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Research Article

Decarbonization potential of hydrogen-based direct reduction of iron ore in Thai steel industry

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Abstract. Steel decarbonization is a global priority due to its high energy use and emissions. In Thailand, this challenge is shaped by reliance on scrap-based EAF systems, where emissions depend on carbon-intensive electricity and limited scrap availability and quality. This study evaluates the environmental competitiveness and decarbonization potential of hydrogen-based direct reduced iron (H₂-DRI) integrated with electric arc furnace (EAF) steelmaking under Thailand-specific conditions. A cradle-to-gate life cycle assessment was conducted to compare 100% scrap-based EAF with four H₂-DRI-EAF scenarios (25%, 50%, 75%, and 100% DRI) using grey, blue, and green hydrogen. The ReCiPe 2016 method was applied to evaluate global warming and endpoint impacts on human health, ecosystem quality, and resource scarcity. Results showed that the baseline scrap-based EAF has the lowest environmental burden. Among hydrogen pathways, blue hydrogen achieves the greatest climate benefits, reaching 551.51 kg CO₂-eq/t, while grey hydrogen exhibits the highest impacts across all categories. Green hydrogen does not outperform the baseline under current conditions due to upstream burdens. Furthermore, endpoint contribution analysis revealed the overall emissions profile, highlighting trade-offs between climate change and other midpoint impact categories. Results suggest that Thailand should pursue a dual-pathway steel decarbonization strategy that combines optimized scrap-based EAF production with the gradual deployment of hydrogen-based DRI-EAF to address future constraints in scrap availability and quality. Compared with conventional natural gas-based DRI-EAF, blue and green hydrogen pathways achieved greenhouse gas reductions of 58.7% and 37.6%, respectively, highlighting their potential to support Thailand's long-term climate and industrial development objectives.

Keywords: Green, blue, and grey hydrogen; Electric arc furnace (EAF); Green steel; Life cycle assessment (LCA); Shaft furnace



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1. Introduction

Steel is among the most widely used materials in modern society, supporting essential sectors such as construction, infrastructure, transportation, and manufacturing, as well as a variety of general-purpose products (Pro *et al.*, 2023). Its high recyclability also positions the steel industry as a cornerstone of circular industrial systems, making it a strategically vital sector for economic development and global infrastructure. Global crude steel production reached approximately 1.89 billion tonnes in 2022, and demand is expected to continue increasing due to ongoing infrastructure needs and limited substitutes (Pro *et al.*, 2023; Luiz and Teixeira, 2025). Despite its economic importance, steelmaking is also among the most energy-intensive industrial activities and a major contributor to greenhouse gas (GHG) emissions. The iron and steel sector accounts for around 7% of global CO₂ emissions. It is the second-largest consumer of industrial energy, accounting for 21% of total consumption, a considerable share of which is lost as waste heat (Bhaskar *et al.*, 2019; International Energy Agency, 2020; Krüger *et al.*, 2018). This dual challenge makes steel decarbonization a priority for climate mitigation and aligns with the Paris Agreement's call for innovative, low-carbon

industrial practices (Hasanbeigi, 2022; Taji Eshkaftaki *et al.*, 2024). Globally, steel is primarily produced through two routes: the blast furnace–basic oxygen furnace (BF–BOF) route and the electric arc furnace (EAF) route. BF–BOF remains the dominant technology, accounting for 73.2% of production, while EAF contributes 26.3%, and the remaining 0.5% is produced using open-hearth and other minor technologies (Shahabuddin *et al.*, 2023). The BF–BOF route relies heavily on coal and coke to reduce iron ore, generating high direct CO₂ emissions. In contrast, EAF steelmaking, which primarily uses scrap steel and electricity, can have substantially lower direct emissions. However, its environmental performance depends strongly on the carbon intensity of the electricity supply, meaning that significant indirect emissions can arise from fossil-based power generation (Bhaskar *et al.*, 2019; Hasanbeigi *et al.*, 2025; Trinca *et al.*, 2023). As a result, alternative reductants and energy carriers, especially hydrogen, have received growing attention for deep decarbonization (Boretti, 2021). Hydrogen-based direct reduced iron integrated with EAF (H₂-DRI-EAF) steelmaking is increasingly regarded as one of the most promising pathways. In the H₂-DRI process, hydrogen replaces coal as the primary reductant, significantly reducing direct CO₂ emissions. When coupled with low-carbon electricity, the H₂-

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DRI-EAF route has the potential to approach near-zero emissions (Hornby, 2021). However, large-scale deployment depends on hydrogen availability, production cost, infrastructure, suitable iron ore quality, and national energy system conditions (Bhaskar *et al.*, 2020; Transition Asia, 2024). Thailand's steel industry is a major pillar of the national economy, supplying key sectors such as construction, automotive manufacturing, and machinery (Allen *et al.*, 2025). However, Thailand has limited upstream capability; it does not produce iron ore domestically and relies heavily on imported raw materials, with domestic production failing to meet national demand (Tongpool *et al.*, 2010). Thailand's steel production is dominated by EAF technology using scrap steel. Although scrap-based EAF routes reduce direct emissions compared with BF-BOF, their environmental performance in Thailand is constrained by two major factors. First, the country's largely fossil-based electricity grid means that electricity consumption can dominate the life-cycle CO₂ emissions of EAF steel production (Juntueng *et al.*, 2021; Juntueng *et al.*, 2014). Second, scrap availability and quality remain critical barriers. Domestic scrap collection is insufficient, while imported scrap may contain impurities (e.g., copper), limiting its use in high-grade applications such as automotive manufacturing. As a result, Thailand continues to import substantial volumes of higher-quality steel products (Tongpool *et al.*, 2010; Juntueng *et al.*, 2014; Navawongse, n.d).

To address these limitations while advancing decarbonization, direct reduced iron integrated with EAF is increasingly considered as a pathway to supplement scrap and enable higher-quality steel production. In particular, H₂-DRI-EAF offers a potentially attractive route for Thailand by reducing dependence on scrap alone while lowering emissions relative to conventional ironmaking (Hornby, 2021). However, the feasibility of this transition depends not only on steelmaking technology but critically on how the hydrogen is produced. Hydrogen can be supplied through grey, blue, or green pathways, each with different environmental implications. Grey hydrogen, produced from natural gas without carbon capture, has relatively high emissions. Blue hydrogen adds carbon capture and storage to fossil-based production, potentially lowering emissions but remaining dependent on fossil resources and capture efficiency. Green hydrogen, produced from water electrolysis using renewable electricity, is often considered the lowest-carbon option, although its performance depends heavily on the electricity source and the impacts of renewable energy infrastructure (Mehmood *et al.*, 2024). Several studies have investigated hydrogen production and its integration into industrial systems. Galitskaya and Zhdanev (2022) investigated hydrogen production via wind-powered water electrolysis and its application for direct reduced iron (DRI) based green steel manufacturing in the Russian Federation. Tubalinal *et al.*, (2024) evaluated green hydrogen production in the Philippines using solar and wind resources, highlighting that although electrolysis-based hydrogen offers environmental advantages, high production costs remain a major barrier. Life cycle assessment (LCA) has been widely applied to compare hydrogen production pathways. Sadeghi *et al.* (2020) compared natural gas reforming, coal gasification, and water electrolysis, demonstrating that electrolysis-based hydrogen generally exhibits lower global warming impacts than fossil-based routes. Similarly, Zhang *et al.*, (2022) evaluated multiple hydrogen production pathways, including proton exchange membrane (PEM) electrolysis integrated with photovoltaic (PV) systems, and reported that PV-driven electrolysis can still lead to significant environmental impacts due to upstream emissions from PV module manufacturing. Jolaoso *et al.*, (2024) further

identified electricity generation as the primary contributor to environmental burdens in fossil-fuel-based hydrogen production. Hydrogen-based ironmaking has been widely recognized as a key pathway for decarbonizing the steel sector. Rosner *et al.*, (2023) reported that substituting natural gas with renewable hydrogen in H₂-DRI processes could reduce direct CO₂ emissions by up to 85%, with economic feasibility improving when hydrogen costs fall below approximately USD 1.63 per kilogram. Likewise, Luiz and Teixeira, (2025) concluded that integrating H₂-DRI with EAF technology could achieve CO₂ emission reductions of up to 90% compared with the conventional blast furnace–basic oxygen furnace route.

Recent research has increasingly focused on integrating renewable energy systems into steel production. Hu *et al.*, (2025) proposed a green steel model linking wind power with EAF operations, demonstrating that renewable electricity can significantly reduce life-cycle carbon emissions relative to fossil-based power systems. Taji Eshkaftaki *et al.*, (2024) developed an integrated framework combining solar-powered solid oxide electrolyzers for hydrogen production with EAF steelmaking, indicating that the use of renewable hydrogen and waste heat recovery can substantially lower global warming impacts. Further studies have compared alternative EAF-based decarbonization pathways. Hu *et al.*, (2024) found that scrap-based EAF routes can reduce CO₂ emissions by up to 77.3%, whereas H₂-DRI options achieve reductions of approximately 31.5%, with further improvements possible when combined with renewable energy and carbon capture technologies. In a complementary study, Wen *et al.*, (2024) applied marginal abatement cost curves and showed that hydrogen-based steelmaking and scrap-based EAF are among the most effective strategies for reducing both greenhouse gas emissions and air pollutants.

In Thailand, however, research on steel-sector decarbonization remains relatively limited. Sodsai and Rachdawong, (2012) analyzed CO₂ emissions from the Thai steel industry and found that electricity consumption accounted for approximately 72% of total emissions in slab production. They suggested that switching to natural gas could reduce emissions by around 4%, while using biomass residues could reduce emissions by up to 26%. Juntueng *et al.*, (2021) assessed energy-saving opportunities and concluded that the direct reduction electric arc furnace route provides a strong balance between emission reduction and economic feasibility, with potential reductions of approximately 1.44 million tonnes of CO₂ equivalent by 2030. At the policy level, Thailand has begun promoting steel-sector decarbonization through initiatives such as the Meranti Green Steel project in Rayong, which aims to establish a 2-million-tonne-per-year DRI-EAF steel plant that will initially utilize natural gas and gradually incorporate hydrogen (Meranti Green Steel (Thailand) Co., 2025). These developments highlight the importance of evidence-based assessments to support technology selection and policy planning.

Although previous studies have extensively examined hydrogen production technologies, renewable energy integration, and alternative steelmaking routes, most focus mainly on green hydrogen-based systems. Comparative evaluations of grey, blue, and green hydrogen pathways within H₂-DRI-EAF steelmaking remain relatively scarce. Moreover, existing research has largely concentrated on major steel-producing regions such as Europe and China, with limited country-specific analysis for Southeast Asia. Based on the literature reviewed for this study, comparative life-cycle assessments simultaneously evaluating green-, blue-, and grey-hydrogen pathways for DRI-EAF steelmaking under Thailand-

specific conditions appear to remain limited. This study therefore contributes a Thailand-specific comparison of green, blue, and grey hydrogen supply pathways for DRI-EAF steelmaking under a consistent life-cycle assessment framework. To address this research gap, the present study evaluates the environmental performance of H₂-DRI-EAF steelmaking in Thailand using a life-cycle assessment approach. The analysis compares green, blue, and grey hydrogen supply pathways across different DRI shares and examines their environmental performance under the energy and steelmaking conditions represented in the Thai context. Particular attention is given to the influence of electricity-related emissions, hydrogen sourcing, and scrap utilization on the environmental performance of the investigated pathways. Based on these findings, the study proposes key considerations, policy and industry recommendations to support the transition toward low-carbon steelmaking pathways in Thailand.

2. Methodological framework

In this study, the methodological framework is designed to evaluate the environmental competitiveness of different steel production pathways in Thailand, with a particular focus on hydrogen-based direct reduction of iron (H₂-DRI) integrated with electric arc furnace (EAF) steelmaking. The framework aims to assess the decarbonization potential of hydrogen-based steelmaking technologies compared with the conventional steel production route currently used in Thailand. The environmental aspect of the study is assessed using LCA, which enables the systematic evaluation of environmental burdens throughout the steel production route from raw material extraction to the final production stage, allowing the estimation of greenhouse gas emissions, resource consumption, and other environmental impacts. The analysis considers three scenarios: scrap-based EAF steelmaking, H₂-DRI-EAF steelmaking, and a hybrid configuration combining different proportions of scrap steel and H₂-DRI. The framework is widely used to assess the environmental impacts associated with a product, process, or service throughout its life cycle. In this study, the LCA methodological framework described in ISO 14040 and ISO 14044:2006 (International Organization for Standardization (ISO), 2006) was used to evaluate the environmental impacts

associated with steel production through H₂-DRI-EAF. Accordingly, the assessment was structured into four main stages: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

2.1. Goal and scope definition

In this study, LCA is conducted to evaluate the environmental competitiveness of hydrogen-based steel production in Thailand, with a particular focus on carbon dioxide (CO₂) emissions. The primary objective is to assess the environmental performance of steel production using H₂-DRI in a shaft furnace integrated with electric arc furnace (EAF) technology. The results are expected to provide insights for policymakers and stakeholders to support the transition toward low-carbon steel production and improved resource efficiency in Thailand's steel industry. The functional unit was defined as 1 tonne of crude steel produced through the scrap-based and H₂-DRI-EAF steelmaking routes. This mass-based functional unit provides a consistent basis for comparing the environmental impacts of the investigated steelmaking configurations. However, it does not account for potential differences in steel quality associated with the use of scrap and DRI, including variations in residual or tramp-element concentrations. Therefore, the comparison in this study is limited to the environmental performance of producing an equivalent mass of crude steel and should not be interpreted as demonstrating functional equivalence in terms of specific steel grades or quality requirements. The LCA followed a cradle-to-gate approach, considering all relevant processes from raw material preparation to crude steel production (Figure 1). The system boundaries included all relevant stages in the steel-making process, from iron ore pellet production, the reduction of iron ore in the shaft furnace, and steel production in the electric arc furnace. The use phase and end-of-life stages of steel products are excluded, as the focus of this study is limited to the steel production stage. Hydrogen is a key input in the DRI process, and three hydrogen production pathways, both renewable and non-renewable sources, are considered in this study: grey hydrogen, blue hydrogen, and green hydrogen. Therefore, the embodied emissions from hydrogen production are considered within the scope of the study. Grey hydrogen is

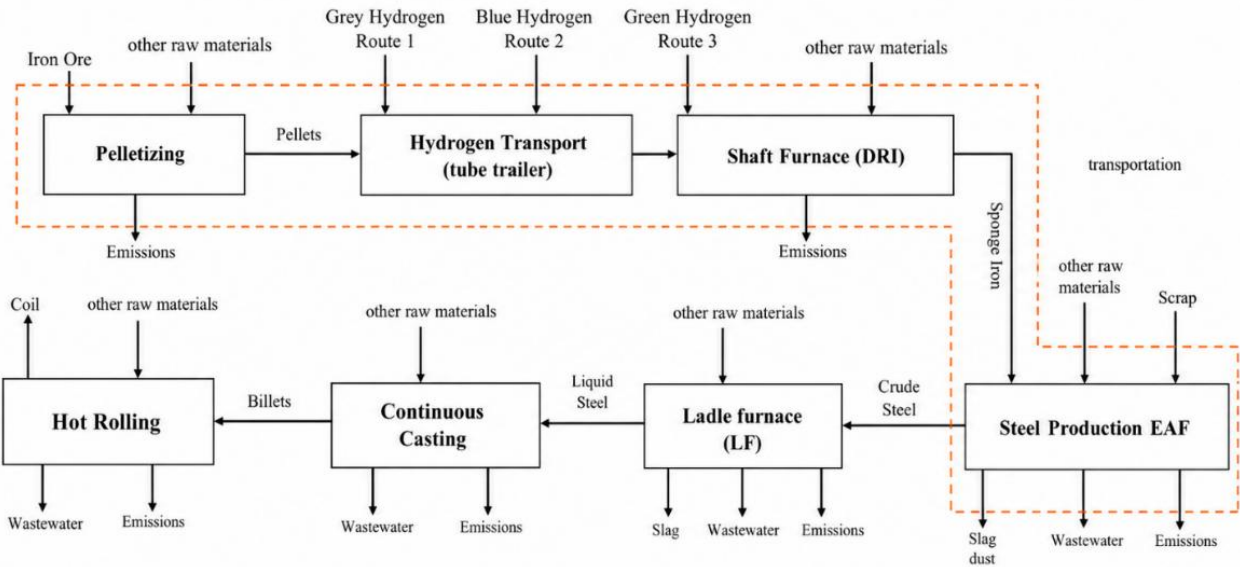


Fig 1. System boundary of the study

produced from natural gas via steam methane reforming. Blue hydrogen is produced through a similar natural gas reforming process but incorporates carbon capture and storage (CCS). Green hydrogen is generated through water electrolysis powered by solar energy (Mehmood et al., 2024).

To comprehensively evaluate the decarbonization potential of hydrogen integration under Thailand's current energy and industrial conditions, a scenario-based approach was applied. The Baseline represents conventional 100% scrap-based EAF steelmaking (0% DRI and 100% scrap). Four alternative H₂-DRI-EAF scenarios were evaluated by progressively substituting DRI for scrap in the EAF metallic feed: DRI25 (25% DRI and 75% scrap), DRI50 (50% DRI and 50% scrap), DRI75 (75% DRI and 25% scrap), and DRI100 (100% DRI and 0% scrap). Thus, the scenarios follow the same overall H₂-DRI-EAF process route and differ primarily in the proportion of DRI and scrap entering the EAF. For each DRI scenario, three hydrogen-production pathways (grey, blue, and green hydrogen) were evaluated.

In addition to these primary scenarios, a natural gas-based DRI-EAF (NG-DRI-EAF) pathway was included as a benchmark to provide a consistent reference for evaluating the decarbonization potential of the hydrogen-based pathways. The NG-DRI-EAF benchmark was assessed using the same functional unit of 1 tonne of crude steel and the same cradle-to-gate system boundary applied to the investigated steelmaking pathways.

This will enable the evaluation of energy requirements, greenhouse gas emissions, and environmental trade-offs associated with hydrogen adoption in Thailand's steel industry, ultimately providing insights to support policymakers and stakeholders in maximizing resource efficiency and minimizing environmental impacts within Thailand's steel industry.

2.2. Life cycle inventory analysis

The life cycle inventory LCI phase involved the systematic collection and quantification of data on all inputs and outputs associated with crude steel production via H₂-DRI-EAF technology in Thailand. The inventory included inputs of raw materials, auxiliary materials, energy carriers, and hydrogen production pathways, as well as outputs such as crude steel, slag, dust, and emissions to air and water within the defined cradle-to-gate system boundary. Foreground process data were obtained from relevant peer-reviewed literature (iron ore pelletizing, direct reduced iron (DRI) production, electric arc furnace (EAF) steelmaking, and hydrogen production pathways). In contrast, background datasets representing upstream processes such as electricity generation, fuel supply, and material production were sourced from the ecoinvent database (v3.9.1). The functional unit was defined as the production of 1 tonne of crude steel. All inventory flows were normalized to this functional unit to ensure comparability between the assessed steelmaking routes. The assessment considered two main production routes: (i) 100% DRI-EAF steelmaking and (ii) 100% scrap-based EAF steelmaking. For the scenario analysis, the inventory data were developed based on a mass-balance approach according to the defined reference flow. The shares of scrap and DRI varied in each scenario, and the corresponding material flows were determined accordingly. In addition, inventory data for hydrogen production pathways were compiled to support the modeling of hydrogen-based DRI systems, including green hydrogen produced by electrolysis, blue hydrogen produced by steam methane reforming (SMR) with carbon capture and storage (CCS), and grey hydrogen produced by SMR without carbon capture. To improve

geographical representativeness, Thailand-specific datasets were applied where available; where such data were not available, global or literature-based datasets were used. Hydrogen transportation is also included for accounting emissions associated with off-site hydrogen supply. As the future hydrogen supply chain for H₂-DRI steelmaking in Thailand has not yet been established, a representative transport distance of 10 km was assumed based on a local industrial-cluster supply scenario in Rayong, where existing hydrogen production facilities are located near proposed green steel developments. Hydrogen was assumed to be transported as compressed gaseous hydrogen using a diesel-powered tube-trailer truck. A trailer capacity of 380 kg H₂ and a diesel consumption rate of 0.224 L km⁻¹ were adopted from published sources. Including the empty return journey, the total transport distance was 20 km per round trip, corresponding to 4.48 L of diesel consumption. As primary plant-level data for hydrogen-based DRI-EAF steelmaking in Thailand are not publicly available, the life cycle inventory was developed using secondary data from published LCA studies, process-modeling literature, technical reports, and established databases. The inventory was cross-checked against multiple studies to improve data reliability and consistency (Bangkok Industrial Gas Co., 2019; International Energy Agency, 2023; Meranti Green Steel (Thailand) Co., 2025; NXPO 2024; Tayarani & Ramji, 2022). The H₂-DRI-EAF inventory was primarily based on Vogl et al., (2018); Bhaskar et al., (2020); Suer et al., (2022); Rosner et al., (2023); Hu et al., (2025). In contrast, the scrap-based EAF inventory was supported by (Pro et al., 2023; Hu et al., 2025). Similarly, green hydrogen inventory data are consistent with PEM electrolysis studies reporting electricity and water requirements (Zhang et al., 2022; Jolaoso et al., 2024; Dincer and Agelin-Chaab, 2025).). The NG-SMR and NG-SMR-CCS inventories used for grey and blue hydrogen, respectively, were traced to Antonini et al. (2020), which Wei et al. (2024) identified as their source. The triangulation results indicate that the selected inventory flows are broadly consistent with published secondary data, as shown in Supplementary Table S7. Since individual studies often lacked complete inventory information, the most comprehensive and transparent sources were selected, normalized to the common functional unit, and integrated into a consistent background LCA modelling framework. All inventory data were normalized to the functional unit of 1 tonne of crude steel to ensure comparability across scenarios. The pelletization and EAF CO₂ and CO flows were traced to the original Li et al. (2021a, 2021b, 2022) inventories and treated as source-reported inventory flows. Pelletization emissions were additionally normalized to the oxide-pellet requirement of the present system, whereas the published EAF inventory did not provide sufficient disaggregated carbon-flow information for independent reconstruction. Detailed inventory traceability is provided in Supplementary Tables S16 and S17. DRI data were sourced from (Graupner et al., 2023). The hydrogen requirement for the DRI process was derived from the adopted DRI inventory and corresponds to approximately 66.3 kg H₂ per tonne of DRI. For the DRI100 scenario, 1,040.83 kg of DRI is required in the EAF to produce 1 tonne of crude steel. Accordingly, the hydrogen requirement was scaled to 69.01 kg H₂ per tonne of crude steel (66.3 kg H₂/t DRI × 1.04083 t DRI/t crude steel). This hydrogen requirement is higher than some values reported in the literature, reflecting differences in process-specific assumptions regarding hydrogen utilization, excess reducing gas, and top-gas recycling. The adopted source considers treatment and recycling of shaft-furnace top gas; however, a single fixed excess-hydrogen ratio and top-gas recycle percentage were not independently specified in the

present LCA model. Therefore, the hydrogen requirement was retained as reported in the adopted DRI inventory rather than recalculated from the theoretical stoichiometric requirement. Electric Arc Furnace (EAF) data were taken from (Li *et al.*, 2022), and scrap-based EAF data were derived from (Yang *et al.*, 2023). The electricity requirement for the DRI-EAF stage (470.6 kWh/t crude steel) was adopted from the HSE process inventory of Li *et al.* (2022). In the present study, the DRI was assumed to be charged hot into the EAF rather than cooled prior to charging, thereby utilizing its retained sensible heat and reducing the electricity required for reheating and melting. This assumption is consistent with Bhaskar *et al.* (2020), who reported approximately 445 kWh/t molten steel for hot DRI charged at around 700 °C, and with Vogl *et al.* (2018), who demonstrated that cooling DRI/HBI before EAF charging increases the subsequent energy requirement. The scrap-EAF inventory used in this study requires 497.5 kWh/t crude steel. The difference between the DRI-EAF and scrap-EAF values should not be interpreted as an inherent energy advantage of DRI, because the two literature-derived inventories represent different charging and operating conditions. EAF electricity demand also depends on charge characteristics, metallization, oxygen and carbon injection, and supplementary chemical energy (Vogl *et al.*, 2018; Bhaskar *et al.*, 2020; Yang *et al.*, 2023). Therefore, these electricity values were treated as process-specific inventory assumptions.

The adopted blue-hydrogen inventory (Wei *et al.*, 2024) routes 5.66 kg CO₂/kg H₂ to geological storage and emits 3.12 kg fossil CO₂/kg H₂, corresponding to an implied overall capture rate of approximately 64.5%. As the blue-hydrogen pathway was represented using an adopted secondary inventory, CCS capture performance, capture configuration and energy penalty, CO₂ transport and storage, and Thailand-specific upstream methane leakage were not independently parameterized in the present model. These factors represent a source of uncertainty in the blue-hydrogen results and should be evaluated using a regionalized hydrogen-production LCA in future studies.

Thailand-specific operational data for hydrogen-based DRI-EAF steelmaking were unavailable; therefore, literature-based EAF inventories were adopted. Yang *et al.* (2023) report only 0.84 kg CO₂-eq/t molten steel as direct emissions for the full-scrap EAF, with most of the life-cycle carbon footprint classified as indirect. In contrast, Li *et al.* (2022) report 178.50 kg CO₂ and 11.23 kg CO per tonne of crude steel as EAF emission flows, for which the published inventory lacks sufficient disaggregated carbon-flow information for independent reconstruction. Accordingly, these source-reported values were not interpreted as an isolated effect of substituting DRI for scrap, and the pathways were compared on a complete life-cycle basis.

For the scrap-based EAF route, the scrap input was modelled using the ecoinvent cut-off system model. Under the cut-off approach, burdens associated with the previous life cycle of the scrap were not assigned to the secondary material, while the burdens associated with the scrap-treatment activities represented by the selected ecoinvent dataset were included. No primary steel production burden was therefore allocated to the incoming scrap. For the treatment of process outputs, no mass- or economic-allocation procedure was applied. The steel product was assigned 100% of the process burden, while slag, EAF dust, and iron waste/splashing were modelled as final waste flows without avoided-product credits. Green hydrogen inventory was sourced from (Nwe *et al.*, 2024) Whereas inventory data for blue and grey hydrogen were sourced from Tables S4 and S5 of the supplementary information

accompanying (Wei *et al.*, 2024). The hydrogen-production inventories were modelled using a foreground-background approach. The quantities of electricity, natural gas, water, chemicals, and other direct process inputs were specified in the foreground inventories adopted from Nwe *et al.* (2024) for green hydrogen and Wei *et al.* (2024) for blue hydrogen. The associated upstream environmental burdens, including electricity generation, natural-gas supply, water treatment, and material production, were represented through the corresponding background datasets available in SimaPro/ecoinvent. However, individual background sub-processes, such as photovoltaic infrastructure and upstream material-production processes, were not independently parameterized as foreground processes because they are not direct inputs to the steelmaking process but are embedded within those direct inputs. In the implemented SimaPro inventory, CO₂ routed to geological storage was represented as a negative CO₂ flow, resulting in a credit in the global warming characterization.

The hydrogen-production inventories were modelled using a foreground-background approach. The quantities of electricity, natural gas, water, chemicals, and other direct process inputs were specified in the foreground inventories adopted from Nwe *et al.* (2024) for green hydrogen and Wei *et al.* (2024) for blue hydrogen. The associated upstream environmental burdens, including electricity generation, natural-gas supply, water treatment, and material production, were represented through the corresponding background datasets available in SimaPro/ecoinvent. However, individual background sub-processes, such as photovoltaic infrastructure and upstream material-production processes, were not independently parameterized as foreground processes because they are not direct inputs to the steelmaking process but are embedded within those direct inputs. In the implemented SimaPro inventory, the CO₂ captured and routed to geological storage was represented as a negative CO₂ flow. Because this captured CO₂ is stored rather than released to the atmosphere, its modelled treatment results in a credit in the global warming characterization.

Electricity consumption for the steelmaking process stages was modelled using Thailand's 2023 national grid electricity mix for 2023 (International Energy Agency, 2023; World Bank, 2023), except for green-hydrogen electrolysis, which used the dedicated Thailand-specific PV electricity dataset described above. The overall mass flow of inputs and outputs associated with crude steel production is illustrated in Figure 2. Energy consumption data covered electricity and other fuels used in shaft furnace reduction, EAF melting, and downstream steel processing steps. Emission data include the expected key pollutants, such as CO₂, SO₂, NO_x, and dust, particularly those generated during steelmaking and refining. Additional process outputs such as molten steel and solid waste byproducts (e.g., slag and dust) are also included in the inventory (Liang *et al.*, 2020). A natural gas-based DRI-EAF (NG-DRI-EAF) pathway was additionally modelled as a benchmark to contextualize the global warming performance of the hydrogen-based DRI-EAF pathways. The natural gas-based direct reduction inventory was derived from Krekel *et al.* (2026) and incorporated into the present LCA framework. The benchmark was evaluated using the same functional unit of 1 tonne of crude steel and the cradle-to-gate system boundary applied in the present study. The inventory was implemented in SimaPro using the background datasets adopted in the present study, including the Thai electricity grid where applicable. The NG-DRI-EAF pathway was evaluated using ReCiPe 2016 v1.1 under the same impact-assessment framework as the other

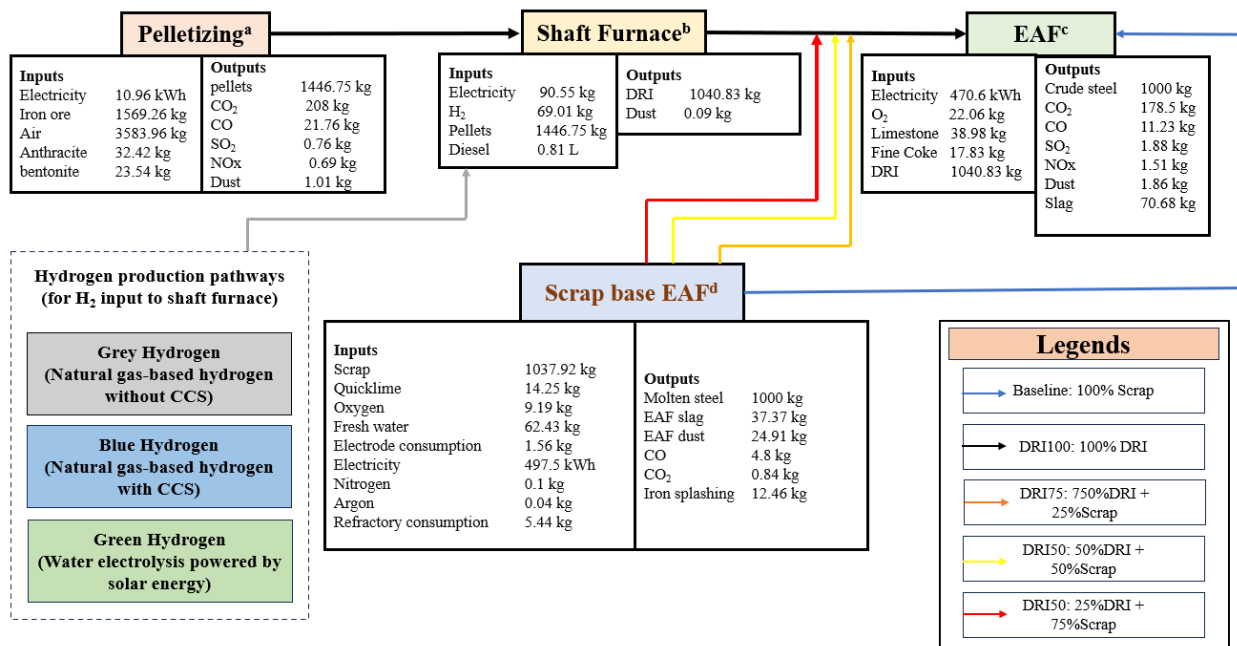


Fig 2. Overall mass flow of 1 tonne of crude steel production (^aLi *et al.* (2021a, 2021b, 2022); ^bGraupner *et al.*, 2023; ^cLi *et al.*, 2022; ^dYang *et al.*, 2023)

investigated pathways. Detailed inventory information for the NG-DRI-EAF benchmark is provided in Table S12 of the Supplementary Material.

To clarify the origin of the reported emissions, the direct emissions in the foreground inventory were checked against the original data sources. For the pelletization stage, both electricity and anthracite were included as inputs because they serve different functions: electricity is used as auxiliary energy for process equipment, while anthracite is used as a thermal fuel in the rotary kiln for pellet induration. Therefore, the CO₂, CO, SO₂, NOx, and dust emissions associated with pelletization were treated as direct pelletization-stage emissions, with fuel-combustion-related contributions from anthracite use.

In contrast, no direct CO₂ or CO emissions were assigned to the H₂-DRI shaft furnace because hydrogen reduction of iron oxides produces water/steam as the main reaction product. For the EAF stage, source-reported emissions from Li *et al.* (2022) and Yang *et al.* (2023) were retained rather than independently recalculated. Electricity-related emissions were accounted for separately through the background electricity dataset. The compiled inventories were subsequently used for the life cycle impact assessment of the DRI-EAF and scrap-EAF steelmaking routes and the associated hydrogen production pathways. Detailed inventory data are provided in Tables S1–S6 of the Supplementary Information.

2.3. Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is used to evaluate the significance of environmental impacts based on the information obtained from the life cycle inventory (LCI). Various methods are available for Life Cycle Impact Assessment (LCIA). In this study, LCIA was performed using the ReCiPe 2016 v1.1 impact assessment method (Hierarchist perspective) in SimaPro 10.2.0.3 software, which enables the assessment of environmental impacts at both midpoint and endpoint levels. Midpoint indicators address specific environmental issues such as climate change, whereas endpoint indicators evaluate broader environmental damages across three areas of protection: human health, ecosystem quality, and resource

scarcity. This study primarily focused on one key midpoint impact category: global warming (GW), which was chosen due to its direct relevance in assessing the decarbonization potential of H₂-DRI steelmaking technologies. However, focusing exclusively on global warming may overlook potential environmental burden shifting between impact categories. Therefore, additional ReCiPe 2016 midpoint indicators were additionally examined through endpoint contribution analysis as complementary indicators to provide a broader environmental perspective and to identify potential trade-offs associated with the alternative steelmaking pathways. These additional midpoint indicators were not used as the primary basis for evaluating decarbonization performance but were included to support a more comprehensive interpretation of the environmental consequences of the investigated scenarios across the three endpoint areas of protection (human health, ecosystem quality, and resource scarcity), while global warming remained the principal basis for evaluating decarbonization potential.

3. Results and discussion

3.1. Climate change

The global warming results reveal substantial differences among the steelmaking pathways evaluated in this study. The scrap-based EAF route served as the reference scenario, while the hydrogen-based DRI-EAF routes exhibited markedly different climate performances depending on both the hydrogen production pathway and the proportion of DRI used in steel production. Across all hydrogen pathways, global warming impacts increased with increasing DRI utilization, indicating that the environmental burden associated with hydrogen production and iron ore reduction becomes increasingly important as scrap is replaced by DRI. Among the hydrogen-based routes, blue hydrogen consistently exhibited the lowest global warming impacts, followed by green hydrogen, while grey hydrogen produced the highest impacts. These differences are primarily explained by the environmental profile of

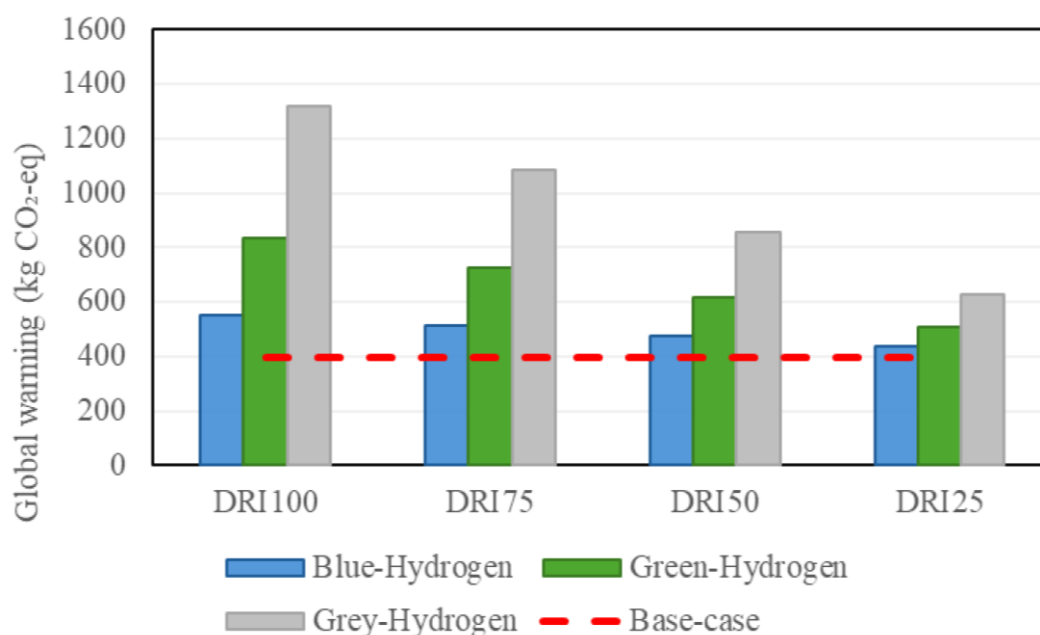


Fig 3. Comparison of global warming for different steel-making scenarios of blue, green, and grey H₂ with base case, in which the base case is 100% Scrap-based steel making, DRI100 is 100% DRI-based steel making, DRI75 is 75% DRI and 25% Scrap-based steel, DRI50 is 50% DRI and 50% Scrap-based steel, DRI25 is 25% DRI and 75% Scrap-based steel

hydrogen production. The integration of carbon capture and storage (CCS) substantially reduced emissions from blue hydrogen production, whereas grey hydrogen remained highly carbon-intensive because it relies on steam methane reforming without carbon capture. Green hydrogen avoided direct fossil fuel-based hydrogen production but remained sensitive to electricity demand and the carbon intensity of the supporting energy system.

The contribution analysis provides a quantitative explanation for the difference between the blue- and green-hydrogen pathways. The modelled global warming impact of green hydrogen was 2.70 kg CO₂-eq/kg H₂, with photovoltaic electricity contributing approximately 2.64 kg CO₂-eq/kg H₂ (97.7%). The remaining contributions were comparatively small, including oxygen production (0.0416 kg CO₂-eq/kg H₂), natural gas (0.0165 kg CO₂-eq/kg H₂), and water supply/treatment (0.0044 kg CO₂-eq/kg H₂). Thus, the modelled green-hydrogen impact was dominated by the life-cycle burden associated with the photovoltaic electricity supply. In comparison, the modelled net global warming impact of blue hydrogen was −1.39 kg CO₂-eq/kg H₂. Upstream natural-gas supply contributed approximately 1.21 kg CO₂-eq/kg H₂, whereas the blue-hydrogen foreground process contributed approximately −2.54 kg CO₂-eq/kg H₂. The adopted Wei et al. (2024) inventory routes 5.66 kg CO₂/kg H₂ to geological storage, while 3.12 kg fossil CO₂/kg H₂ remains as an atmospheric emission. In the implemented SimaPro inventory, the CO₂ captured and routed to geological storage is represented as a negative CO₂ flow. Because this captured CO₂ is stored rather than released to the atmosphere, its modelled treatment results in a credit in the global warming characterization. This storage credit substantially offsets the net climate-change impact of the blue-hydrogen pathway and is the principal factor contributing to its lower modelled GW relative to green hydrogen. The difference between the modelled green and blue hydrogen footprints was approximately 4.09 kg CO₂-eq/kg H₂. For the DRI100 scenario, the hydrogen requirement of 69.01 kg H₂/t crude steel, this corresponds to approximately 282.4 kg CO₂-eq/t crude steel,

which is equal to the observed difference between the green-H₂ DRI100 (834.03 kg CO₂-eq/t) and blue-H₂ DRI100 (551.51 kg CO₂-eq/t) scenarios. Contribution analysis of the reduced iron production stage confirms that hydrogen supply is the primary hotspot across all hydrogen pathways. Reduced iron production represented the major source of climate impacts, with hydrogen production accounting for the largest share of emissions. The contribution from oxidized iron pellets remained relatively constant across scenarios, while electricity consumption from the Thai grid provided an additional but smaller contribution. The influence of hydrogen production was most pronounced in the grey hydrogen pathway, whereas the modeled CO₂-storage credit substantially offsets the contribution associated with blue hydrogen production.

Overall, the results demonstrate that the environmental performance of H₂-DRI-EAF steelmaking is largely governed by the upstream hydrogen supply chain. Under the inventories and modeling assumptions adopted in this study, blue hydrogen provided the lowest climate burden among the hydrogen pathways evaluated, while the scrap-based EAF route remained the lowest-emission option under the assumptions of this study. These findings highlight that the decarbonization potential of hydrogen-based steelmaking depends not only on replacing carbon-intensive reducing agents with hydrogen but also on ensuring low-carbon hydrogen production and cleaner electricity systems throughout the steel value chain. The overall results are shown in Figure 3 and summarized in the Supplementary data Table S8. The NG-DRI-EAF benchmark resulted in a global warming impact of 1,336.41 kg CO₂-eq/t crude steel. The natural gas-based reduced-iron process was the largest contributor, accounting for 943.86 kg CO₂-eq/t crude steel, followed by the direct crude-steel process contribution (178.50 kg CO₂-eq/t crude steel) and electricity supplied by the Thai grid (173.39 kg CO₂-eq/t crude steel). Smaller contributions were associated with oxygen (23.41 kg CO₂-eq/t), coke (17.08 kg CO₂-eq/t), and limestone (0.16 kg CO₂-eq/t). Compared with this benchmark, the DRI100 blue- and green-hydrogen pathways, with global warming impacts of 551.51 and

834.03 kg CO₂-eq/t crude steel, respectively, showed reductions of approximately 58.7% and 37.6%. In contrast, the DRI100 grey-hydrogen pathway resulted in 1,316.87 kg CO₂-eq/t crude steel, corresponding to only an approximately 1.5% reduction relative to the NG-DRI-EAF benchmark. For context, the Baseline (100% scrap-EAF) showed the lowest global warming impact at 396.51 kg CO₂-eq/t crude steel. A comparative summary of the NG-DRI-EAF benchmark and hydrogen-based pathways is provided in Table S15 of the Supplementary Material.

3.1.1. Comparison with published H₂-DRI-EAF studies

The global warming results obtained in the present study were compared with previously published assessments of hydrogen-based and DRI-EAF steelmaking to place the Thailand-specific results in a broader context. However, direct numerical comparison should be made cautiously because the available studies differ in geographical scope, system boundaries, electricity supply, hydrogen-production pathways, DRI characteristics and charging conditions, scrap/DRI ratios, and assumptions regarding future energy systems. Therefore, the published results are used here primarily as literature benchmarks rather than as directly equivalent reference systems.

Vogl *et al.* (2018) assessed a prospective hydrogen direct-reduction steelmaking system and demonstrated that the environmental performance of hydrogen-based steelmaking is strongly dependent on the availability of low-carbon electricity. The study also showed that EAF energy requirements are affected by DRI/HBI charging conditions and metallization. Similarly, Bhaskar *et al.* (2020) evaluated an HDRI-EAF system and demonstrated that the electricity requirement of the EAF is influenced by DRI charging temperature, metallization, and impurity content. These studies therefore provide important process-level benchmarks, although their energy-system and process assumptions differ from the Thailand-specific conditions considered in the present study.

Suer *et al.* (2022) reported a carbon footprint of approximately 0.75 kg CO₂-eq/kg steel, equivalent to approximately 750 kg CO₂-eq/t steel, for hydrogen-based steel production under a European sustainable electricity scenario for 2040. This value is of a similar order of magnitude to the 834.03 kg CO₂-eq/t steel obtained for the DRI100 green-hydrogen scenario in the present study. The difference should be interpreted in the context of the different geographical background systems, electricity assumptions, process inventories, and system boundaries used in the two assessments.

Graupner *et al.* (2023) performed a prospective cradle-to-gate assessment of H₂-DRI-EAF steelmaking in Germany using PEM electrolysis supplied by either the German electricity mix or onshore wind electricity. For the wind-based hydrogen pathway, the reported GHG emissions were approximately 0.38–0.73 t CO₂-eq/t crude steel across the investigated future scenarios. These values are lower than the 0.834 t CO₂-eq/t steel obtained for the DRI100 green-hydrogen scenario in the present study. However, Graupner *et al.* (2023) considered a prospective German energy system for 2025–2040 and an EAF charge containing approximately 85% sponge iron and 15% scrap, whereas the present DRI100 scenario represents a Thailand-specific, static cradle-to-gate system with 100% DRI. The difference therefore reflects not only the hydrogen pathway but also differences in electricity supply, background-system decarbonization, geographical conditions, and metallic charge composition.

Hu *et al.* (2025) evaluated the life-cycle carbon footprint of EAF steelmaking in China under different combinations of scrap, DRI, and hot metal. For the DRI-scrap configurations, the reported life-cycle carbon footprint increased from 636.7 to 1,484.1 kg CO₂-eq/t molten steel as the DRI share increased from 20% to 100%. The 100% DRI value is higher than the DRI100 results obtained in the present study for green hydrogen (834.03 kg CO₂-eq/t) and blue hydrogen (551.51 kg CO₂-eq/t), and is also somewhat higher than the grey-hydrogen result (1,316.87 kg CO₂-eq/t). However, Hu *et al.* modelled DRI production using hydrogen-rich coke-oven gas in the Chinese steelmaking context rather than dedicated green, blue, or grey hydrogen. Their DRI was also considered at 25 °C with a metallization rate of 88.54%, and the Chinese electricity system used in the assessment had a reported emission factor of 0.731 kg CO₂-eq/kWh. These differences in reducing gas, electricity carbon intensity, DRI properties, charging conditions, and geographical background contribute to the divergence between the reported carbon footprints. A comparison of the present results with previously published studies is provided in Supplementary Table S14.

Overall, comparison with the published literature demonstrates that there is no single representative GW value for H₂-DRI-EAF steelmaking. Reported impacts depend strongly on electricity carbon intensity, hydrogen-production pathway, DRI properties and charging conditions, metallic charge composition, geographical background system, and system-boundary assumptions. Consequently, the results of the present study should be interpreted as Thailand-specific estimates under the defined inventory and energy assumptions rather than as universally representative values for H₂-DRI-EAF steelmaking.

3.1.2. Limitations of the study

Several limitations should be considered when interpreting the results of this study. First, primary plant-level data for hydrogen-based DRI-EAF steelmaking in Thailand were not available because commercial-scale H₂-DRI-EAF production has not yet been established in the country. Consequently, the foreground life-cycle inventory was primarily constructed using peer-reviewed literature and established databases and adapted to the Thai context using geographically representative background datasets where available. Although the inventory was cross-checked against published sources, differences between literature-derived process conditions and future commercial operation in Thailand may remain. In addition, the DRI-EAF and scrap-EAF foreground inventories originate from different literature sources and therefore retain source-specific differences in operating conditions and direct-emission accounting conventions, which should be considered when interpreting the magnitude of the difference between these pathways.

Second, the present assessment represents the electricity system using the defined Thai electricity conditions and therefore constitutes a static rather than prospective assessment. Future decarbonization of Thailand's electricity system could change the environmental performance of electricity-intensive processes within the DRI-EAF pathway. The results should therefore be interpreted as representing the electricity conditions and datasets assumed in the present model rather than future electricity-system conditions.

Third, the study focuses on environmental life-cycle performance and does not include a detailed techno-economic assessment. Capital expenditure, hydrogen and electricity prices, infrastructure investment, operating costs, hydrogen

storage requirements, and future technology-learning effects were outside the defined scope. Consequently, a pathway showing lower environmental impacts should not automatically be interpreted as the most economically feasible pathway for implementation in Thailand.

Finally, several process parameters, including hydrogen-production characteristics, DRI properties, CCS assumptions for blue hydrogen, and steelmaking energy requirements, were derived from secondary literature. Differences in these assumptions contribute to variations between the present results and those reported in other studies. Future research incorporating primary operational data from Thai hydrogen and DRI-EAF facilities, prospective electricity scenarios, and integrated techno-economic assessment would improve the representativeness of the analysis.

3.2. Endpoint impact categories

The impact of global warming varied significantly among the steelmaking routes. However, climate change alone does not fully represent the overall system's full environmental performance. To address this limitation, an endpoint contribution assessment was performed to evaluate aggregated environmental damage across human health, ecosystem quality, and resource scarcity. This provides a more integrated interpretation of environmental performance and a comprehensive understanding of policy-relevant evaluation, as well as the trade-offs among different scrap- and hydrogen-based steelmaking routes. Each endpoint indicator combines multiple midpoint impact categories. To interpret the endpoint results, a contribution (pathway) analysis was conducted that quantifies how much each midpoint category contributes to the endpoint and is expressed as percentages of the net endpoint total for (i) Human health (DALY), (ii) Ecosystem damage (species.yr), and (iii) Resource depletion (USD2013) in each scenario. From an inventory perspective, the endpoint results are driven by a limited number of upstream inputs. In the scrap-

based EAF route, Thai grid electricity is the main contributor to climate- and energy-related burdens, while scrap processing is more important for toxicity-related impacts. In the blue hydrogen route, the burden shifts towards climate change and particulate matter and toxicity: crude steel production dominates particulate and acidification pathways, whereas reduced iron production is the main contributor to most toxicity-related and resource depletion impacts. In the green hydrogen route, climate burdens are shared more evenly among reduced iron production, crude steel production, and grid electricity, but reduced iron remains the principal hotspot for toxicity and mineral resource scarcity. Under grey hydrogen, reduced iron production becomes the dominant overall hotspot, particularly for global warming and fossil resource depletion, while crude steel production remains the major source of particulate matter and acidification-related damage. Overall, the endpoint patterns are therefore shaped not only by the impact pathway itself, but also by the upstream energy and material inputs embedded in the DRI system.

3.2.1. Human health endpoint

For the scrap-based EAF route (baseline), human health impacts are primarily driven by global warming and fine particulate matter formation, with additional contributions from human carcinogenic and non-carcinogenic toxicity. Together, global warming and particulate matter formation account for the majority of the total human health burden. These impacts are mainly associated with electricity consumption and direct EAF process emissions, including CO₂, CO, and particulate emissions generated during high-temperature steelmaking operations. Upstream production of auxiliary materials such as lime, electrodes, and refractories further contributes to toxicity-related impacts, while the remaining impact categories contribute only marginally to the overall endpoint result.

Under blue hydrogen conditions, human health impacts increase across all DRI-EAF scenarios relative to the baseline,

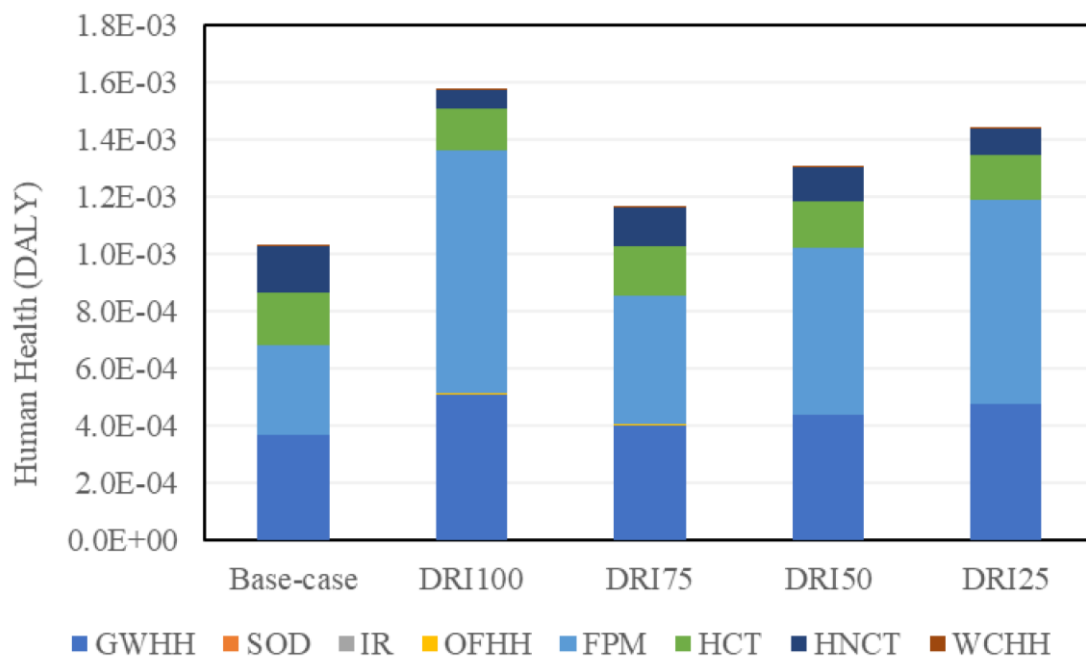


Fig 4. Overall contribution of midpoint impact categories to total human health damage (DALY) for blue hydrogen pathways, including global warming (GWHH), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation (OFHH), fine particulate matter formation (FPM), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), and water consumption (WCHH)

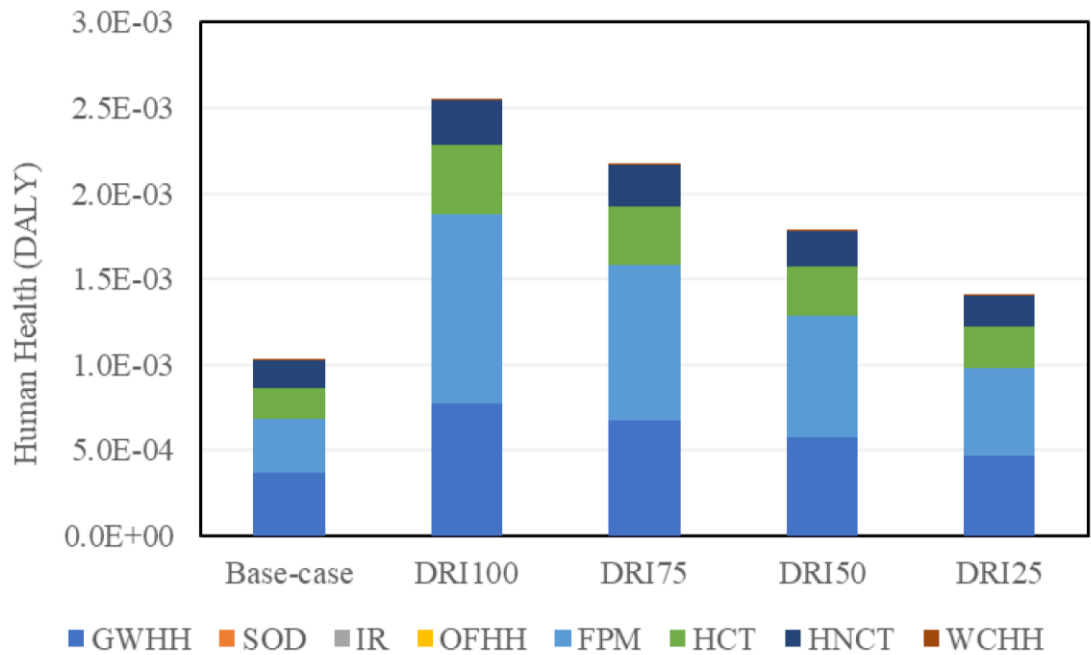


Fig 5. Overall contribution of midpoint impact categories to total human health damage (DALY) for green hydrogen pathways, including global warming (GWHH), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation (OFHH), fine particulate matter formation (FPM), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), and water consumption (WCHH)

with the highest burden observed for DRI100, followed by DRI75, DRI50, DRI25 and the baseline (Figure 4). When compared across midpoint impact categories, contribution analysis identifies global warming, fine particulate matter formation, human carcinogenic toxicity, and human non-carcinogenic toxicity as the dominant contributors to total human health damage. The increase in global warming impacts is primarily associated with reduced iron production, blue hydrogen production, electricity use, and upstream natural gas extraction and processing. Although carbon capture is integrated into blue hydrogen production, residual greenhouse gas emissions remain due to natural gas supply, reforming processes, and energy requirements throughout the hydrogen production chain. Fine particulate matter formation also contributes substantially to the overall burden and is mainly linked to fuel combustion, electricity generation, thermal processing, and upstream industrial activities. Human carcinogenic and non-carcinogenic toxicity are associated with material extraction, metal processing, electricity supply, and industrial emissions, whereas stratospheric ozone depletion, ionizing radiation, and water consumption contribute only minor shares. These findings indicate that blue hydrogen can reduce some climate-related impacts compared with conventional fossil-based hydrogen production; however, significant human health burdens remain because of continued dependence on natural gas and energy-intensive processing.

Under green hydrogen conditions, human health impacts also increase compared with the baseline, with DRI100 exhibiting the highest total burden, followed by DRI75, DRI50, DRI25, and the Baseline (Figure 5). Electricity consumption, reduced iron production, hydrogen production, and oxidized iron input are identified as the principal hotspots. Fine particulate matter formation emerges as the largest contributor to total human health damage, followed by global warming and toxicity-related impacts. Although green hydrogen eliminates direct fossil fuel-based hydrogen production, hydrogen generation through electrolysis requires substantial electricity as well as renewable energy and electrolyzer infrastructure,

which contribute to particulate precursor emissions and trace metal releases across their supply chains. Global warming impacts remain significant because electricity-consuming processes such as reduced iron production, steelmaking operations, and supporting industrial processes outside green hydrogen production continue to rely on the Thai grid mix. Human carcinogenic and non-carcinogenic toxicity are primarily associated with upstream electricity generation, material extraction, renewable energy infrastructure, electrolyzer manufacturing, and industrial emissions. The contribution analysis further indicates that the iron reduction stage is a major source of human health impacts, with particulate matter and toxicity burdens largely driven by the hydrogen supply chain rather than direct process emissions from iron ore reduction. While green hydrogen reduces dependence on fossil-based hydrogen, the environmental burden is shifted toward electricity-intensive processes and infrastructure requirements.

Under grey hydrogen conditions, human health impacts generally increase with increasing DRI utilization compared with the Baseline (Figure 6). The highest total impact is observed for DRI100, followed by DRI75, DRI50, DRI25, and the Baseline. Reduced iron production, crude steel production, electricity consumption, and grey hydrogen production are identified as the principal hotspots. Similar to the blue hydrogen pathway, global warming and fine particulate matter formation dominate the overall human health burden. The increase in global warming impacts is largely attributable to the energy-intensive nature of reduced iron production, pellet processing, electricity consumption, and hydrogen supply. Fine particulate matter formation also increases due to emissions from fuel combustion, thermal processing, electricity generation, and upstream material production. Grey hydrogen production remains a significant contributor because natural gas extraction, processing, and steam methane reforming generate substantial greenhouse gas and air pollutant emissions throughout the

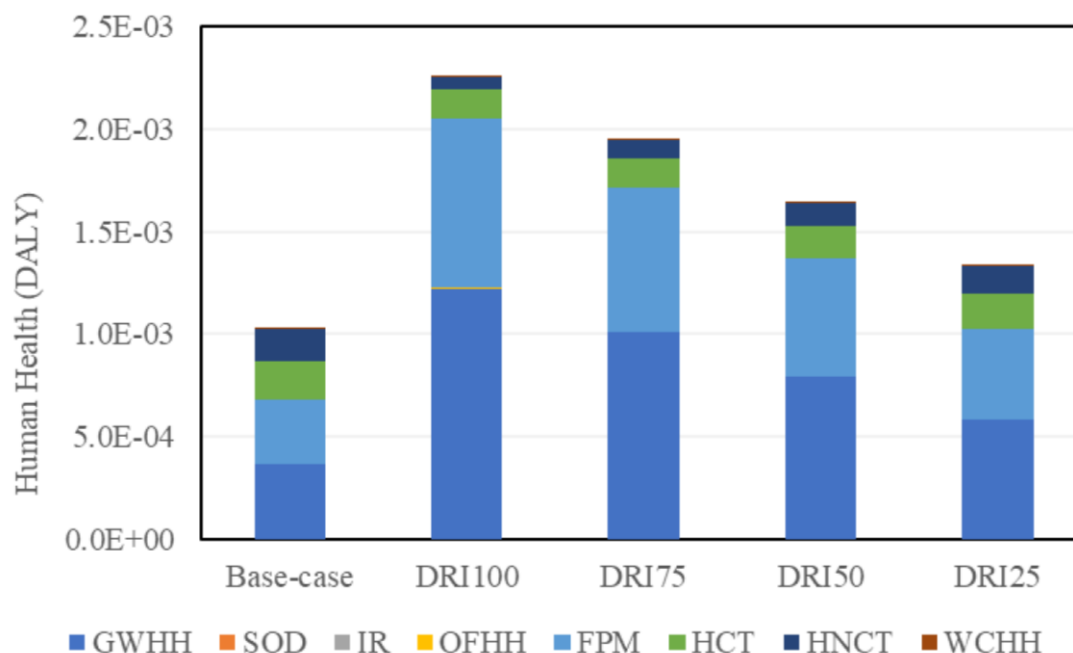


Fig 6. Overall contribution of midpoint impact categories to total human health damage (DALY) for grey hydrogen pathways, including global warming (GWHH), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation (OFHH), fine particulate matter formation (FPM), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), and water consumption (WCHH)

hydrogen supply chain. Consequently, although the DRI-EAF route reduces reliance on conventional coal-based ironmaking, the human health benefits are limited by the fossil fuel-based hydrogen supply system.

A comparison of the three hydrogen pathways reveals that human health impacts are strongly influenced by the source of hydrogen and associated upstream energy requirements. Grey hydrogen exhibits the greatest contribution from climate-related impacts because of fossil fuel-based hydrogen production, while blue hydrogen partially mitigates these impacts through carbon capture but remains dependent on natural gas. In contrast, green hydrogen substantially reduces reliance on fossil-based hydrogen production; however, environmental burdens shift toward electricity consumption, renewable energy infrastructure, and electrolyzer manufacturing. Across all pathways, global warming and fine particulate matter formation remain the dominant contributors to human health damage, highlighting the importance of low-carbon electricity supply, efficient hydrogen production, and improved energy performance throughout the DRI-EAF steelmaking system. The contribution results for blue, green, and grey are provided in Supplementary Data Table S9.

3.2.2 Ecosystem damage endpoint

For the scrap-based EAF route (baseline), ecosystem damage is dominated by global warming, followed by terrestrial acidification, freshwater eutrophication, land use, and terrestrial ozone formation. Climate-related impacts arise primarily from electricity consumption and upstream CO₂ emissions, together with direct emissions from EAF operations. Secondary contributions stem from acidifying emissions from electricity generation and auxiliary material production, while eutrophication impacts arise from nutrient releases in upstream supply chains. Overall, ecosystem damage in the base case is largely driven by climate change, with comparatively smaller contributions from acidification and eutrophication. Under blue

hydrogen conditions, ecosystem damage increases relative to the base case, reaching its highest value in DRI100 before declining progressively from DRI75 to DRI25 (Figure 7). When compared across midpoint impact categories, global warming remains the dominant contributor across all scenarios, reflecting residual greenhouse gas emissions associated with natural gas extraction, processing, and reforming despite the application of carbon capture. Terrestrial acidification and ozone formation represent the second and third largest contributors, respectively, and are mainly linked to emissions from hydrogen production, electricity consumption, fuel combustion, and industrial processing activities. Freshwater eutrophication, land use, ecotoxicity, and water consumption contribute smaller shares of total ecosystem damage. Stage-level analysis indicates that blue hydrogen production and reduced iron production are the principal hotspots, while Thai grid electricity provides an additional contribution through fossil-based electricity generation. These results suggest that carbon capture reduces climate-related ecosystem damage compared with grey hydrogen; however, significant burdens remain due to continued dependence on natural gas and energy-intensive processing.

Under green hydrogen conditions, ecosystem damage exhibits a more distributed contribution pattern than either blue or grey hydrogen. Total ecosystem damage increases from the Baseline to DRI100 and subsequently declines through DRI75, DRI50, and DRI25 (Figure 8). Although global warming remains the largest contributor, its relative dominance is reduced because acidification, ozone formation, eutrophication, land use, and ecotoxicity contribute more substantially to the overall endpoint profile. This pattern reflects the shift from fossil-based hydrogen production toward renewable electricity and electrolysis systems. Green hydrogen production, renewable energy infrastructure, and electrolyzer manufacturing contribute to ecosystem damage through material

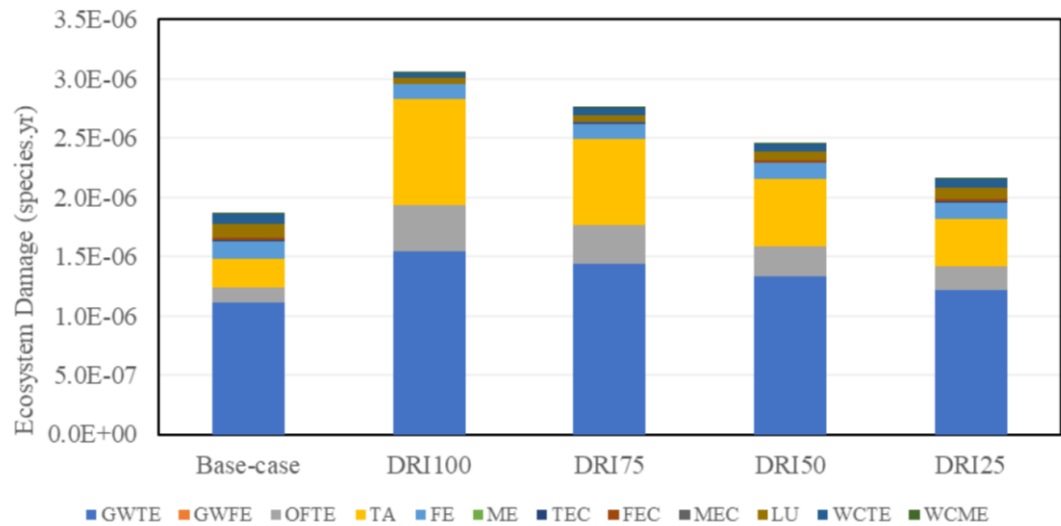


Fig 7. Overall contribution of midpoint impact categories to total ecosystem damage (species.yr) for blue hydrogen pathways, including global warming-terrestrial ecosystems (GWTE), global warming-freshwater ecosystems (GWFE), ozone formation-terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TEC), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), land use (LU), water consumption-terrestrial ecosystems (WCTE), and water consumption-aquatic ecosystems (WCME)

requirements, land occupation, and upstream emissions, while reduced iron production remains an important hotspot. Consequently, ecosystem burdens are distributed across multiple environmental pathways rather than being concentrated in climate change alone. The results indicate that green hydrogen provides the most balanced ecosystem profile among the hydrogen pathways and substantially reduces climate-related ecosystem damage compared with fossil-based hydrogen production.

Under grey hydrogen conditions, ecosystem damage is strongly dominated by global warming and increases substantially with increasing DRI utilization. The highest endpoint damage is observed for DRI100, followed by DRI75, DRI50, and DRI25, although the overall contribution pattern

remains largely unchanged, as shown in Figure 9. The dominance of global warming reflects the high greenhouse gas emissions associated with natural gas extraction, processing, and steam methane reforming used for hydrogen production. Terrestrial acidification and ozone formation are the next most important contributors, arising primarily from emissions generated throughout the fossil fuel supply chain and electricity production. In contrast, freshwater eutrophication, marine eutrophication, land use, and water consumption contribute relatively minor shares of total ecosystem damage. Contribution analysis identifies grey hydrogen production as the primary hotspot, followed by reduced iron production and electricity consumption. As a result, ecosystem damage under grey hydrogen is concentrated in climate-related pathways,

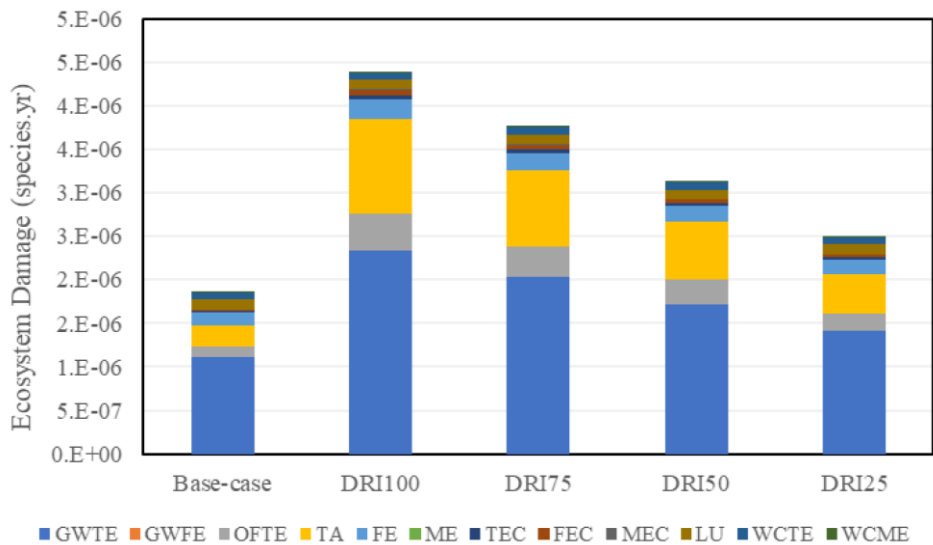


Fig 8. Overall contribution of midpoint impact categories to total ecosystem damage (species.yr) for green hydrogen pathways, including global warming-terrestrial ecosystems (GWTE), global warming-freshwater ecosystems (GWFE), ozone formation-terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TEC), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), land use (LU), water consumption-terrestrial ecosystems (WCTE), and water consumption-aquatic ecosystems (WCME)

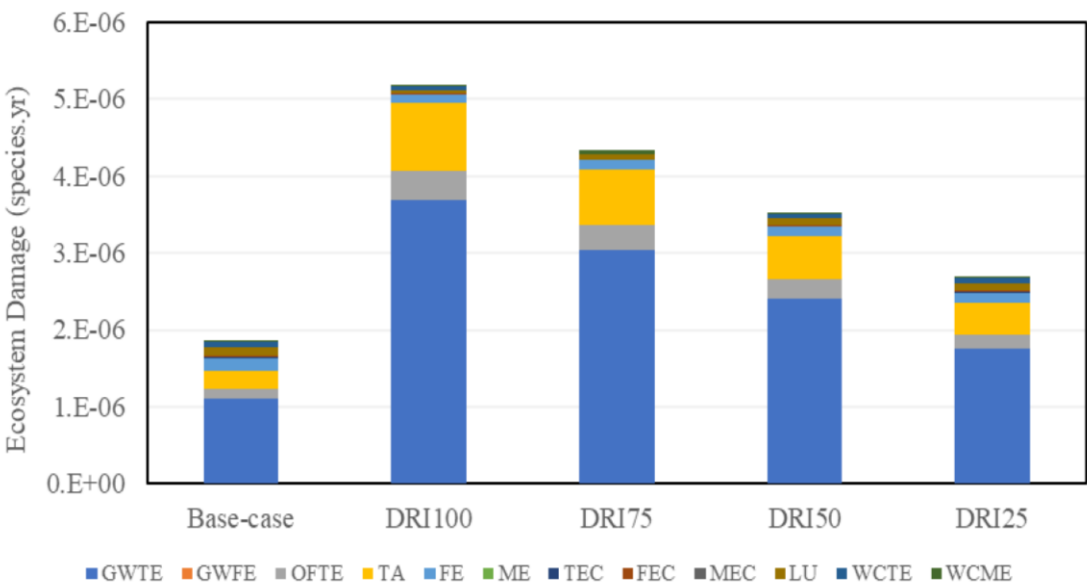


Fig 9. Overall contribution of midpoint impact categories to total ecosystem damage (species.yr) for grey hydrogen pathways, including global warming-terrestrial ecosystems (GWTE), global warming-freshwater ecosystems (GWFE), ozone formation-terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TEC), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), land use (LU), water consumption-terrestrial ecosystems (WCTE), and water consumption-aquatic ecosystems (WCME)

highlighting the environmental limitations of fossil-based hydrogen production.

Comparison of the three hydrogen pathways demonstrates that ecosystem damage is highly dependent on the hydrogen production route. Grey hydrogen exhibits the strongest climate-related ecosystem burden because of fossil fuel-based hydrogen production, whereas blue hydrogen partially mitigates this burden through carbon capture but remains dependent on natural gas. Green hydrogen provides the most favorable ecosystem profile by substantially reducing climate-related impacts and distributing environmental burdens across multiple categories rather than concentrating them in global warming. Across all pathways, global warming remains

the dominant contributor to ecosystem damage, emphasizing the importance of low-carbon electricity, efficient hydrogen production, and reduced upstream emissions in achieving environmentally sustainable DRI-EAF steel production. The ecosystem damage contribution results for blue, green, and grey hydrogen are provided in Supplementary Data Table S10.

3.2.3. Resource depletion endpoint

The resource depletion endpoint is structurally simpler than the human health and ecosystem endpoints because it is determined by only two midpoint categories: fossil resource scarcity and mineral resource scarcity. In the scrap-based EAF

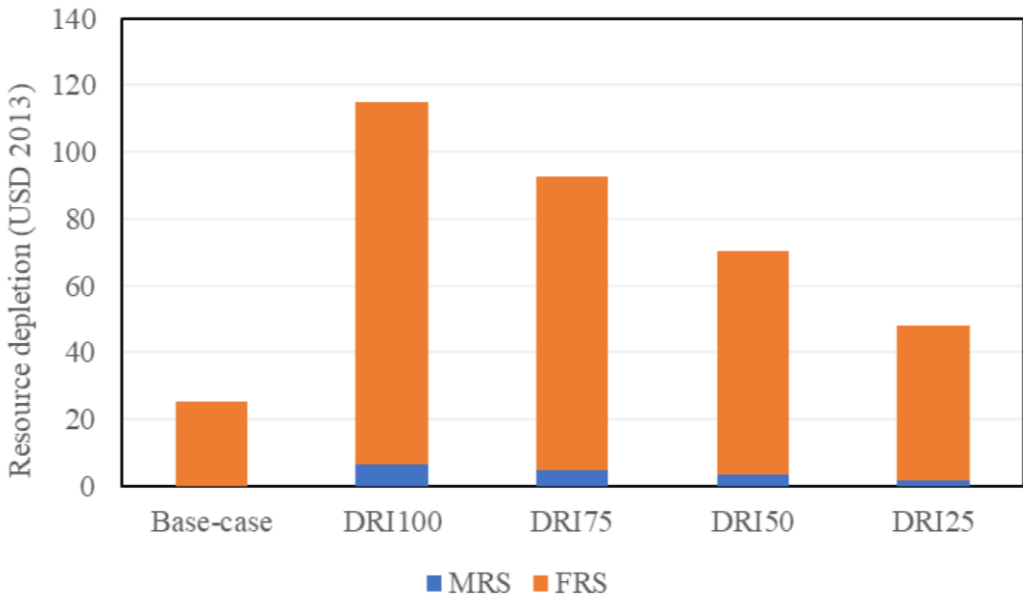


Fig 10. Overall contribution of midpoint impact categories to endpoint resource depletion (USD2013) for blue hydrogen production pathways, including Mineral resource scarcity (MRS), and Fossil resource scarcity (FRS)

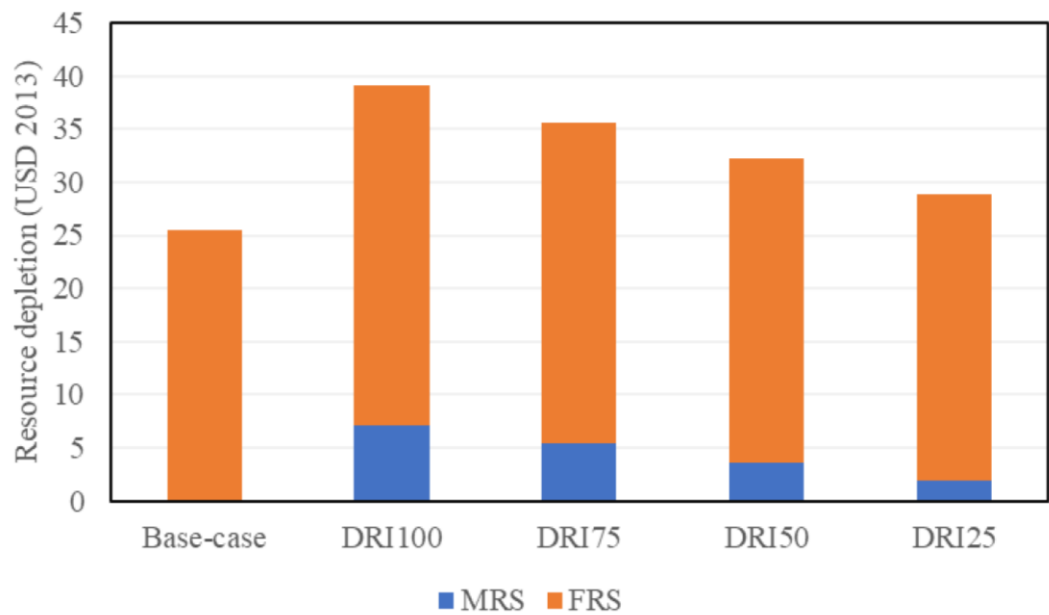


Fig 11. Overall contribution of midpoint impact categories to endpoint resource depletion (USD2013) for green hydrogen production pathways, including Mineral resource scarcity (MRS), and Fossil resource scarcity (FRS)

route (base case), resource depletion is overwhelmingly dominated by fossil resource scarcity, indicating that the primary burden arises from fossil fuel consumption associated with electricity generation, EAF operations, and upstream material supply chains. In contrast, mineral resource scarcity contributes only a minor share of the total endpoint result, suggesting that mineral extraction is not a major driver of resource depletion in the conventional scrap-based steelmaking route.

Under blue hydrogen conditions, resource depletion increases substantially relative to the Baseline, with the highest impact observed for DRI100, followed by DRI75, DRI50, and DRI25. The endpoint remains strongly dominated by fossil resource scarcity because blue hydrogen production relies on natural gas as both a feedstock and energy source. Although carbon capture is integrated into the hydrogen production process, it does not eliminate the need for natural gas extraction, processing, reforming, compression, and transportation. Contribution analysis identifies blue hydrogen production as the primary hotspot, while electricity consumption and oxidized iron pellet production provide smaller secondary contributions. Consequently, carbon capture reduces greenhouse gas emissions but does not substantially reduce fossil resource dependence. Mineral resource scarcity increases slightly across the DRI scenarios due to additional material requirements associated with hydrogen production systems, carbon capture infrastructure, and supporting process equipment; however, its contribution remains small compared with the dominant fossil resource burden.

Under green hydrogen conditions, the resource depletion profile changes considerably. Although fossil resource scarcity remains the largest contributor, its relative importance decreases compared with the blue and grey hydrogen pathways. Green hydrogen production through electrolysis significantly reduces direct dependence on natural gas, resulting in lower fossil resource depletion. However, the transition toward renewable electricity and electrolysis systems increases the contribution of mineral resource scarcity because electrolyzers, renewable energy technologies, and associated infrastructure require substantial quantities of metals and minerals. As a result, resource depletion shifts from fossil fuel

consumption toward greater dependence on material-intensive technologies. Stage-level analysis identifies hydrogen production, electricity supply, and associated infrastructure as the principal contributors to mineral resource scarcity, whereas oxidized iron pellet production contributes comparatively little. These findings indicate that green hydrogen offers the lowest fossil resource burden among the assessed pathways, although this benefit is accompanied by increased reliance on mineral resources.

Under grey hydrogen conditions, resource depletion is almost entirely dominated by fossil resource scarcity and increases substantially with increasing DRI utilization. Grey hydrogen production via steam methane reforming requires large quantities of natural gas as both feedstock and energy source, making hydrogen production the dominant hotspot across all scenarios. Natural gas extraction, processing, transportation, and reforming collectively account for most of the fossil resource burden, while electricity consumption and oxidized iron pellet production contribute comparatively smaller shares. Similar to the base case, mineral resource scarcity remains negligible, indicating that resource depletion in the grey hydrogen pathway is primarily driven by continued dependence on fossil fuel supply chains rather than mineral extraction. Consequently, grey hydrogen exhibits the highest fossil resource burden among the hydrogen pathways evaluated.

Comparison of the three hydrogen pathways demonstrates that the choice of hydrogen source strongly influences the nature of resource depletion within the DRI-EAF steelmaking system. Grey hydrogen performs worst from a resource perspective because of its heavy reliance on natural gas. Blue hydrogen partially reduces climate-related impacts through carbon capture but remains highly dependent on fossil resources. In contrast, green hydrogen substantially reduces fossil resource depletion by eliminating direct fossil-based hydrogen production; however, it increases the relative importance of mineral resource scarcity because of the material requirements associated with electrolysis and renewable energy infrastructure. These findings highlight that hydrogen pathway selection affects not only greenhouse gas emissions but also the

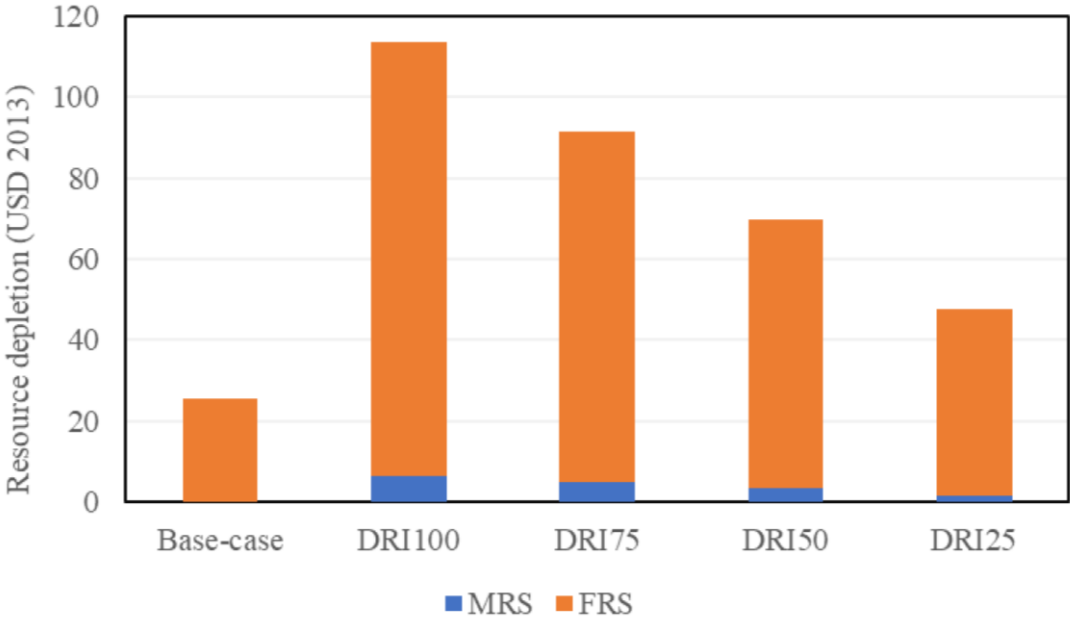


Fig 12. Overall contribution of midpoint impact categories to endpoint resource depletion (USD2013) for grey hydrogen production pathways, including Mineral resource scarcity (MRS), and Fossil resource scarcity (FRS)

type of resource dependence embedded within future low-carbon steel production systems. The resource depletion results are presented in Figures 10–12, while the corresponding numerical values are provided in Supplementary Data Table S11.

4. Policy recommendations

The findings of this study suggest that Thailand should adopt a dual-pathway strategy for steel sector decarbonization that simultaneously maximizes the environmental benefits of scrap-based steel recycling while strategically developing hydrogen-based DRI-EAF capacity to support future industrial transformation. Although the scrap-based EAF route exhibited the lowest overall environmental burden under current Thai conditions, it should not be regarded as a standalone long-term solution. The environmental advantage of scrap-based production is largely attributable to the absence of an iron ore reduction stage, which is inherently required in primary steelmaking routes. Consequently, direct comparisons between scrap-based EAF and hydrogen-based DRI-EAF may underestimate the true decarbonization potential of hydrogen because they represent fundamentally different production systems. A more appropriate benchmark is the comparison between hydrogen-based and natural gas-based DRI-EAF routes, both of which produce primary steel from iron ore. To evaluate the decarbonization potential of hydrogen under equivalent production conditions, the natural gas-based direct-reduction inventory was derived from Krekel et al. (2026) and incorporated into the present modelling framework to construct the NG-DRI-EAF benchmark, as described in Section 2.2 and Supplementary Data Table S12. and served as a representative conventional fossil-based reference pathway for comparison. Using natural gas-based DRI-EAF as the reference pathway, the results reveal substantial greenhouse gas reduction potential through hydrogen adoption. Blue hydrogen-based DRI-EAF reduced global warming impacts from 1336.41 to 551.51 kg CO₂-eq, representing a 58.7% reduction, while green hydrogen-based DRI-EAF achieved a reduction of 37.6%, decreasing

emissions to 834.03 kg CO₂-eq. Both pathways demonstrate meaningful decarbonization potential, with blue hydrogen exceeding Thailand's unconditional and conditional Nationally Determined Contribution (NDC) targets of 30% and 40%, respectively, while green hydrogen surpasses the unconditional target and approaches the conditional target. In contrast, grey hydrogen achieved only a marginal reduction of 1.5% and therefore offers limited climate benefits. These findings suggest that replacing fossil-based iron ore reduction with low-carbon hydrogen can make a substantial contribution to Thailand's climate commitments and long-term net-zero objectives.

At the same time, Thailand's steel industry faces structural challenges that cannot be addressed through scrap-based production alone. Domestic scrap availability remains constrained in both quantity and quality, while dependence on imported scrap exposes the industry to international market volatility and supply risks. Furthermore, the growing demand for high-quality steel required for electric vehicles, battery manufacturing, advanced infrastructure, and high-value industrial applications necessitates tighter control of impurities and material composition than can often be achieved through scrap recycling alone. Thailand's ambition to become a regional electric vehicle manufacturing hub under the 30@30 policy and associated EV incentive programs is expected to further increase demand for premium-grade steel products (Thailand Board of Investment, 2024). These developments reinforce the need for a complementary primary steel production route based on iron ore reduction. In parallel, Thailand has begun laying the foundations for a hydrogen economy through the development of national hydrogen roadmaps, pilot projects, and emerging regulatory frameworks governing hydrogen production, transport, storage, and utilization (NXPO 2024). The planned development of green steel projects, including the Meranti Green Steel initiative, further highlights the strategic importance of establishing domestic expertise in hydrogen-based steelmaking. Therefore, DRI-EAF should be viewed not as a replacement for scrap-based EAF but as a complementary upgrading pathway capable of enhancing industrial competitiveness, improving supply security, and supporting

future demand for high-quality steel (Meranti Green Steel (Thailand) Co., 2025).

The choice of the hydrogen pathway is equally important. Based on the environmental assessment, grey hydrogen should not be promoted due to its negligible emission reduction potential and unfavorable environmental performance. Under the inventories and CCS assumptions adopted in this study, blue hydrogen showed the lowest modelled GW among the hydrogen pathways and could therefore serve as a potential transitional option while hydrogen infrastructure and renewable energy capacity continue to develop. However, its reliance on fossil resources and associated environmental trade-offs limits its suitability as a permanent solution. Green hydrogen, although currently constrained by Thailand's carbon-intensive electricity mix, offers the most sustainable long-term pathway, as its environmental performance is expected to improve substantially with increased deployment of renewable electricity. Consequently, green hydrogen should remain the ultimate target for future steel decarbonization strategies. Accordingly, Thailand's steel decarbonization policy should adopt a phased three-stage approach. In the short term, policy efforts should focus on maximizing the environmental and economic benefits of scrap-based EAF production by improving scrap collection systems, enhancing sorting technologies, tightening impurity controls, increasing recycling efficiency, and accelerating power sector decarbonization. In the medium term, policymakers should support hybrid DRI–scrap EAF configurations and blue hydrogen deployment to facilitate industrial learning, improve steel quality, reduce dependence on imported high-grade scrap, and achieve substantial greenhouse gas reductions that exceed Thailand's NDC targets. In the long term, policy support should prioritize the development of renewable electricity infrastructure, green hydrogen production capacity, and hydrogen-based DRI-EAF facilities to establish a competitive low-carbon primary steel industry aligned with Thailand's net-zero ambitions. Such a dual-transition strategy, combining optimized scrap recycling with the gradual deployment of hydrogen-based iron ore reduction, provides a more resilient and realistic pathway than reliance on any single production route. This approach simultaneously delivers near-term environmental benefits, strengthens industrial competitiveness, enhances raw material security, and positions Thailand to meet future demand for high-quality low-carbon steel.

5. Future Research Recommendations

Although this study provides a comprehensive LCA of hydrogen-based DRI-EAF steelmaking pathways under Thai conditions, several areas require further investigation to support the long-term decarbonization of the steel sector. First, future studies should evaluate biomass-derived hydrogen with carbon capture and storage (CCS) as a complementary pathway to conventional blue and green hydrogen production. Second, future scenario analyses should evaluate renewable electricity integration in both hydrogen production and steelmaking processes to quantify potential reductions in global warming, human health, ecosystem damage, and resource depletion impacts. Third, future studies should expand the assessment beyond environmental impacts to include techno-economic and policy dimensions to provide a more comprehensive understanding of the feasibility of hydrogen-based steelmaking pathways. Overall, these research directions would provide a stronger evidence base for the development of low-carbon steel production systems in Thailand and support informed decision-

making regarding future hydrogen, energy, and industrial transition strategies.

6. Sensitivity to hydrogen demand

A sensitivity analysis was conducted to evaluate the influence of the assumed hydrogen requirement in the DRI process on the midpoint global warming results. The base-case hydrogen demand of 66.3 kg H₂/t DRI was compared with lower hydrogen-consumption levels of 58, 54, and 51 kg H₂/t DRI, while all other inventory parameters were kept unchanged. The results show that hydrogen demand has a substantial influence on the global warming impact of the hydrogen-based steelmaking pathways, although its magnitude differs considerably among the hydrogen production routes. For the green-hydrogen DRI100 pathway, reducing hydrogen demand from 66.3 to 58, 54, and 51 kg H₂/t DRI decreased the global warming impact from the base value of 834.03 kg CO₂-eq/t crude steel to 810.68, 799.43, and 790.99 kg CO₂-eq/t crude steel, respectively. A stronger response was observed for the grey-hydrogen pathway because of its higher upstream GW per unit of hydrogen. The corresponding impact decreased from 1,316.87 kg CO₂-eq/t crude steel at the base hydrogen demand to 1,233.07, 1,192.69, and 1,162.40 kg CO₂-eq/t crude steel at 58, 54, and 51 kg H₂/t DRI, respectively. In contrast, the blue-hydrogen pathway showed an inverse response. Its global warming impact increased from 551.51 kg CO₂-eq/t crude steel at 66.3 kg H₂/t DRI to 563.51, 569.29, and 573.63 kg CO₂-eq/t crude steel at hydrogen demands of 58, 54, and 51 kg H₂/t DRI, respectively. This inverse trend results from the negative GW contribution of the adopted blue-hydrogen inventory (−1.39 kg CO₂-eq/kg H₂); consequently, reducing hydrogen consumption decreases the magnitude of the negative contribution associated with the blue-hydrogen inventory and increases the resulting total steelmaking GW. This behavior is therefore specific to the life-cycle inventory and CCS accounting assumptions adopted for blue hydrogen in the present study. Importantly, the sensitivity analysis did not reverse the relative ranking of the blue- and green-hydrogen pathways. At the lowest hydrogen-demand case of 51 kg H₂/t DRI, the global warming impacts of the blue- and green-hydrogen pathways were 573.63 and 790.99 kg CO₂-eq/t crude steel, respectively, compared with 551.51 and 834.03 kg CO₂-eq/t crude steel under the base hydrogen-demand assumption. Thus, although lower hydrogen demand narrowed the difference between the two pathways, the blue-hydrogen pathway retained a lower impact than the green-hydrogen pathway across the hydrogen-demand range evaluated. These results indicate that hydrogen consumption is an influential parameter, particularly for grey and green hydrogen, while the blue-over-green ranking remains robust to the hydrogen-demand sensitivity range considered here under the adopted life-cycle inventories.

6. Conclusions

This study evaluated the environmental competitiveness and decarbonization potential of hydrogen-based direct reduced iron integrated with electric arc furnace steelmaking (H₂-DRI-EAF) under Thailand-specific conditions using a cradle-to-gate life cycle assessment. The results demonstrate that environmental performance is strongly influenced by both the hydrogen production pathway and the proportion of DRI used in the steelmaking system. Among the evaluated pathways, the scrap-based EAF route exhibited the lowest overall environmental impacts across most midpoint and endpoint categories. However, comparisons with hydrogen-based DRI-

EAF should be interpreted cautiously because the two routes represent fundamentally different production systems. Scrap-based EAF avoids the energy- and emission-intensive iron ore reduction stage, which is a major source of environmental impacts in primary steel production. In contrast, DRI-EAF enables the production of primary steel and may help address future challenges associated with limited scrap availability and quality. The results showed that global warming impacts increased with increasing DRI utilization across all hydrogen pathways, reflecting the growing contribution of hydrogen production and iron ore reduction processes. Compared with the modelled NG-DRI-EAF benchmark of 1336.41 kg CO₂-eq/t crude steel, blue hydrogen achieved the greatest decarbonization benefit, reducing global warming impacts by 58.7%, while green hydrogen reduced emissions by 37.6%. In contrast, grey hydrogen provided only marginal climate benefits, indicating that hydrogen substitution alone does not guarantee substantial environmental improvement unless low-carbon hydrogen production pathways are adopted. Overall, the study demonstrates that hydrogen-based DRI-EAF can play an important role in reducing emissions from primary steel production in Thailand, particularly where future demand for high-quality steel cannot be fully met through scrap recycling alone. While scrap-based EAF remains the most environmentally favorable option under current conditions, hydrogen-based DRI-EAF provides a viable pathway for decarbonizing iron ore-based steelmaking. The results further suggest that continued decarbonization of Thailand's electricity sector and expansion of low-carbon hydrogen production will be critical for maximizing the environmental benefits of hydrogen-based steelmaking. Future research should integrate prospective renewable electricity scenarios, technological improvements in hydrogen production, and techno-economic assessments to evaluate the long-term feasibility and competitiveness of alternative steel decarbonization pathways.

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Author Contributions

M.S: Writing- original draft, methodology, formal analysis, visualization, conceptualization, and data curation. A.F: Writing-review & editing, visualization, and data curation. S.G: Writing-review & editing, supervision, project administration, and data curation. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Availability of Data and Materials

The data supporting the findings of this study are provided within the article and its supplementary materials. Additional data and information can be obtained from the corresponding author upon reasonable request.

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