally, the discussion will acknowledge and address the limitations, uncertainties, and system boundaries inherent to this study, highlighting areas for further research and potential avenues for improvement.

### 5.1 Economics, Operational Complexity and Grid Stability in Steel Plant Scenarios

Each scenario highlights particular strengths and limitations when incorporating DR operation in steel production in regards to the researched aspects of the research objectives. As this section discusses the meaning of results from the MILP optimisation it focusses on research objective one with regards to the economic performance, operational complexity as well as grid stabilising effects of steel plant scenarios.

The results show that in general the flexibility and DR potential of the scenarios is particularly realised by shutting units or the whole plant down at times of insufficient wind generation or high electricity prices. The inherent flexibility of electrolyzers or flexible electricity demand in steel making by the use of virtual equipments is used only minimally. When run for economic profits the steel plants run on full possible capacity and rather shut down either the reduction unit or the whole plant than running on reduced capacity. The plant is only running on reduced capacity when the goal of the operation is to offer a stable load profile. This shows one contradiction of the two objectives of steel plant operation. When power prices fluctuate, maintaining a steady load profile results in lost profit or increased expense. However, the given load profile can be constructed in any other way, such as using the pattern of the power price itself rather than a stable flat line. This would result in a higher feed in times of high prices and a lower feed in times of low prices, but with a constant exchange with the grid, as opposed to no exchange at low prices and a full feed in times of high prices. This capability of steel plants to adjust their operation in response to grid conditions could potentially add a source of momentum and stability to the grid, which is becoming increasingly valuable as traditional generators with rotating masses are being phased out. Notably, this study appears to be one of the first to investigate the potential of future steel plants, particularly those using hydrogen-based production scenarios, to provide this type of stability to the grid. While further

research on various goal load patterns would offer more insights into the ability of these scenarios to match exchange with the grid and follow a specific shape, the use of a flat line goal load can still serve as a reasonable estimate of each scenario's potential.

Among all the analysed cases, the one with the best ability to utilise its flexibility to profit from varying electricity prices or balance fluctuations in the grid is the *Demand Response Steel Making* scenario. This is primarily due to the flexibility of its reduction unit and the ability to schedule extended downtimes of the whole steel plant up to 20 hours when electricity prices exceed €100/MWh. These downtimes are made feasible by the larger capacity of the steel making unit, which enables the same production output over a shorter total operating period. However this has the downside of increasing the operational complexity as the plant is often switching between downtime and production, leading to several issues related to temperature regulation, workforce allocation, and additional scheduling challenges. Additionally the larger steel making unit has high installation cost. In comparison to the *Constant Steel Making* scenario additional installation cost in the whole scenario amount to 200 mio €, as planned by Hölling et al. (2021). However this scenario has the lowest mean selling price of electricity meaning it can not use its available flexibility potential as well. With the values of this model the additional cost of the *Demand Response Steel Making* scenario would pay off through higher electricity selling prices after 14 years.

Nevertheless in further consideration *Constant Steel Making* high foresight for operational planning with less downtimes and longer and persistent production periods. This is enabled by the opportunity to utilise the large hydrogen tank in times of low wind generation. The integrated fuel cell enables steel plant operation at times of insufficient generation below 100 MW. At the same time this scenario shows a medium but still above average performance for providing grid stability by goal load matching. However, the increased energy demand of this setup limits capacities for flexibility and reduces available electricity for sale during high-price periods showing the weakness of this storage system: higher energy losses, which is also reflected in the slightly higher total electricity demand to produce one ton of steel.

The *H<sub>2</sub>-DRI Import* scenario, in contrast, is constrained by its inability to consume a large share of the generated electricity during peak wind conditions due to the fixed load profile of the steel making unit and missing flexible electrolyzers. As a result, a significant portion of electricity is fed back into the grid during these periods when prices tend to be low. Still, this scenario achieves the second-highest mean selling price. However the ability to match its power exchange to a given goal load is tremendously worse compared to the other two scenarios as no electrolyzers are available.

Interestingly, the use of virtual equipment representing flexible steel making unit operation, plays nearly no role when the objective is profit maximisation. With the objective of minimising power exchange deviation from a goal load virtual equipment is utilised more often but still only sporadically. In both affected scenarios steel making unit flexibility is utilised when power generation decreases below the threshold required to run the virtual 100% capacity unit in combination with a running rolling unit. This behaviour, as it was also planned by Hölling et al. (2021), is most evident in the

*Demand Response Steel Making* scenario, where a gradual shift to 80% and then 60% capacity batches can be observed in periods of decreasing wind generation. The models however still continues utilising 100% capacity virtual equipment use by separating running steel making and rolling unit processes from each other. This results in time series with alternating turned on and off steel making and rolling batch production. The deployment of this practice in real steel plants is unrealistic due to temperature and logistic management issues. This showcases the limited use cases of steel making flexibility beyond batch starting time variation in this model and its depiction of the rolling unit. It is only deployed in times of reduced renewable generation if steel makers are incentivised to match loads a given profile. This implies that, under present-day conditions with current steel plant setups where EAFs are solely used for secondary steel making without a reduction unit and electrolyser to integrate, utilising flexibility of steel making unit does not offer significant economic advantages. However this observation has to be researched further with future developments in the electricity market as currently the price spread since in the electricity market is increasing (Schill et al. 2025).

These findings provide valuable insights but simultaneously raise further questions how renewable variability can be integrated into real world scheduling and operation management. As production planning generally relies on power forecasts with limited temporal resolution of days or maximum weeks, more generalised rules and adaptive control systems would be necessary to cope with such highly uncertain and dynamic inputs.

An additional interesting issue for future research on operation management would be the inclusion of solar generation infrastructure in the energy supply. Due to its structural predictable but highly flexible diurnal behaviour, solar power could enhance the operational flexibility and mitigate some of the issues associated with wind variability. In particular, the contrast between comparatively stable renewable power output of offshore wind and the more temporally structured solar generation may present complementary advantages for flexible steel plant operation or just increase limits of flexibility.

## **5.2 Environmental Impacts in Steel Plant Scenarios**

In the assessment of the second research objective the pLCA of the examined steel production scenarios reveals several critical insights across environmental impact categories. A predominant driver of environmental performance is the source of electricity, both in the foreground as local wind park and the background system as electricity mix. This influence is reflected in the contribution analysis, where wind park installation and operation show substantial environmental effects in all impact categories.

Among all scenarios, integrated steel plants based on local renewable energy demonstrate the least environmental impacts. However, this advantage does not hold across all categories. In particular, metal depletion potential is lower for steel produced in current BF-BOF route and Grid Mix, H<sub>2</sub>-based steel in all years from 2023 to 2050 as fossil energy carriers are still deployed and

less renewable electricity generation units need to be installed. However, all steel plant scenario outperform traditional blast furnace–basic oxygen furnace route production in all other categories, particularly in climate-related metrics like GWP and Fossil Energy Source Depletion.

Nonetheless the pLCA results show that CO<sub>2</sub> and equivalent emissions from H<sub>2</sub>-based steel production do not fall to zero even by 2050. This is primarily attributable to the assumptions embedded in the global background SSP2 RCP 1.9 scenario, which reflects a middle of the road decarbonisation trajectory globally. The production of materials and infrastructure required for steel plants, like wind turbines, electrolyzers, and auxiliary systems, even in 2050 still involves fossil-based inputs. These are not direct emission from steel producer who claim to be able to reduce direct CO<sub>2</sub> and equivalent emissions in the depicted green steel production processes down to 50 g CO<sub>2</sub> per kilogram of steel or lower (Hölling et al. 2021). Furthermore, the background scenario only models future developments in steel and electricity sectors and excludes possible improvements in transportation, heating, cement production, or fuel supply chains. Consequently, emissions associated with marine transport of DRI remain a significant contributor, particularly to GWP and acidification.

A further nuance arises when comparing the contribution analysis of *Constant Steel Making* and *Demand Response Steel Making* scenario infrastructure. While the first benefits from slightly reduced infrastructure such as less wind park capacity due to its constant operation, this is offset by additional environmental impacts from storage technologies, particularly fuel cell and hydrogen tank. An open question remains as how these impacts might change with other selected technology. For example if the *Constant Steel Making* plant was located near geological salt cavern hydrogen storage, which would require less installation materials but for which no life cycle inventory was found. Another relevant consideration for an altered technology selection would be the use of low-, instead of high-temperature electrolyzers and fuel cells due to safety or construction reasons. These low temperature technologies rely more heavily on platinum group metals, which shift could significantly influence impact categories, particularly metal resource depletion, where the demand for scarce and critical materials is especially sensitive to such changes.

The optimisation shows, that not the whole amount of electricity produced in the wind park is used within the steel production. Environmental impacts of park construction are included totally in the impact assessment of the steel, which would cut off its impacts within other products which would be produced with it. This highlights the problems in LCA of production system producing multiple products. This is due to the narrative of the scenarios and focus on infrastructure and technology installation. If the wind park electricity production would have been included based on energy contribution this would additionally reduce the impacts of these two scenarios, however not in a significant manner.

When interpreting the contribution analysis results of the *H<sub>2</sub>-DRI Import* scenario, it is essential to consider the differences between the two production sites, Germany and Australia. The German site's environmental impacts are primarily driven by the wind park and the steel making unit. In contrast, the Australian site aggregates wind generation, electrolysis, a small hydrogen tank, and the direct reduction unit. This results in comparatively higher environmental impacts compared

to the other two scenarios. However, these results carry a high degree of uncertainty due to the use of generic background data for wind energy with the “Rest of World” location parameter and the absence of locally accurate life cycle inventories. This uncertainty especially originates from the local offshore wind capacity factor, which significantly affects environmental outcomes as it influences the required constructed capacity of wind mills. Near Port Hedland, Australia’s largest iron ore export hub and the assumed export location in this scenario, the offshore wind capacity factor is among the lowest in the country (Briggs et al. 2021). This would imply higher environmental burdens in the assumed case. However, actual impacts would depend heavily on how Australian actors choose to organise the local green iron production and electricity supply. This remains uncertain and deserves further investigation.

Adding to this uncertainty in the LCA of Australian production site is the impact of assuming the background scenario for the steel market to be applied to the global steel market. This was done due to consistency reasons for the large share of production located in Germany. However installations using steel in Australia are now assuming German steel market conditions, which distorts the results and would required Australia specific steel market scenarios.

Furthermore, the assumptions of transportation within this situation must be addressed. The other scenarios do not involve importing DRI but rather iron ore and pellets, which are presumed to be sourced from the global market with a standardised average transport distance for iron pellets globally. This is smaller than the almost maximum global transportable distance from Port Hedland, Australia, to Bremen, as assumed for DRI. If iron pellets from the alternative steel production scenarios are imported from the same iron production location, the environmental impacts would be equivalent to or potentially higher than those associated with DRI imports, due to the increased mass of iron ore and pellets compared to DRI. An enhanced model of material transport in the steel sector would yield improved outcomes in this respect.

Among all background assumptions, the electricity grid mix has the greatest influence on overall environmental performance. The changes of the German electricity mix background scenario are reflected in the results of the directly grid mix dependent steel production but also indirectly in infrastructure results of the contribution analysis. This becomes evident as environmental indicators track closely with grid mix patterns. On the foreground side, wind energy consistently outperforms other electricity generation options in nearly all categories, except for metal depletion. This is consistent with broader literature findings that identifies wind as one of the energy source with the least environmental impacts (Marashli et al. 2022). The findings of this study also show that, from an environmental standpoint, it has little impact for the studied cases in steel production whether the variability of additional renewable capacity is balanced through highly flexible demand response production strategies or large-scale hydrogen storage systems with flexible electrolyzers.

### **5.3 Comparison, Trade-Offs and Recommendations**

Each scenario comes with individual strengths and weaknesses in various areas. An overview of performance comparison was given with the information system for sustainable development

in Section 4.3 and Table 6. This subsection discusses these aggregated results for both two research objectives and tries to develop what can be derived from this for recommendations of further development in the intersection of steel and energy sector.

From an operational perspective, the *Constant Steel Making* scenario offers clear advantages in terms of planability. The presence of a dedicated hydrogen storage system ensures reliable energy availability and minimal downtimes, reducing complexity in operational scheduling. Additionally, this scenario does not rely on flexibility in steel making, thereby avoiding another dimension of variability in the process. In contrast, the *Demand Response Steel Making* scenario introduces greater complexity in planning due to its higher reliance on process flexibility. Frequent downtimes and restarts of the reduction unit, or even the entire plant, require detailed operational coordination. The *H<sub>2</sub>-DRI Import* scenario, by excluding the reduction unit, reduces the complexity of operations. However, it also loses the flexibility that an electrolyser-based reduction unit could provide. Nevertheless, from the viewpoint of a steel plant operator the planning advantage of the *Constant Steel Making* scenario is clashing with low economic profits from selling unused electricity as low amounts can be dispatched at unfavourable moments of lower prices.

The trade-off between operational complexity and economically optimal energy consumption in steel production remains an open question in reality. From the perspective of steel plant operators, this trade-off can be approached through the depicted scenarios, including high DR scheduling and operational complexity, large storage capacities with higher costs, or outsourcing the problem by importing DRI but missing out on large flexibility potentials. However, this trade-off can be influenced by higher-level stakeholders, namely grid operators and policy makers who can change system setting and price structures.

Grid operators are interested in maintaining a stable grid, which can be best achieved through *Demand Response Steel Making* or, as a secondary option, *Constant Steel Making*. This suggests that grid operators have a vested interest in having large capacities of electrolysers available in the region. Nevertheless, since electrolysers are not directly accessible to grid operators and their flexibility potential is highest when combined with flexible steel making, it is essential to consider the interactions between these stakeholders and how they negotiate price of electricity and flexibility demand.

This is accomplished through both direct encounters and trade negotiations, as well as market mechanisms. How this market is organised is mostly managed by policymakers with a broader perspective from the landscape level. This study aims to provide policymakers with insights into how to reduce overall environmental impacts, as well as environmental burdens both locally and worldwide. From this perspective, it is noteworthy that *Demand Response Steel Making* with high DR and *Constant Steel Making* with large storage systems do not exhibit significant differences in environmental impacts. However, importing DRI would have higher environmental impacts and add dependence on Australian decisions on how to decarbonise DRI production. This suggests that policy makers should support the construction of regional reduction unit capacities but the

decision on how to organise the management of renewable variability depends on the interaction between Niche and Regime level. However, from this high level perspective, it would be interesting to see a comparison of additionally available technologies, offering similar stability potentials such as lithium iron batteries. Nevertheless, choosing these alternative technologies would mean neglecting to build up hydrogen based steel production capacities or not utilising their inherent flexibility potentials.

Considering these trade-offs and stakeholder interaction makes the recommendation of a single optimal scenario selection impossible. Instead, a more realistic and adaptable approach should involve a diverse mix of steel plant configurations across Germany, tailored to regional strengths and provide a holistic approach. This would start with the large-scale deployment of reduction units along the German North Sea coast. These units could initially operate as hybrid systems using both natural gas and hydrogen, transitioning over time to fully rely on locally produced renewable hydrogen. The produced DRI could either be stored, be transported inland or used locally in small-scale steel making units. These northern steel making units would make use of flexible, demand-response production strategies and could even utilise hot DRI to further increase energy efficiency. Additionally a small capacity of northern steel plant could apply the *Constant Steel Making* scenario approach and use large-scale energy storage systems, particularly hydrogen storage with later reconversion to electricity via fuel cells for powering steel making processes for higher cost. This hydrogen storage can additionally be useful for other sectors or technologies requiring hydrogen. Yet for steel making a steel plant constructed as *Demand Response Steel Making* can utilise stored DRI sponges as are a more efficient and lower-loss sink.

Meanwhile largest shares of steel making facilities, without reduction unit but EAF and rolling, could remain in central industrial areas where infrastructure and skilled labour are already established. These inland plants would use cold DRI, slabs and billets either transported from the coast or imported, since the North Sea's renewable energy capacity is still limited and may not be sufficient to cover all hydrogen demand for sufficient DRI production. Additionally steel plants in these regions would continue to draw electricity from the grid mix. As steel making and rolling are less energy intensive than reduction processes, the environmental impact of relying on the grid in these areas is comparatively lower and the grid mix is expected to gradually decarbonise. As DR grid stabilising performance of plants with only steel making and rolling unit is worst, this needs to be managed by other sectors and technologies. In these steel plants the focus could shift more toward specialised steel products and downstream processing as these facilities would not need to follow demand response logic but could instead be optimised for production efficiency and logistical considerations.

This diversified setup would make it possible to fully exploit the flexibility potential of coastal steel plants, allowing them to absorb wind-generated electricity directly, thereby reducing the need for grid expansion and minimising curtailment. At the same time, their controlled electricity feed-in could help stabilise the overall power supply by smoothing out fluctuations in wind generation.

## 5.4 Limitations, Uncertainties and System Boundary Consideration

The optimisation model and the pLCA presented in this study are subject to several limitations, uncertainties, and boundary considerations that must be acknowledged when interpreting the results and applying them to real-world contexts.

One of the most significant uncertainties lies in the weather data used, particularly the wind generation profile. Wind energy production is inherently volatile and difficult to predict, especially on an annual scale. This introduces a high degree of uncertainty into the amount of electricity a wind park can generate in a given year. In this study, the most favourable year in a twelve-year dataset was selected to represent wind generation as depicted in Figure 4. This best-case scenario leads to a potential overestimation of energy availability and does not reflect the challenges faced in years with significantly lower generation. For example 2021, a year with a 20% reduction in capacity factor dispatches the ability to meet fixed annual production target of one million tonnes of steel. Strategies to adapt to such shortfalls must be developed, ranging from installing backup energy systems to adopting a broader and long term demand response strategy. This approach would involve reducing total steel production in years of low renewable generation and increasing output when conditions are more favourable, mirroring natural energy availability instead of rigid production planning.

This issue reveals also limitations on short-term operational decisions. In practice, plant operators must decide whether to shut down reduction units or even entire steel plants without knowing the renewable energy availability for the remainder of the coming months or year. This contrasts with the model, which assumes perfect foresight over the annual energy supply, but day-ahead electricity prices and wind forecasts are only available for short-term scheduling and downtime planning.

Another assumption linked to the selected weather data is for *Constant Steel Making* scenario to start with a full hydrogen tank offering free 24 GWh of hydrogen for the year. This is assumed due to operation issues as the model was not feasible with less available energy. This highlights the limitations of this tight energy planning, aiming for reducing installed capacities but at the same time maintaining the requirement to meet the fixed target of producing one million tonnes of steel.

Additional uncertainties come from the economic data used in the model. The electricity prices are based on 2012 data, which may not reflect current price range and market dynamics. The year was chosen because it was the only one in the dataset that provided sufficient wind energy, linking this limitation again to the weather-related uncertainty. Furthermore, the model excludes future developments in grid charge structures and tax factors, which could significantly influence the economic viability of different operational strategies.

Heading to influential limits in life cycle assessment method it is important to keep in mind that the life cycle assessment of *H<sub>2</sub>-DRI Import* scenario does not directly include electricity drawn from grid as the optimisation showed to be necessary. It is also important to note that the prospec-

tive background scenario used in this study, based on SSP2, was only applied to the steel and electricity sectors. Sectors such as transportation, cement, and chemicals, which also interact directly and indirectly with modelled steel production, were excluded. Additionally, the life cycle inventories for the steel making and rolling processes are based on quite old data from 2005, which could increase uncertainty and reduce representativeness of the results. The left out assessment of LCI data precision, completeness, uncertainty and reproducibility lead to a deviation from real world environmental impacts, however the required effort would not correspond to the principle of Occam's Razor. This leads also to another essential challenge to life cycle assessment methodology noted by Stamp et al. (2013), highlighting the strong interconnected, dynamic, and multifunctional processes in metal production reducing accuracy of such static LCI models. In this thesis this multifunctionality is represented in the issue, that the modelled steel plants do not only produce steel but also electricity which is fed into the grid. This additional product is not considered, especially increasing raising the environmental impacts of *Demand Response Steel Making* and *H<sub>2</sub>-DRI Import* scenario as they show a large overproduction of electricity which is left out due to this issue. This problem could be met in the future with a process oriented, diversified and value based allocation method of environmental impacts.

This issue also emphasises a key omission that influences the MILP optimisation: the economic value of the produced steel products. This aspect was not included in the optimisation, yet it plays a crucial role in assessing whether diverting electricity for grid feed-in during peak price periods is economical compared to continuing steel production. This is an interesting decision-making factor that needs to be researched in future work.

An additional limit in this model is, it does not account for workforce planning. Frequent and short-notice shutdowns may result in inefficient labour utilisation, with personnel left idle during downtimes. Furthermore, abrupt shift cancellations or changes can negatively impact employee satisfaction and retention, contributing to a more volatile workforce. Also if demand-responsive production strategies were to be deployed at a larger scale across the steel industry, these labour-related implications would need to be considered in an integrated manner securing jobs and an efficient industry transformation at the same time. The ongoing transformation of the German steel industry, combined with persistently high energy prices, has already led to reductions in production and widespread redundancies. However, annual drops in renewable energy generation represent a different kind of challenge rooted in well known but difficult to forecast natural variability rather than ever changing structural and economic factors.

A quite uncommon assumption of this model is that the same actor owns both, the wind park and the steel plant. This simplifies real-world ownership structures, where in most current cases, the steel producer does not own large scale renewable generation assets. Therefore, any profits from selling electricity would instead go to the wind park owner unless a direct contractual relationship exists for that. Such contracts, where the steel plant operator agrees to consume electricity only during favourable conditions defined by the wind producer, however are increasingly discussed

(Schrotenboer et al. 2022; Mittler et al. 2025). Based on the contract steel maker would benefit from overall reduced electricity prices, while the wind park operator could benefit from higher revenues during peak price periods. This arrangement supports higher renewable integration into the energy system and reduces the need for costly storage or grid expansion. However, implementing such integrated business models requires further regulatory and market development.

When heading to the assumptions of the indicator system it is important to stress the missing uncertainty analysis of parameter and setups. This system serves as a first estimation and comparison of overall performance between the scenarios. The stakeholder perspectives were developed on a literature research and experience within the systems and can not depict the complex reality of interests. Also the indicators themselves are object of assumptions and limitations. The limits of the simulated processes are specifically responsible for the decrease of measuring operational complexity entirely based on downtime distribution. In actuality, the operational complexity is more susceptible to numerous variables and managerial factors than the overall downtime of steel plants.

## 6 Conclusion

This thesis has explored the integration of DR operations into hydrogen-based steel production. The research was motivated by the demand to develop a perspective of future green steel production in Germany. While currently steel producers face lay-offs and economical problems the decarbonisation requires integration of renewable energy generation into steel production. As this and the electricity grid requires balancing efforts for the high fluctuation of renewables, flexible steel plant operation based on available renewable electricity offers a pathway to reduce green steel production cost and manage congestion in the grid. The literature review revealed significant gaps in current understanding of the potential and challenges of incorporating DR into hydrogen-based steel production, including economic gains, operational complexity, and grid stabilisation potential, as well as environmental impacts. For this, two research objectives were devised, each with an own method to approach.

A MILP optimisation was used to model steel plant operation, economic performance, and power dynamics, while a pLCA was used to depict environmental implications in future settings. The work assesses the scenario's performance using both methodologies in a multi-level information system, with the goal of offering insights into the most significant components for sustainable development in this sector from multiple perspectives.

The findings show that demand-response steel plant operation of reduction and steel making units, offers significant potential to reduce congestion and stabilise the grid. It can also generate profits by turning off reduction unit or even the whole steel production and sell the unused electricity at times of high prices. At the same time prospective environmental impacts of DR steel plant

operation are similarly low as production practices deploying large storage system to enable higher self consumption rates as well as constant steel making production.

The comparison of three green steel plant configurations differing in operation and energy supply strategies highlights the efficiency of flexibility over large-scale hydrogen energy storage. A storage system based on a large hydrogen tank and a fuel cell enables simpler scheduling and planning of production. However it raises the energy demand as the storage system only offers a round trip efficiency of 45% and suffers of a tight energy budget. The import of DRI shows many weaknesses as environmental impacts increase, and operational flexibility only offers medium profits or low stabilising potential as the flexibility of electrolyzers of the reduction unit are missing.

However, the study also reveals critical limitations, especially related to the tight energy planning required to meet fixed production targets, uncertainties in wind generation, and oversimplifications within current optimisation modelling frameworks in temperature and logistic management. Ultimately, this work underscores the need for more holistic, adaptive system designs that consider spatial separation of production units, realistic workforce and market conditions, and cross-sectoral interactions with other sectors. While high DR in steel production seems to offer the overall best performance of the assessed scenarios, due to its operational complexity no single scenario emerges as universally optimal. A diverse deployment of adapted steel plant layouts across Germany looks to be the most promising path for the steel sector's economically and environmentally sustainable transition. This comprises flexible operational reduction units, an integrated steel plant along the coast, and a focus on specialised steel products in traditional industrial steel producing regions.

## 7 Table of Symbols

Table 7: Symbols and Description of Sets in Optimisation Model

|           | Description                                                                                                                                                |
|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $T$       | All time steps ( $t \in T$ )                                                                                                                               |
| $U$       | All steel making units in modelled green steel production plant. One unit aggregates electric arc furnace, ladle oven and continuous casting ( $u \in U$ ) |
| $V_u$     | Virtual versions of an equipment $u$ , due to different types of raw materials, or production modes ( $v \in V_u$ )                                        |
| $Z_{u,v}$ | Time steps in a batch of virtual equipment $v$ ( $z \in Z_{u,v}$ )                                                                                         |

Table 8: Symbols, Domain and Description of Parameter in Optimisation Model

| Symbol                          | Domain                | Description                                                                                                                 |
|---------------------------------|-----------------------|-----------------------------------------------------------------------------------------------------------------------------|
| $T^{total}$                     | $\mathbb{N}$          | Total number of time steps in $T$                                                                                           |
| $\Delta t$                      | $\mathbb{R}_{\geq 0}$ | Size of a discrete time step in the model - a value of 1 equals a step size of one hour                                     |
| $m^{total}$                     | $\mathbb{R}_{\geq 0}$ | Mass of steel, which needs to be produced in $T$                                                                            |
| $G_t$                           | $\mathbb{R}_{\geq 0}$ | Generated electricity output from renewable sources at time step $t$                                                        |
| <b>Reduction Unit Parameter</b> |                       |                                                                                                                             |
| $C^{WEL,max}$                   | $\mathbb{R}_{\geq 0}$ | Maximal power capacity utilisation of water electrolysis to produce hydrogen. Can also be interpreted as installed capacity |
| $C^{WEL,min}$                   | $\mathbb{R}_{\geq 0}$ | Minimum power capacity utilisation of electrolysis                                                                          |
| $\eta^{WEL}$                    | $\mathbb{R}_{\geq 0}$ | Efficiency of water electrolysis                                                                                            |
| $C^{SH_2}$                      | $\mathbb{R}_{\geq 0}$ | Storage capacity of energy content in hydrogen tank                                                                         |
| $S_{init}^{H_2}$                | $\mathbb{R}_{\geq 0}$ | Initial storage content level of hydrogen tank                                                                              |
| $Q^{H_2 \rightarrow DRI}$       | $\mathbb{R}_{\geq 0}$ | Energy quantity of hydrogen needed to produce one unit of direct reduced iron                                               |
| $S_{init}^{DRI}$                | $\mathbb{R}_{\geq 0}$ | Initial amount of DRI in its storage                                                                                        |
| <b>Fuel Cell Parameter</b>      |                       |                                                                                                                             |
| $C^{FC}$                        | $\mathbb{R}_{\geq 0}$ | Maximal power capacity of fuel cell to produce electricity                                                                  |
| $\eta^{FC}$                     | $\mathbb{R}_{\geq 0}$ | Efficiency of fuel cell                                                                                                     |
| <b>Steel Making Parameter</b>   |                       |                                                                                                                             |
| $L_{u,v,z}^{STM}$               | $\mathbb{R}_{\geq 0}$ | Electricity load profile of $v$ th virtual equipment of $u$ th unit - vector for each time step $z$ of one batch            |
| $Q_{u,v}^{DRI \rightarrow STM}$ | $\mathbb{R}_{\geq 0}$ | Quantity of DRI units used for a batch in $v$ th virtual equipment of $u$ th unit                                           |
| $O_{u,v}^{STM}$                 | $\mathbb{R}_{\geq 0}$ | Output of produced steel products like slabs and billets, in one batch in $v$ th virtual equipment of $u$ th unit           |

|                                 |                       |                                                                                                                                                                                                                           |
|---------------------------------|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $T_{u,v}^{STM}$                 | $\mathbb{N}$          | Number of time steps of one batch in $v$ th virtual equipment of $u$ th unit; equals length of $Z_{u,v}$                                                                                                                  |
| $T_u^{pause}$                   | $\mathbb{N}$          | Number of steps of minimum downtime after production of a steel making batch in unit $u$                                                                                                                                  |
| <b>Rolling Parameter</b>        |                       |                                                                                                                                                                                                                           |
| $T_u^{ROL}$                     | $\mathbb{N}$          | Number of time steps rolling of unit $u$ is running                                                                                                                                                                       |
| $L_u^{ROL}$                     | $\mathbb{R}_{\geq 0}$ | Power load which the rolling of unit $u$ demands if it is running                                                                                                                                                         |
| $\eta_u^{ROL}$                  | $\mathbb{R}_{\geq 0}$ | Efficiency of rolling, mass loss in rolling intermediate products from steel making to rolled steel in unit $u$ .                                                                                                         |
| <b>Power Exchange Parameter</b> |                       |                                                                                                                                                                                                                           |
| $P^{goal}$                      | $\mathbb{R}_{\geq 0}$ | Goal Load to match power exchange between plant and grid. In models maximising profit, its mean power exchange serves as goal load. This value is also used as a goal load in models minimising deviation from goal load. |
| <b>Economics Parameter</b>      |                       |                                                                                                                                                                                                                           |
| $p_t^{\epsilon}$                | $\mathbb{R}_{\geq 0}$ | Price of electricity at time step $t$                                                                                                                                                                                     |

Table 9: Symbols, Domain and Description of Decision Variables in Optimisation Model

| Symbol                           | Domain                | Description                                                                                           |
|----------------------------------|-----------------------|-------------------------------------------------------------------------------------------------------|
| $\Lambda_{u,v,t}^{STM}$          | $\{0,1\}$             | 1 if $v$ th virtual equipment of $u$ th steel making unit at time step $t$ is turned on; 0 otherwise  |
| $\Lambda_t^{WEL}$                | $\{0,1\}$             | 1 if water electrolysis is running at time step $t$ ; 0 otherwise                                     |
| $L_t^{WEL}$                      | $\mathbb{R}_{\geq 0}$ | Load of electrolysis at time step $t$                                                                 |
| $G_t^{FC}$                       | $\mathbb{R}_{\geq 0}$ | Power generation by fuel cell at time $t$                                                             |
| $Q_t^{H_2 \rightarrow DRI}$      | $\mathbb{R}_{\geq 0}$ | Quantity of hydrogen used for direct reduction of iron ore at time step $t$                           |
| $Q_t^{H_2 \leftrightarrow tank}$ | $\mathbb{R}$          | Quantity of hydrogen flowing in (positive) or out (negative) of the hydrogen storage at time step $t$ |
| $P_t^{buy}$                      | $\mathbb{R}_{\geq 0}$ | Power drawn from grid at time step $t$                                                                |

Table 10: Symbols, Domain and Description of Derived Variables in Optimisation Model

| Symbol                                  | Domain                | Description                                                                                                                                                          |
|-----------------------------------------|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Reduction Unit Derived Variables</b> |                       |                                                                                                                                                                      |
| $S_t^{H_2}$                             | $\mathbb{R}_{\geq 0}$ | Energy content of the hydrogen storage at time $t$                                                                                                                   |
| $S_t^{DRI}$                             | $\mathbb{R}_{\geq 0}$ | Stored mass of direct reduced iron in storage at time step $t$                                                                                                       |
| <b>Steel Making Derived Variables</b>   |                       |                                                                                                                                                                      |
| $L_{u,t}^{STM}$                         | $\mathbb{R}_{\geq 0}$ | Load profile of unit $u$ at time step $t$                                                                                                                            |
| $\mu_{u,v,t}^{STM}$                     | $\{0, 1\}$            | Binary variable for running virtual equipment - 1 if $v$ th virtual equipment of $u$ th unit at time step $t$ is running; 0 otherwise                                |
| $\mu_{u,t}^{STM}$                       | $\{0, 1\}$            | Binary variable for running equipment - 1 if $u$ th unit at time step $t$ is running; 0 otherwise                                                                    |
| $S_{u,v,t}^{STM}$                       | $\mathbb{R}_{\geq 0}$ | Stored mass of intermediate steel products which have been produced in steel making virtual equipment $v$ until time step $t$ and were not rolled from rolling unit. |
| <b>Rolling Derived Variables</b>        |                       |                                                                                                                                                                      |
| $\mu_{u,t}^{ROL}$                       | $\{0, 1\}$            | Binary variable for running rolling unit - 1 if rolling unit for unit $u$ is running, 0 if not                                                                       |
| $L_{u,t}^{ROL}$                         | $\mathbb{R}_{\geq 0}$ | Electricity load of the rolling equipment for unit $u$ at time step $t$                                                                                              |
| $S_{u,t}^{steel}$                       | $\mathbb{R}_{\geq 0}$ | Stored, or also total mass of produced rolled steel from unit $u$ until time step $t$                                                                                |
| <b>Power - Derived Variables</b>        |                       |                                                                                                                                                                      |
| $P_t^{sell}$                            | $\mathbb{R}_{\geq 0}$ | Power fed into grid at time step $t$                                                                                                                                 |
| $P_t$                                   | $\mathbb{R}$          | Power exchange between plant and grid at time step $t$ .                                                                                                             |
| $\bar{P}$                               | $\mathbb{R}$          | Mean value of $P_t$ over all time steps                                                                                                                              |
| $D_t^{above}$                           | $\mathbb{R}_{\geq 0}$ | Distance between current power exchange $P_t$ and mean power exchange $\bar{P}$ , if $P_t$ exchange is above the mean $\bar{P}$ .                                    |
| $D_t^{below}$                           | $\mathbb{R}_{\geq 0}$ | Distance between current power exchange $P_t$ and mean power exchange $\bar{P}$ , if the exchange $P_t$ is below the mean $\bar{P}$ .                                |
| <b>Economics - Derived Variables</b>    |                       |                                                                                                                                                                      |
| $M_t^{sell}$                            | $\mathbb{R}_{\geq 0}$ | Monetary profits of selling electricity at day ahead market at time step $t$                                                                                         |
| $M_t^{buy}$                             | $\mathbb{R}_{\geq 0}$ | Monetary costs of buying electricity at day ahead market at time step $t$                                                                                            |

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# Appendices

## A Additional Information

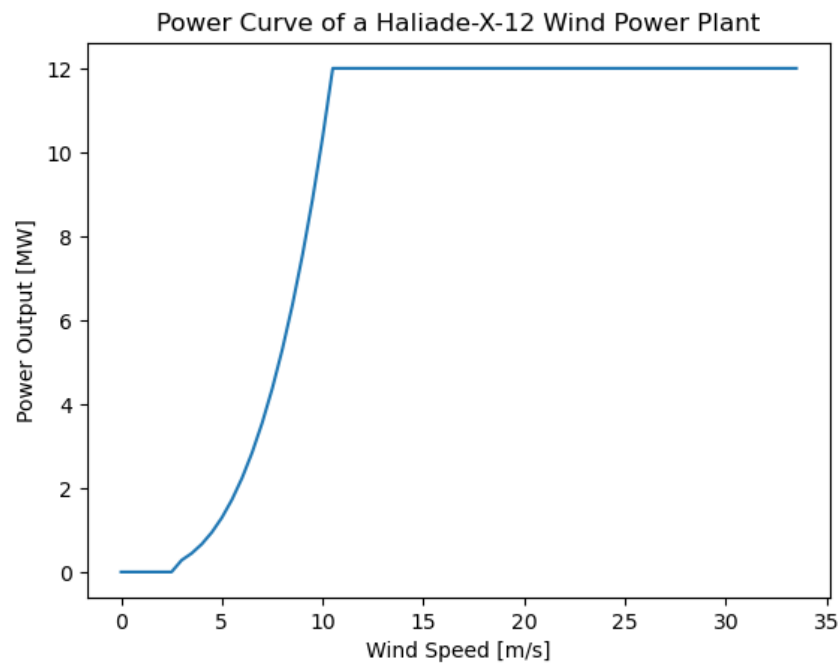


Figure 26: Power Curve for Wind Generation Profile from Hölling et al. (2021) with an maximal output of 12 MW till speeds of 34 m/s, a rated speed of 10.5 m/s and a start-up speed 3 m/s.

Table 11: Parameter Values for each Steel Plant Scenario in Optimisation Model

| Parameter                       | DR Steel Making                                                     | Constant Steel Making | H <sub>2</sub> -DRI Import                                         |
|---------------------------------|---------------------------------------------------------------------|-----------------------|--------------------------------------------------------------------|
| $T^{total}$                     | 52704                                                               | 52704                 | 52704                                                              |
| $\Delta t$                      | 1/6                                                                 | 1/6                   | 1/6                                                                |
| $m^{total}$                     | 1,000,000                                                           | 1,000,000             | 1,000,000                                                          |
| $G_t$                           | 2012 weather data as described in Section 3.2.1.1                   |                       |                                                                    |
| Reduction Unit Parameter        |                                                                     |                       |                                                                    |
| $C^{WEL,max}$                   | 555                                                                 | 563                   | 0                                                                  |
| $C^{WEL,min}$                   | 100                                                                 | 100                   | 0                                                                  |
| $\eta^{WEL}$                    | 0.63                                                                | 0.63                  | 0                                                                  |
| $C^{S^{H_2}}$                   | 400                                                                 | 24,000                | 0                                                                  |
| $S_{init}^{H_2}$                | 0                                                                   | 1                     | 0                                                                  |
| $Q^{H_2 \rightarrow DRI}$       | 2.079                                                               | 2.079                 | 0                                                                  |
| Fuel Cell Parameter             |                                                                     |                       |                                                                    |
| $C^{FC}$                        | 0                                                                   | 171                   | 0                                                                  |
| $\eta^{FC}$                     | 0                                                                   | 0.71                  | 0                                                                  |
| Steel Making Parameter          |                                                                     |                       |                                                                    |
| $L_{u,v,z}^{STM}$               | Electricity load profiles of equipments depicted in Section 3.2.1.1 |                       |                                                                    |
| $Q_{u,v}^{DRI \rightarrow STM}$ | $v_{60\%}$ : 75.60<br>$v_{80\%}$ : 100.81<br>$v_{100\%}$ : 126.01   | $v_{100\%}$ : 93.88   | 0                                                                  |
| $O_{u,v}^{STM}$                 | $v_{60\%}$ : 107.11<br>$v_{80\%}$ : 142.82<br>$v_{100\%}$ : 178.52  | $v_{100\%}$ : 133     | $v_{60\%}$ : 107.11<br>$v_{80\%}$ : 142.82<br>$v_{100\%}$ : 178.52 |
| $T_{u,v}^{STM}$                 | 4                                                                   | 4                     | 4                                                                  |
| $T_u^{pause}$                   | 2                                                                   | 2                     | 2                                                                  |
| Rolling Parameter               |                                                                     |                       |                                                                    |
| $T_u^{ROL}$                     | 6                                                                   | 6                     | 6                                                                  |
| $L_u^{ROL}$                     | 69                                                                  | 54                    | 69                                                                 |
| $\eta_u^{ROL}$                  | 93.98%                                                              | 93.98%                | 93.98%                                                             |
| Economics Parameter             |                                                                     |                       |                                                                    |
| $p_t^\epsilon$                  | Given by price data as described in Section 3.2.1.1                 |                       |                                                                    |

Table 12: Power Generation Technology Shares in German Electricity Mix of "Direct Electrification" Scenario in "BEniVer" (Aigner et al. 2023)

| Generation Technology | unit | 2023   | 2030   | 2040   | 2050   |
|-----------------------|------|--------|--------|--------|--------|
| Coal                  | TWh  | 0.11   | 0.04   | 0.03   | 0.02   |
| Coal CHP              | TWh  | 28.08  | 1.43   | 1.59   | 0.05   |
| Gas                   | TWh  | 20.09  | 1.62   | 7.42   | 1.71   |
| Gas CHP               | TWh  | 59.35  | 42.06  | 26.43  | 28.38  |
| Geothermal            | TWh  | 2.33   | 7.68   | 16.67  | 22.51  |
| Hydro Reservoir       | TWh  | 2.84   | 3.54   | 3.13   | 2.97   |
| Hydro Run Of River    | TWh  | 17.01  | 23.35  | 22.83  | 23.49  |
| Lignite               | TWh  | 49.48  | 1.28   | -      | -      |
| Lignite CHP           | TWh  | 103.35 | 36.48  | 1.48   | 0.05   |
| Nuclear               | TWh  | 7.47   | -      | -      | -      |
| Oil                   | TWh  | 7.49   | 0.01   | 0.02   | -      |
| Solar PV              | TWh  | 64.20  | 170.39 | 382.26 | 397.19 |
| Solid Biomass         | TWh  | 13.33  | 6.92   | 20.15  | 21.08  |
| Waste                 | TWh  | 12.14  | 0.23   | 8.67   | 1.61   |
| Wind Offshore         | TWh  | 28.99  | 27.81  | 290.63 | 296.55 |
| Wind Onshore          | TWh  | 131.41 | 301.32 | 356.15 | 359.65 |

Table 13: Steel Production Pathway Shares in German Steel Production of "Electrification Scenario" by Harpprecht et al. (2022)

| Production Pathway | unit | 2023 | 2030 | 2040 | 2050 |
|--------------------|------|------|------|------|------|
| BF-BOF             | Mt   | 29.5 | 15.3 | 10   | -    |
| Scrap-EAF          | Mt   | 12.6 | 17.2 | 20.1 | 24.2 |
| NG-DRI-EAF         | Mt   | 0.5  | 6    | -    | -    |
| H2-DRI-EAF         | Mt   | -    | 4    | 11.3 | 11.3 |
| EW-EAF             | Mt   | -    | -    | 1.1  | 7.1  |

## B Life Cycle Inventories

Table 14: Life Cycle Inventory of a 9.5 MW Wind Turbine by Benitez et al. (2024)

| name                                                         | location | amount   | unit          |
|--------------------------------------------------------------|----------|----------|---------------|
| Tower                                                        | DE       | 500000   | kilogram      |
| Foundation                                                   | DE       | 996000   | kilogram      |
| Nacelle                                                      | DE       | 267000   | kilogram      |
| Rotor CFRP/GFRP                                              | DE       | 81500    | kilogram      |
| Rotor GFRP                                                   | DE       | 109000   | kilogram      |
| market for transport, freight, lorry 16-32 metric ton, EURO5 | RER      | 15000000 | ton kilometer |
| Substation                                                   | DE       | 550      | kilogram      |
| Transmission grid 33kV, construction                         | DE       | 35000    | kilogram      |
| Transmission grid 245kV, construction                        | DE       | 67000    | kilogram      |

Table 15: Life Cycle Inventory of 1 kilogram Tower for a reference Offshore Wind Turbine by Benitez et al. (2024)

| name                                           | location                   | amount | unit     |
|------------------------------------------------|----------------------------|--------|----------|
| epoxy paint primer/topcoat production          | RER                        | 0.02   | kilogram |
| market for ferrous metal, in mixed metal scrap | Europe without Switzerland | -0.98  | kilogram |
| market for steel, low-alloyed [LW]             | DE                         | 0.98   | kilogram |

Table 16: Life Cycle Inventory of 1 kilogram Foundation for a reference Offshore Wind Turbine by Benitez et al. (2024)

| name                              | location | amount | unit     |
|-----------------------------------|----------|--------|----------|
| market for concrete block         | DE       | 0.03   | kilogram |
| market for gravel, round          | RoW      | 0.01   | kilogram |
| market for reinforcing steel [LW] | DE       | 0.96   | kilogram |

Table 17: Life Cycle Inventory of 1 kilogram of Nacelle for a reference Offshore Wind Turbine by Benitez et al. (2024)

| <b>name</b>                                      | <b>location</b>                       | <b>amount</b> | <b>unit</b> |
|--------------------------------------------------|---------------------------------------|---------------|-------------|
| cast iron production                             | RER                                   | 0.21          | kilogram    |
| market for aluminium, cast alloy                 | GLO                                   | 0.17          | kilogram    |
| market for aluminium, in mixed metal scrap       | RoW                                   | -0.17         | kilogram    |
| market for copper scrap, sorted, pressed         | GLO                                   | -0.17         | kilogram    |
| market for copper, cathode                       | GLO                                   | 0.07          | kilogram    |
| market for ferrous metal, in mixed metal scrap   | Europe<br>without<br>Switzer-<br>land | -0.54         | kilogram    |
| market for glass fibre                           | GLO                                   | 0.03          | kilogram    |
| market for lubricating oil                       | RER                                   | 0.01          | kilogram    |
| market for permanent magnet, for electric motor  | GLO                                   | 0.02          | kilogram    |
| market for steel, chromium steel 18/8 [LW]       | DE                                    | 0.42          | kilogram    |
| market for steel, low-alloyed [LW]               | DE                                    | 0.08          | kilogram    |
| market for waste glass                           | DE                                    | -0.0195       | kilogram    |
| market for waste mineral oil                     | Europe<br>without<br>Switzer-<br>land | -0.01         | kilogram    |
| market for waste plastic, industrial electronics | RoW                                   | -0.0105       | kilogram    |

Table 18: Life Cycle Inventory of 1 kilogram of Rotor made of a mixture of Glass Fibre Reinforced Plastic and Carbon Fibre Reinforced Plastic for a reference Offshore Wind Turbine by Benitez et al. (2024)

| <b>name</b>                                                             | <b>location</b> | <b>amount</b> | <b>unit</b> |
|-------------------------------------------------------------------------|-----------------|---------------|-------------|
| glass fibre reinforced plastic production, polyamide, injection moulded | RER             | 0.83          | kilogram    |
| market for carbon fibre reinforced plastic, injection moulded           | GLO             | 0.12          | kilogram    |
| market for epoxy resin, liquid                                          | RoW             | 0.02          | kilogram    |
| market for steel, chromium steel 18/8 [LW]                              | DE              | 0.1           | kilogram    |

Table 19: Life Cycle Inventory of 1 kilogram of Rotor made of Glass Fibre Reinforced Plastic for a reference Offshore Wind Turbine by Benitez et al. (2024)

| name                                                                    | location | amount | unit     |
|-------------------------------------------------------------------------|----------|--------|----------|
| market for cast iron                                                    | GLO      | 0.33   | kilogram |
| market for glass fibre reinforced plastic, polyamide, injection moulded | GLO      | 0.98   | kilogram |
| market for epoxy resin, liquid                                          | RER      | 0.01   | kilogram |
| market for steel, chromium steel 18/8 [LW]                              | DE       | 0.09   | kilogram |
| market for steel, low-alloyed [LW]                                      | DE       | 0.09   | kilogram |
| market for wood chips, dry, measured as dry mass                        | RER      | 0.01   | kilogram |

Table 20: Life Cycle Inventory of a Substation for an Offshore Wind Park by Benitez et al. (2024)

| name                                             | location | amount | unit     |
|--------------------------------------------------|----------|--------|----------|
| market for aluminium, cast alloy                 | GLO      | 0.01   | kilogram |
| market for concrete block                        | DE       | 0.63   | kilogram |
| market for lubricating oil                       | RER      | 0.02   | kilogram |
| market for steel, chromium steel 18/8 [LW]       | DE       | 0.29   | kilogram |
| market for steel, low-alloyed [LW]               | DE       | 0.02   | kilogram |
| market for wood chips, dry, measured as dry mass | RER      | 0.01   | kilogram |
| polyester resin production, unsaturated          | RoW      | 0.01   | kilogram |

Table 21: Life Cycle Inventory of 1 kilogram Transmission Grid 33kV, Construction for an Offshore Wind Wark by Benitez et al. (2024)

| name                                           | amount | location | unit     |
|------------------------------------------------|--------|----------|----------|
| market for polyvinylchloride, bulk polymerised | 0.4    | GLO      | kilogram |
| market for copper, cathode                     | 0.4    | GLO      | kilogram |
| market for steel, low-alloyed [LW]             | 0.15   | DE       | kilogram |
| market for aluminium, cast alloy               | 0.05   | GLO      | kilogram |

Table 22: Life Cycle Inventory of 1 kilogram Transmission grid 245kV, construction for an offshore wind park by Benitez et al. (2024)

| name                                           | amount | location | unit     |
|------------------------------------------------|--------|----------|----------|
| market for polyvinylchloride, bulk polymerised | 0.35   | GLO      | kilogram |
| market for copper, cathode                     | 0.1    | GLO      | kilogram |
| market for steel, low-alloyed [LW]             | 0.1    | DE       | kilogram |
| market for aluminium, cast alloy               | 0.35   | GLO      | kilogram |
| market for lead                                | 0.1    | GLO      | kilogram |

Table 23: Life Cycle Inventory of 1MW Solid Oxide Water Electrolyser Stack Manufacturing by Gerloff (2021)

| <b>name</b>                                               | <b>region</b>               | <b>amount</b> | <b>unit</b>      |
|-----------------------------------------------------------|-----------------------------|---------------|------------------|
| market for aluminium oxide, metallurgical                 | IAI Area,<br>EU27 &<br>EFTA | 6.4           | kilogram         |
| market for barium oxide                                   | GLO                         | 6.4           | kilogram         |
| market for boric oxide                                    | GLO                         | 6.4           | kilogram         |
| market for cerium oxide                                   | GLO                         | 91.5          | kilogram         |
| market for lanthanum oxide                                | GLO                         | 21.0          | kilogram         |
| market for nickel, class 1                                | GLO                         | 144.1         | kilogram         |
| market for praseodymium oxide                             | GLO                         | 9.0           | kilogram         |
| market for samarium-europium-gadolinium oxide             | GLO                         | 37.7          | kilogram         |
| market for sheet rolling, chromium steel                  | GLO                         | 8976.1        | kilogram         |
| market for silicone product                               | RER                         | 6.4           | kilogram         |
| market for steel, chromium steel 18/8, hot rolled         | GLO                         | 8976.1        | kilogram         |
| market for steel, chromium steel 18/8, hot rolled<br>[LW] | DE                          | 0.0           | kilogram         |
| market for strontium carbonate                            | GLO                         | 21.0          | kilogram         |
| market for zirconium oxide                                | GLO                         | 170.7         | kilogram         |
| market group for electricity, low voltage                 | WEU                         | 122224.433    | kilowatt<br>hour |

Table 24: Life Cycle Inventory of 1MW Solid Oxide Water Electrolyser Balance of Plant by Gerloff (2021)

| name                                                   | region | amount  | unit             |
|--------------------------------------------------------|--------|---------|------------------|
| market for welding, arc, steel                         | GLO    | 33.3    | meter            |
| market for electronics, for control units              | GLO    | 100.0   | kilogram         |
| market for steel, low-alloyed                          | GLO    | 1503.6  | kilogram         |
| market for extrusion, plastic pipes                    | GLO    | 534.0   | kilogram         |
| market group for electricity, low voltage              | GLO    | 76420.2 | kilowatt<br>hour |
| market for aluminium, wrought alloy                    | GLO    | 401.0   | kilogram         |
| market for steel, low-alloyed [LW]                     | DE     | 0.0     | kilogram         |
| market for concrete, normal strength                   | CH     | 2.3     | cubic me-<br>ter |
| market for sheet rolling, aluminium                    | GLO    | 100.0   | kilogram         |
| market for steel, chromium steel 18/8, hot rolled [LW] | DE     | 0.0     | kilogram         |
| market for steel, low-alloyed, hot rolled [LW]         | DE     | 0.0     | kilogram         |
| market for acrylonitrile-butadiene-styrene copolymer   | GLO    | 1.4     | kilogram         |
| market for tube insulation, elastomere                 | GLO    | 176.6   | kilogram         |
| market for cast iron                                   | GLO    | 3000.0  | kilogram         |
| market for reinforcing steel [LW]                      | DE     | 0.0     | kilogram         |
| market for injection moulding                          | GLO    | 1.4     | kilogram         |
| market for copper, cathode                             | GLO    | 428.5   | kilogram         |
| market for steel, low-alloyed, hot rolled              | GLO    | 2250.0  | kilogram         |
| market group for electricity, low voltage              | WEU    | 0.0     | kilowatt<br>hour |
| market for reinforcing steel                           | GLO    | 14136.6 | kilogram         |
| market for steel, chromium steel 18/8, hot rolled      | GLO    | 16215.4 | kilogram         |
| market for polyethylene, low density, granulate        | GLO    | 534.0   | kilogram         |
| market for sheet rolling, chromium steel               | GLO    | 16215.4 | kilogram         |
| market for wire drawing, copper                        | GLO    | 428.5   | kilogram         |
| market for sheet rolling, steel                        | GLO    | 12487.2 | kilogram         |
| market for ethylene glycol                             | GLO    | 35.0    | kilogram         |

Table 25: Life Cycle Inventory 1750 litre Type III Hydrogen Tank from Agostini et al. (2018)

| name                                                   | location | amount | unit     |
|--------------------------------------------------------|----------|--------|----------|
| sheet rolling, aluminium                               | RER      | 375    | kilogram |
| market for steel, chromium steel 18/8, hot rolled [LW] | DE       | 315    | kilogram |
| market for epoxy resin, liquid                         | RER      | 210    | kilogram |
| carbon fiber                                           | DE       | 12.5   | kilogram |

Table 26: Life Cycle Inventory Solid Oxide Fuel Cell, Stack, Manufacturing, 250kW by Bicer and Khalid (2020)

| name                                                                      | location | amount | unit             | categories                  |
|---------------------------------------------------------------------------|----------|--------|------------------|-----------------------------|
| Benzyl alcohol                                                            |          | 8.26   | kilogram         | water:<br>:surface<br>water |
| Carbon dioxide, fossil                                                    |          | 108    | kilogram         | air                         |
| Ethanol                                                                   |          | 28     | kilogram         | air                         |
| Methyl ethyl ketone                                                       |          | 54.24  | kilogram         | air                         |
| market for benzyl alcohol                                                 | GLO      | 8.26   | kilogram         |                             |
| market for carbon black                                                   | GLO      | 0.46   | kilogram         |                             |
| market for electricity, medium voltage                                    | DE       | 55000  | kilowatt<br>hour |                             |
| market for ethanol, without water, in 99.7% solution state, from ethylene | RER      | 28     | kilogram         |                             |
| market for ethylene glycol                                                | GLO      | 9      | kilogram         |                             |
| market for methyl ethyl ketone                                            | RER      | 54     | kilogram         |                             |
| market for nickel, class 1                                                | GLO      | 150    | kilogram         |                             |
| market for steel, chromium steel 18/8, hot rolled [LW]                    | DE       | 3500   | kilogram         |                             |
| market for yttrium oxide                                                  | GLO      | 5      | kilogram         |                             |
| market for zircon                                                         | GLO      | 62     | kilogram         |                             |
| polyester-complexed starch biopolymer production                          | RER      | 10.6   | kilogram         |                             |
| rare earth oxides production, from rare earth carbonate concentrate       | RoW      | 0.62   | kilogram         |                             |

Table 27: Life Cycle Inventory Solid Oxide Fuel Cell, System, Installation, 250kW by Bicer and Khalid (2020)

| <b>name</b>                                            | <b>location</b> | <b>amount</b> | <b>unit</b>   |
|--------------------------------------------------------|-----------------|---------------|---------------|
| Solid Oxide Fuel Cell, Stack, Manufacturing, 250kW     | DE              | 1             | unit          |
| inverter production, 500kW                             | RER             | 0.5           | unit          |
| market for cast iron                                   | GLO             | 2050          | kilogram      |
| market for electricity, medium voltage                 | DE              | 12000         | kilowatt hour |
| market for reinforcing steel [LW]                      | DE              | 12200         | kilogram      |
| market for steel, chromium steel 18/8, hot rolled [LW] | DE              | 3600          | kilogram      |
| market for zinc oxide                                  | GLO             | 4080          | kilogram      |
| natural gas, burned in gas turbine                     | DE              | 110000        | megajoule     |
| production of nickel-based catalyst for methanation    | RER             | 1970          | kilogram      |

Table 28: Life Cycle Inventory 1 kilogram Container for a Battery System by Han et al. (2023)

| <b>name</b>                                                                                              | <b>location</b>       | <b>amount</b> | <b>unit</b>   |
|----------------------------------------------------------------------------------------------------------|-----------------------|---------------|---------------|
| market for aluminium, primary, ingot                                                                     | IAI Area, EU27 & EFTA | 1             | kilogram      |
| metal working factory construction                                                                       | RER                   | 4.6E-10       | unit          |
| sheet rolling, aluminium                                                                                 | RER                   | 1             | kilogram      |
| transport, freight, lorry, all sizes, EURO6 to generic market for transport, freight, lorry, unspecified | RER                   | 0.1           | ton kilometer |
| transport, tractor and trailer, agricultural                                                             | RoW                   | 0.2           | ton kilometer |

Table 29: Life Cycle Inventory 1 kilogram of Battery Management System by Han et al. (2023)

| <b>name</b>                                                                                              | <b>location</b>            | <b>amount</b> | <b>unit</b>   |
|----------------------------------------------------------------------------------------------------------|----------------------------|---------------|---------------|
| integrated circuit production, logic type                                                                | GLO                        | 0.0528        | kilogram      |
| market for copper, anode                                                                                 | GLO                        | 0.5           | kilogram      |
| market for printed wiring board, through-hole mounted, unspecified, Pb free                              | GLO                        | 0.089         | kilogram      |
| market for steel, chromium steel 18/8 [LW]                                                               | DE                         | 0.4           | kilogram      |
| market for transport, freight train                                                                      | Europe without Switzerland | 0.2           | ton kilometer |
| plastic processing factory construction                                                                  | RER                        | 2.3E-10       | unit          |
| sheet rolling, steel                                                                                     | RER                        | 0.4           | kilogram      |
| transport, freight, lorry, all sizes, EURO6 to generic market for transport, freight, lorry, unspecified | RER                        | 0.1           | ton kilometer |
| wire drawing, copper                                                                                     | RER                        | 0.5           | kilogram      |

Table 30: Life Cycle Inventory 1 kilogram of Lithium Iron Phosphate for Battery by Li et al. (2024b)

| name                                                                               | location                   | amount    | unit          | categories |
|------------------------------------------------------------------------------------|----------------------------|-----------|---------------|------------|
| Ammonia                                                                            |                            | 0.000123  | kilogram      | air        |
| BOD5, Biological Oxygen Demand                                                     |                            | 0.0000925 | kilogram      | water      |
| COD, Chemical Oxygen Demand                                                        |                            | 0.000921  | kilogram      | water      |
| Carbon dioxide, fossil                                                             |                            | 0.00171   | kilogram      | air        |
| Nitrogen, organic bound                                                            |                            | 0.0000013 | kilogram      | water      |
| Phosphorus                                                                         |                            | 4.98E-08  | kilogram      | water      |
| Sulfur trioxide                                                                    |                            | 0.000203  | kilogram      | air        |
| Suspended solids, unspecified                                                      |                            | 0.0000429 | kilogram      | water      |
| lithium iron phosphate                                                             | DE                         | 1         | kilogram      |            |
| air separation, cryogenic                                                          | RER                        | 0.00929   | kilogram      |            |
| ammonia production, steam re-forming, liquid                                       | RNA                        | 1.77      | kilogram      |            |
| heat and power co-generation, hard coal                                            | DE                         | 1.8       | megajoule     |            |
| hydrogen peroxide production, product in 50% solution state                        | RER                        | 0.375     | kilogram      |            |
| market for electricity, high voltage [LW]                                          | DE                         | 3.5       | kilowatt hour |            |
| market for glucose                                                                 | GLO                        | 0.1       | kilogram      |            |
| market for iron pellet                                                             | GLO                        | 0.373     | kilogram      |            |
| market for lithium carbonate                                                       | GLO                        | 0.25      | kilogram      |            |
| market for phosphoric acid, industrial grade, without water, in 85% solution state | GLO                        | 0.763     | kilogram      |            |
| market for tap water                                                               | Europe without Switzerland | 0.817     | kilogram      |            |
| sulfuric acid production                                                           | RER                        | 0.672     | kilogram      |            |
| water production, deionised                                                        | Europe without Switzerland | 8.51      | kilogram      |            |

Table 31: Life Cycle Inventory 1 kWh Lithium Iron Phosphate Battery System for Grid Scale Application by Li et al. (2024b)

| name                                                       | location | amount     | unit        | categories        |
|------------------------------------------------------------|----------|------------|-------------|-------------------|
| COD, Chemical Oxygen Demand                                |          | 0.00063    | kilogram    | water             |
| Carbon monoxide, fossil                                    |          | 0.00000433 | kilogram    | air               |
| NMVOC, non-methane volatile organic compounds              |          | 0.0132     | kilogram    | air               |
| Nitrogen oxides                                            |          | 0.00312    | kilogram    | air               |
| Nitrogen, organic bound                                    |          | 0.0000958  | kilogram    | water:<br>:ground |
| Phosphorus                                                 |          | 0.0000028  | kilogram    | water             |
| Sulfur dioxide                                             |          | 0.0000175  | kilogram    | air               |
| Suspended solids, unspecified                              |          | 0.000126   | kilogram    | water             |
| Water                                                      |          | 1.26       | cubic meter | water             |
| Battery Cell Container                                     | DE       | 1.02       | kilogram    |                   |
| Battery Management System                                  | DE       | 0.158      | kilogram    |                   |
| N-methyl-2-pyrrolidone production                          | RER      | 0.12       | kilogram    |                   |
| acrylonitrile-butadiene-styrene copolymer production       | RER      | 0.58       | kilogram    |                   |
| aluminium alloy production, Metallic Matrix Composite      | RoW      | 0.67       | kilogram    |                   |
| carboxymethyl cellulose production, powder                 | RER      | 0.02       | kilogram    |                   |
| dimethyl carbonate production                              | RER      | 1.07       | kilogram    |                   |
| ethylene carbonate production                              | RoW      | 0.65       | kilogram    |                   |
| evaporation of natural gas                                 | BR       | 1.67       | cubic meter |                   |
| graphite production, battery grade                         | RoW      | 1.16       | kilogram    |                   |
| lithium hexafluorophosphate production                     | RoW      | 0.38       | kilogram    |                   |
| lithium iron phosphate                                     | DE       | 2.67       | kilogram    |                   |
| market for carbon black                                    | GLO      | 0.07       | kilogram    |                   |
| market for chemical, organic                               | GLO      | 0.12       | kilogram    |                   |
| market for copper, anode                                   | GLO      | 1          | kilogram    |                   |
| polyethylene production, high density, granulate, recycled | RoW      | 0.02       | kilogram    |                   |
| polypropylene production, granulate                        | RER      | 0.01       | kilogram    |                   |

Table 32: Life Cycle Inventory for Demand Response Steel Making Steel Plant Scenario

| <b>name</b>                                           | <b>location</b> | <b>amount</b> | <b>unit</b> |
|-------------------------------------------------------|-----------------|---------------|-------------|
| offshore wind park construction, 9.5MW turbines       | DE              | 853           | megawatt    |
| electrolyzer production, 1MWe, SOEC, Stack            | RER             | 555           | unit        |
| electrolyzer production, 1MWe, SOEC, Balance of Plant | RER             | 555           | unit        |
| blast furnace production [LW]                         | DE              | 1             | unit        |
| hydrogen tank production, 350bar, 1750l               | DE              | 5             | unit        |
| electric arc furnace converter construction [LW]      | DE              | 1.35          | unit        |
| lithium iron phosphate battery production, 1kWh       | DE              | 7500          | unit        |
| rolling mill production                               | RER             | 1.62          | unit        |

Table 33: Life Cycle Inventory for Constant Steel Making Steel Plant Scenario

| <b>name</b>                                           | <b>location</b> | <b>amount</b> | <b>unit</b> |
|-------------------------------------------------------|-----------------|---------------|-------------|
| offshore wind park construction, 9.5MW turbines       | DE              | 828           | megawatt    |
| electrolyzer production, 1MWe, SOEC, Stack            | RER             | 563           | unit        |
| electrolyzer production, 1MWe, SOEC, Balance of Plant | RER             | 563           | unit        |
| hydrogen tank production, 350bar, 1750l               | DE              | 17143         | unit        |
| Solid Oxide Fuel Cell, System, Installation, 250kW    | DE              | 684           | unit        |
| blast furnace production [LW]                         | DE              | 1             | unit        |
| electric arc furnace converter construction [LW]      | DE              | 1             | unit        |
| rolling mill production                               | RER             | 1.26          | unit        |

Table 34: Life Cycle Inventory for H<sub>2</sub>-DRI Import Steel Plant Scenario

| <b>name</b>                                      | <b>location</b> | <b>amount</b> | <b>unit</b> |
|--------------------------------------------------|-----------------|---------------|-------------|
| offshore wind park construction, 9.5MW turbines  | DE              | 288           | megawatt    |
| electric arc furnace converter construction [LW] | DE              | 1.35          | unit        |
| lithium iron phosphate battery production, 1kWh  | DE              | 7500          | unit        |
| rolling mill production                          | RER             | 1.62          | unit        |