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Assessing Low-Carbon Steel Pathways in Europe: A Spatially and Temporally Explicit TEA-LCA Framework

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Abstract

Decarbonizing the European steel industry requires production pathways that differ substantially in environmental and economic performance. Here we present a spatially and temporally explicit framework combining techno-economic assessment (TEA) and life-cycle assessment (LCA) for conventional and low-carbon steelmaking routes: blast furnace-basic oxygen furnace (BF-BOF), BF-BOF with carbon capture and storage (BF-BOF-CCS), and direct reduced iron-electric arc furnace routes using natural gas (NG-DRI-EAF) or hydrogen (H2-DRI-EAF), each with optional biochar integration.

Spatially resolved data on electricity, hydrogen, biochar, and CCS availability are applied at 0.1° × 0.1° resolution across all current European primary steel production sites, for the present day (2025) and prospective scenarios for 2030, 2040, and 2050.

Conventional BF-BOF remains the cheapest pathway today, at approximately 875 €/t crude steel (CS), while H2-DRI-EAF with biochar achieves the lowest greenhouse gas emissions, at approximately 0.60 t CO2/t CS. BF-BOF-CCS with biochar is the next-lowest-emission option and remains cost-competitive in many regions. Falling hydrogen costs substantially improve the competitiveness of H2-DRI-EAF by 2050, though regional differences in renewable energy and biomass availability mean no single low-carbon steelmaking pathway dominates across Europe.

Introduction

The iron and steel industry plays a central role in the global economy, providing essential materials for infrastructure, manufacturing, and technological development. At the same time, it represents one of the largest industrial sources of greenhouse gas emissions. In 2024, the industrial sector accounted for approximately 21% of total CO_2 emissions in the European Union, with the iron and steel industry responsible for about one quarter of these emissions[1]. Due to its reliance on high-temperature processes and carbon as a chemical reductant, steel production is widely considered a hard-to-abate sector, characterized by long asset lifetimes, high capital intensity, and strong exposure to international competition[2]. In response to the European Green Deal and the commitment to achieving climate neutrality by 2050, the decarbonization of steel production has therefore become a key challenge for both industrial transformation and climate policy[3–6].

Current steel production in Europe is based on a set of established process routes that differ in terms of technological principles, resource requirements, and emission profiles. Primary steelmaking is traditionally dominated by the blast furnace-basic oxygen furnace (BF-BOF) route, in which iron ore is reduced using fossil carbon, primarily coke, and subsequently refined into steel. While this route benefits from technological maturity and large-scale deployment, it is associated with high direct CO_2 emissions[7,8]. To mitigate these emissions within existing infrastructure, the integration of carbon capture and storage (CCS) into BF-BOF systems has been proposed as a potential transition pathway[9,10]. As an alternative, direct reduced iron (DRI) production combined with electric arc furnaces (EAFs) has

gained increasing attention. These systems can be operated using either natural gas (NG-DRI-EAF) or hydrogen (H2-DRI-EAF) as reducing agents. While natural gas-based routes enable moderate emission reductions compared to conventional production, hydrogen-based systems offer the potential for near-zero direct emissions when supplied with low-carbon electricity[11]. However, both DRI-based pathways are characterized by higher electricity demand and a strong dependence on energy prices and infrastructure availability[12–15].

Given these fundamental trade-offs, assessing low-carbon steelmaking pathways requires a comprehensive evaluation that jointly considers economic and environmental performance. Several studies have therefore applied techno-economic assessments (TEA) and life cycle assessments (LCA) to analyze individual production routes and decarbonization strategies[10,16–18]. TEA enables the systematic evaluation of production costs, investment requirements, and economic competitiveness, while LCA captures environmental impacts across the full value chain, including upstream energy and material supply processes. When applied in combination, these approaches allow for the identification of trade-offs between cost and emissions and help to avoid burden shifting across system boundaries. Existing studies demonstrate that hydrogen-based DRI pathways can substantially reduce emissions, but often at significantly higher production costs compared to conventional BF-BOF routes[16,17]. Similarly, the integration of CCS into conventional processes can lower emissions but is associated with high capital and operational expenditures[18,19].

A critical challenge in evaluating low-carbon steelmaking pathways lies in the strong regional variability of key input parameters[20]. Electricity prices and carbon intensities, availability of renewable energy, hydrogen production costs, and infrastructure conditions differ substantially across Europe, leading to significant variations in both economic and environmental performance[21]. Several studies have highlighted the importance of such spatial differences. For instance,[17] demonstrates that hydrogen-based DRI-EAF production costs vary considerably across European countries, ranging from 380–722 €/ton of crude steel (CS), depending on renewable energy availability, while[22] shows that overall abatement costs are highly sensitive to regional electricity prices and energy system conditions. Despite these insights, many existing assessments rely on country-level averages or simplified assumptions regarding key input parameters, thereby neglecting intra-regional heterogeneity and localized resource conditions[23–25].

In addition to spatial heterogeneity, the evaluation of low-carbon steelmaking pathways is further complicated by the temporal dynamics of the underlying energy and industrial systems. Many of the considered technologies are currently at different stages of technological maturity, ranging from commercially established processes to emerging concepts under pilot and demonstration conditions[10,16]. At the same time, key input parameters such as electricity prices, hydrogen production costs, carbon prices, and the carbon intensity of energy supply are expected to change significantly over time as the energy transition progresses[26,27]. Several recent studies explicitly highlight the importance of incorporating such temporal dynamics. For instance,[28] shows that the environmental performance of

steel production pathways evolves substantially across long-term climate scenarios up to 2060, depending on energy system decarbonization. Similarly,[29] demonstrates that the competitiveness of hydrogen-based steel production is highly sensitive to future market diffusion, policy frameworks, and CO_2 pricing trajectories. In addition,[30] emphasizes that prospective TEA and LCA results are strongly influenced by the dynamic interaction between technological development and evolving socio-economic boundary conditions.

Beyond these primary technological pathways, the use of biogenic carbon sources has gained increasing attention as a complementary strategy to reduce fossil CO_2 emissions in steel production. In particular, biochar can be integrated into existing processes such as BF-BOF and EAF systems as a partial substitute for fossil carbon inputs. Although it does not enable reductions in process-related emissions, it decreases scope 3 emissions without requiring a complete transformation of the production route[8,31–35]. Compared to hydrogen-based pathways, biochar-based approaches may offer advantages in terms of compatibility with existing infrastructure and lower upfront investment requirements, but their overall potential is constrained by biomass availability, competing sectoral demands, and sustainability considerations[22,36,37]. At the same time, the techno-economic and environmental performance of biochar integration is highly context-dependent, as biomass supply costs, regional availability, and supply chain characteristics vary significantly across locations[22,38].

Despite the extensive research on low-carbon steel production, a systematic and integrated comparison of alternative steelmaking pathways that simultaneously account for spatial and temporal heterogeneity remains largely absent. Existing studies typically focus on individual technologies, specific regions, or single points in time, and often assess either techno-economic performance or environmental impacts in isolation. As a result, a consistent evaluation of multiple steelmaking routes under harmonized assumptions, which captures both regional variability and dynamic system evolution, is still missing. In particular, the combined assessment of fossil-based, hydrogen-based, and bio-based decarbonization pathways within a unified, spatially and temporally resolved TEA-LCA framework has not yet been comprehensively addressed in the literature.

Against this background, this study aims to provide a comparative assessment of conventional and alternative steel production routes in Europe by integrating TEA and LCA within a spatially explicit and temporally differentiated modeling framework. The analysis includes BF-BOF, BF-BOF-CCS, NG-DRI-EAF, and H2-DRI-EAF pathways, while additionally considering the integration of biochar as a complementary decarbonization option. By explicitly accounting for regional differences in key input parameters and their evolution over time, the study seeks to identify context-specific trade-offs between economic and environmental performance and to provide a more robust basis for evaluating future steel production pathways in Europe. In addition to the present-day assessment (2025), prospective scenarios for 2030, 2040, and 2050 are considered, incorporating projected developments in energy systems, technology performance, and production costs. To this end, a spatially explicit techno-economic and life-cycle assessment framework is applied at a resolution of 0.1° × 0.1° across all current primary steel

production sites in Europe, combining present-day and prospective (2030–2050) cost and emission data to enable a consistent, regionally differentiated comparison of the investigated pathways.

Results

Environmental performance of steel production pathways

The environmental assessment reveals substantial differences in GWP across steel production pathways, process configurations, and time, as shown in Fig. 1. Under current conditions, conventional BF-BOF exhibits the highest emissions, with values exceeding 2.0 t CO_2/t CS, reflecting its reliance on fossil carbon. The integration of CCS reduces emissions significantly to 1.44 t CO_2/t CS, corresponding to a reduction of around 30%.

Across all routes, the partial substitution of fossil carbon with biochar consistently lowers GWP, as indicated by the dashed lines in Fig. 1. For BF-BOF, emissions decrease by approximately 30% when eucalyptus-based biochar is applied, while even stronger reductions are observed for BF-BOF with CCS, where GWP drops below 0.82 t CO_2/t CS. As detailed in the SI, differences between eucalyptus- and poplar-based biochar remain marginal across all pathways.

Among the alternative production routes, NG-DRI-EAF shows intermediate emission levels with 1.14 t CO_2/t CS under current conditions, while H2-DRI-EAF pathways achieve substantially lower emissions. However, the environmental performance of hydrogen-based routes strongly depends on the electricity source. When grid electricity is used, GWP remains above 1.0 t CO_2/t CS, whereas renewable electricity leads to significantly lower emissions. In particular, wind-based hydrogen production results in the lowest GWP values of 0.64 t CO_2/t CS, followed by solar-based configurations.

The prospective assessment, shown for the SSP2-RCP2.6 scenario in Fig. 1, indicates a consistent decline in emissions across all pathways due to the decarbonization of energy systems. This effect is most pronounced for the hydrogen-based route. By 2050, H2-DRI-EAF with renewable electricity reaches values below 0.40 t CO_2/t CS, representing the lowest emission levels among all investigated options. In contrast, emission reductions for fossil-based routes remain more limited over time, even when CCS is applied.

Overall, the results indicate a clear ranking of future steelmaking pathways: H2-DRI-EAF consistently achieves the lowest emissions, followed by BF-BOF with CCS combined with biochar, reaching GWP levels slightly above 0.6 t CO_2/t CS. In comparison, NG-DRI-EAF remains substantially higher even with biochar integration, with emissions around 0.9 t CO_2/t CS, highlighting its more limited long-term decarbonization potential.

Techno-economic performance of steel production pathways

Complete TEA results for all investigated locations, years, and pathways are provided in the SI; Fig. 2 presents a selection of these results for Duisburg and Kosice in 2025 and 2050.Across all investigated locations, total production costs are primarily driven by steel production, including alloy additions, pig iron production, and energy-related expenditures.

Under current conditions (2025), BF-BOF represents the lowest-cost route, with production costs of approximately 875 €/t CS across all investigated sites. The integration of biochar increases production costs depending on both the required substitution amount and regional biochar supply costs. Across all locations, biochar integration increases production costs for both BF-BOF routes by 9–98 €/t CS. The implementation of CCS adds a further 206–213 €/t CS, resulting in total production costs of 1,092 – 1,188 €/t CS for BF-BOF-CCS with biochar.

NG-DRI-EAF exhibits intermediate cost levels of 1,027 – 1,041 €/t CS and is only marginally affected by biochar integration due to the comparatively low biochar demand. In contrast, H2-DRI-EAF remains the most expensive pathway in 2025, with production costs ranging from 1,169 to more than 1,300 €/t CS depending on location and hydrogen supply route. As shown in Fig. 2, steel production itself remains the largest single cost component across all routes. However, hydrogen production represents the most important variable cost component in H2-DRI-EAF and is therefore the main determinant of regional cost differences. Within hydrogen production, electricity supply accounts for the largest share of production costs, highlighting the importance of access to low-cost renewable electricity.

The prospective assessment assumes a substantial decline in hydrogen-related costs. Consequently, production costs of H2-DRI-EAF decrease considerably between 2025 and 2050. For example, production costs in Duisburg (Germany) decrease from approximately 1,231 €/t CS in 2025 to around 1,113 €/t CS in 2050, while production costs in Kosice (Slovakia) decrease from approximately 1,314 €/t CS to 1,154 €/t CS over the same period. These reductions are mainly driven by declining hydrogen production costs, which decrease from 3.89 to 2.29 €/kg H_2 in Duisburg and from 5.24 to 2.98 €/kg H_2 in Kosice. Nevertheless, H2-DRI-EAF remains more expensive in Kosice and, in several scenarios, also more expensive than BF-BOF-CCS with biochar. This can largely be attributed to the combination of comparatively high hydrogen production costs and low regional biochar costs with 231 €/t biochar in Kosice compared to 375 €/t biochar in Duisburg, which improves the competitiveness of biochar-based BF-BOF-CCS pathways.

In contrast, BF-BOF and BF-BOF-CCS exhibit only moderate cost changes over time, as their cost structures are dominated by process-related expenditures rather than future reductions in renewable electricity and hydrogen costs. NG-DRI-EAF likewise remains relatively stable throughout the assessment period. The economic impact of biochar remains largely constant over time, since biochar supply costs show only limited changes compared to the projected reductions in hydrogen production costs.

Carbon avoidance costs

Carbon avoidance costs were used to directly compare the economic performance of the LCA and TEA results across pathways, expressed relative to the emission reductions achieved compared to the conventional BF-BOF reference route. Figure 3 summarizes the resulting carbon avoidance costs and the corresponding carbon footprint of each pathway across all investigated sites for 2025 and 2050. The carbon avoidance costs differ substantially between decarbonization strategies (SI). Among all investigated measures, the integration of biochar into conventional BF-BOF steelmaking represents the most cost-effective mitigation option. Depending on location-specific biochar supply costs, carbon avoidance costs range from approximately 20–157 €/t CO_2 in 2025 and generally decrease slightly over time. The lowest values are observed in regions with low biochar production costs, such as Hungary, the Czech Republic, Poland, and Slovakia, where avoidance costs remain below 30 €/t CO_2.

In contrast, the implementation of CCS in BF-BOF results in substantially higher avoidance costs exceeding 300 €/t CO_2. This is primarily attributable to the combination of high capture and conditioning costs, additional transport and storage expenditures, and the comparatively moderate emission reductions achieved relative to the conventional BF-BOF route. Combining CCS with biochar significantly improves the economic performance of the BF-BOF pathway. Carbon avoidance costs decrease to approximately 160–253 €/t CO_2. The additional emission reductions achieved through biochar substitution therefore compensate for a substantial share of the CCS-related expenditures.

For H2-DRI-EAF, carbon avoidance costs are initially high, reaching approximately 216–322 €/t CO_2 in 2025 depending on the hydrogen supply route and location. However, owing to declining renewable electricity and hydrogen production costs, avoidance costs decrease considerably over time. By 2050, values between approximately 133–181 €/t CO_2 are observed, making H2-DRI-EAF competitive or even more attractive than BF-BOF-CCS with biochar in several regions. The additional integration of biochar further improves the economics of hydrogen-based steelmaking and results in marginal avoidance costs close to zero or even slightly negative in selected locations, indicating that the additional mitigation potential can outweigh the associated biochar expenditures.

Compared with the other pathways, NG-DRI-EAF exhibits relatively stable carbon avoidance costs throughout the assessment period. Values generally remain between 150–180 €/t CO_2 and are only moderately affected by prospective developments in energy systems and technology costs.

Focusing on the two lowest-emission pathways identified in the environmental assessment in Fig. 1, namely BF-BOF-CCS with biochar and H2-DRI-EAF with biochar, reveals a narrowing economic gap over time. While BF-BOF-CCS with biochar remains the more cost-effective option in the near term, declining hydrogen costs increasingly favour H2-DRI-EAF. By 2050, both pathways achieve similarly low emission levels, whereas the hydrogen-based route approaches or even undercuts the carbon avoidance costs of BF-BOF-CCS with biochar in regions with favourable renewable energy resources.

Spatial comparison of BF-BOF-CCS with biochar and H2-DRI-EAF with biochar

Figure 3 compares the production costs of BF-BOF-CCS with biochar and H2-DRI-EAF with biochar for an integrated steel plant producing 5 Mt CS annually. Positive values indicate a cost advantage for BF-BOF-CCS with biochar, while negative values favour H2-DRI-EAF with biochar.

In 2025, BF-BOF-CCS with biochar is economically preferred across Europe due to the high costs of renewable hydrogen. By 2050, declining hydrogen and electricity costs substantially improve the competitiveness of H2-DRI-EAF, making it the lower-cost option in large parts of Northern and Western Europe. In contrast, BF-BOF-CCS with biochar remains advantageous in several Eastern European regions, where lower biomass costs reduce the overall cost of biochar integration.

Nevertheless, it should be mentioned that the analysis only considered eucalyptus- and poplar-based biochar. Since both feedstocks exhibit relatively low yields in Northern Europe, regional biochar costs may be overestimated. The inclusion of alternative woody biomass feedstocks could therefore improve the competitiveness of BF-BOF-CCS with biochar in these regions.

Sensitivity analysis

A sensitivity analysis is conducted to assess the influence of key uncertain parameters on both steel production costs and carbon avoidance costs. The analysis focuses on three parameters that were identified as particularly relevant for future low-carbon steel production pathways, renewable electricity and hydrogen costs and biochar production costs. Production costs of CS and carbon avoidance costs were recalculated for the representative steel production sites Duisburg and Kosice for both 2025 and 2050. The complete results are provided in the SI.

Electricity and hydrogen costs were selected because they constitute the most important variable cost component of H2-DRI-EAF pathways and are subject to substantial uncertainty regarding future renewable electricity deployment, electrolyzer cost reductions, and market developments. Biochar costs were investigated due to uncertainties related to future biomass availability, competing biomass demands, and feedstock selection. While the present study only considers eucalyptus- and poplar-based biochar, additional biomass sources, including residues from sustainable forest management, could lead to different future biochar production costs.

The sensitivity analysis shows that the competitiveness of H2-DRI-EAF is highly dependent on future electricity and hydrogen costs. In Duisburg, H2-DRI-EAF with biochar becomes cost-competitive with BF-BOF-CCS with biochar by 2050 under the baseline assumptions with 1,118 €/t CS for H2-DRI-EAF with biochar and 1,128 €/t CS for BF-BOF-CCS with biochar. However, a 50% increase in electricity and hydrogen costs reverses this ranking, as production costs increase to 1,207 €/t CS, making BF-BOF-CCS with biochar the economically preferred low-carbon option. Conversely, a 50% reduction in electricity and

hydrogen costs further improves the competitiveness of H2-DRI-EAF, reducing production costs to approximately 1,029 €/t CS.

A similar trend is observed in Kosice, although the lower regional biochar costs strengthen the economic position of BF-BOF-CCS with biochar. Under baseline assumptions for 2050, BF-BOF-CCS with biochar remains around 58 €/t CS cheaper than H2-DRI-EAF with biochar. Even under a 50% reduction in electricity and hydrogen costs H2-DRI-EAF only achieves a modest cost advantage, whereas higher energy prices further increase the cost gap between both routes.

Variations in biochar costs mainly affect the relative attractiveness of biochar-based mitigation strategies. For BF-BOF with biochar, carbon avoidance costs range from approximately 20–146 €/t CO_2 in Duisburg and from − 5 to 73 €/t CO_2 in Kosice. The negative carbon avoidance cost in Kosice indicates that under favorable biomass conditions, biochar integration can simultaneously reduce production costs and emissions.

Discussion

The feasibility of large-scale CCS deployment and hydrogen-based steelmaking has been extensively discussed in the literature, with key challenges including CO_2 transport and storage infrastructure, renewable electricity availability, hydrogen production capacities, and the required investments in new process facilities[2,13,29]. In contrast, the availability of sustainable biomass for biochar production has received comparatively limited attention in the context of European steel decarbonization, despite its importance for several of the investigated pathways.

The results indicate that biochar integration can represent a cost-effective decarbonization option, particularly for BF-BOF and BF-BOF-CCS. However, its large-scale implementation is constrained by biomass availability. Based on the substitution rates applied in this study, BF-BOF requires approximately 0.21 t biochar per t CS, whereas DRI-EAF routes require around 0.02 t biochar per t CS. Consequently, an integrated steel plant producing 5 Mt CS annually would require more than 1 Mt biochar per year for BF-BOF operation. Such quantities exceed current European biochar production capacities by a considerable margin and would likely intensify competition for sustainable biomass resources across sectors[22,36–38].

Therefore, while biochar may be difficult to deploy as a primary decarbonization strategy in large BF-BOF plants, it remains attractive as a complementary measure. In particular, the comparatively low biochar demand of DRI-EAF routes enables additional emission reductions of approximately 5–10% with substantially lower biomass requirements. This suggests that biochar represents an attractive complementary decarbonization option across both conventional and direct reduced steelmaking pathways. While large-scale deployment in BF-BOF may be constrained by biomass availability, the consistent emission reductions achieved across all investigated routes indicate that investments in

sustainable biochar production facilities could support the decarbonization of both current and future steelmaking technologies.

From a practical perspective, the results suggest that biochar can provide an attractive decarbonization option for both conventional and hydrogen-based steelmaking routes. Investments in sustainable biochar production and supply infrastructure may therefore support multiple transition pathways and increase the flexibility of future steel decarbonization strategies.

Although the study aimed to provide a comprehensive spatially and temporally explicit assessment, several limitations remain. First, the biochar assessment is restricted to eucalyptus- and poplar-based feedstocks, while alternative biomass sources and forest residues may result in different regional production costs and availabilities, particularly in Northern Europe. Second, future developments in energy markets, biomass supply chains, hydrogen imports, and CCS infrastructure remain uncertain and may influence the relative competitiveness of individual pathways. Apart from that, the prospective assessment is based on predefined technology and cost trajectories and therefore cannot fully capture future policy changes, market developments, or technological breakthroughs. Furthermore, although the applied spatial resolution allows for a detailed European assessment, local factors such as site-specific infrastructure constraints, permitting procedures, or regional biomass markets are not explicitly represented.

Another important aspect concerns the industrial scalability of hydrogen-based direct reduction routes. While H2-DRI-EAF exhibits the lowest greenhouse gas emissions among the investigated pathways, its large-scale implementation requires substantial investments in renewable electricity generation, hydrogen production, storage, and transport infrastructure. The availability of sufficient quantities of low-cost renewable hydrogen at the scale required by the European steel industry remains uncertain and will become a limiting factor for widespread deployment. Consequently, future assessments should further investigate infrastructure requirements, regional hydrogen supply constraints, and the interaction between steel demand and competing hydrogen-consuming sectors.

In addition to decarbonization performance, the global competitiveness of European steel production must be considered. The transition towards low-carbon steel production is associated with increased production costs, particularly for hydrogen-based routes. While carbon pricing mechanisms and sustainability requirements may improve the competitiveness of low-carbon steel within Europe, European producers continue to compete with international suppliers operating under different regulatory frameworks and energy cost structures. The long-term success of steel decarbonization strategies will therefore depend not only on technological developments but also on policy instruments such as carbon border adjustment mechanisms, green public procurement, investment support schemes, and international climate policies that help ensure a level playing field.

Future research should therefore expand the analysis toward additional biomass feedstocks, dynamic biomass availability scenarios, and international hydrogen trade. The integration of policy instruments such as carbon prices, subsidies, carbon border adjustment mechanisms, and biomass sustainability

criteria could further improve the relevance of future assessments. Moreover, dynamic modeling approaches that incorporate technological learning effects, infrastructure development, and evolving energy systems may provide additional insights into the scalability, competitiveness, and long-term transition pathways of low-carbon steel production.

Methodology & materials

To evaluate the techno-economic and environmental performance of alternative steel production pathways, a spatially and temporally resolved modeling framework is developed, combining TEA and LCA, as illustrated in Fig. 1. The framework integrates process-level modeling with region-specific input data and scenario-based analyses to enable a consistent comparison of multiple steelmaking routes under varying boundary conditions.

Goal and scope

The objective of this study is to compare conventional and alternative CS production pathways by integrating TEA and LCA within a unified analytical framework. The assessment considers current economic conditions for 2025 ($€_{2025}$) as well as projected environmental and economic scenarios for 2030, 2040 and 2050, with the aim of identifying trade-offs between greenhouse gas emissions and production costs.

The analysis focuses on primary steel production routes, including BF-BOF, BF-BOF with CCS, as well as DRI-EAF systems using either NG-DRI-EAF or H2-DRI-EAF. In addition, the partial substitution of fossil carbon inputs with biochar is considered as a complementary decarbonization option across selected process routes, based on findings from recent literature[31–33]. The environmental assessment is based on global warming potential (GWP), while the economic assessment evaluates production costs in $€_{2025}$ per ton. The functional unit is defined as 1 t of CS.

The analysis is conducted for Europe, reflecting both the economic pressures from international competition and the environmental requirements associated with the European Green Deal[5]. The assessment is performed for all currently operating primary steel production sites in Europe identified by[5], with plant locations and corresponding production capacities summarized in the Supplementary Information (SI). To ensure a realistic and regionally differentiated assessment, TEA and LCA are implemented in a spatially explicit manner, as illustrated in Fig. 4. Spatially resolved inputs are modelled at a resolution of 0.1° × 0.1°, particularly for parameters that vary strongly within countries, such as hydrogen, electricity and biochar costs, which are key drivers of both production costs and GHG emissions. In contrast, parameters that are only available or modelled at the national level, including natural gas prices, are incorporated country-specifically.

System boundaries

The environmental and economic assessment was conducted using a harmonized cradle-to-gate system boundary encompassing the production of one metric tonne of CS at the outlet of the BOF or EAF. The selected system boundaries were applied consistently across all investigated steel production routes, namely BF-BOF, BF-BOF-CCS, NG-DRI-EAF, and H2-DRI-EAF, to ensure comparability between the different technological pathways.

The assessment includes all upstream and foreground processes required for the production of molten CS. For the BF-BOF route, this comprises the extraction and processing of raw materials, coke production, iron ore agglomeration, meaning iron sintering and pelletizing, blast furnace ironmaking, and steel refining in the basic oxygen furnace. For the DRI-EAF routes, the system boundaries include iron ore beneficiation and pelletizing, direct reduction using either natural gas or hydrogen, and subsequent melting and refining in the EAF. A flowchart of the system boundaries under consideration is depictured in Fig. 6. The production and supply of all relevant energy carriers, reducing agents, auxiliary materials, alloys, fluxes, and consumables are included in the SI. Furthermore, infrastructure-related contributions provided by the underlying life cycle inventory database are considered.

Special attention is given to decarbonization technologies. In the BF-BOF-CCS route, the system boundaries include carbon dioxide capture, compression, transport, and geological storage. Consequently, additional energy requirements, solvent consumption, and transport and storage infrastructure associated with CCS are explicitly considered. The assumptions and modeling approach for CCS are discussed in detail in Section 4.3.2.

For scenarios involving biochar integration, the system boundaries additionally include biomass cultivation, harvesting, transportation, pyrolysis, biochar upgrading, and delivery to the steel plant. Biochar is considered as a substitute for fossil carbon carriers such as coke, pulverized coal, or hard coal, depending on the investigated pathway. The underlying assumptions regarding biomass availability, biochar production costs, and substitution rates are presented in Section 4.3.3.

Secondary metallurgy, continuous casting, rolling, downstream processing, product use, and end-of-life treatment are excluded from the assessment. Consequently, differences in alloying strategies, casting operations, and product-specific finishing steps do not influence the comparison of the investigated steelmaking routes. Likewise, transport of the final steel products to customers is not considered.

Under the cut-off approach, recyclable by-products leaving the system boundary, such as blast furnace slag, basic oxygen furnace slag, blast furnace gas, dusts, and sludges, do not carry upstream environmental burdens into subsequent product systems. Credits are assigned where secondary materials or energy carriers substitute primary products. This approach ensures a consistent treatment of recycling flows and secondary resources across all steel production routes investigated.

The TEA follows the same system boundaries as the LCA and includes raw material costs, energy costs, auxiliary materials, carbon capture and storage costs, biochar supply costs, operational expenditures (OPEX), and annualized capital expenditures (CAPEX). For CCS and hydrogen-based routes, additional

costs associated with capture units, electrolysis systems, hydrogen infrastructure, compression, transport, and storage are explicitly considered. The alignment of the TEA and LCA system boundaries enables a direct comparison of environmental and economic performance indicators across all investigated scenarios.

Input data and assumptions

Levelized costs for electricity and hydrogen

Electricity costs represent the dominant component of hydrogen production costs and are therefore a key determinant of the economic performance of H2-DRI-EAF pathways[12,39]. To capture regional differences in renewable energy availability and costs, a spatially explicit approach is applied, using capacity factors as a proxy for wind and solar resource potential[40].

Spatially resolved CF data for wind and solar energy are derived from global datasets and mapped onto a 0.1° x 0.1° grid across Europe[41,42]. These inputs are used to calculate location-specific levelized costs of electricity (LCOE) based on[43–46], which subsequently determine the levelized cost of hydrogen (LCOH). Hydrogen production is modeled based on electrolysis, with cost assumptions based on[47–50].

In addition to the present-day assessment, a prospective analysis is conducted for the years 2030, 2040, and 2050 to account for expected developments in technology performance and energy systems. This includes adjustments in key parameters such as electrolyzer efficiency, capital costs, and electricity prices[47,50].

Detailed formulations of the LCOE and LCOH calculations, all underlying techno-economic assumptions, the resulting spatial distributions of electricity and hydrogen costs, and a validation of the modeled country-level LCOH values against an independent reference dataset developed by[51] are provided in the SI.

Carbon Capture and Storage

CCS is considered as a decarbonization option for selected BF-BOF-based steel production. Among the available capture technologies, post-combustion CO_2 capture using monoethanolamine (MEA) is applied as the reference approach, as it is widely regarded as the most mature and technically feasible option for blast furnace gas streams[28,52]. For this study, a CO_2 capture rate of 83.08% is assumed[28].

The techno-economic representation of the CCS system is based on a modular approach, distinguishing between CO_2 capture, conditioning, transport, and storage. Capture costs are derived from process-level assessments of amine-based systems, while additional cost components are considered separately to reflect the full CCS value chain. The key assumptions are summarized in Table S7. The LCI is based on[28] and is documented in the SI. All numbers are projected to the year 2025 with the producer price index (PPI) according to Table S6.

For transport cost calculations, all European CO_2 storage sites listed by[53] were considered. Information on storage type and storage capacity was obtained from the database, while transport distances were determined as the direct distance between each steel production site and its nearest CO_2 storage location.

For the prospective assessment, CO_2 capture and conditioning costs are assumed to decline over time due to expected improvements in process efficiency and reductions in capital expenditures[54,55]. As the time horizons reported in these studies do not directly align with the scenario years considered in this work, the reported cost trajectories are interpolated to match the selected time steps. This results in cost reductions of 2.56% for 2030, 6.83% for 2040, and 11.1% for 2050 relative to 2025.

Further details on all foreground and background datasets, country-specific input parameters, life cycle inventories, techno-economic assumptions, validation procedures, and the corresponding data sources are provided in the SI.

Substitution of fossil carbon sources with biochar

The substitution of fossil carbon inputs with biochar is modeled based on an energy-equivalent replacement approach across the main process steps of iron and steel production. The amount of biochar required is calculated using a three-step procedure. First, the quantity of fossil fuel replaced is determined as:

$$FS_{ij} = F_{ij} \times R_i$$

Second, a heat balance conversion factor is applied to account for differences in the lower heating value (LHV) between fossil fuels and biochar:

$$e_j = \frac{LHV_j}{LHV_b}$$

Finally, the required biochar input is calculated as:

$$BS_{ij} = FS_{ij} \times e_j$$

where $i = 1 \ldots X$ represents the major process steps in steel production, and j corresponds to hard coal and coke, respectively. FS_{ij} denotes the amount of fossil fuel substituted (t per t CS), F_{ij} the original fuel input, and R_i the process-specific substitution ratio, also taking the necessary carbon content into account. The parameter e_j reflects the energy-equivalent adjustment based on the ratio of LHVs, and BS_{ij} represents the resulting biochar demand.

The analysis is limited to biochar derived from woody biomass, specifically eucalyptus- and poplar-based feedstocks, as these materials are widely recognized for their favorable properties for thermochemical conversion and metallurgical applications. Previous studies have shown that wood-

based biomass, including eucalyptus, provides suitable characteristics for biochar production and can be effectively utilized as a partial substitute for fossil carbon in iron and steelmaking processes[56–58].

The applied LHVs for biochar and fossil fuels are summarized in Table S8, while process-specific substitution ratios are derived from literature[10,32] and complemented by own calculations, as presented in Table S9 in the SI. Based on these substitution ratios, biochar demand differs substantially between production routes. BF-BOF pathways require approximately 0.21 t biochar per t CS, whereas DRI-based routes require only around 0.02 t biochar per t CS due to their considerably lower demand for fossil carbon inputs.

Biochar production costs are incorporated in a spatially explicit manner and are calculated for each 0.1° × 0.1° grid cell based on the methodology developed by[59]. This allows for the consistent integration of regional differences in biomass availability, production costs, and supply chain characteristics into the TEA.

The life cycle inventory (LCI) underlying the biochar production, as well as all additional foreground and background data used in the LCA, is provided in detail in the SI.

TEA & LCA

An integrated life cycle-based framework is applied to assess the techno-economic and environmental performance of the investigated steel production pathways.

For the environmental assessment, foreground data are derived from process modelling and literature, while background data are obtained from the ecoinvent 3.11 database. Country-specific electricity and natural gas markets are incorporated where relevant. The impact assessment focuses on Global Warming Potential (GWP) over a 100-year time horizon (IPCC 2013), following established LCA standards[60]. GWP is selected as it represents the dominant environmental dimension of steel production and a suitable indicator for analyzing trade-offs between cost and climate mitigation[61,62]. In addition, previous studies have shown that GWP often reflects broader environmental trends across impact categories[63,64]. Biogenic carbon flows, particularly related to biochar, are accounted for separately following established guidelines[63].

For the TEA, production costs are calculated in $€_{2025}$ per t CS using the same system boundaries and inventories as in the LCA. The analysis includes all relevant cost components for materials, energy carriers, hydrogen, biochar, and CCS. Spatially resolved costs (e.g., hydrogen and biochar) are modelled at 0.1° × 0.1°, while nationally defined parameters such as natural gas prices are incorporated at country level. All costs are harmonized to a common reference year using the producer price index[65], consistent with previous studies[66,67].

A prospective analysis is conducted for 2030, 2040, and 2050. For the LCA, future background systems are modelled using the *Premise* framework based on REMIND scenarios SSP2-RCP2.6 and SSP2-

RCP1.9[68]. For the TEA, future developments in electricity, hydrogen, and CCS costs are incorporated based on literature and model-based assumptions.

Declarations

Data availability

The data supporting the findings of this study, comprising the Supplementary Information document and the underlying Supplementary Data (life cycle inventory and techno-economic data; steel plant location and capacity data), are available in the Zenodo repository at https://zenodo.org/records/21493145. Background life cycle inventory data were obtained from the ecoinvent 3.11 database and are available under license from the ecoinvent Association (https://ecoinvent.org); these data are not included in the deposited dataset due to licensing restrictions.

Author contributions

J.K. conceived and designed the study, developed the methodology, performed the analysis, and wrote the manuscript. C.G. contributed to the conceptualization of the study and co-wrote parts of the manuscript. A.A. contributed to the conceptualization of the study and reviewed and edited the manuscript. G.W. reviewed and edited the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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Figures

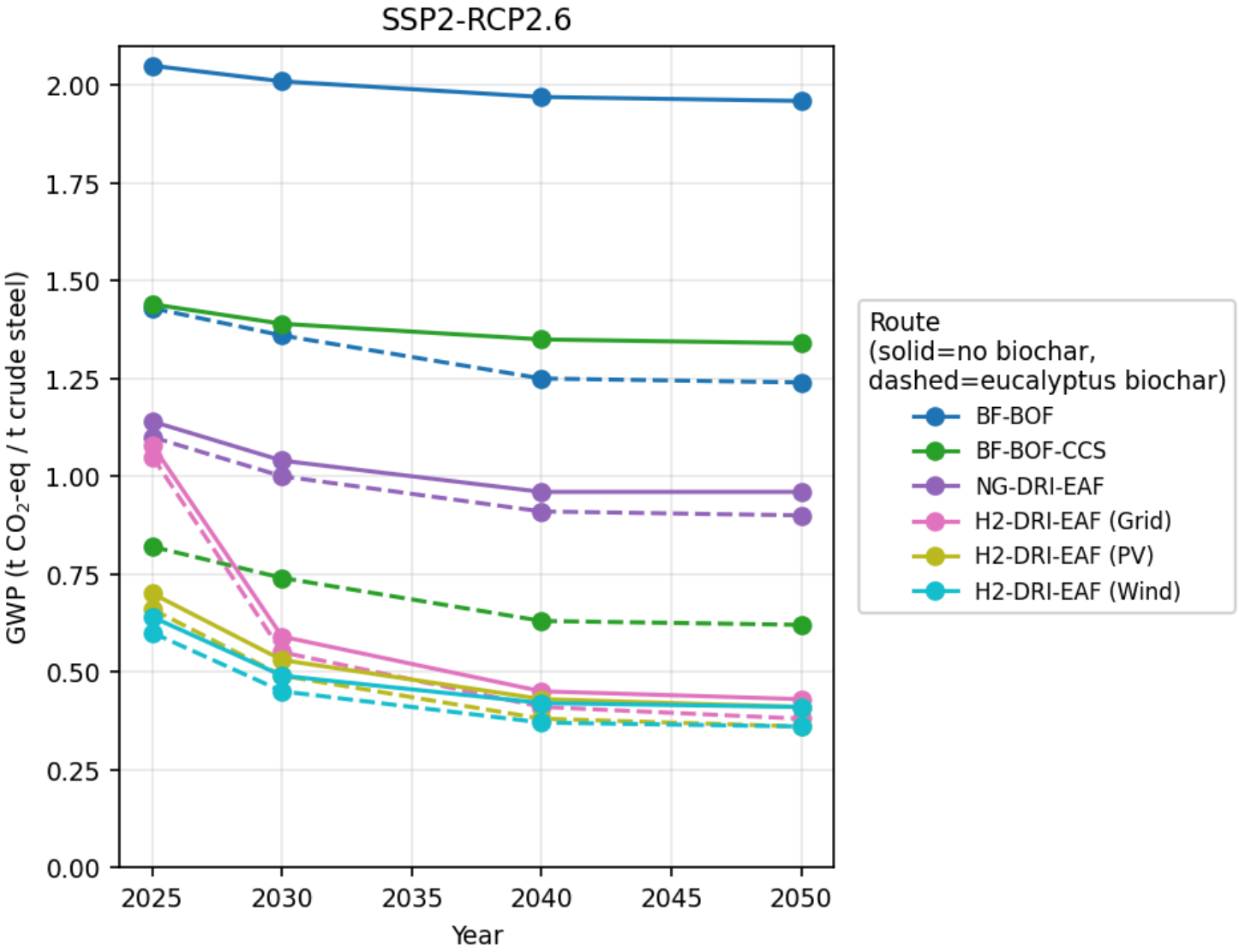


Figure 1

Carbon footprint of CS production pathways today and in the future for the scenario SSP2-RCP2.6

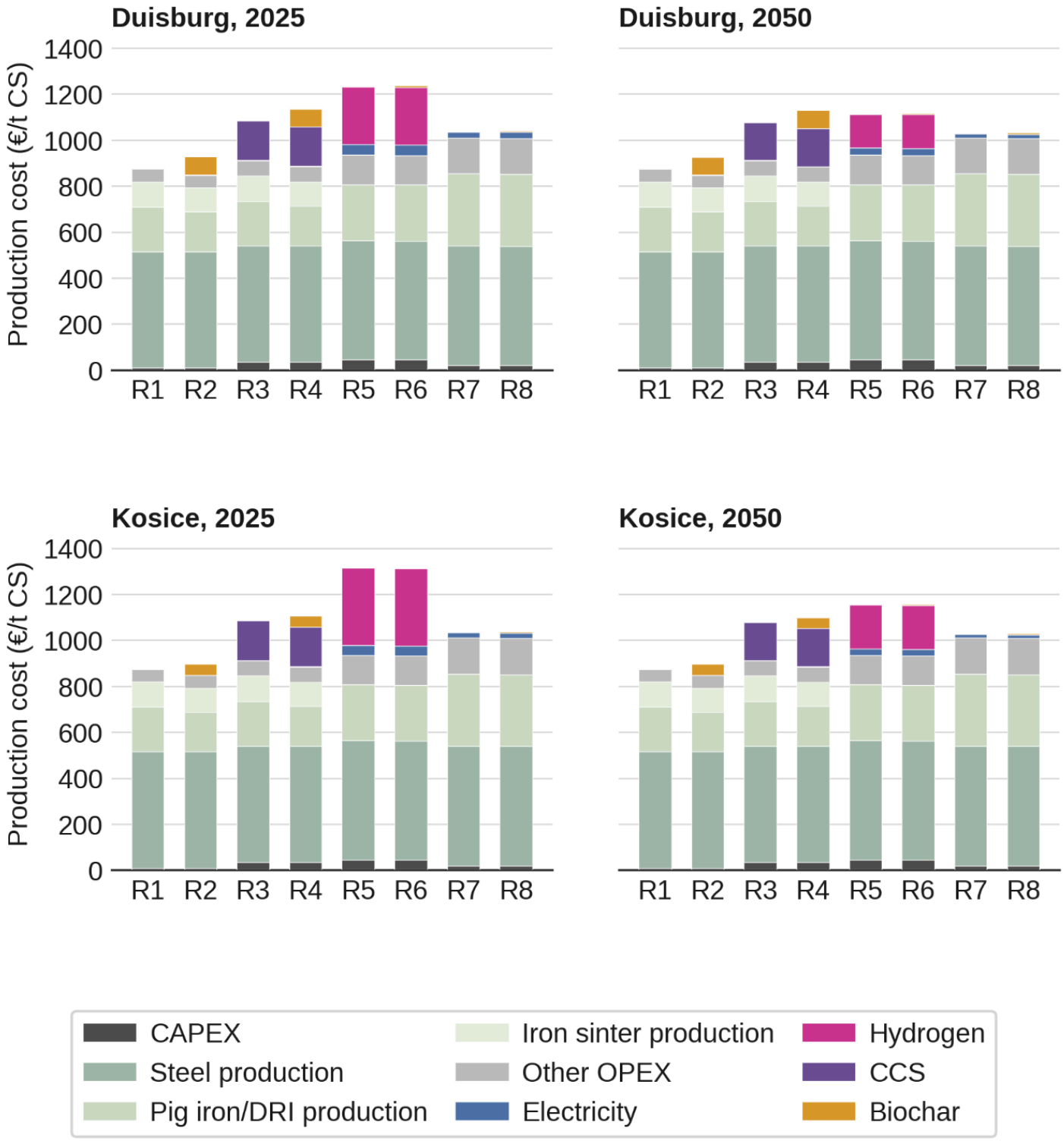


Figure 2

Production cost of 1 ton low-alloyed CS in Duisburg and Kosice in 2025 and 2050 in $€_{2025}$. R1 = BF-BOF, R2 = BF-BOF + biochar, R3 = BF-BOF-CCS, R4 = BF-BOF-CCS + biochar, R5 = H2-DRI-EAF, R6 = H2-DRI-EAF + biochar, R7 = NG-DRI-EAF, and R8 = NG-DRI-EAF + biochar.

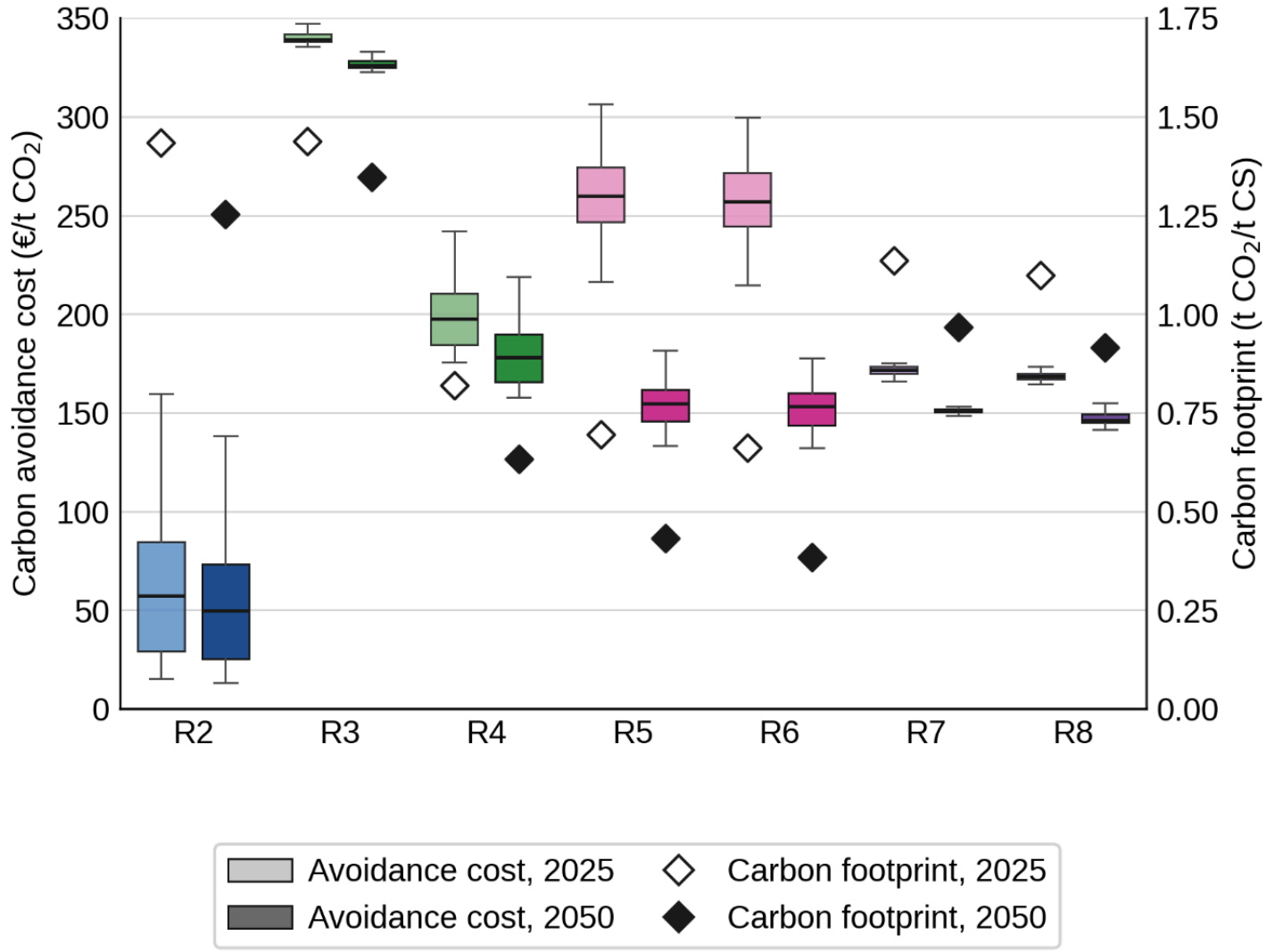


Figure 3

Carbon avoidance costs and carbon footprint of low-carbon steelmaking pathways relative to conventional BF-BOF. Boxplots (left axis) show carbon avoidance costs (€/t CO_2) across all investigated primary steelmaking sites in Europe (n = 27) for 2025 and 2050, based on the SSP2-RCP1.9 scenario with eucalyptus-based biochar; light boxes, 2025; dark boxes, 2050. Diamonds (right axis) show the corresponding carbon footprint (t CO_2/t CS) of each pathway; open diamonds, 2025 (base year); filled diamonds, 2050 (SSP2-RCP1.9 scenario). R2 = BF-BOF + biochar, R3 = BF-BOF-CCS, R4 = BF-BOF-CCS + biochar, R5 = H2-DRI-EAF, R6 = H2-DRI-EAF + biochar, R7 = NG-DRI-EAF, and R8 = NG-DRI-EAF + biochar.

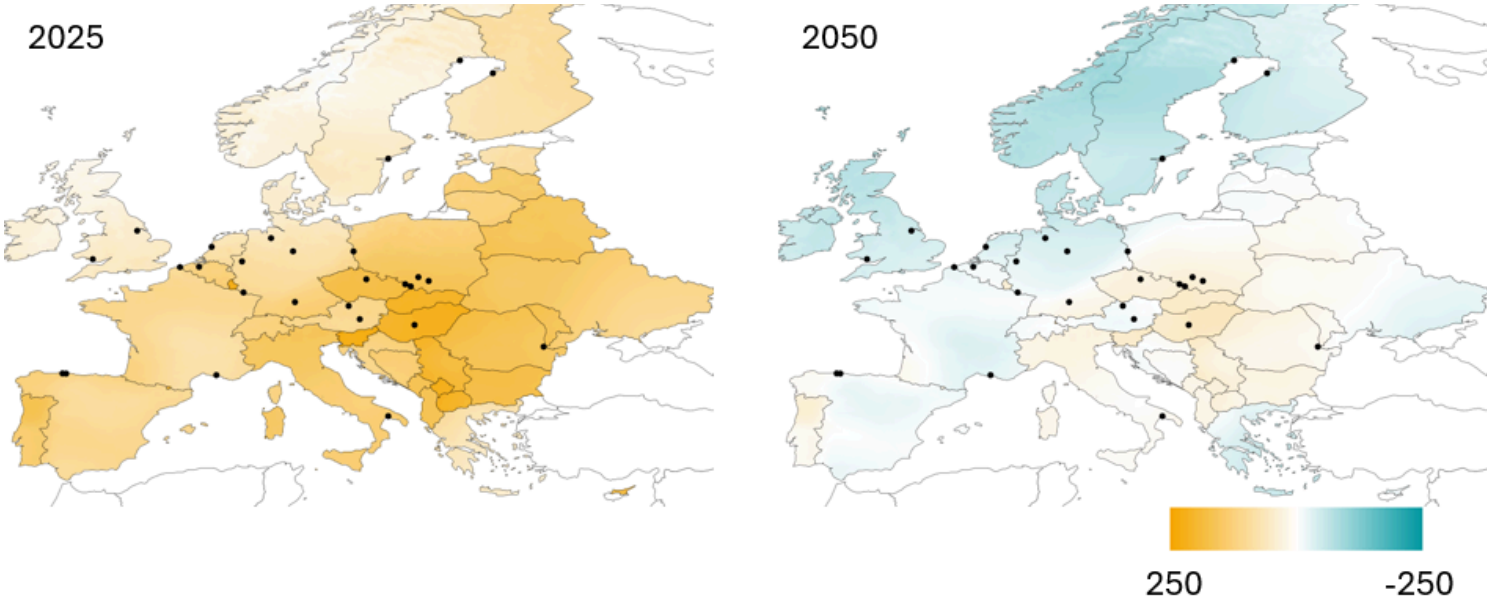


Figure 4

Difference in production costs between BF-BOF-CCS with biochar and H2-DRI-EAF with biochar in Europe for 2025 and 2050, expressed in €/t CS. Black dots indicate existing primary steel production sites.

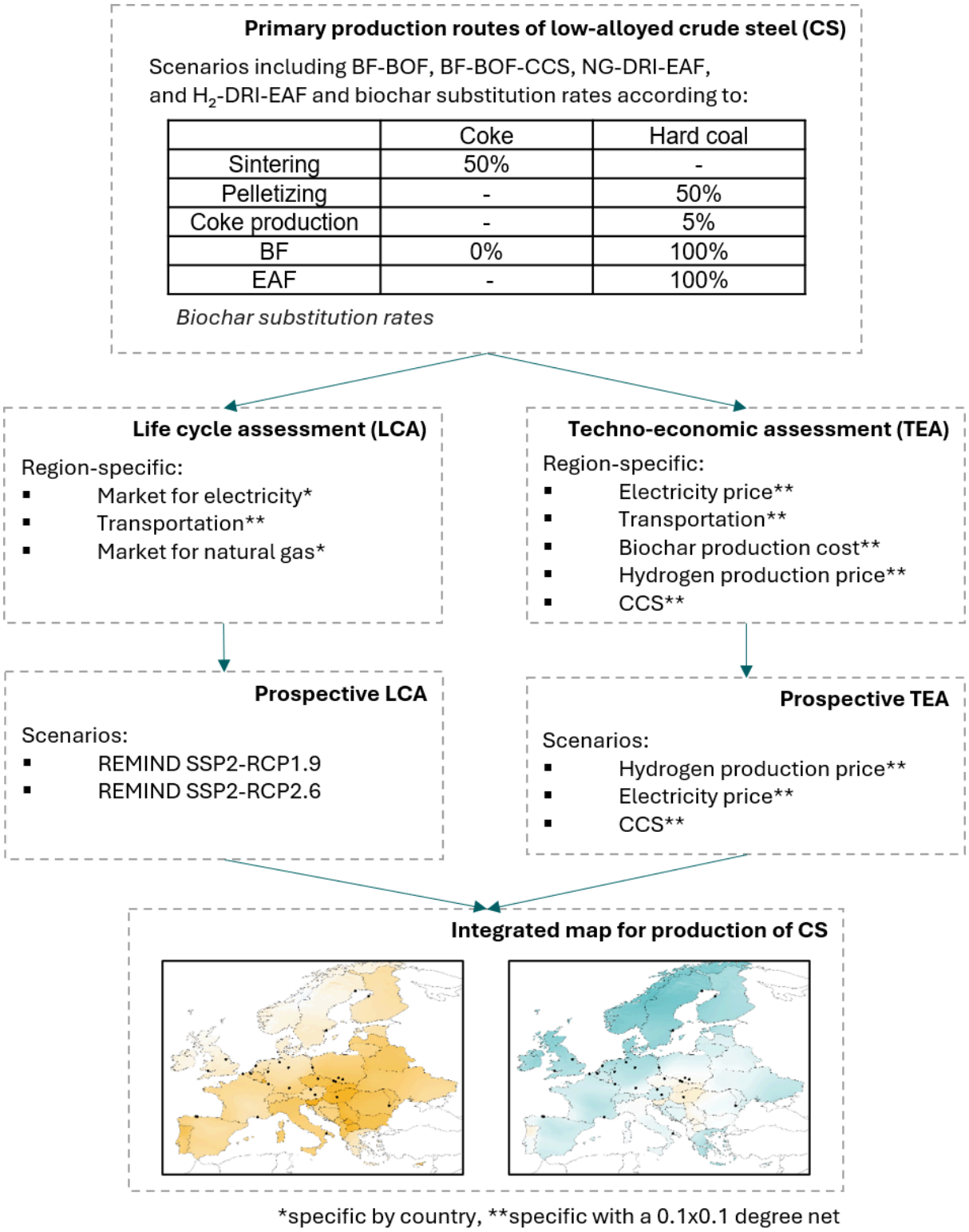


Figure 5

Methodological framework

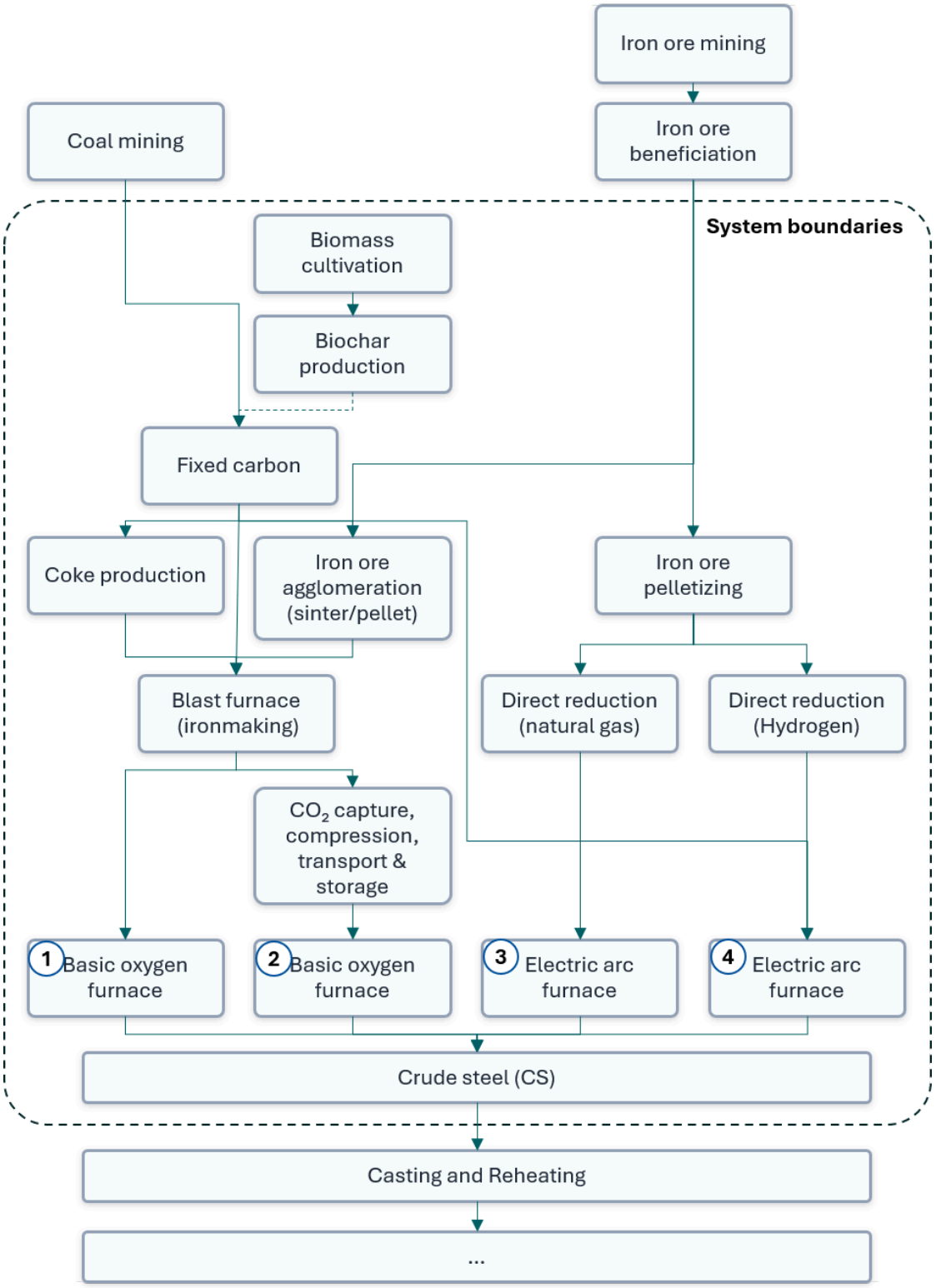


Figure 6

Process flow of production of 1 t molten low-alloyed CS. Process 1 = BF-BOF; Process 2: BF-BOF-CCS; Process 3: NG-DRI-EAF; Process 4: H2-DRI-EAF

Supplementary Files

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