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Designing the technological transformation toward sustainable steelmaking: A framework to provide decision support to industrial practitioners

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Abstract

Climate change and the resultant requirement to reduce greenhouse gas emissions have become one of society's main challenges. High emissions occur in the industrial sector and particularly in steelmaking. Due to energy-intensive carbon-based production processes, there is a significant potential to reduce greenhouse gas emissions in the steel industry. In this context, a promising technology is the hydrogen-based direct reduction of iron ore that can be used instead of coal-based blast furnaces. However, the transformation toward sustainable steelmaking implies various regulatory, technological, and economic challenges. For example, decision-makers must decide about strategic investments in the context of an uncertain political environment and unpredictable development pathways of future technologies. These courses have a direct impact on the competitiveness of steelmaking corporations. Consequently, decision-makers in industrial practice waver to design and evaluate advantageous transformation pathways for their corporations. We propose a framework of a decision support tool to design and evaluate the transformation toward sustainable steelmaking. To this end, we model the relevant steelmaking processes based on activity analysis and link them to optimization packages. Decision-makers can evaluate alternative future market scenarios and determine the optimal transformation pathway for their corporation. We discussed our framework with decision-makers from steelmaking. They confirm the effectiveness of our approach to support them in evaluating advantageous transformation pathways for their corporation.

Keywords: Sustainable raw material processing; steelmaking; hydrogen; activity analysis

1. Introduction

Anthropogenic climate change and the commitment of 191 Parties to limit global warming to a maximum of two degrees Celsius require a significant reduction of greenhouse gas emissions in all sectors [1]. With a share of approximately 7% of global greenhouse gas emissions from the energy system, the steel industry is one of the main contributors to climate change [2]. Therefore, several projects to minimize greenhouse gas emissions in steelmaking have been initiated. Some projects explore the electrolysis of iron ore, such as Siderwin (Europe) [3]. However, most projects focus on hydrogen-based technologies, such as SALCOS (Germany), tkH2Steel (Germany), HYBRIT (Sweden), H2Future (Europe), and COURSE50 (Japan) [4–8].

At present, the most used technology for primary steelmaking is the coal-based blast furnace-basic oxygen furnace (BF–BOF) route. Short- and medium-term, carbon capture and storage technologies provide a way to reduce the emission of greenhouse gases from these production processes into the atmosphere [9,10]. Furthermore, increasing the rate of scrap-based secondary steelmaking leads to lower greenhouse gas emissions. Unfortunately, scrap availability is limited and does not suffice to meet demand alone. Currently, scrap-based production in electric arc furnaces or induction furnaces accounts for about 20% of global crude steel production.

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Additionally, scrap is also used at a rate of 15–20% in the BF–BOF production and at a rate of about 10% in the direct reduction of iron ore [11]. In the long term, hydrogen-based direct reduction (H–DR) and electrolysis of iron ore are considered more promising solutions to avoid climate-damaging emissions. To prevent nearly all greenhouse gas emissions, obtaining electricity from renewable sources is required. An advantage of H–DR compared to the electrolysis of iron ore is the possibility to decouple the electricity demand and the unsteady supply of renewable energy through hydrogen storage [9,12]. Furthermore, the direct reduction can also be based on natural gas, which already results in lower greenhouse gas emissions compared to the coal-based BF–BOF production [13]. This is particularly promising in the initial phase of the transformation process, in which the availability of green hydrogen might not be sufficient to cover all desired applications [14]. As a result, medium-term reductions in greenhouse gas emissions are achievable. In contrast, the electrolysis of iron ore requires further technological development until it reaches competitiveness [15]. Therefore, H–DR is currently the most promising technology for the medium- and long-term avoidance of greenhouse gas emissions.

However, besides the ecological advantages of H–DR, there are additional economic expenses that lead to an increase in the specific costs of crude steel [16]. Moreover, an uncertain regulatory environment complicates long-term decision-making [17,18]. From a technological point of view, interdependencies of the production stages resulting from the occurrence and consumption of by-products, such as gases and dust, must be considered. If the production volumes of certain production processes change, the increased or decreased occurrence of specific by-products has to be compensated by alternative process media. These ecological, economic, regulatory, and technological aspects indicate that decision-makers in the steel industry are operating in a highly complex environment. Therefore, strategic decisions regarding the transformation toward sustainable steelmaking must be supported using quantitative techno-economic planning approaches.

In this article, we present an approach for modeling steelmaking processes based on activity analysis and link them to optimization packages. To this end, the remainder of the article is structured as follows. In Section 2, an overview of existing literature regarding hydrogen-based steelmaking pathways and the application of quantitative methods in steelmaking is given. In Section 3, the framework for a decision support tool is presented. Based on the modeling of steelmaking processes and the optimization of production quantities in each production stage, industrial practitioners are supported in strategic decision-making. To ensure the effectiveness of our approach, we develop it in cooperation with a major German steel manufacturer. In Section 4, this paper concludes with a discussion of the developed framework and an outlook on future research areas.

2. Literature overview

Several research studies focus on scenarios and pathways for the decarbonization of steelmaking based on hydrogen. This section provides a brief overview of previous research relating to these topics. Requirements for a decision support tool are defined and previous literature on quantitative approaches is presented. Eventually, we identify research gaps regarding the evaluation and design of transformation pathways toward hydrogen-based steelmaking.

2.1. Pathways toward hydrogen-based steelmaking

Gielen et al. [19] and Vogl et al. [16] focus on the assessment of a H–DR in the context of sustainable steelmaking. Gielen et al. state that the development of commercial-scale hydrogen-based steelmaking needs to be a priority from 2025 onwards to reduce greenhouse gas emissions significantly. They state that the main contribution toward this is a higher carbon price, which increases the competitiveness of climate-friendly technologies. In addition, the findings of Vogl et al. indicate that current production costs of sustainable steelmaking are generally higher compared to conventional primary steelmaking. However, low electricity costs or a high carbon price can lead to the economic competitiveness of sustainable technologies in the upcoming years. Arens et al. [12] analyze pathways to low carbon steelmaking until 2030. According to their study, most new technologies to reduce greenhouse gas emissions will not be commercially available in sufficient quantities medium-term. Thus, efficient use of by-products and waste heat must contribute to reducing greenhouse gas emissions short- and medium-term. In the long term, technologies such as H–DR are required to avoid all climate-damaging emissions. Karakaya et al. [20] focus on potential transitions of the steel industry in Sweden. Their findings indicate that the steel industry in this country will most likely transition toward hydrogen-based steelmaking in the upcoming decades. To date, though, this transformation process has not been detailed.

The brief literature overview indicates that several studies already evaluate technologies or propose transformation pathways for hydrogen-based steelmaking. However, to support industrial practitioners in decision-making, more detailed considerations of these transformation pathways are required. Based on the literature overview, we derive the following requirements for supporting the evaluation of transformation pathways toward hydrogen-based steelmaking. Industrial decision-makers are operating in a highly complex environment. Since the required infrastructure to completely avoid greenhouse gas emissions is not fully available at this point, a dynamic view of the transformation process is required. To this end, different scenarios of future regulatory, technological, and economic developments must be considered, e.g., regarding the price and availability of green hydrogen, natural gas, and carbon media. As the competitiveness of steel manufacturers is mainly driven by the price of their products, a cost-efficient transformation must be pursued. To account for the high importance of by-products to the economic success of steelmaking, detailed modeling of all decision-relevant processes of the BF–BOF and H–DR routes is required. Finally, an assessment of multiple stages of the life cycle of steel is required. To this end, a modular design of the decision support tool must be ensured to allow for relevant extensions, such as a more detailed consideration of the energy sector. Thus, the impact of other life cycle stages on environmental, economic, and social sustainability can be taken into account.

2.2. Quantitative methods in steelmaking

This section presents methodical approaches in the context of steelmaking that relate to the previously described requirements. To integrate environmental and social impacts in addition to economic aspects, the life cycle sustainability assessment (LCSA) is a suitable method. This approach addresses the economic, environmental, and social impacts of products across the product lifecycle [21]. The application of life cycle analysis in the context of the environmental impacts of steelmaking is proposed, among others, by Liang et al. [22], Olmez et al. [23], Scaife et al. [24], and Yellishetty et al. [25]. Further publications focus on the assessment of social aspects of steelmaking along the supply chain. A social life cycle assessment in the Indian steel industry is carried out by Singh and Gupta [26]. However, the presented approaches do not consider multiple periods and there is no focus on cost-efficiency. Additionally, their research is not based on the modeling of all decision-relevant processes. Using material flow analysis and life cycle assessment, Fröhling et al. [27] aim at enhancing the resource efficiency in steelmaking and recycling processes. Their methodical approach enables an economic and ecological assessment of mass and energy flows. The modeling approach can be extended to include additional production stages or plants. However, there is no dynamic view of the transformation process. In addition, Fröhling et al. focus on resource and energy efficiency instead of an overall cost-efficiency in the considered production network.

A modeling approach that allows including multiple stages of the life cycle, a modular design, an economic focus, and a dynamic view of the transformation process is activity analysis. First introduced by Koopmans [28] in 1951, activity analysis is an algebraic modeling approach used for describing the transformation of materials and products through production and transportation processes. Thereby, it allows a quantity- and value-based description of commodities within transformation processes. Meyer et al. [29] model recycling operations for steelmaking based on activity analysis. Thus, the consideration of resource flows between different processes and production stages of steelmaking is possible. The integration of cost functions into a planning model also enables an economic evaluation of recycling operations. Multiple periods are included in the planning approach. However, the approach focuses on operative recycling planning. Dynamic developments, which can occur in the context of strategic decision-making, are not included. Moreover, the cost-oriented approach is not extended by environmental aspects. Combining activity analysis and sustainability assessment in the context of global supply chains has been introduced by Thies et al. [30]. Therefore, detailed modeling of decision-relevant processes is possible. In addition to economic aspects, ecological and social aspects are included. However, the approach does not allow a dynamic view of the decision situation. In addition, the research work is not based on a planning model that enables cost-efficient optimization.

To summarize, none of the presented approaches meets all identified requirements. Particularly, the combination of detailed process modeling with a cost-oriented focus in the context of a dynamic view of the transformation process is not fully addressed by any approach. Nevertheless, activity analysis based modeling is a promising method that was already applied in the context of steelmaking. Based on the results of the literature analysis, a framework for supporting industrial practitioners in strategic decision-making regarding the transformation toward hydrogen-based steelmaking is presented below.

3. Decision support framework

In this section, we develop a suitable decision support framework to support the transformation toward sustainable steelmaking and validate it with industrial practitioners.

3.1. Goal and scope of the decision support framework

The presented decision support framework aims to support industrial practitioners in designing and evaluating transformation pathways toward hydrogen-based steelmaking. It consists of two major packages. The first package contains the modeling of the decision-relevant processes of steelmaking based on activity analysis. This package enables the economic and ecological evaluation of steelmaking sites. The second package consists of a planning model, which is solved iteratively throughout the considered periods to provide results for the decision-makers. The required data can be obtained from public databases or corporate data records, e.g., cost unit structures or parts lists.

The modeling of the decision-relevant processes uses input parameters such as the capacity of production stages, time periods of capacity expansions and reductions, price and market trends, and assumptions on political and regulatory developments. The goal is to evaluate the economic and ecological dimensions of steelmaking plants. To this end, the reported indicators include the development of crude steel production costs, expected cash flows, production quantities, capacity utilization, expected demand of energy carriers, and greenhouse gas emissions.

The main objective of the planning model is to achieve a minimization of the crude steel production costs throughout the transformation process. For this purpose, various periods are considered in which the expansion steps and capacity changes of production stages are externally determined by the decision-makers. The planning model decides on the production quantities of available production facilities in the planning period to facilitate a cost-efficient design of the transformation pathway. Both input data and results are dynamically depicted

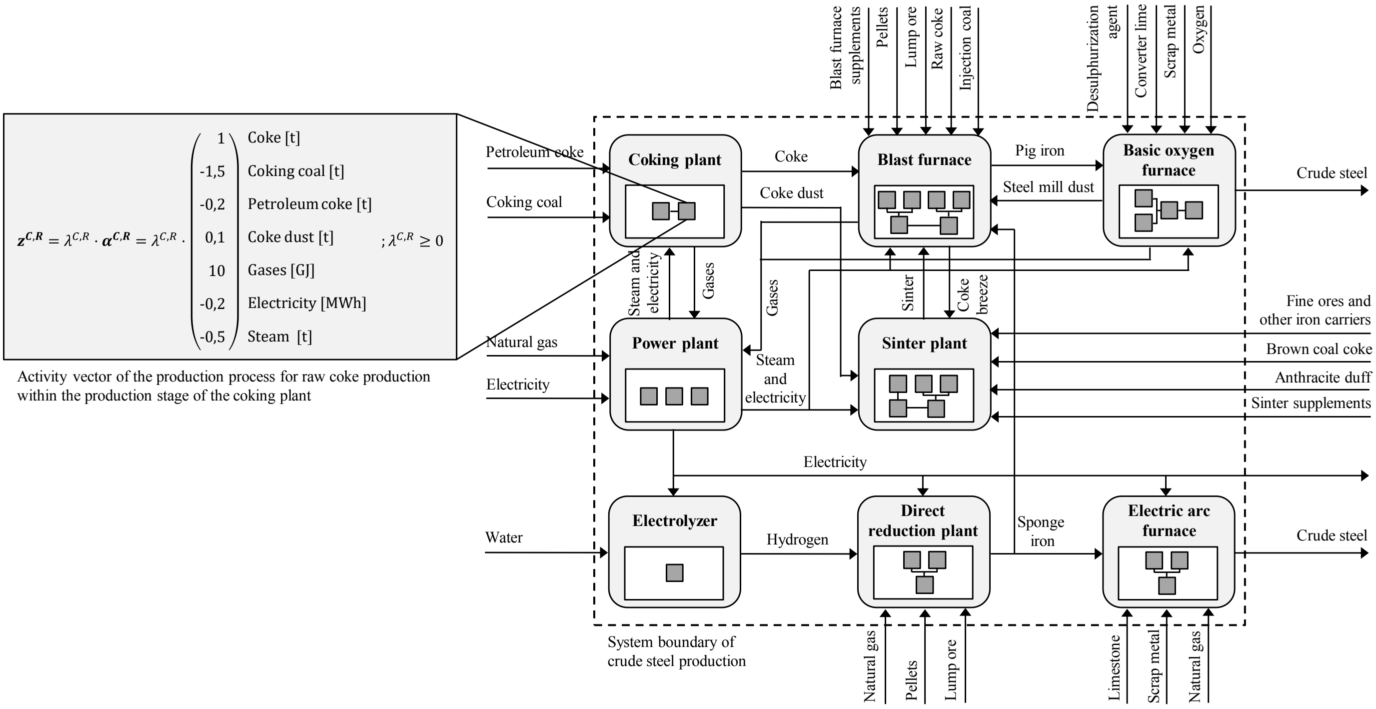

Figure 1: Simplified illustration of the production stages and processes of crude steel production

in the model. Due to a modular design, the degree of aggregation can be adjusted depending on the information required by decision-makers. Therefore, the previously derived requirements are fulfilled. Given the long-term planning horizon, uncertainties regarding the development of future market prices as well as political decision-making have to be considered. To this end, various scenarios are evaluated. Moreover, sensitivity analysis of input parameters is performed to estimate the impact of different policy instruments on the design of the transformation process.

3.2. Activity analysis based modeling of steelmaking processes

Activity analysis is used to describe the transformation of (raw, intermediate, and by-)products in steelmaking. Production stages, processes, and products can be depicted at a low or high level of aggregation depending on the requirements. Further stages of the life cycle can be included easily. Following, activities $\rho = 1, \dots, \pi$ describe production processes in steelmaking. The object types $k = 1, \dots, \kappa$ constitute inputs and outputs of these activities, which are also referred to as exchanges. To describe the quantities of object types k that are consumed or generated by an activity ρ, an activity vector $z^\rho = (z_1^\rho, \dots, z_k^\rho, \dots, z_\kappa^\rho)^T$ is used. If z_κ^ρ is negative, the object type k is an input. Otherwise, object type k is an output. In the case of linear technology, a basic activity a^ρ can be introduced which is normalized to one unit of the created reference commodity. The activity level $\lambda^\rho \geq 0$ describes how often a basic activity is carried out ($z^\rho = \lambda^\rho \cdot a^\rho$) [30,31].

All decision-relevant object types are included in the modeling scope. Object types are decision-relevant if their quantitative occurrence depends on the production quantities of specific production stages. This must be accompanied by a significant impact on the cost of steelmaking. To be able to measure the economic influence of objects, a value structure in addition to the quantity structure is required. To this end, cost functions are used, which consist of fixed and variable cost components. Thereby, the variable costs depend on how often the activities are carried out [29]. Similarly, the ecological effects of using activities can be added. This allows determining the environmental impact of decisions in the context of the transformation process. Applying this modeling approach for the considered use case of BF–BOF and HD–R steelmaking results in the simplified quantity structure illustrated in Figure 1.

The BF–BOF and H–DR routes are split into production stages, which contain one or more production processes, each of which consists of one or more alternative activities. Activity analysis enables the description of joint production processes between the production stages of both process routes. Thus, the impacts of interdependencies between production stages can be evaluated. The addition of constraints in a planning model allows limiting the activity level to a minimum or maximum value. Thus, process requirements are included in the model. For example, a maximum share of lump ores in the blast furnaces is specified as a process-related restriction.

Shifting to sustainable steelmaking, the stages upstream of the steelmaking processes are particularly relevant. Using the BF–BOF or H–DR routes leads to crude steel with the same physical properties. Thus, the choice of production processes can be assumed to have no direct influence on the downstream stages of the product life cycle. However, different raw materials and energy sources are required depending on the selected steelmaking processes. This leads to changes in the

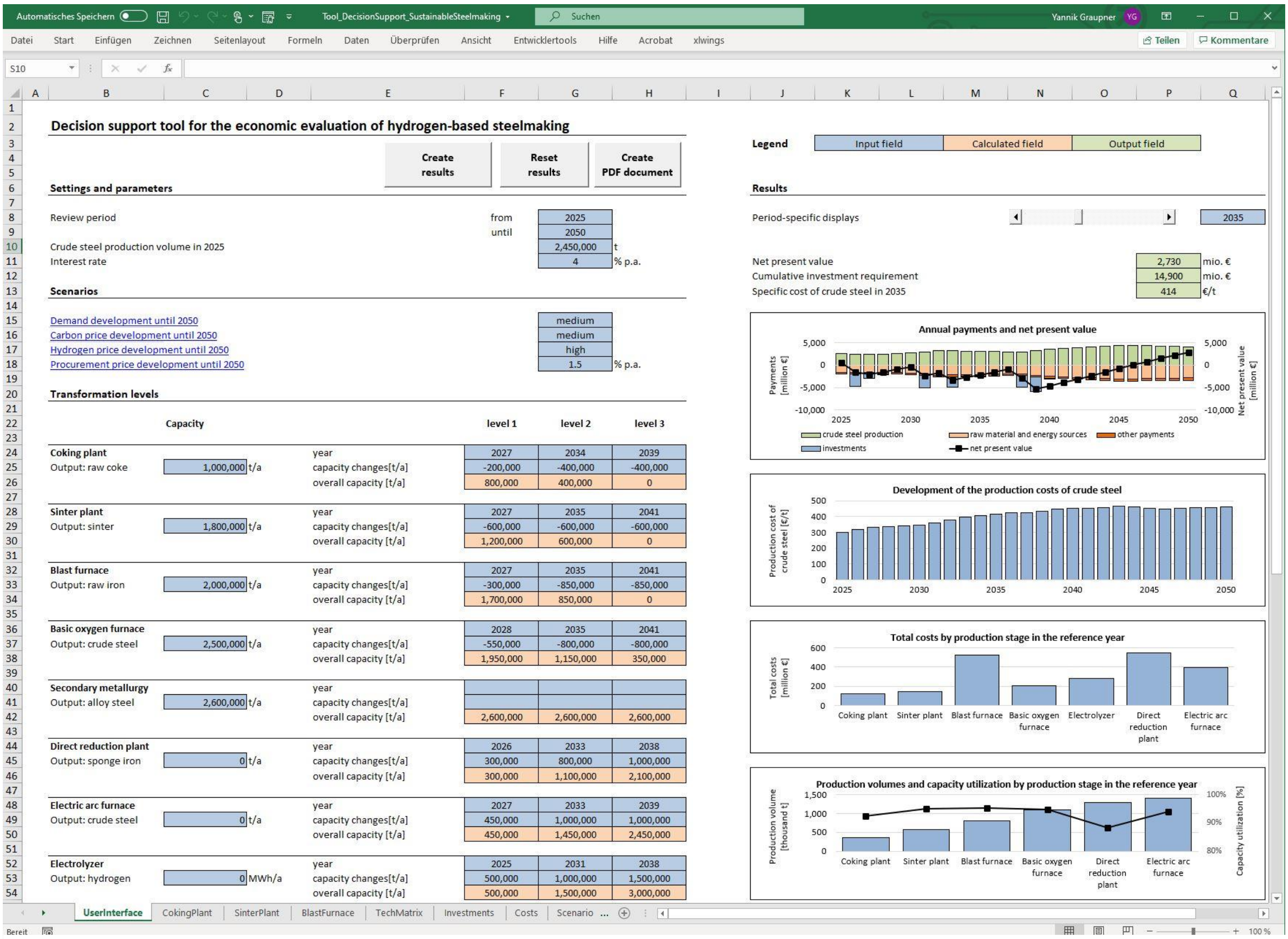

Figure 2: User interface of the decision support tool with exemplary results (Used with permission from Microsoft.)

upstream procurement processes. For example, the required quantities of pellets, lump ores, and raw coke change during the transformation process toward hydrogen-based steelmaking. At the same time, requirements on the energy sector change. Moreover, effects on the recycling processes require consideration in a holistic approach. The decision support framework is capable of depicting these relations.

3.3. Structure of the decision support framework

The decision support framework is based on the modeling approach described above. The underlying data is stored in a spreadsheet software. The activities are converted into matrix form and are implemented in a planning model using the Python programming language. The objective of the planning model is to utilize available production capacities in a way that the costs of steelmaking are minimized. The planning model is solved repeatedly for each period within the planning timeframe. Thus, results are created for the full planning timeframe iteratively. Afterward, the results are again transmitted to the spreadsheet software, where they are stored and visualized in a user interface. This user interface is illustrated in Figure 2. The presented results are chosen as examples to demonstrate the structure of the user interface. The developed tool allows decision-makers to specify the period and extent of capacity expansions and reductions within the considered production stages. Additionally, the quantities and costs assigned to the object types within the activities can be modified depending on current developments and trends. For this purpose, the input parameters are stored in a spreadsheet software and can be adjusted by the decision-makers.

4. Conclusion and outlook

We introduced a framework for a decision support tool that can support decision-makers in the design of the transformation pathway toward hydrogen-based steelmaking. The literature review indicates that no research work exists to date that meets all the derived requirements. In the context of a transformation toward hydrogen-based steelmaking, designing a cost-efficient transformation pathway is required. Therefore, multiple periods are included. Furthermore, technical dependencies due to joint production processes are considered. Additionally, a modular extendibility of the approach is required to adjust the level of aggregation and to include upstream stages of the life cycle. To this end, activity analysis based modeling of the decision-relevant processes of the BF–BOF and H–DR routes is applied. The activities are transformed into matrices and are then implemented in a planning model using Python. The planning model is solved iteratively over various periods to facilitate a cost-efficient design of the transformation pathway. So far, a validation of the activity analysis based modeling of the processes was performed using sensitivity analysis. This was discussed with industrial practitioners from steelmaking who confirmed the valid behavior of our model. The chosen approach thereby extends the current state of research. By including dynamic parameter developments and detailed modeling of decision-relevant material and energy flows, the evaluation and design of specific transformation pathways is enabled. This allows industrial decision-makers to verify technology choices as well as the timing and scope of capacity additions and reductions in a complex environment.

Based on the proposed framework, future research will address several different research areas. First, potential market scenarios for the price development of energy carriers and raw materials must be identified. This includes, besides others, natural gas, electricity, carbon, and hydrogen prices. Second, the current modeling scope will be further extended. For example, a connection to the energy sector will be included. This enables decision-makers to specify requirements for the energy sector to transform steelmaking most effectively. Third, based on the identified requirements and the derived concept, the planning model will be mathematically specified and implemented in Python. Afterward, the presented approach will be applied to a specific use case from steelmaking. Thus, the effectiveness of the developed framework will be evaluated. Fourth, we will investigate the tradeoffs arising from the integrated consideration of economic and ecological objectives. Against this background, a linkage with LCSA methods is possible. Activity analysis provides quantitative relationships between exchanges in steelmaking processes. Relevant exchanges required for an inventory analysis will be added to the activities of steelmaking processes. Afterward, the inventory results are linked to impact categories. The presented approach focuses primarily on the highly important greenhouse gas emissions of steelmaking processes.

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