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Towards fossil-free steel: Life cycle assessment of biosyngas-based direct reduced iron (DRI) production process

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ABSTRACT

Given the urgent need for transitions towards global net zero emissions, decarbonisation of the iron and steel industry is critical. Deep decarbonising this sector requires a breakaway from current blast furnace-basic oxygen furnace (BF-BOF) technologies that largely depend on fossil resources. Biosyngas is considered to be a promising alternative to fossil energy and reductants used in existing ironmaking due to its renewability, technological maturity and compatibility for use in existing furnaces. The present work assesses the environmental impacts of biosyngas-based direct reduced iron production followed by electric arc furnace (DRI-EAF) routes for crude steel production. Further, the proposed routes are compared with the other steelmaking routes, including BF-BOF, natural gas (NG)-based and hydrogen-based direct reduction routes by performing life cycle assessment (LCA). The results indicate that the global warming potential (GWP) value for the biosyngas-based DRI-EAF system is 75% lower than the existing NG-based DRI-EAF route and 85% lower than the BF-BOF route. Moreover, the proposed system possibly has lower GWP values than the renewable hydrogen-based DRI-EAF route. The proposed system has an estimated cradle-to-gate GWP of 251 kg CO_2 eq./t crude steel, of which 80% is from upstream emissions. Combined with CO_2 storage, the GWP of the proposed system is a net negative, estimated at −845 kg CO_2 eq./t crude steel for the selected system boundary. In addition to GWP, other non-climate impact indicators are also evaluated to identify potential burden shifting. The results highlight the emissions reduction potential of the novel biosyngas DRI production route. Large-scale deployment, however, requires sustainable forest management and adequate CCS infrastructure, along with a strong, long-term policy framework to incentivise the transitions.

1. Introduction

The iron and steel industry is a major sector of greenhouse gas (GHG) emissions, responsible for around 7% of global CO_2 emissions (IEA, 2020). Hence, the decarbonisation of this sector plays an important role in achieving the climate target. Unlike the power sector, decarbonising the steel sector is more challenging due to its heterogeneity, emissions intensity, trade and price sensitivity, and long lifetime of facility, thereby limiting the speed and range of solutions for deep emission reductions (Nurdiawati and Urban, 2021). Stronger climate policies have however fostered the development of disruptive technologies to reach net-zero emissions in the steel sector.

In response to the increasing environmental and societal pressures, the European steel industry set ambitious targets to cut carbon emissions by 55% by 2030 compared to 1990 and to achieve climate neutrality by 2050 (The European Steel Association (EUROFER), n. d.). Since the current dominant Blast Furnace - Basic Oxygen Furnace (BF-BOF) production route is highly CO_2-intensive and most EU steel mills are operating at near optimum efficiency, the industry is increasingly focusing on diverting large capital investments from BF-BOF production to scrap-based steel production/electric arc furnace (EAF) route, and exploring hydrogen-based steelmaking to decarbonise the sector (Somers, 2022). The shift to scrap-based steelmaking will however lead to a lack of high-quality scrap, which can be replaced with fossil-free sponge iron, or commonly called direct reduced iron (DRI).

DRI is one of the essential feedstock of EAF steelmaking and a high-

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quality substitute for scrap. It is primarily produced through gas-based direct reduction using natural gas, such as the MIDREX process (Lu et al., 2019). However, to achieve fossil-free steel production, several projects globally are developing processes using hydrogen (H_2) to replace fossil-based reductants, such as the HYBRIT project in Sweden. In addition to the fact that the technology has not yet been commercially proven, hydrogen production requires large amounts of renewable electricity and adequate infrastructures for distribution and storage. An alternative to the use of natural gas or H_2 in the production of DRI is synthesis gas produced by the gasification of biomass.

Currently, syngas is mainly derived from fossil fuels, with a total global production of around 6000 PJ/yr, corresponding to almost 2% of the total global energy consumption (Boerrigter and Drift, 2004). With the increasing number of policies favoring renewable energy and growing political commitment to achieve climate neutrality, sustainable bioenergy will become increasingly important to meet the climate target (IPCC, 2019). Renewable syngas from gasification of biomass, or "biosyngas" thus could be an important intermediary in the future energy system for the production of renewable electricity, fuels, chemicals as well as gaseous energy carriers (Bolívar Caballero et al., 2022). It plays a role in replacing fossil gases, e.g., natural gas, that are currently used in metallurgical processes. Moreover, the utilisation of biosyngas as reducing agent is beneficial since no modification is needed to existing DRI furnaces. In the DRI-EAF steelmaking route, the biosyngas could fully replace the fossil gas reductant, and combining this with CCS, the so-called BECCS, offers potential for delivering negative emissions of CO_2.

Gasification is a recognised, mature, and flexible technology widely adopted in multiple applications. Despite the fact that biomass gasification, DRI process and CCS are at a relatively high technology readiness level (TRL), no commercial DRI plant uses biosyngas today. Moreover, the feasibility study of integrating these processes to produce fossil-free steel is scarce in the literature. Novel integration of those processes is worth to be evaluated from technical, economic and environmental aspects, among others, as a promising alternative pathway to decarbonise the steel sector.

It is clear that comprehensive and scientific assessments are crucial for decision makers in considering various design alternatives for building new plants. Earlier work by Zaini et al. (2023) has identified and mapped possible sub-processes and unit operations within the biosyngas DRI production process and performed process modelling to evaluate the efficiencies of different process configurations. It is found that the energy consumption of the biosyngas DRI production process is comparable to that of the MIDREX process, showing the potential of the process for fossil-free steel production. However, a comprehensive and comparative environmental impact assessment has not been carried out for such systems from a life cycle perspective.

Life cycle assessment (LCA) is an established method to evaluate environmental impacts and has been widely used in the iron and steel industry. Completing an LCA can support businesses, policymakers, and other organisations to make better informed decisions to advance toward sustainability while considering tradeoffs among a broad range of factors. Previous LCA studies of steel have focused on assessing the environmental performance of conventional steel production via the most commonly used BF-BOF process. For instance, Burchart-Korol (2013) performed an LCA of integrated steel production and EAF routes in Poland, concluding that pig iron production in BFs has the largest impact on GHG emissions. Similarly, Backes et al. (2021) performed a cradle-to-gate environmental evaluation of steel production in an integrated German steel plant of ThyssenKrupp Steel Europe AG, while Renzulli et al. (2016) carried on an environmental analysis of the steel production in the city of Taranto in southern Italy. Despite variation in the carbon footprints of steel presented in those studies (between 1.6 kg CO_2 eq./kg steel up to 2.3 kg CO_2 eq./kg steel), mainly due to site-specific data, methodological choices, and assumptions (Suer et al., 2022), these studies highlighted that the BF and coke oven processes are among the most impacting phases over the entire life cycle of steel. Hence, innovative iron and steelmaking are desirable.

Comparative analysis of the energy and carbon emission intensity of conventional BF-BOF route with innovative iron and steelmaking technologies has emerged in the literature. For example, Larsson et al. (2006) evaluated the CO_2 emissions of the existing BF-BOF route as well as integration of other processes, e.g., an EAF, DRI processes, COREX and a novel smelting reduction process. They pointed out that a DRI-EAF process could be an alternative that would substantially reduce emissions. Process data from various sources were used for the modelling of new process technologies. Sarkar et al. (2018) analysed the energy and emission values of different MIDREX systems (exploring different reducing gases: natural gas, coke oven gas, or syngas from coal gasification). A thermochemical model was developed for the MIDREX reduction shaft furnace to obtain the mass and energy balance. Several studies also look into the environmental performance of an emerging steel production via a H_2-based direct reduction process combined with an EAF. For instance, Vogl et al. (2018) assessed a potential design for a fossil-free steelmaking process based on an H_2-based direct reduction process with regards to their associated energy demands and emissions. The model, however, includes only basic chemical process calculations, and not all emissions from the integrated route are included. Similarly, Rechberger et al. (2020) evaluated energy demands and emissions of H_2-based direct reduction processes and compared them to natural gas-based DRI production processes. However, some emissions related to upstream and downstream processes, such as iron ore mining, pelletizing, electric arc furnace, and transport, are not included. Bhaskar et al. (2020) developed a mass and energy flow model based on an open-source software (Python). The model is used to compare the energy and emission intensity of BF-BOF and H_2-based steelmaking processes. Energy use and emissions related to iron ore mining, transport, and pellet making have also not been considered in this model. Although the abovementioned studies are comprehensive, none of these follow the LCA methodology according to ISO standards (ISO, 2006a, 2006b) for identifying potential environmental impacts of innovative steelmaking processes. Moreover, given emerging technologies are usually at low technology readiness levels (TRL) and consequently characterised by inherent data scarcity and high uncertainty, none of these studies include uncertainty or sensitivity analysis in their assessment.

A complete LCA for steel production via biosyngas DRI plants coupled with EAF is not available in the literature. Few LCA studies have focused on alternative low-carbon steel production utilising biomass. For instance, Fan and Friedmann (2021) assessed available decarbonisation technologies in steelmaking, including solid biomass substitution and combinations of bioenergy and CCS. Tanzer et al. (2020) assessed CO_2 mitigation potential of different steel production routes (BF, HIsarna smelt reduction, MIDREX and ULCORED direct reduction) combined with BECCS. The study concluded that CO_2-negative steel is possible through an aggressive deployment of both bioenergy and CCS. However, none of these studies includes the overall emissions from the biomass supply chain. Further, the previous studies focused only on the carbon footprint assessment of the steelmaking operations, and no other potential environmental impacts were explored.

The presented study fills the abovementioned gap in the literature by providing a holistic LCA assessment according to ISO standards for innovative biosyngas DRI production and subsequent use in steel production with EAF, with and without subsequent CO_2 storage. This study also aims to compare the cradle-to-gate environmental impacts, both climate and non-climate impacts, of the proposed systems with the existing commercial iron and steel production technology as well as processes currently under development. Scenario-based sensitivity analyses are carried out to explore the significance of the foreground and background systems and other assumptions on the environmental performance of the proposed systems.

For better accuracy in the LCA, processes located in Sweden were taken into consideration. Sweden's vast forest resources, combined with technological development and political commitments aiming toward net zero emissions by 2045 (Government Offices of Sweden, 2018), provide an excellent potential for producing fossil-free steel. Overall, the major novel contributions of our work are i) Presentation of an LCA on the environmental impact of novel, innovative biosyngas-based DRI technology and subsequent crude steel production in Sweden; ii) Upscaling of the proposed technology was conducted through process modelling data; iii) Use of scenario-based sensitivity analysis to the key operational parameters while incorporating socio-technical aspects, such as policy domain and market dynamics. The study could serve as a source of information to support policy development and investment decision-making.

2. Process description

The most common technology for producing DRI is the MIDREX process, which typically uses syngas, a mixture of CO and H_2, produced from steam reforming of natural gas or from coal gasification. In the MIDREX process, the iron oxides in the form of pellets or lump are directly converted into DRI by syngas. The proposed system uses biosyngas instead of fossil-based syngas as the reductant. The biosyngas DRI production system was developed in the earlier work (Zaini et al., 2023) to produce hot DRI with 92% metallisation and 2% carbon content. The proposed system comprises a biomass dryer, a gasifier, a tar reforming, a gas heater, a DRI shaft furnace (similar to the MIDREX furnace), and a CO_2 separation process, as depicted in Fig. 1.

The biosyngas-DRI-EAF process consists of the following steps (Zaini et al., 2023).

(i) the drying of biomass to reduce its moisture content
(ii) gasification, where dried biomass is converted to generate raw biosyngas, unreacted char and ash
(iii) tar reforming process to crack undesired tar compounds into permanent gases
(iv) CO_2 removal process to produce a reducing gas that meets the optimum reduction potential (RP) value, $(H_2+CO)/(H_2O + CO_2)$
(v) gas heating to preheat the reducing gases to the required temperatures
(vi) DR shaft furnace, where the pellets are reduced inside the shaft furnace to metallic iron (DRI) using biosyngas. In addition, the carburising gas is fed to the furnace to increase the carbon content of the DRI to 2%
(vii) EAF process, where the hot DRI along with carbon source and fluxes are charged to the EAF to produce crude steel
(vii) CO_2 removal process, so the top gas can be recycled back to the shaft furnace.

The separated CO_2 is released back into the atmosphere in the base scenario. Alternatively, it is compressed, liquefied, and transported to be permanently stored in a suitable geological formation. More details on the process description and characteristics of the reducing gas can be found in the Supplementary Material.

Possible sub-processes and unit operations within the biosyngas DRI production process have been identified and mapped by (Zaini et al., 2023). The upscaling production system was modelled and evaluated using Aspen Plus V12 software package to generate the mass and energy balance. Two process configuration alternatives were considered for this LCA study: steam dual fluidized bed (DFB)-based scenarios and steam-oxygen blown circulating fluidized bed (CFB)-based scenarios. The differences in process configurations have been considered in the additional scenarios, reported as sensitivities, in Section 4.3. The flow diagram of the two process configurations can be seen in the Supplementary Material (Figures A1–A2). It should be noted that the most optimum process configuration is context-dependent, depending on local conditions such as resource availability, electricity price and CO_2 storage site.

In the crude steel production, the biosyngas DRI route is followed by the EAF process (Biosyngas-DRI-EAF). The proposed system performance is compared with commercial technologies, including the blast furnace followed by basic oxygen furnace (BF-BOF) and the natural gas-based direct reduction of iron followed by Electric Arc Furnaces (NG-DRI-EAF), as shown in Fig. 2. Additionally, hydrogen-based direct reduction (H_2-DRI-EAF), an emerging alternative DRI production process, is included in the carbon footprint comparison. In the H_2-based direct reduction pathway, the reducing gas is hydrogen produced from water electrolysis. This technology is currently in a demonstration stage on an industrial scale, such as the HYBRIT project in Sweden (Pei et al., 2020).

3. Materials and methods

In this work, an attributional LCA is performed according to the ISO 14040 and 14044 guidelines (ISO, 2006a, 2006b). Attributional LCA is selected as the study mainly assesses the potential environmental impacts of the integrated processes, rather than the consequences from changes in the studied system. The standardised LCA methodology consists of four main stages: the goal and scope definition, inventory analysis, impact assessment and results interpretation. In this section, the scope of the LCA model, methodological approach, key assumptions, selected impact categories, scenarios investigated and how data inventory is accomplished are presented.

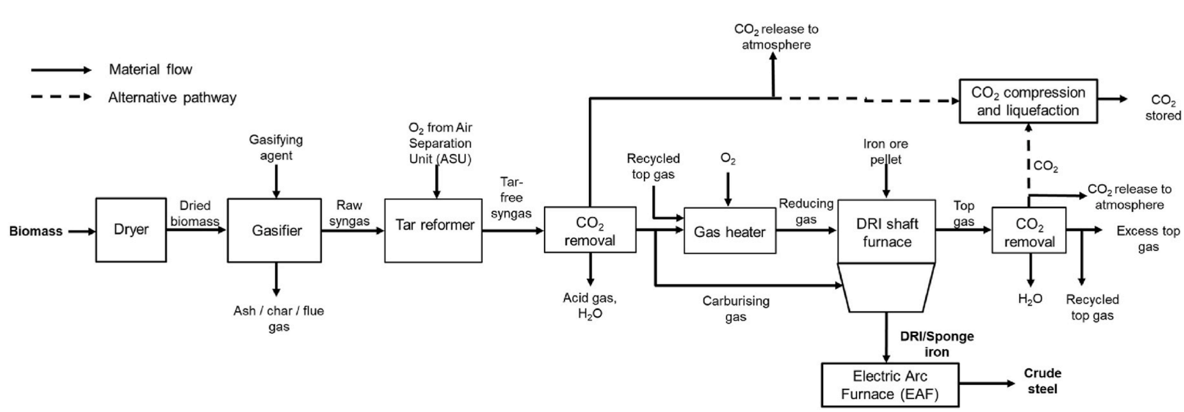

Fig. 1. The general overview of the proposed biosyngas DRI production system. Adapted from (Zaini et al., 2023).

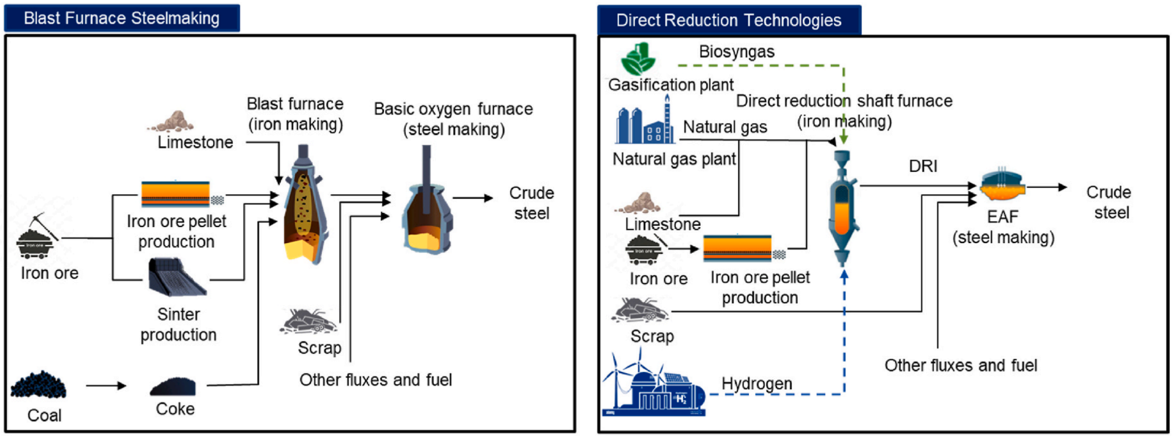

Fig. 2. (Left) Schematic diagram of crude steel production via traditional blast furnace-basic oxygen furnace steel making. (Right) Schematic diagram of alternative crude steel production via natural gas-based DRI process followed by EAF. The dashed line shows the alternative gas reductants replacing natural gas, either biosyngas (green dashed line) or hydrogen (blue dashed line), both would enter the direct reduction unit at the same point but are shown entering at different points for clarity. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1. Scope of LCA model and functional unit

The scope of the study includes all the process steps outlined in Fig. 1. The steps considered are biosyngas production, CO_2 separation, direct reduction process, crude steel production (EAF) and CO_2 liquefaction, including feedstock supply chains. The SimaPro 9.2.0.2 multiuser software was used together with the associated Ecoinvent 3.7 database and emission factor from literature in order to model and carry out the LCA. The LCA was designed to evaluate the environmental impact of the biosyngas DRI production routes and compare them to the other iron and steel production routes. Thus, 1 tonne (t) of crude steel produced is selected as the functional unit.

3.2. System boundary, methodological approach and assumptions

The present work adopts the cradle-to-gate perspective of steel production, where gate refers to crude steel as shown in Fig. 3.

The upstream activities include the raw materials supply chain: biomass harvesting, iron ore pellet production and their transports from collecting sites to the processing sites. The biomass feedstocks considered are forest biomass, specifically tree tops and branches (so called "GRenar Och Toppar/GROT in Sweden) and wood pellet. GROT is usually left after harvesting round wood.

In order to reduce the extent and complexity of the study, the system boundaries were adjusted and some elements are left out of the scope of this analysis, while still achieving the study objectives properly. Some elements excluded are production of capital goods for equipment manufacturing (machines and facilities), internal transport, the use phase and end-of-life stages.

This study applies a cut-off allocation approach, by which the burden of treating waste material is borne by the primary user of the material, while recycled materials are available zero-burden (Lai et al., 2022). The cut-off approach is commonly used because it is easy to apply and lowers the uncertainties of future recycling and reuse scenarios. The cut-off allocation is also chosen to reflect the EU Renewable Energy Directive (RED) II, Annex V point 18, for feedstocks considered waste or residue such as branches and tops, where no impact from upstream processes is allocated to these feedstocks (European Commission, 2018). Therefore, in the base scenario, the system boundary is chosen to exclude forest plantation and management (see Fig. 3), considering tops and branches as a waste stream of logging activities, thereby not contributing to the environmental burdens of the system examined. Instead, environmental burdens from forest establishment and maintenance are allocated completely to timber/pulp products.

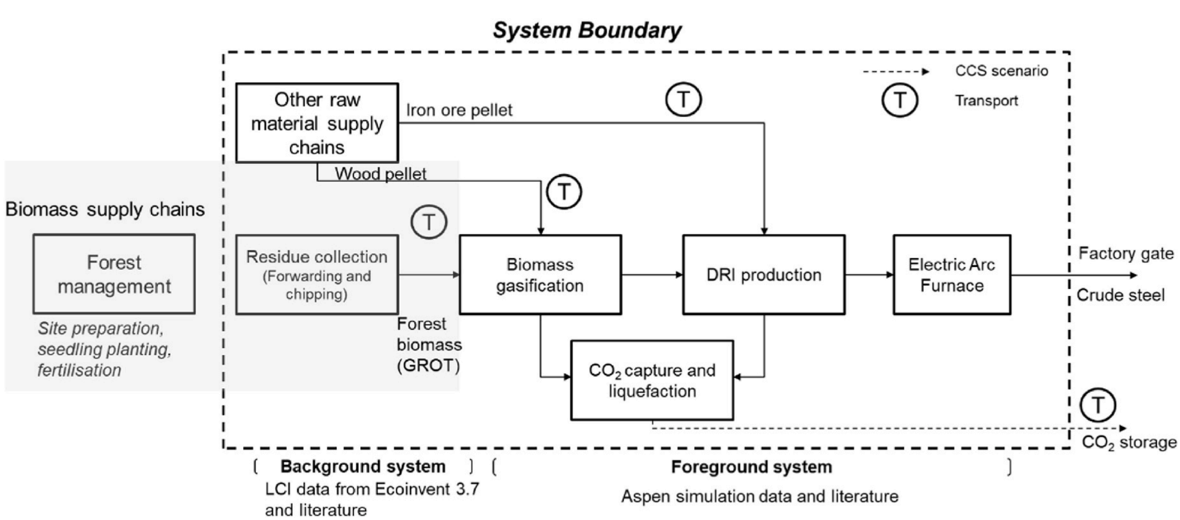

Fig. 3. The system boundary of this study.

At the time of writing, the proposed new EU Directive (RED III) had yet to be finalised. However, there is a proposal to reclassify tops and branches from residues to primary feedstock (European Commission, 2021), implying that the burden from forest production and management (e.g., soil preparation, planting, thinning, and harvest) should then also be divided between the co-products. Thus, an allocated burden from the forest biomass production to crude steel production is included in the scenario-based sensitivity analysis (See alternative scenario 1, Table 1). The details of the forest inventory and allocation method can be found in Supplementary Materials (Table A6).

Average Swedish data is used to model energy consumption, resource usage and emission factors when possible. When Swedish data is not available, European datasets are preferred over global datasets. An 8000 h/year operation is assumed for all of the process units. All consumed electricity in the crude steel production is assumed to come from 100% wind energy. This choice deviates from the typical attributional LCA that uses average electricity data, i.e., national electricity mix; however, this better reflects the interest in procuring 100% renewable electricity from wind farms for the plant operation. For generic data, Ecoinvent's 'cut off by classification' database is used.

3.3. Impact categories

In this study, the climate change impact category is in focus. However, in order to avoid problem shifting, some impact categories affected by the increased resource and energy use by conversion processes and CCS are included. Besides CO_2, the other polluting gas emissions mainly considered in this study are CO, SO_x, NO_x, and particulate matter (PM). The selected impact categories relevant to the system of study and available inventory data include Climate change/global warming potential (GWP), photochemical ozone formation (POF), eutrophication potential (EP) and acidification potential (AP), resource use/abiotic depletion potential (ADP) and cumulative energy demand (CED), as tabulated in Table A5 (Supplementary Material). Those are common impact categories of steel products as captured in LCI reports by the World Steel Association (Hughes et al., 2012) and particularly relevant to the evaluation of bioenergy systems (Murphy et al., 2013). In the assessment of non-climate impact categories, the H_2-DRI-EAF process is excluded due to the incomplete emissions inventory associated with this technology.

The EN 15804 A2+ method is used since it is commonly used as sustainability standards for creating EPDs in the construction sector in the EU. According to EN 15804 A2+, biogenic carbon emissions cause the same amount of climate impact as fossil carbon but can be neutralised by removing this carbon from the atmosphere (e.g., CO_2 uptake by biomass via photosynthesis).

3.4. Biogenic carbon modeling

To calculate life cycle impact assessment (LCIA), all biogenic and non-biogenic carbon emissions and removals should be considered (SIS, 2015). In this study, the CO_2 uptake in biomass during the growth phase is included in the model as negative biogenic CO_2 flow contributing with a negative global warming potential. When the biogenic carbon in the material is released, these biogenic CO_2 emissions contribute to the overall CO_2 emissions from the system. This approach is in line with EN 15804 A2+ methods and the approach recommended by EPD (2020) for basic products from forestry. The value of CO_2 uptake for tops and branches is calculated based on the carbon content of biomass (Ågren et al., 2021). The carbon content of forest biomass was assumed to be 50% (Alamia et al., 2017). To convert carbon into CO_2, the tonnes of carbon are multiplied by the ratio of the molecular weight of CO_2 to the atomic weight of carbon (44/12), which corresponds to CO_2 uptake value of 1.83 t CO_2/t dry biomass. On the other hand, when biogenic carbon is permanently stored in a geological site with negligible leakage to the atmosphere, the resulting GWP factor is −1.

According to EU RED (European Commission, 2018), annual emissions from carbon stock changes due to land use change must be included in calculating GHG emissions. Several modelling studies showed that forest fuel extraction in conventional forestry could lead to carbon stock changes in the forest, which impacts climate change (Hammar et al., 2015). Despite the importance, quantifying the soil organic carbon (SOC) stock changes for forestry systems based on modelling could pose uncertainties linked to limitations and complexity in the model. In this study, it is assumed that forest plantations are managed sustainably, meaning no change in annual forest productivity, no land use changes and no below ground biogenic carbon losses. According to Product Category Rules (PCR) for basic products from forestry (EPD, 2020), land-use change GWP due to forest residue extraction can be assumed to be zero if the forest area where the product is harvested is certified under a forest management certification scheme that includes performance-based measurement criteria. This assumption would simplify calculations by avoiding forest carbon stock modelling. However, given the importance of the impact of forest residue extraction on SOC stock changes, a discussion on this based on the literature review and expert interviews is presented in Section 5.

3.5. Scenarios investigated

To better understand the impact of different design parameters and assumptions on the overall performance of the biosyngas-DRI-EAF technology, additional scenarios are considered, as tabulated in Table 1.

The details of each scenario, together with the data inventory, are presented in the following subsection.

Table 1
Overview of different scenarios investigated. The numbering in brackets refers to the code of the scenario.

Parameter	Base scenario	(Code) Alternative scenario
Biomass feedstock	Forest biomass (100% tops and branches), assuming to carry zero environmental burden from the forest management (i.e., planting, thinning and final felling) Direct delivery of wet woodchips to the gasification plant.	(1) Tops and branches, carrying allocated environmental burden from the forest management (2) 100% wood pellet with no burden of sawdust production allocated to steel production
Electricity source	100% onshore wind power	(3) Sweden's electricity production mix
Fuel use in transporting biomass	100% Low-sulfur diesel	(4) 100% HVO
Process configuration	Circulating fluidized bed (CFB) gasifier is employed [Biosyngas (CFB)-DRI-EAF]. 100% DRI charged to EAF No biochar production	(5) Steam-blown dual fluidized bed (DFB) gasifier is employed [Biosyngas (DFB)-DRI-EAF]. This configuration has a lower electricity consumption than CFB configuration. (6) Biochar co-production
Product	Crude steel production via hot DRI	(7) Crude steel via cold DRI
Transport distance	Location of DRI plant: Central Sweden Biomass to DRI plant: 200 km Iron ore pellet supplier: Domestic supply	(8) Varies from 100 to 300 km (9) Import from Canada
CO_2 storage	No	(10) Yes

3.6. Data inventory

Transparency in communicating LCA data and study limitations is crucial for the credibility of LCA study. LCI data for this study have been obtained from different sources such as scientific literature, industrial report, process simulation data, data from research institutes and from general database Ecoinvent 3.7. The collected data can be summarised as reported below.

- Data on forest biomass production have been obtained from relevant research institute (Ågren et al., 2021) and scientific literature (Karlsson et al., 2021; Lindholm et al., 2010a, b), wood pellet production data have been obtained from research institute report (Hagberg et al., 2009).
- Data on iron ore pellet production have been retrieved from Ecoinvent 3.7 database based on EU Best Available Technology (BAT) reference document for iron and steel production (Remus et al., 2013), while the carbon footprint value is adapted using data from relevant industry (Hallberg and Dahllöf, 2021).
- The LCI data from various transport modes and data for upstream raw materials are obtained from the Ecoinvent database. Examples of these process materials include lime, MEA, coal, while the full list of datasets is presented in Table A15 (Supplementary Materials).
- Data on conversion of biomass to biosyngas have been provided by relevant projects with input from industries: FerroSilva project (Zaini et al., 2023) and GobiGas project in Sweden (Larsson et al., 2013).
- Data on biosyngas-based direct reduction processes have been provided by relevant projects with input from industries (Zaini et al., 2023), data on natural gas-based direct reduction process has been collected from relevant real plant data (Lockwood Greene, 2000), while data on hydrogen-based direct reduction process has been collected from scientific literature (Rechberger et al., 2020). Typical emissions from DRI-EAF processes have been obtained from literature (Ren et al., 2018).
- Data on the EAF process has been collected from relevant real plant data (Lockwood Greene, 2000) and EU BAT reference (Remus et al., 2013).

In the data matching, the data come from two or more different sets of data should have common identifiers in terms of geographies, product, technological/process, and unit matching to ensure that data are coherence and compatible. During the inventory stage, it has been necessary to assess data quality in terms of geographical validity, time frame, precision, consistency and completeness of data to ensure the reliability of the whole study. General information related to the data quality of this study is presented in Table A17 (Supplementary Materials).

3.6.1. Biosyngas-DRI-EAF route

In the proposed biosyngas-DRI-EAF route, five main subsystems have been defined:

- biomass feedstock
- gasification
- DRI production and CO_2 capture
- crude steel production (EAF)
- CO_2 liquefaction

Each of the subsystems is explained below. The inventory data for each subsystem are presented in Tables A6–A14 in the Supplementary Material.

3.6.1.1. Biomass feedstock. The biomass feedstock consists of tree tops and branches (GROT) and wood pellets. In Sweden current potential for forest energy biomass, specifically, tree tops and branches, is around 24–40 TWh, as estimated by Skogsstyrelsen (2022) in their *Dagens Potential* (today's potential) scenario. The upper range value represents the potential of tops and branches from the final felling and thinning, while the lower range value only considers tops and branches after the final felling. The potential takes into account ecological restrictions according to the Swedish Forest Agency's recommendations, but not economic or technical restrictions. Tops and branches are primarily used for energy purposes, with around one-third of the total gross potential currently being extracted from Swedish forests (Sandin et al., 2019).

The first step in the biomass supply chain is the collection and transport of tops and branches. Tops and branches are the biomass feedstock selected in the base scenario and enter the gasifier in the form of wood chips. It is collected from central Sweden, where the DRI plant is assumed to be located. Since tops and branches are by-products of final felling, it needs only marginal additional forest operations for collection and forwarding to the roadside by a forwarder, followed by a chipping process. The chipped biomass is then assumed to be transported 200 km to the DRI plant.

Fuel consumption for forwarding and chipping of tops and branches was collected from various working reports from Skogforsk (the Forestry Research Institute of Sweden), as listed in Table A6 (Supplementary Material). The exhaust emissions from these machineries were taken from Ecoinvent database (Diesel, burned in building machine/GLO U) based on fuel consumption. In this study, all road transport to and from the production facility are modelled using a Euro 5 truck–32 t in the Ecoinvent database which has a more complete exhaust emission inventory and its fuel consumption per tkm is only slightly different from the 64-t truck commonly used in Swedish forestry.

In the alternative feedstock scenario of using wood pellet (scenario 3), stand-alone pellet plants using wet saw mill residues as raw material were assumed according to a study by Hagberg et al. (2009). This study calculated the typical emissions from the Swedish pellet plant, including the average transport distance for raw material and pellets. To align with the cut-off approach described previously, the burden allocated to sawdust production is removed. The inventory data for wood pellet production can be found in Table A7 (Supplementary Material).

In alternative scenario 4, the truck transporting biomass will use HVO (hydrotreated vegetable oil) instead of diesel, considering the 2030 sustainability targets of some major agricultural and forestry companies to reduce fossil emissions. For modelling the production of HVO, the average mix of HVO production using different feedstocks in Sweden was estimated based on statistics published by the Swedish Energy Agency for 2018 (Swedish Energy Agency, 2021) and using well-to-wheel LCI data for HVO fuels presented by Fransson (2020).

3.6.1.2. Gasification and DRI production. The subsystems consist of a biomass dryer, a gasifier, a tar reforming process, a DRI shaft furnace (similar to the MIDREX furnace), and a CO_2 removal process, as presented in Fig. 1. The key component of the direct reduction process is a shaft furnace, where the reduction of iron ore to DRI by using biosyngas or other gaseous reducing agents takes place. Given the importance of the mass balance of the shaft furnace in assessing the whole process, a concise and clear description of the modelling approach is presented in Section 3 of Supplementary Materials.

For the environmental impact assessment, it is assumed that the conversion plant is located in central Sweden with a production capacity of 500 kt DRI/yr. Mass and energy balances for the biosyngas-DRI production pathways are estimated based on data obtained from specific calculations performed using the process simulation software Aspen Plus in earlier work (Zaini et al., 2023). Electricity, energy and resource demand used as initial input data in constructing the LCA model are presented in Table 2.

To reach a reduction degree of the hot DRI product of 92%, 1.39 t of iron ore pellet (see Table A2 for the composition) per t of DRI is required for the biosyngas-DRI process (Zaini et al., 2023). Based on the referred

Table 2
Initial data used in the LCA of the biosyngas-DRI-EAF process (base case).

Input data	Values	Unit	References	Comments
Forest biomass (GROT)	0.65	t db./t DRI	Zaini et al. (2023)	Assuming biomass is transported in wet conditions, moisture content of 40%. LHV = 18.7 MJ/kg db. Based on process simulation data.
Electricity for biosyngas production	91	kWh/t DRI	Zaini et al. (2023)	Electricity for oxygen production via air separation unit (ASU).
Olivine	0.004	t/t DRI	Larsson et al. (2013)	Used as active bed material used in gasifiers. Based on industrial demonstration plant.
Limestone	0.003	t/t DRI	Larsson et al. (2013)	The additive used in a product gas filter after gasifier. Based on industrial demonstration plant.
Cooling water	2	m^3/t DRI	Zaini et al. (2023)	Data is obtained from process simulation.
Monoethanolamine (MEA)	1.744	t/t DRI	Zaini et al. (2023)	Data is obtained from process simulation, assuming a 95% removal rate.
Electricity for MEA regeneration	607	kWh/t DRI	Zaini et al. (2023)	Data is obtained from process simulation, assuming energy demand of 972 kWh/t CO_2 (Bui et al., 2018).
Electricity for CO_2 liquefaction	114	kWh/t DRI	Zaini et al. (2023)	Data is obtained from process simulation, assuming energy demand 105 kWh/t CO_2 (Seo et al., 2016)
Iron ore pellet	1.39	t/t DRI	Zaini et al. (2023)	Data is obtained from process simulation.
Lime charged to EAF	0.025	t/t crude steel	Remus et al. (2013)	Based on EU BAT document for iron and steel production.
Refractory lining	0.007	t/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.
Electricity for oxygen (EAF)	38.7	kWh/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.
Natural gas	2.18	kg/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.
Electricity for EAF	698	kWh/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.
Coal	0.0094	t/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.
Graphite electrode	0.0043	t/t crude steel	(Lockwood Greene, 2000)	Based on real plant data.

process simulation of the evaluated system, the simulation results in biomass demand of approximately 0.65 t db./t DRI for the base case (see Table A1 for the composition). Mass balance diagram of biosyngas-DRI production route is presented in Fig. A6 Supplementary Material.

Electricity is required mainly for Air Separation Unit (ASU) to produce oxygen. Oxygen is used as a fluidising agent in the gasifier, tar reformer and for partial oxidation reaction in the gas heater to increase the temperature of the reducing gas. Further, since the proposed system requires CO_2 removal process to achieve optimum quality of reducing gas, electricity is also required for amine solvent regeneration. The amount of monoethanolamine (MEA) solvent used is based on process simulation data, assuming 95% capture efficiency. For scenarios including CO_2 storage, electricity is also required for CO_2 liquefaction.

The CFB configuration is selected for the reference of biosyngas DRI production technology, as currently CFB gasifier is more proven on a larger scale (>150 MW) compared to its alternative dual fluidized bed (DFB) gasifier. In alternative scenario 5, the DFB gasifier is assumed to replace the CFB configuration (See Figs. A1-A2, Supplementary Materials). The DFB gasifier configuration also allows biochar co-production, which can be used to replace coal in iron and steel production. This possibility to co-produce biochar is also captured in the alternative scenario 6.

The material, energy and resource flows considered in the iron pellet production are shown in Table A8 (Supplementary Material). The work assumes the use of iron ore pellet from LKAB Swedish mining company, in Malmberget, Northern Sweden. The composition of iron ore and pellet used in this study is thus typical quality for LKAB, which is characterised by low Si and high MgO, as presented in Table A2. Three major transportation modes (rail, trucks, and ship) are considered for iron pellet transport. The distance between sites is obtained from Google Maps (Google Maps, n.d.), while the distance between ports is obtained from (Ports.com, n. d.). In alternative scenario 9, it is assumed that iron pellet is supplied from Canada via Port Rotterdam. The data and assumptions in the iron pellet transport can be found in Table A9 (Supplementary Material).

3.6.1.3. Crude steel production. The produced DRI is charged to an electric arc furnace (EAF), in which it is melted and refined into liquid crude steel. In both BOF and EAF furnaces, oxygen is injected to reduce the carbon in the steel to the required level. Electricity is required for oxygen production and the melting process in the EAF. Steel scrap and fluxes (e.g. lime) could be added to the EAF to control the required composition. Graphite electrode is used as a conductive material in EAF, and it is consumed during the smelting process. As can be seen in Table 2, the parameters and carbon emission of steelmaking are taken from Lockwood Greene (2000), which was the most complete reference model available. The report provides detail mass and carbon balances in the EAF, which is useful to approximate both the fossil and biogenic carbon emission from the conversion of biosyngas DRI in the steelmaking process. For the other GHG emissions (NO_x, SO_x and PM), typical emissions from the DRI-EAF process obtained from literature are used (Ren et al., 2018).

For the direct reduction route, 100% hot DRI charge (2 wt% carbon) to EAF was assumed in the base scenario, representing an integrated iron and steelmaking plant with a transport hot DRI system. Meanwhile, alternative scenario 7 is developed to show the impact of cold DRI charging to the EAF.

3.6.1.4. CO_2 liquefaction. In the CCS scenario, the separated CO_2 will be liquefied at a delivery pressure of 15 bar and transported in a ship-based CCS chain. The total electricity consumption of the CO_2 compression and cooling is assumed to be 105 kWh/t CO_2 (Seo et al., 2016). The emissions from transporting liquefied CO_2 by ship and injecting the CO_2 are outside the system boundary.

3.6.2. Reference technologies

The main parameters of the four ironmaking technologies evaluated in this study are summarised in Table 3, including input of fuels, electricity, iron ore pellets, sinter and flux. Further details regarding the full inventory of DRI production via different pathways are presented in the Supplementary Material (Tables A10–A12).

The main parameters of steelmaking technologies are summarised in Table 4, while a complete inventory for EAF process can be found in

Table 3
Summary of input parameters for ironmaking models (Basis 1 tonne of DRI produced).

	Biosyngas-DRI	Blast furnace	Natural gas-DRI	H_2-DRI
Furnace type	Direct reduction	Smelt reduction	Direct reduction	Direct reduction
Current status	Conceptual integration, gasification (TRL[a] 7–9), DRI (commercial), post combustion CO_2 capture (Amine system TRL 9)	Fully commercialised	Fully commercialised	Demonstration plant
Iron ore requirement, per tonne of iron	1.39 t iron pellet	1.05 t sinter, 0.15 t iron ore, 0.4 t iron pellet	1.61 t iron pellet	1.39 t iron pellet
Fuel demand[b], per tonne of pig iron/DRI	0.65 t db. (3388 kWh) treetops and branches	0.15 t (1206 kWh) coal 0.36 t (2861 kWh) coke 0.002 t (25 kWh) natural gas	0.24 t (3075 kWh) natural gas	0.035 t (442 kWh) natural gas
Electricity demand, per tonne of iron	697 kWh	none	115 kWh	3500 kWh (for producing hydrogen at 741 $m^3{}_{STP}$/t DRI)[c]
Flux demand, per tonne of pig iron/DRI	none	0.01 t limestone	none	none
Main data source	FerroSilva project (Zaini et al., 2023)	EU BAT reference (Remus et al., 2013)	(Lockwood Greene, 2000)	Rechberger et al. (2020)

[a] The technology readiness levels (TRL) are a nine-point scaling system used to qualitatively evaluate the maturity level of a technology (Nurdiawati and Urban, 2021), from basic idea to full commercialisation which is established by means of a literature review.
[b] Values in brackets represent fuel input in an energy basis, obtained using lower heating value of energy carriers listed in (Ecoinvent, 2007).
[c] Hydrogen Is produced through water electrolysis with an efficiency of 75% (3.54 kWh/$m^3{}_{STP}$) (Rechberger et al., 2020).

Table 4
Summary of input parameters for steelmaking models (FU 1 tonne crude steel produced).

Material/energy input	Basic oxygen furnace	Electric arc furnace
Iron	0.865 t hot metal	1.01 t DRI
External scrap	0.232 t	None (100% DRI charge)
Flux	0.045 t lime	0.025 t lime
Fuel	1 kg natural gas and 9 kg coke	2.2 kg natural gas and 9 kg coal
Oxygen	78 kg	13.5 kg
Electricity	24 kWh	698 kWh (excluding electricity for oxygen production)
Main data source	EU BAT reference (Remus et al., 2013)	(Lockwood Greene, 2000)

Supplementary Materials (Tables A13–14).

The data input inventory for steel produced via BF-BOF (shown in Tables 3 and 4) is taken from Ecoinvent 3.7 (see Table A15). This dataset assumes a 17% scrap rate following EU Best Available Technology (BAT) reference for iron and steel production (Remus et al., 2013). To allow a consistent comparison with other technologies, some inventories were adapted, such as excluding equipment manufacturing and alloys, as well as adapting the inventory data (e.g., electricity source, natural gas and iron pellet) to represent the Swedish context.

4. Results and discussion

This section presents the results of this LCA study. The results are shown and discussed per functional unit: "1 tonne of crude steel produced" as defined earlier in Section 3. The results in relation to the base scenario are presented first (Section 4.1), followed by a comparison to the BF-BOF, natural gas-DRI-EAF and H_2-DRI-EAF routes are shown (Section 4.2). Finally, alternative scenarios are presented in Section 4.3.

4.1. Potential cradle-to-gate climate impact of biosyngas DRI-EAF route

Potential environmental impacts that can be attributed to biosyngas-based DRI production and subsequent crude steel production are quantified from the perspective of the steel producer. The cradle-to-gate climate impact of the crude steel production via the proposed biosyngas DRI-EAF route is presented in Fig. 4. The proposed system has an estimated GWP of 251 kg CO_2 eq./t crude steel, of which 200 kg CO_2 eq./t crude steel, or around 80%, is from upstream emissions. Upstream

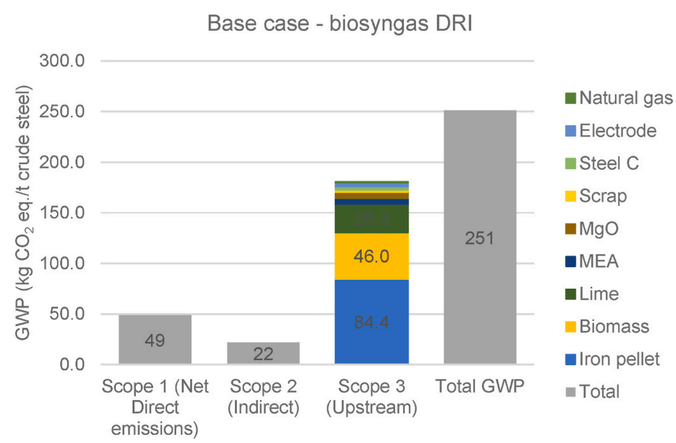

Fig. 4. Cradle-to-gate GWP of crude steel production via biosyngas-DRI-EAF route without CO_2 storage. Scope 1 refers to net direct emissions, including biogenic emissions, fossil emissions and CO_2 uptake by the plant. Scope 2 emissions are indirect GHG emissions associated with the purchase of electricity. Scope 3 emissions are all indirect emissions (emissions from the extraction, processing and transportation of raw materials), not included in Scope 2.

emissions are defined as all GHG emissions taking place before the raw material enters the processing plant. The supply chain for iron ore pellet, biomass and lime are the three major contributors to the upstream emissions. The electricity consumption is moderate, which contributes around 9% of the total GWP. The remaining GWP stems from net direct emissions calculated from the difference between biomass CO_2 uptake, fossil emissions and biogenic emissions from the system. It should be noted that in the base scenario, the separated CO_2 is released back into the atmosphere along with other biogenic emissions from exhaust flue gases.

The breakdown of GWP per activity of each subsystem to the overall GWP, as shown in Fig. 5, allows for identifying environmental hotspots where improvement efforts are most required. The biomass supply chain contributes around 18.5% to the overall climate impact of the proposed system. This value is obtained by dividing the GWP of the biomass supply chain, including GROT forwarding, chipping, and transport of biomass to the DRI plant, with the total GWP of the biosyngas-DRI-EAF process. The GWP of biomass supply chain is mainly driven by feedstock transportation, i.e. transport fuel combustion. To see the impact of fuel

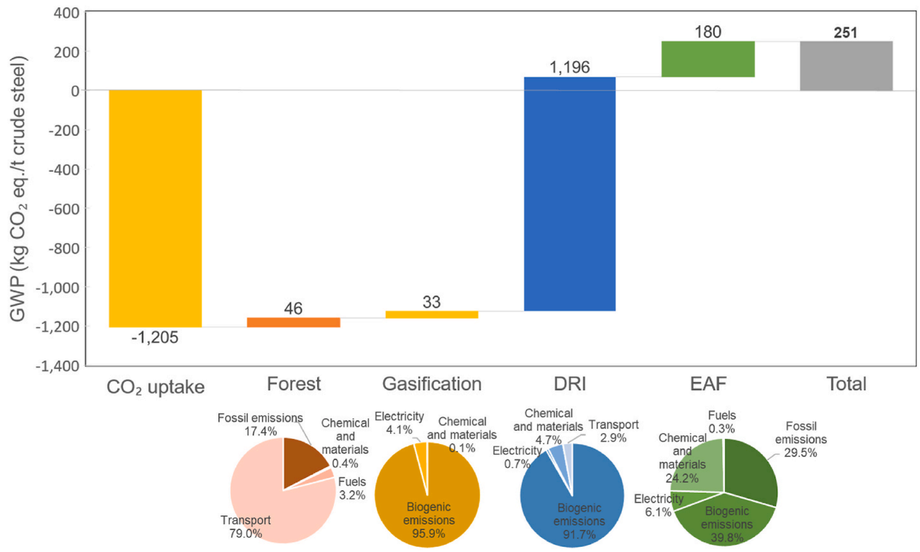

Fig. 5. Cradle-to-gate GWP of crude steel production via biosyngas-DRI-EAF route without CO_2 storage. The GWP is presented per subsystem, each includes both direct and indirect emissions. The pie charts show the percentage of emissions contribution.

shifting from fossil diesel to low carbon fuels (i.e. HVO), an alternative scenario is evaluated in the next subsection.

Drying and gasification units have a minor contribution to the overall GWP, in which emissions stem from the exhaust flue gas after drying and indirectly from electricity consumption. High biogenic CO_2 emissions are formed due to the combustion of biomass and released as high concentrated biogenic CO_2 after the CO_2 removal unit.

Indirect emissions from the iron pellet supply chain (production and transportation) contribute the most to the DRI subsystem's climate impact, which is around 84 kg CO_2 eq./t crude steel. This represents the main environmental hotspot. Currently, the LKAB mining company is experimenting with fossil-free iron pellets production (Pei et al., 2020), which once widely available in the market, could be used to improve the performance of the proposed system.

Amine-based CO_2 removal technology is assumed here due to its technological maturity and scalability. In the CO_2 removal unit, electricity is used as an additional energy source for solvent regeneration, contributing slightly to the indirect emissions.

Despite the high electricity consumption in the EAF process, the contribution of electricity to the climate impact of EAF process is only 6.1%. This is mainly due to the low carbon intensity of wind-based electricity (0.0146 kg CO_2 eq./kWh) assumed in this study. Direct emissions from the use of fossil carbon sources such as coal, natural gas, and graphite electrode consumption rather dominate the climate impact of the EAF process. Moreover, indirect emissions from material production, including lime, coal, refractory lining, and graphite electrode, contribute around 24% to the climate impact of the EAF process, as can be seen in Fig. 5. This is one of the primary hotspots, and to reduce these emissions, it may be of interest to explore the feasibility and sustainability of using renewable carbon material, such as upgraded biochar, to replace coal and graphite in the EAF process.

Lime also has a considerable contribution to the GWP of the EAF subsystem. There are a number of studies that seek the potential of partially replacing primary lime with a number of CaO-containing wastes from the pulp and paper industry, such as lime mud, calcined lime mud and fly ash. For instance, Jarnerud et al. (2020) investigate the

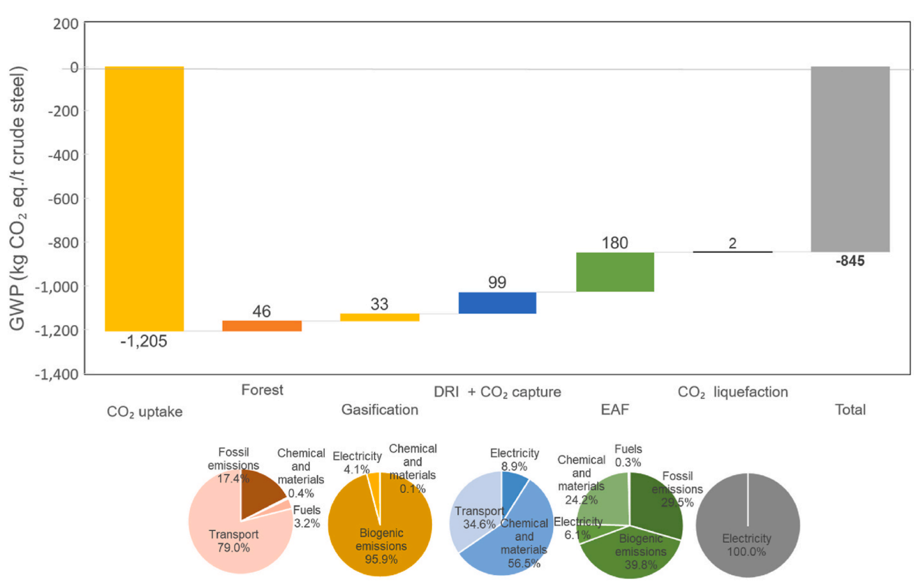

Fig. 6. Cradle-to-gate GWP of crude steel production via biosyngas-DRI-EAF with CO_2 storage. The GWP is presented per subsystem, each includes both direct and indirect emissions. The pie charts show the percentage of emissions contribution.

impact of using fly ash to partially substitute primary lime in the EAF pilot trials. They found that increasing the amount of fly ash could reduce the amount of alloy and slag required, showing good possibilities for partial replacement of primary lime (Jarnerud et al., 2020). However, further development is still needed to explore the impact of substituting primary lime, especially regarding the steel quality and the process stability.

The GWP for CCS scenarios, in which the separated CO_2 is compressed and liquefied to be transported and permanently stored in a geological formation, is shown in Fig. 6. Liquefaction of the CO_2 was selected since ship transportation to storage site in Norway is likely to become the transport mode of choice in the Sweden context (Kjärstad et al., 2016). It can be seen that the additional CO_2 liquefaction has a relatively small contribution to the net GWP of the proposed system. Further, the GWP in the biosyngas DRI route–CCS scenario is a net negative, estimated at −845 kg CO_2 eq./t crude steel for our selected system boundary.

The method of CO_2 transportation is a matter of logistics optimisation in which the amount of CO_2 relative to the transport distance favours either pipeline, ship transport or hybrid systems. In the Nordic context, ship transport could be the most economical method of transporting CO_2, as studied previously by Kjärstad et al. (2016). By assuming some transport scenarios for CO_2 transportation and storage (see Table A16, Supplementary Material), it is found that the GWP of transporting and storing the liquid CO_2 ranges from 23 to 67 kg CO_2 eq./t crude steel, depending on the transport method of CO_2 to the port (truck or pipeline) and the location of CO_2 receiving terminal in Sweden. This estimation can provide a useful indication of the magnitude of the potential climate impacts of CO_2 transport and storage in Sweden's context, despite the uncertainties in the future CO_2 transport systems.

Large-scale demonstration projects covering CCS full chains have not yet taken place in the EU. Infrastructure development for CCS will require access to suitable storage sites. Given that transportation and storage of CO_2 can go across the border makes geography an essential factor and coordination across spatial scales an important policy domain for speeding up the implementation of CCS/BECCS (Nurdiawati and Urban, 2022).

4.2. Comparative LCA

This section compares the impact assessment results for the proposed biosyngas-DRI-EAF technology (base scenario) against the environmental impact of conventional and other emerging iron and steel production routes. The assessment of climate impact is reported in Section 4.2.1, while the other impact categories are presented jointly in Section 4.2.2.

4.2.1. Climate impact

The GWP comparison between different technological pathways, both the base case and the CCS scenario, is presented in Fig. 7. A carbon footprint comparison to the emerging alternative of H_2-DRI-EAF steelmaking is also shown below.

The biosyngas-DRI-EAF route could offer approximately 75% and 85% GHG emissions reduction from iron and steel production compared to NG-DRI-EAF and BF-BOF routes, respectively. Negative life cycle emissions in steelmaking are only possible through the use of bioenergy combined with the capture and permanent storage of CO_2. If only partial CCS is applied for NG-DRI-EAF and BF-BOF routes, the GWP of those systems is still higher than the base case of biosyngas-DRI-EAF route.

In the case of no CO_2 storage, the proposed system may have a comparable GWP with the emerging H_2-DRI-EAF steelmaking, considering the same system boundary, as can be seen in Fig. 7. It is estimated that the GWP of the H_2-DRI-EAF pathway is around 365 kg CO_2 eq./t crude steel, which is mainly driven by electricity consumption, iron pellet production and transportation. In the H_2-DRI-EAF pathway, the carbon source for maintaining the carbon content of the DRI is assumed from natural gas (Rechberger et al., 2020), which in turn influences the GWP value of the system.

Current typical scrap-based steelmaking would release 100% of fossil emissions from the use of fossil carbon sources (i.e. additional coal or graphite consumed through the process) and the carbon content in the scrap. In the EAF, the scrap melts, and the carbon content is reduced due to oxidation resulting in CO_2 emissions. In contrast, for the proposed system, partly biogenic emissions are released from the biogenic carbon content in the DRI charged to the EAF.

4.2.2. Other non-climate impacts

When attempting to reduce carbon emissions, there is potential for burden shifting, i.e. collateral damage to other impact categories. A comparative evaluation of non-climate change-related impact categories for different iron and steel production technologies is presented in Fig. 8.

The biosyngas-DRI-EAF route outperforms the conventional BF-BOF in most selected non-climate change-related impact categories, except for resource use of metals and minerals (see Fig. 8). This is mainly due to the reduction in the emissions of NO_x and ammonia (main drivers of the AP and EP category), SO_2 (main drivers for AP category), organic compounds (contributing to the ozone formation burdens). These emissions mainly come from refining and combustion of fossil fuels. The primary environmental advantage of the direct reduction route is that it can operate without coke or sinter. This prospect could avoid the requirement for coking and sinter plants that have a considerable environmental impact. Removing coking plants reduces emissions to air of dust and volatile organic carbons from the ovens and various organic

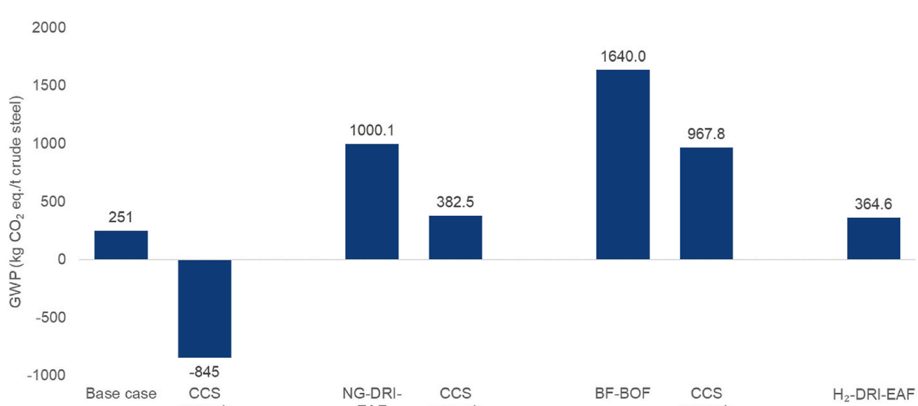

Fig. 7. Comparative evaluation of GWP of different iron and steel production technologies. Partial CCS is applied to all routes, which covers the capture of pure CO_2 streams from DR shaft furnace or blast furnace gas only, while the emissions from EAF and upstream processes are not captured. For the biosyngas-DRI-EAF route, however, CO_2 from biosyngas (gasifier unit) is also removed, as a part of the process requirement, to achieve optimum quality of the reducing gas.

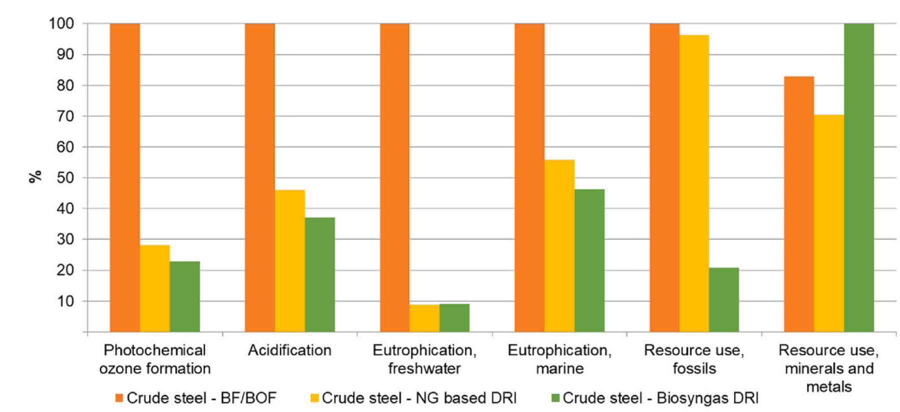

Fig. 8. Comparative evaluation of environmental profiles for different iron and steel production technologies. The value of each impact category is normalized and expressed as a percentage. POF = photochemical ozone formation, AP = acidification potential, EP = Eutrophication potential, Resource use.

chemicals into air and water from by-product plants (Remus et al., 2013). Additionally, removing sinter plants could lower the releases of metallic/nonmetallic dust and gaseous pollutants such as SO_2 to the atmosphere. For the DRI routes, the iron pellet supply chain is the main driver of the POF, AP and EP categories.

The biosyngas DRI-EAF route performs slightly better than NG-DRI-EAF in the POF and AP categories due to lower iron pellet requirement estimated from the process modelling. Moreover, as can be seen from Fig. 8, burden-shifting takes place in the biosyngas DRI route, which displays a worse value in resource use of metal-minerals category compared to the BF-BOF route. The resource use of metal increases by 10%, mainly due to an increase in wind electricity consumption for the biosyngas-DRI-EAF route. Wind electricity contributes around 64% of the total burden (resource use of metal and mineral impact) in the base scenario. Although wind energy produces low CO_2 emissions per kWh of electricity, it has high material requirements (Hertwich et al., 2015). Wind energy generation and distribution needs relatively large requirements for mining iron, manganese, nickel and chromium, which derive from use of steel in e.g., overhead lines and masts, and also copper. The risk of burden shifting from global warming to metal depletion has also been found as an unintended environmental impact from the low-carbon transition in the electricity sector (Baumgärtner et al., 2021) and the aviation sector (Lai et al., 2022).

The primary energy demand of evaluated systems is listed in Table 5. It is clear that the biosyngas-DRI-EAF route offers much fewer fossil fuels, leading to a 70% reduction in the fossil resource use category. The biosyngas-DRI-EAF route's main energy sources are biomass and electricity, which account for 55% and 25% of total cumulative energy demand, respectively. Meanwhile, the alternative NG-DRI-EAF route still largely depends on fossil fuels.

The impact on biodiversity due to the production of biomass-based DRI is outside the scope of this study, although we recognise the importance of these impacts. The main constraint to be addressed is the lack of specific, reliable tools to assess the impact on biodiversity and limited data availability. The issue of how forest fuel extraction affects biodiversity has been briefly discussed in a report by the Swedish Energy Agency (2014). Current knowledge indicates that the consequences of extracting branches/tops (e.g. of spruce) are relatively limited with regards to the total effects of other forestry operations and the measures taken to promote biodiversity (Swedish Energy Agency, 2014). Since biodiversity impacts are a complex issue, this should be analysed carefully in a separate study.

Table 5
The primary energy demand for producing 1 tonne of crude steel via different production pathways.

Parameter	Unit	Biosyngas-DRI-EAF	NG-DRI-EAF	BF-BOF
Non-renewable, fossil	MJ, LHV	2880	14700	15600
Non-renewable, nuclear	MJ, LHV	437	482	831
Renewable, biomass	MJ, LHV	12350	40.5	168
Renewable wind	MJ, LHV	5690	3430	194

4.3. *Additional assessed scenarios*

This section reports scenario-based sensitivity analysis that evaluates the influence of feedstock, processes, products and transport distance on the climate impact of the proposed technologies. Socio-technical aspects such as policy domain (i.e., EU RED) and market dynamic (e.g., DR-grade iron ore pellet market) were considered in the scenario development.

4.3.1. *The impact of different feedstock, processes and products*

The LCA results are sensitive to the selected parameters and assumptions. In the alternative scenario 1, following the EU RED III proposal, the impact of allocation burden from forest production, including silviculture (plant production, soil preparation, fertilization, clearing and thinning) and harvesting, to tops and branches was evaluated using mass-based allocation, as suggested by (Ågren et al., 2021). However, the impact from forwarding and onward transport is not allocated, but each product bears its own burden. The result shows that the impact of including the upstream burden of forestry on GWP value is insignificant. This is due to the relatively small contribution of silviculture (0.5%) and harvesting (0.4%) to the overall climate impact of the tops and branches supply chain (See Fig. A5, Supplementary Materials). The environmental impact of tops and branches supply chain is rather driven by the forwarding, chipping and road transport of GROT to the processing site, which has been included in the base scenario.

Changing feedstock from forest residue to wood pellet (scenario 2) slightly decreases the GWP of the system, as shown in Fig. 9, but depending on the average transport distance and allocation approach chosen, it could give a contrasting result.

The source of electricity can greatly influence the climate impact of systems. This study assumes that the plant will only use wind electricity. For sensitivity analysis, it can be seen that changing the electricity supply to the Swedish electricity grid mix could increase the GWP of the base case by 12%.

From the previous discussion, transporting biomass is one of the primary environmental hotspots. Fuel shifting from diesel to HVO is found to be able to reduce the GWP by 10%. This scenario is in line with

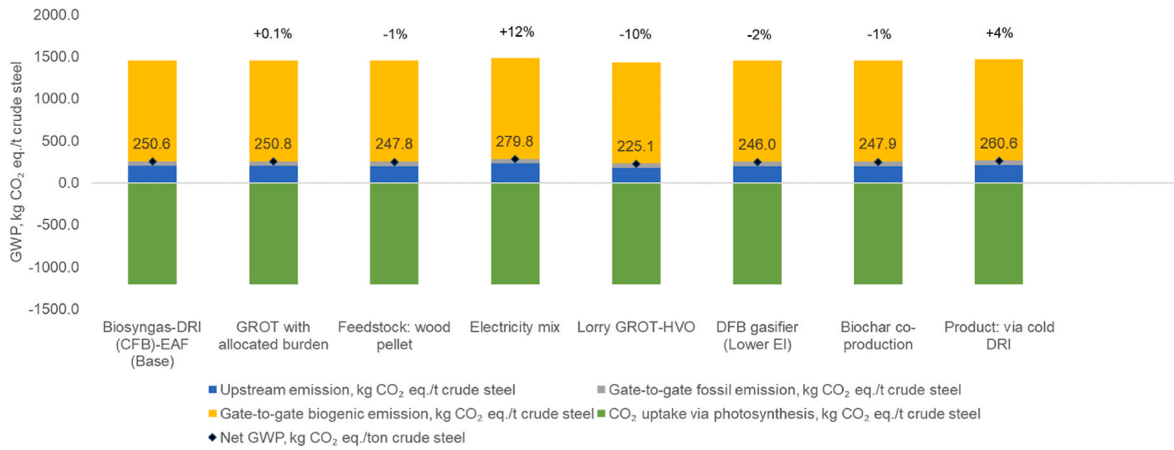

Fig. 9. Comparative evaluation of GWPs for different alternative scenarios. From left to right: (0) Base scenario (1) GROT carries environmental burden from forest production (silviculture and harvest), using mass-based allocation (2) Wood pellet is assumed to replace GROT as the biomass feedstock (3) Swedish electricity grid mix is applied based on Ecoinvent 3.7. (4) HVO replaces fossil diesel used in trucks (5) Dual fluidized bed gasification configuration is used, leading to a higher biomass use, but lower electricity consumption (6) Biochar is co-produced, no specific co-product allocation method is applied (7) Produced DRI is cooled down and charged to the EAF as a cold DRI, leading to loss of efficiency. The percentage shown in the above bar chart represents the difference compared to the base case.

the sustainability strategies of major agricultural/forestry firms to reduce their overall emissions by 2030. In the long term, electrifying heavy-duty vehicles would allow further emission reduction in transport activities.

The CFB gasifier is the technology selected for the base case to produce biosyngas. Changing the process to DFB configurations gives a 2% lower GWP value than the CFB gasifier technology. This is mainly due to lower electricity consumption for this configuration since the impact from equipment manufacturing is excluded in this study.

The scenario where the process is designed to co-produce biochar was also evaluated. However, in this study, we choose a conservative approach where all the environmental impact is allocated to the main crude steel product. Thus, the change in GWP, as seen in Fig. 9, is mainly due to lower electricity consumption of DFB configuration for biochar co-production.

In this study, the hot DRI is assumed to be charged directly to the EAF for crude steel production. Alternatively, it can be cooled down and transported as cold DRI, or the hot DRI can also be compacted at high temperature to produce so-called hot-briquetted iron. In the last scenario, assuming cold DRI charging to EAF, an increase of 4% GWP compared to the base case is observed due to the loss of energy efficiency in cold DRI production.

4.3.2. The impact of transport distance

DRI is expected to underpin low-carbon steel production, while iron ore pellet supplies needed may see a deficit without more investments in mines and processing plants. Thus, an alternative scenario where high-grade iron ore pellet is imported from outside Sweden was evaluated in this study. Canadian-produced iron ore pellet is considered due to its high quality and is sought after by steelmakers globally.

Importing iron pellets from Canada will substantially increase the GWP by approximately 20% compared to the base case where iron pellets are supplied domestically (Fig. A4, Supplementary Material). This is mainly due to a longer transport distance. In order to meet the need for increased local DRI production capacity, more investment is necessary for different parts of the supply chain.

Plant location has a decisive role in supply chain network design and planning. In the base case, we assume that the DRI plant is located in Dalarna, central Sweden. According to the estimation from Börjesson (2021), if 50% of the tops and branches supply is allocated to a facility with an annual need of 200,000 t db., a transport distance is of up to 72 km. The estimation is based on the gross potential of tops and branches derived from forest impact assessments in 2015 (SKA-15) by the Swedish Forest Agency (Börjesson, 2021). Given the plant design capacity of 500 kt DRI/yr, around 330 kt db. Tops and branches will be needed for the proposed facility. The required forest biomass is equivalent to 1.7 TWh/yr or around 4–7% of tops and branches potential in Sweden. For the assumed plant capacity, an average transport distance could be around 100 km, assuming 50% of tops and branches is available. In this study, the average biomass transport distance of 200 km assumed is therefore considered a conservative assumption.

The geographical density of each raw material differs between different counties, which in turn affects transport distances. Thus, locating a DRI plant in another county with a lower potential and geographical density of biomass residues requires a longer transport distance of biomass. The impact of changing biomass transport distance, ranging from 100 to 300 km (represented by the error bar), is presented in Fig. A4 (Supplementary Material), assuming a homogeneous distribution of tops and branches. The GWP could increase linearly by 0.8% per additional 10 km of biomass transport distance compared to the base case. Further supply chain optimisation based on biomass potential will be needed to minimise the CO_2 emission-based facility location.

Hypothetically speaking, if the current steel production of 4.7 million tonnes of crude steel in Sweden (Nurdiawati and Urban, 2021) are entirely converted to the proposed biomass-DRI route and assuming 100% DRI charged to EAF, 16 TWh of biomass/yr would be needed, or equal to 40–67% of the GROT potential in Sweden. However, the adoption of the biosyngas-DRI-EAF route would depend very much on the future demand for steel, scrap availability, the development of other iron and steelmaking technologies and their related commercial viability, as well as socio-political considerations. Additionally, the availability of forest biomass for the steel sector could be influenced by the increased competition for biomass with other energy and industrial sectors. However, this and related economic considerations are outside the scope of this study.

5. The impact of forest residue harvesting on soil organic carbon (SOC) stock changes

Soil organic carbon (SOC) stock changes can be a major impact of land use change (LUC) associated with bioenergy feedstock production. When forest biomass is left to decompose in the soil, a part of the carbon in the biomass goes into the soil and could increase SOC. Therefore, harvesting the forest biomass residues could reduce SOC, and this may influence the GHG balance of a biofuel. Meta-analyses evaluating the effects of forest residue removal on soil C stocks have shown diverging results ranging from a slight decrease in soil C (Achat et al., 2015) to no effects (Clarke et al., 2015; Hume et al., 2018; Jurevics et al., 2016). In contrast, direct measurement of mineral soils in the Swedish forests shows increased C stock from 1990 to 2017, despite substantial harvests from the forests (Högberg et al., 2021). Due to uncertainties and complexities regarding how forest residues harvesting affects SOC dynamics, this section does not quantify the consequences of removing harvesting residues but rather brings up the latest discussion regarding this matter from the currently available literature.

Agostini et al. (2014), in the EU Joint Research Centre (JRC) report, reviewed the available literature on forest bioenergy carbon accounting. The reviewed studies indicated that 'the use of stemwood from dedicated harvest for bioenergy would cause an actual increase in GHG emissions compared to those from fossil fuels in the short-and medium term (decades), while it may start to generate GHG savings only in the long-term (several decades to centuries), provided that the initial assumptions of carbon neutrality of biomass remain valid'. The review further stated that emissions increase in the forest bioenergy systems is however more limited (in size and/or duration) with forest residues.

Several modelling studies have shown that forest residue extraction in conventional forestry can lead to carbon stock changes in the forest, which has an impact on climate change. For instance, Hammar et al. (2015) performed an LCA of harvesting logging residues for bioenergy, using a single-stand perspective (*i.e.,* one field or forest stand). Emissions due to changes in biogenic carbon were evaluated based on a theoretical forest stand in central Sweden (Dalarna), taking into account the current forest growth rate and management of the forest. The study found that the harvest of logging residues gave slightly reduced soil carbon content after 50 years from harvest, but the forest residue system has lower GWP compared to the fossil fuel alternatives.

Much of the SOC modelling studies are based on the stand perspective. At the local scale or stand level, the increased harvest of wood for bioenergy can cause a temporary loss of the carbon stock compared to what would otherwise happen without harvesting (Agostini et al., 2014; Högberg et al., 2021). However, it should be noted that forest dynamics cannot be understood by studying individual trees or a single harvest and subsequent regeneration of the felled trees (Holtsmark, 2012). The abovementioned studies highlighted that lack of methodological consensus related to handling biogenic carbon in climate impact assessments of forestry systems could lead to differences in results.

In the context of fast-changing climate and global warming, modelling and predicting the dynamics of soil carbon stocks in forest ecosystems are vital but challenging. Modelling the dynamics of SOC in the soil is complicated by the fact of numerous influencing parameters, thus there are often assumptions and simplifications that have to be made. A clear evidence base, i.e. direct measurements, thus can provide a more realistic estimate of SOC dynamics, and is needed for informed discussions of best management practices.

Sweden has a long-term Forest Soil Inventory, which sampled forest soil to monitor long-term balance between inputs and losses under the prevailing climate, management or disturbance regime (Nilsson et al., 2015). According to the measurement and compiled data shown in the report by Högberg et al. (2021), in Nordic countries, forest management involving rotational silviculture does not lead to a decrease in the C stock of living tree biomass and the soil. On the contrary, the data from the three Nordic countries (Sweden, Finland and Norway) show that intensive management involving high rates of harvesting, coupled with improved regeneration and other management methods including effective fire suppression, increased the C stock in living tree biomass and the soil during the period of 1990–2017 (Högberg et al., 2021). Sweden has a modest increase in C in soils, above 100 kg C ha^{-1} yr^{-1} over the period according to National Inventory Reports to UNFCCC (United Nations Framework Convention on Climate Change) (Swedish Environmental Protection Agency, 2022).

Evidence-based measurements thus show that so far mineral soils in the Swedish forests on average sequester carbon, despite substantial harvests from the forests (P. Högberg, personal communication, September 6, 2022). This is also due to the fact that Swedish and Nordic forest has a high growth rate, mainly as a result of management. The modelling study in the currently available literature so far is limited based on current forestry management and climate conditions, meaning that besides model uncertainties, the results do not consider future management changes or changing practices in the forestry system (Karlsson et al., 2021). The majority of the reviewed literature above concluded that the extraction of forest residues like tops and branches has a relatively limited impact on SOC stock changes. This section particularly highlights the importance of sustainable forest management systems in preventing or lowering the potential adverse impact of extracting forest biomass.

6. Conclusions and future works

The LCA of the novel steelmaking process of the biosyngas DRI-EAF routes is studied in this work based on the Swedish context. Under the assumption that no burdens are allocated to forest residue as feedstock, the proposed biosyngas DRI system has an estimated cradle-to-gate GWP of 251 kg CO_2/t crude steel, of which around 80% stems from upstream emissions. The biosyngas-DRI-EAF route could reduce the value of GWP from steelmaking by 75% compared to NG-DRI-EAF and 85% compared to BF-BOF routes on a cradle-to-gate basis, while exhibiting a comparable climate impact with H_2-DRI-EAF route.

Our findings show that the biosyngas-DRI-EAF route outperforms the conventional BF-BOF in most selected non-climate change-related impact categories (ozone formation, acidification, eutrophication and resource use-fossil), with the exception of resource use of metals and minerals. For the biosyngas-DRI-EAF route, electricity generation and distribution is major contributor to the metal depletion impact, which highlights the need to enlarge the scope of current environmental assessments beyond climate change to avoid potential undesirable side-effects. This study, nevertheless, has some limitations related to the inventory emission data for emerging processes that has not been commercialised yet. More detailed modelling on DRI-EAF and direct measurement of GHG emissions from such facilities in the future will be needed to address this limitation.

The proposed biosyngas DRI production route inherently enables the production of pure CO_2 ready for transport/use, thereby creating substantive opportunity to produce carbon-negative steel once the CO_2 is permanently stored. The combination of biosyngas-DRI-EAF process and CCS resulted in net negative emissions, estimated at −845 kg CO_2 eq./t crude steel for our selected system boundary. Around 425 kt of permanently negative emissions per year could be obtained from the proposed system. Aiming towards net negative emissions after 2045, Sweden is currently looking into policy instruments and economic incentives to implement BECCS in industry. This could incentivise further development of the proposed system. While CO_2-negative steel is technically possible, it will need substantial changes along the supply chain: sustainable biomass, a high-efficiency gasification process, and infrastructure for CO_2 transport and storage. A consistent policy framework and long-term vision related to the utilisation of forest residues and biomass in general for bioenergy purposes are paramount.

Soil organic carbon (SOC) stock changes could influence the climate assessments of forest residue-based bioenergy systems. However, despite large variability in the impacts of forest residue removal (branches, stumps, foliage or combination of these items) on soil organic matter in the currently available literature, the removal of only tops and branches could have a more limited impact on SOC, especially in the long-term perspective. The complexity of forest dynamics could lead to uncertainties in GHG estimates. Future research could focus on the more robust SOC modelling and assessment of climate impacts over time, i.e., time-dynamic LCA.

Extracting forest residues and converting them to biosyngas would produce high biogenic CO_2 emissions, although this CO_2 would otherwise be released over a longer time period through decomposition if they are just being left in the forest. Under the condition that the forest is sustainably managed, forest residue may better be used as a feedstock to biosyngas than left unharvested to decay in forests while at the same time maintaining the fossil-based iron and steelmaking. The biomass energy that would be required to produce biosyngas-based DRI with a capacity of 500 kt/yr is around 330 kt db./yr (1.7 TWh/yr). Technically, that biomass needs is equivalent to around 4–7% of tops and branches (GROT) potential from final felling in Sweden.

The results of the LCA show that the proposed biosyngas-based DRI technologies represent an alternative with significantly lower environmental impacts than other existing processes, thereby supporting its adoption as cleaner technologies to produce fossil-free steel. The proposed biosyngas-based DRI technologies supports the achievement of a net-zero climate target, providing the possibility for net negative GHG emissions. Furthermore, the results can help to determining the key factors, i.e., identify environmental hot spots, affecting the environmental impact of the proposed technology.

Credit author statement

Anissa Nurdiawati: Conceptualization, Methodology, Investigation, Formal analysis, Software, Writing – original draft, Visualization, Writing- Reviewing and Editing. **Ilman Nuran Zaini**: Methodology, Investigation, Writing- Reviewing and Editing. **Wenjing Wei**: Methodology, Writing- Reviewing and Editing. **Rutger Gyllenram**: Conceptualization, Writing- Reviewing and Editing, Project administration, Funding acquisition. **Weihong Yang**: Conceptualization, Writing-Reviewing and Editing. **Peter Samuelsson**: Conceptualization, Writing-Reviewing and Editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is provided in the Supplementary Material.

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Appendix A. Supplementary data

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