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Can bioenergy with carbon capture and storage result in carbon negative steel?

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ABSTRACT

This paper explores the potential of achieving negative emissions in steelmaking by introducing bioenergy with carbon capture and storage (BECCS) in multiple steelmaking routes, including blast furnace and HIsarna smelt reduction, and Midrex and ULCORED direct reduction. Process modelling and life cycle assessment were used to estimate CO_2 balances for 45 cases.

Without bioenergy or CCS, the estimated life cycle CO_2 emissions for steelmaking were 1.3–2.4 t CO_2/t steel. In our model, aggressive BECCS deployment decreased net CO_2 to the order of −0.5 t to 0.1 t CO_2/t steel. CCS showed a larger mitigation potential than bioenergy, but combined deployment was most effective.

As BECCS use increased, CO_2 from background supply chains became more relevant. In the high BECCS cases, if decarbonized electricity is assumed, net CO_2 estimates decreased by 400 − 600 kg CO_2/t steel. Conversely, at 700 g CO_2/kWh, all cases appeared to be net CO_2-positive. Accounting for the "carbon debt" of biomass, beyond biomass supply chain emissions, increased net CO_2 estimates by approximately 300 kg CO_2eq/t steel.

We conclude that CO_2-negative steel is possible, but will require significant interventions throughout the production chain, including sustainable biomass cultivation; efficient steel production; CO_2 capture throughout steel and bioenergy production; permanent storage of captured CO_2; and rigorous monitoring.

1. Introduction

Preventing catastrophic climate change requires the rapid and immediate decarbonization of human activities to sharply reverse the current trajectory of increasing greenhouse gas emissions, likely even beyond carbon neutrality (IPCC, 2014). Indeed, all scenarios limiting global warming to 1.5 °C in the IPCC special report entailed global net negative greenhouse gas emissions within the next 50 years (IPCC, 2018). Negative emissions are intended to both remove historic CO_2 from the atmosphere and to compensate for continued residual emissions. In the IPCC 1.5 °C scenarios, these negative emissions result from agriculture, forestry, land use change, and from the use of bioenergy and carbon capture and storage (BECCS).

As illustrated in Fig. 1, BECCS involves the uptake of atmospheric carbon by biomass, which is later combusted for energy, and the resulting biogenic CO_2 is captured and sent to permanent storage. Achieving negative CO_2 emissions requires the physical removal of CO_2 from the atmosphere followed by permanently preventing that CO_2 from re-entering the atmosphere. Furthermore, any emissions resulting from the process of removal and storage, (e.g. from losses, energy use, biomass production, land use change, infrastructure construction, production of combustible co-products) must be accounted for. To result in a decrease of atmospheric CO_2, the net carbon balance of the entire negative emission technology system must be negative (Tanzer and Ramírez, 2019).

The IPCC 1.5 °C scenarios include 100–1100 Gt CO_2 of cumulative negative emissions through the end of the century. The interquartile range of scenarios assume large-scale BECCS use beginning in 2030 and scaling up to 7–16 Gt CO_2/yr by 2100. However, the feasible scale of negative emissions is under debate from both biophysical and technoeconomic perspectives (e.g. Smith et al., 2015; Smith and Torn, 2013). Furthermore, top-down decarbonization scenarios typically do not consider *where* BECCS could feasibly be incorporated. Decarbonization scenarios allocate BECCS use to power sector (IPCC, 2018), to an unspecified combination of power and industry (IPCC, 2014; UNEP, 2017; Kriegler et al., 2014; Millar et al., 2017), or to power and transport fuel production (Muratori et al., 2017). The IEA (2017) is more specific, allocating 4.5 Gt of cumulative CO_2 reductions to 2060 from BECCS use in the industrial sector and 15 Gt in power.

Many studies have focused on the design, economics, and

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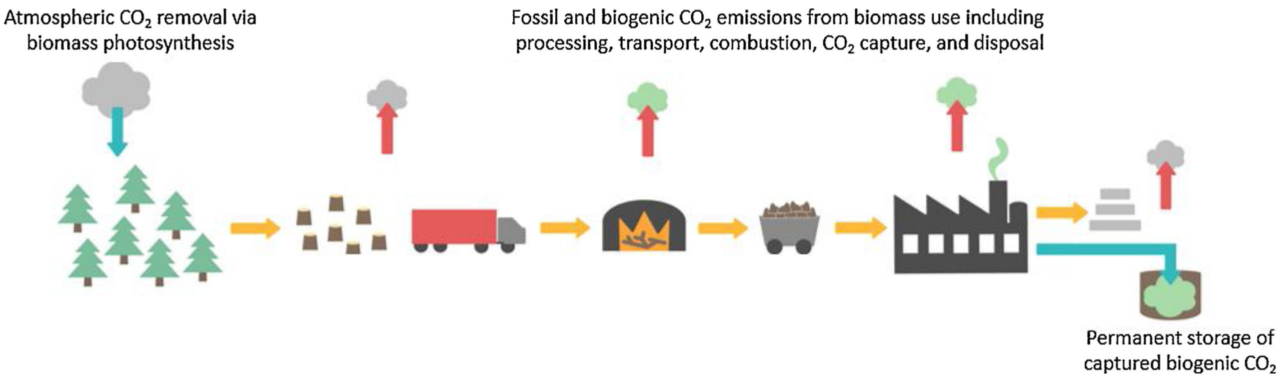


Fig. 1. Bioenergy and CCS (BECCS), simplified. Negative CO_2 emissions can result when the quantity of atmospheric CO_2 removed and stored is greater than the CO_2 emissions of the bioenergy and CCS supply chains. Adapted from Tanzer and Ramírez (2019).

environmental impacts of BECCS in power (e.g. Meerman et al., 2013; Schakel et al., 2014; Mac Dowell and Fajardy, 2017). A demonstration-scale power plant using bioenergy with carbon capture has recently come online the UK (Drax Group plc, 2019), though the fate of the captured CO_2 is still undecided. If the CO_2 is reused for short-lived applications, such as fuel, fertilizer, or carbonated beverages, it will be re-emitted to the atmosphere, and therefore cannot result in negative emissions.

In industry, there is already an extant BECCS installation: a bioethanol plant with integrated CCS in Illinois, USA (Office of Fossil Energy, 2017). Industries, such as steel, cement, ethanol, and ammonia emit CO_2 directly in processes such as combustion, reduction, calcination, and fermentation. Additionally, these industries are responsible for indirect CO_2 emissions from electricity use, which vary depending on the level of electrification of the specific industrial installation and the CO_2 intensity of the electricity provision. Further CO_2 emissions arise in upstream and downstream supply chains. Therefore, the technical viability of BECCS or other negative emission technologies must be evaluated for individual industrial configurations.

Steel is the largest industrial emitter of CO_2, directly emitting 2.1 Gt of CO_2 globally in 2010 (Fischedick et al., 2014), primarily from the combustion of 1000 Mt of coal (World Steel Association, 2019). Decarbonization options for steel include increasing the efficiency of existing carbon-based iron-reduction (DOE, 2015), reducing iron using hydrogen, or electrolysis of iron using renewable energy (Quader et al., 2016 Abdul Quader et al., 2016), all of which could move steelmaking towards carbon neutrality. However, BECCS is the only substantive opportunity to integrate atmospheric carbon removal and storage into steelmaking, and thus the only substantive opportunity to produce carbon-negative steel. Steelmaking slag does contain an alkali fraction that could be carbonated by atmospheric CO_2, but due to its uncertain and relatively low carbon storage potential ($0.1 - 0.6$ kg CO_2/kg slag) (Renforth, 2019; Huijgen et al., 2005), slag carbonation was not included in this study.

Currently, there is little knowledge available on the use of BECCS or other negative emission technologies in the steel industry. However, bioenergy and CCS use are both existing concepts in steel production. The partial replacement of blast furnace coal with charcoal is an established procedure in Brazilian steelmaking (Sonter et al., 2015). Charcoal has also been shown to be a viable partial replacement for fuel used in ore agglomeration and coke making processes (Suopajärvi et al., 2018).

The use of carbon capture at steel mills is in early commercialization, with approximately 1.0 Mt of fossil CO_2 per year captured at Emirates Steel in the United Arab Emirates, ArcelorMittal in Belgium, and Shougang Steel in China, though in all cases, the CO_2 is destined for reuse in other industries (Global CCS institute, 2018). Reuse of captured CO_2, also called CO_2 utilization or carbon capture and utilization (CCU) can reduce CO_2 emissions by displacing the need to produce the carbon-based products by other means, but unless it results in long-term storage, CO_2 reuse will result in net positive CO_2 emissions.

As of April 2020, the only publicly available research on specific BECCS configurations in steel production is Mandova et al. (2019). The authors consider cost-optimized BECCS scenarios for 30 blast furnace steel plants in Europe, concluding that BECCS could be used to achieve carbon neutrality within the boundaries of the steel mill itself. However, as the paper notes, a gate-to-gate CO_2 assessment is insufficient to determine whether negative emissions can be achieved. Our work further fills this knowledge gap by expanding the system of consideration to encompass the cradle-to-grave supply chains of steel, bioenergy, and CCS, and including steelmaking technologies beyond the blast furnace.

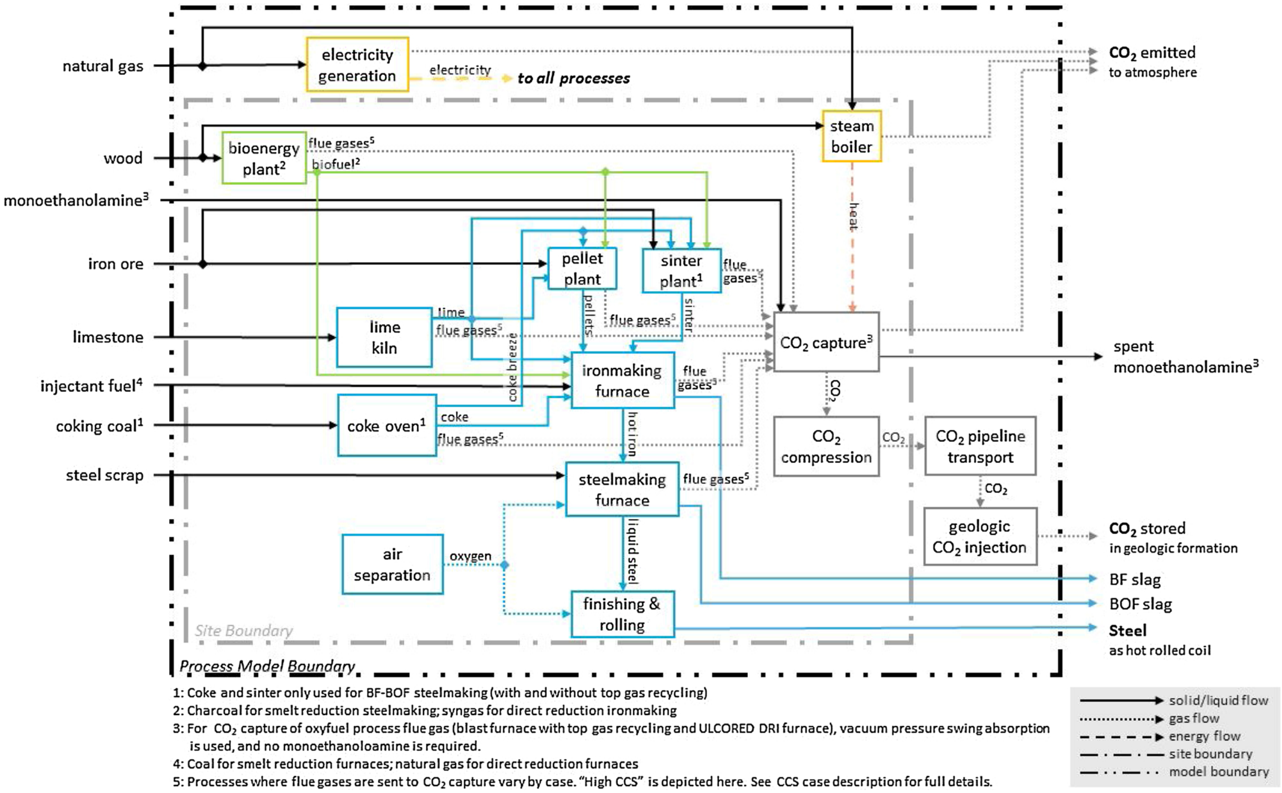
This paper estimates a first-order decarbonization potential of BECCS-in-steel as part of a larger research project investigating the scale on which carbon-negative industries could contribute to global decarbonization. The intention is not to provide a comprehensive or optimized assessment of BECCS-in-steel configurations, but rather to explore the possibility and scale of negative emissions in commercial and emerging steelmaking technologies.

This paper considers the integration of BECCS into several steelmaking technologies, including the commercial technologies of blast furnace ironmaking with basic oxygen furnace steelmaking (BF-BOF) and Midrex direct reduction of iron with electric arc furnace ironmaking (DRI-EAF), as well as the novel technologies of BF-BOF steelmaking with top gas recycling, HIsarna ironmaking with BOF steelmaking, and ULCORED DRI-EAF. For each technology, we estimated life cycle CO_2 emissions for nine cases of wood-based bioenergy use and CCS. To allow for a more equal basis of comparison, all technologies were modeled as if they are available on a commercial scale, regardless of their current state. Each case assumed that the steel mill was situated in a generic western European site. This “what if 2050 technology were available today” scenario ignores potential changes in the background supply chains (such as biomass production or electricity generation) that may also occur towards 2050, to reduce the potential confounding effects of additional uncertainty in these systems. A series of sensitivity analyses explore the significance of these background systems, and other model assumptions, to understand what changes may need to be made if BECCS-in-steel is to be implemented on a large scale in the decades to come.

2. Methodology

To achieve carbon negative steel, three things must occur:

1 Fossil sources of carbon must be replaced with atmospheric sources of carbon. E.g., carbon removed from the atmosphere via the by photosynthesis of biomass.
2 The removed atmospheric carbon must be permanently prevented from returning to the atmosphere. E.g., by the capture and geologic



1: Coke and sinter only used for BF-BOF steelmaking (with and without top gas recycling)
2: Charcoal for smelt reduction steelmaking; syngas for direct reduction ironmaking
3: For CO_2 capture of oxyfuel process flue gas (blast furnace with top gas recycling and ULCORED DRI furnace), vacuum pressure swing absorption is used, and no monoethanoloamine is required.
4: Coal for smelt reduction furnaces; natural gas for direct reduction furnaces
5: Processes where flue gases are sent to CO_2 capture vary by case. "High CCS" is depicted here. See CCS case description for full details.

Fig. 2. Process model with system boundaries, including bioenergy and CCS use.

storage of CO_2 produced from the combustion of biomass.

3 CO_2 emissions elsewhere in the supply chains of steelmaking, atmospheric carbon removal, and CCS cannot exceed the atmospheric carbon removed and permanently stored.

Thus, to explore the possibility of negative CO_2 emissions, it is necessary to consider the carbon balance over the complete life cycle of the technology under consideration. Therefore, we constructed a process model that included steel production, biofuel processing, CO_2 capture and storage, and electricity generation. We used the resulting mass balances to estimate upstream and downstream CO_2 removals and emissions using generalized data from a life cycle inventory database. Together, the CO_2 removals and CO_2 emissions of the cradle-to-grave steel life cycle were used to estimate the overall CO_2 balance for each technology.

Our process models were designed to estimate the material and energy inflows, product and waste outflows, and direct CO_2 emissions for each case of steelmaking technology, bioenergy, and CCS use. The boundaries and flows of the model are summarized in Fig. 2. These models included the iron and steel furnaces, steel rolling plant, electricity generation and, as needed, lime kilns, coke ovens, ore agglomeration, and/or air separation. Biofuel processing was included in the bioenergy cases, and the CCS cases additionally included CO_2 capture, compression, transport, injection into geological storage, and associated energy production.

Initially, the five steelmaking technologies were modeled without any bioenergy or CCS as a baseline case. Then, for each technology, we considered cases of limited and high bioenergy use and limited and high CCS. These 45 cases were analyzed to explore the impact of steelmaking technology, bioenergy use, and CCS use on the CO_2 balances. A series of sensitivity analyses further explored key assumptions in the model, including electricity generation, steam boiler efficiency, CO_2 transport distance, methane emissions, carbon debt of biomass, steel composition, and biofuel production efficiency.

Section 2.1 describes the process models for each steelmaking technology. Section 2.2 describes the bioenergy and CCS cases with their relevant model changes. Finally, Section 2.3 describes the life cycle CO_2 accounting methods.

2.1. Steelmaking process models

For each case, process models estimate the inflows and outflows of the production of hot rolled coil (HRC) of carbon steel. A custom python model was built to calculate mass balances for each of the unit processes shown in Fig. 2, linking the process flows to generate mass balances for the steel plant as a whole. The models used fixed ratios of inputs and outputs based on pre-existing literature models, as detailed in the technology descriptions below. The models focus on flows of metal, carbonaceous materials, and energy carriers. While they do not extensively account for chemical reactions or enthalpy flows within individual processes, these models allows for a standardized comparison of a greater number of configurations, thus to explore the impacts of different system configurations on the overall CO_2 balance of emerging technologies.

For each technology, the process models assumed commercial-scale production, using efficiencies from modern western European steelmaking. The ironmaking process is unique for each technology and they are described in Section 2.1.1. As much as possible, auxiliary processes, detailed in Section 2.1.3, used the same data sources and assumptions for all technologies, to increase the comparability of the results. Additionally, the energy content and emission factors of fuels were standardized, using factors from the IPCC (2019), shown in Table 1. Fuel was assumed to be fully combusted. Similarly, limestone and other carbonated fluxes were assumed to be fully calcinated. In all cases, the reference data and assumptions were verified with additional literature, as noted throughout the following sections.

Modern steel mills recycle waste heat and combustible offgases to satisfy the heat demand of endothermic processes, with blast furnace gases typically providing about 5 GJ/t HRC (Joint Research Centre, 2010). Commonly, the offgas energy exceeds the process heat demand,

Table 1
Energy contents and emission factors of fuels used in this model. (IPCC, 2019)

Fuel type	GJ/t	kg CO_2/GJ
coking coal	28.2	94.7
bituminous coal	25.8	96.1
natural gas	48.0	56.0
charcoal	29.5	111.9

and is used to co-generate electricity or exported (IEAGHG, 2013; Joint Research Centre, 2010). To maintain the comparability of the models, the reuse of offgases in steel mill processes was kept in alignment with the reference models, but co-generation of electricity or export heat was disregarded. All electricity was assumed to be imported from the grid. The integration of bioenergy and CO_2 capture was assumed to not impact the existing heat integration. Any additional heat required by CO_2 capture or bioenergy processes was assumed to be produced via an independently-fired steam boiler.

2.1.1. Ironmaking technologies

The primary characteristics of the five ironmaking technologies are summarized in Table 2, including inflows of fuels, electricity, iron ore pellets and sinter, oxygen, and flux. The features of each technology are discussed in Sections 2.1.1.1 to 2.1.1.5. Full reduction of iron was assumed, and the hot iron was assumed to be immediately converted to to steel in a steelmaking furnace with an inflow of 83% hot metal and 17% scrap steel. The unalloyed liquid steel was then cast and rolled, exiting the steel mill as hot rolled coil.

2.1.1.1. Blast furnace ironmaking. In the modern blast furnace steelmaking process, powdered iron ore is agglomerated into pellets and/or sinter. The agglomerated ore is combined in the blast furnace at 1600 − 2000 °C with coke as the primary energy source and reducing agent. Fluxes of lime, limestone, and/or dolomite are used to remove impurities, such as sulfur. Pulverized coal injection (PCI) and supplemental oxygen are commonly used to increase productivity and reduce coke demand. Less commonly, natural gas, oil, waste plastic, or charcoal is injected instead of pulverized coal (Joint Research Centre, 2010). The resulting liquid iron, containing 3–5% of carbon, is sent to a basic oxygen furnace (BOF) for steelmaking. The BF-BOF process is responsible for 70% of global steel production, with CO_2 emissions of 2.0–3.0 t CO_2/t steel (Hasanbeigi et al., 2016)

Our BF-BOF model is based on the reference design in IEAGHG (2013), whose parameters are summarized in Table 2. Fuel use aligns with the average EU blast furnace fuel consumption reported in the *Best Available Techniques Reference Document for Iron and Steel* (Joint Research Centre, 2010), though Kurunov (2010) and Lungen and Schole (2019) report fuel use of 300 kg coke and 200 kg pulverized coal. The ore burden is also in line with the Joint Research Centre (2010), and both higher and lower fractions of pellet use is reported in Lungen and Schole (2019).

2.1.1.2. Blast furnace ironmaking with top gas recycling. Top gas recycling (TGR) is an emerging technology to reduce the demand for fresh coke and coal in a standard blast furnace by recycling its offgases back into the furnace, supplemented with oxygen to increase combustion efficiency. The offgases contain uncombusted CO and H_2 and typically have an energy content of 2.7–4.0 MJ/Nm^3 (Joint Research Centre, 2010). Their reinjection can reduce the demand for fresh coke and coal. In pilot tests at Tata Steel in IJmuiden, the Netherlands, the use of TGR reduced blast furnace coke demand from 360 to 230 kg per tonne of iron (Stel et al., 2014). The parameters in the commercial-scale model of TGR ironmaking in IEAGHG (2013), shown in Table 2, were used in this model and are aligned with the pilot test results in Stel et al. (2014).

2.1.1.3. HIsarna smelt reduction of iron. HIsarna ironmaking uses a multi-stage furnace with an oxygen environment and counterflow of combustible gases to maintain smelting temperatures. This allows for the use of low-quality coal and iron pellets or fines, rather than coke and sinter. The resulting liquid iron is essentially the same as from a blast furnace and can be processed to steel in a basic oxygen furnace (Meijer et al., 2015). The HIsarna model in this study is based on the published results of pilot testing (Meijer et al., 2015), as well as communication with a research manager at Tata Steel. The pilot tests were conducted with a 40 kt/yr furnace at Tata Steel in IJmuiden, Netherlands. The construction of a 500 kt/yr HIsarna demonstration plant in Jamshedspur, India was announced at the end of 2018 (Waard, 2018).

In the pilot tests, 750 kg coal was needed per tonne of iron, as the small furnace size led to energy losses of 26% (Meijer et al., 2015). A commercial 1 Mt/yr HIsarna furnace is expected to reduce heat loss to 11% (Meijer et al., 2015), and this higher efficiency was used in this model. The oxygen demand and iron ore demand, in Table 2, have been kept the same as in the pilot testing, with additional data from Tata steel.

2.1.1.4. Midrex direct reduction of iron. Direct reduction of iron (DRI) accounted for 7% (89 mt) of global steel production in 2017 (World Steel Association, 2018). DRI reduces iron ore without liquefaction, producing a porous solid form known as sponge iron. DRI requires less energy than blast furnace iron reduction (DOE, 2015), but sponge iron is unstable and is typically processed to steel in electric arc furnaces (EAF).

Globally, over 60% of DRI uses the Midrex process (Midrex Technologies, 2019), which typically uses natural gas or a syngas produced from coal or other steelmaking offgases. The fuel gas is converted into a H_2 and CO rich reducing gas via a reformer, which is also used to recycle furnace gases. The model in this study, whose primary parameters are in Table 2, was based on the Midrex model from Lockwood Greene Technologies (2000). This model has slightly higher energy use ($< +1.0$ GJ/t iron) than DOE (2015) or Joint Research Centre (2010), but was the most complete reference model available.

2.1.1.5. ULCORED direct reduction of iron. ULCORED is a proposed DRI furnace with an oxygen environment and uses partial oxidation to prepare the furnace gas. The offgases from the ULCORED furnace are expected to be nearly pure CO_2, and CO_2 removal is integrated into the design of the gas recycling process. This technology has been modeled in simulation. Pilot testing has been proposed by ULCOS and LKAB but has not begun (IEA, 2017). The model in this study follows the ULCORED model detailed in Sikstrom (2013), with parameters in Table 2.

2.1.2. Steelmaking

Liquid iron from smelt reduction ironmaking is converted into steel in a basic oxygen furnace (BOF). Sponge iron from DRI is sent to an electric arc furnace (EAF), which melts it prior to its conversion into steel. In both BOF and EAF furnaces, oxygen is injected to reduce the steel's carbon content. Steel scrap, iron, and/or fluxes are added to the steelmaking furnace to control the composition. In all models a 17% scrap rate was assumed, following IEAGHG (2013). Afterwards, the liquid crude steel is sent for alloying and shaping. Our study assumes the production of hot rolled coil of pure carbon steel, without any alloying metals. The parameters of steelmaking and finishing are given in Table 3.

2.1.3. Auxiliary processes

The model for each steel production route included the production of coke, pellets, sinter, lime, oxygen, and electricity. In reality, steel

Table 2
Summary of input parameters for ironmaking furnace models.

	BLAST FURNACE	BLAST FURNACE WITH TOP GAS RECYCLING	HISARNA	MIDREX	ULCORED
Process identifier	BF-BOF	BF-BOF with TGR	HIsarna-BOF	Midrex DRI-EAF	ULCORED DRI-EAF
Furnace type	Smelt reduction	Smelt reduction	Smelt reduction	Direct reduction	Direct reduction
Current status[1]	Fully commercialized	Pilot plant	Demonstration plant	Fully commercialized	Pending pilot testing
Characteristics	Dominant ironmaking technology worldwide	Recycling of blast furnace gas, increasing energy efficiency and concentration of CO_2 in flue gas stream. Can be retrofitted into existing blast furnaces.	Oxygen-fed multistage furnace, allowing the use of lower-grade coal and iron fines	Dominant DRI technology. Efficient on smaller scales than blast furnaces. Uses gaseous fuel as energy source and reducing agent.	Oxygen-fed DRI, with high-purity CO_2 flue gas stream
Steelmaking process	Basic oxygen furnace	Basic oxygen furnace	Basic oxygen furnace	Electric arc furnace	Electric arc furnace
fuel demand, per tonne of iron	355 kg coke and 150 kg pulverized coal (13.9 GJ)	253 kg coke and 150 kg pulverized coal (11.1 GJ)[2]	610 kg bituminous coal (15.7 GJ)[3]	244 kg natural gas (11.7 GJ)	173 kg natural gas (8.3 GJ)
flux demand[2], per tonne of iron	7 kg CaO	3 kg CaO	14 kg CaO	none	none
iron ore burden, per tonne of iron	352 kg pellets and 1120 kg sinter	353 kg pellets and 1096 kg sinter	1700 kg pellets	1640 kg pellets	1330 kg pellets
oxygen demand, per tonne of iron	69 kg	361 kg	1070 kg	0 kg	228 kg
electricity demand, per tonne of iron	104 kWh	35 kWh	104 kWh[4]	130 kWh	60 kWh
data sources	IEAGHG (2013)	IEAGHG (2013)	Meijer et al. (2015), Interview with Tata Steel research manager (26 August 2019)	Lockwood Greene Technologies (2000)	Sikstrom (2013)

[1] : In this paper, all technologies are modelled as if fully commercialized today.
[2] : Flux may enter the furnace in the form of CaO, $CaCO_3$, and/or $CaMg(CO_3)_2$, but has been here standardized to CaO using calcination CO_2 equivalences.
[3] : Based on the estimated consumption of a 1 Mtpa HIsarna plant (Meijer et al., 2015).
[4] : Actual electricity use unknown. Assumed to be the same as in the base blast furnace.

Table 3
Summary of steelmaking process model parameters.

Parameter	Value
BASIC OXYGEN FURNACE STEELMAKING	*per tonne of liquid steel*
liquid iron demand	901 kg
steel scrap demand	190 kg
flux demand (as CaO)	76 kg
oxygen demand	75 kg
electricity demand	20 kWh
data source	IEAGHG (2013)
ELECTRIC ARC FURNACE STEELMAKING	*per tonne of liquid steel*
sponge iron demand	901 kg
steel scrap demand	190 kg
flux demand (as CaO)	12 kg
oxygen demand	15 kg
fuel demand	21 kg natural gas
electricity demand	698 kWh
data source	Lockwood Greene Technologies (2000)
STEEL FINISHING AND ROLLING	*per tonne of hot rolled coil*
steel losses	74 kg
flux demand (as CaO)	5 kg
oxygen demand	10 kg
electricity demand	141 kWh
data source	IEAGHG (2013)

Table 4
Summary of auxiliary process parameters (from IEAGHG (2013) unless otherwise noted).

Parameter	Value
SMELT FURNACE PELLET PRODUCTION	*per tonne of pellet*
fuel demand	0.7 GJ bituminous coal
flux demand	19 kg
electricity demand	75 kWh
DRI FURNACE PELLET PRODUCTION	*per tonne of pellet*
based on Lockwood Greene Technologies (2000)	
fuel demand	1.3 GJ natural gas
flux demand	14 kg
electricity demand	70 kWh
SINTER PRODUCTION	*per tonne of sinter*
fuel demand	1.8 GJ coke breeze
flux demand	75 kg
electricity demand	32 kWh
LIME PRODUCTION	*per tonne of lime*
electricity demand	30 kWh
COKE PRODUCTION	*per tonne of coke*
coking efficiency	78%
electricity demand	35 kWh
OXYGEN PRODUCTION	*per tonne of* O_2
electricity demand	385 kWh
ELECTRICITY GENERATION	
fuel type	natural gas
generation efficiency	57%
STEAM HEAT GENERATION	*per GJ of steam*
fuel type	natural gas
combustion efficiency (LHV)	90%
electricity demand	5 kWh

mills may purchase some or all of these products rather than produce them on-site. However, our model internalized these processes to understand their influence on the system. Table 4 lists the parameters used for the auxiliary processes. Values from IEAGHG (2013) were used for as many processes as possible, to increase standardization between cases. The exceptions are the DRI-specific pellet production and EAF steelmaking (Table 3), which are from the Midrex DRI model source, Lockwood Greene Technologies (2000), verified with DOE (2015). The heat demand of these auxiliary processes were assumed to be satisfied via heat integration at the steel mill, in accordance with the reference models. Therefore, the exact distribution of heat was not modeled. It was assumed all electricity was produced using natural gas in a combined cycle power plant. The emission intensity of electricity generation was explored in a sensitivity analysis.

2.2. BECCS cases

The decarbonization potential of BECCS in steelmaking is largely unknown, though several options of biofuel use (Suopajärvi and Fabritius, 2012) and carbon capture (IEAGHG, 2018) are available. Therefore, for each technology, nine cases of bioenergy use and CCS were explored. These included the use of bioenergy alone, the use of CCS alone, the use of both bioenergy and CCS, and a base case of no bioenergy or CCS. Cases of both "limited" and "high" bioenergy use and "limited" and "high" CCS use were included. The limited cases considered only bioenergy use and/or CCS at the iron-making furnace, which is the largest source of CO_2 emissions in the steelmaking process. The high cases consider highly ambitious but still technologically feasible uses of bioenergy and CCS. The bioenergy cases are summarized in Table 5 and the CCS cases in Table 6.

2.2.1. Bioenergy use

In BF-BOF steelmaking, the replacement of coal and coke with biofuel is limited by the need to maintain certain mechanical properties to control the burn rate of the fuel. This study uses charcoal replacement rates that likely allow for the quality of the product to be maintained without significant alteration to the production process (Suopajärvi and Fabritius, 2012). For HIsarna steelmaking, bioenergy use cases were based on discussions with a research manager from Tata Steel. All charcoal was assumed to be produced in hot tail kilns, which are used for the charcoal produced for the steel industry in Brazil (Pennise et al., 2001). The model parameters for charcoal production are summarized in Table 7.

For the DRI steelmaking models, a wood-based biosyngas replaced natural gas as the reducing agent in the DRI furnace. Theoretically, Midrex DRI can use 100% syngas; this is already seen with syngas derived from coal, coke oven gas, and other steelmaking offgases (Midrex, 2014). In theory, any fuel gas with a quality ratio of $\frac{\%CO + \%H_2}{\%CO_2 + \%H_2O} > 2$ can be used for DRI, but in practice, a ratio of 11 or higher is desired (Cheeley, 1999). Therefore, a high-purity and high-energy biosyngas was assumed, based on a model of commercialized production of biosyngas intended for Fischer-Tropsch fuel synthesis (Zhu et al., 2011), using the model parameters are summarized in Table 7.

2.2.2. Carbon capture and storage

The model parameters of CO_2 capture are summarized in Table 8. For each steelmaking technology, the CO_2 capture technology and energy use was chosen to align with the differences in process, CO_2 concentration, and available literature, based on IEAGHG (2018). Vacuum pressure swing absorption (VPSA) was assumed for high-concentration CO_2 streams from the oxygen environment furnaces in BF-BOF with TGR, HIsarna, and ULCORED DRI ironmaking, as well as for biosyngas production. For flue gases from all other processes, MEA-based amine scrubbing was used. The limited CCS cases considers the capture of offgases from only the ironmaking, except in the DRI cases with bioenergy use, where CO_2 capture is also applied to the high-purity CO_2 stream in biosyngas production, which only requires compression and transport. In the high CCS cases, all flue gas streams of steel and biofuel production are captured, except those from electricity and steam generation.

Table 5
Cases of bioenergy use cases considered in this study.

Steelmaking Technology	Limited Bioenergy Use (LB)	High Bioenergy Use (HB)
BF-BOF	Replacement of PCI with pulverized charcoal, and 100% replacement of steam boiler natural gas with wood chips	As LB, plus 5% charcoal replacement of coking coal, and 50% replacement of agglomeration coal with charcoal, and 100% replacement of steam boiler natural gas with wood chips
BF-BOF with TGR	Replacement of PCI with pulverized charcoal, and 100% replacement of steam boiler natural gas with wood chips	As LB, plus 5% charcoal replacement of coking coal, 50% replacement of agglomeration fuel with charcoal, and 100% replacement of steam boiler natural gas with wood chips
HIsarna-BOF	20% replacement of furnace coal with charcoal, and 100% replacement of steam boiler fuel with wood chips	45% replacement of furnace coal with charcoal, 50% replacement of agglomeration fuel with charcoal, and 100% replacement of steam boiler natural gas with wood chips
MIDREX DRI-EAF	50% replacement of DRI natural gas with wood biosyngas, and 100% replacement of steam boiler natural gas with wood chips	100% replacement of DRI fuel with wood biosyngas, 50% replacement of agglomeration fuel with charcoal, and 100% replacement of steam boiler natural gas with wood chips
ULCORED DRI-EAF	50% replacement of DRI natural gas with wood biosyngas, and 100% replacement of steam boiler natural gas with wood chips	100% replacement of DRI fuel with wood biosyngas, 50% replacement of agglomeration fuel with charcoal, and 100% replacement of steam boiler natural gas with wood chips

Table 6
Cases of CO_2 capture considered in this study.

Steelmaking Technology	Limited CCS (LC)	High CCS (HC)
BF-BOF	Capture of blast furnace gas only	Capture of all steelmaking and charcoal production flue gas streams
BF-BOF with TGR	Capture of blast furnace gas only	Capture of all steelmaking and charcoal production flue gas streams
HIsarna-BOF	Capture of HIsarna furnace gas only	Capture of all steelmaking and charcoal production flue gas streams
Midrex DRI-EAF	Capture of pure CO_2 streams from DRI and biosyngas production only	Capture of all steelmaking and biosyngas production flue gas streams
ULCORED DRI-EAF	Capture of pure CO_2 streams from DRI and biosyngas production only	Capture of all steelmaking and biosyngas production flue gas streams

Table 7
Summary of model parameters for biofuel production.

Parameter	Charcoal Production *(hot tail kiln)*	biosyngas production *(Fischer-Tropsch synthesis quality)*
Feedstock demand *(per tonne of biofuel)*	1520 kg wood (dry basis)	2930 kg wood chips (dry basis)
CO_2 production *(per tonne of biofuel)*	1382 kg (flue gas)	1240 kg (pure) 193 kg (flue gas)
Other inputs *(per tonne of biofuel)*		192 kg O_2 2 kg MEA
biofuel energy content *(per tonne of biofuel)*	29.5 GJ	21.5 GJ
biofuel CO_2 emission factor *(per GJ of biofuel)*	112 kg	65 kg
data source	Pennise et al. (2001)	Zhu et al. (2011)

Some processes, such as the ULCORED DRI gas recycling and biosyngas production produce pure CO_2 streams as part of their process design. In the “no CCS” cases, these pure CO_2 streams are assumed to be vented or used in short-lived products. Therefore, all CO_2 produced within the system boundaries in the “no CCS cases” is treated as emissions.

For all CCS cases, the captured CO_2 was compressed to supercritical conditions, using 90 kWh per tonne of CO_2 (IEAGHG, 2013). The compressed CO_2 was transported 100 km by long-distance pipeline to onshore geologic storage, with a fugitive emission rate of 1% of CO_2 transported (IPCC, 2005), and assuming electricity use of 7 kWh/t CO_2 for repressurization and injection (Khoo and Tan, 2006).

In this study, no specific steel mill location was assumed. As access to suitable storage can vary widely, a sensitivity analysis was performed

Table 8
Summary of model parameters for CO_2 capture.

Parameter	BF-BOF	BF-BOF with TGR	HIsarna	Midrex DRI	ULCORED	Auxiliary Processes[1]
Capture Type	MEA-based amine scrubbing	VPSA	VPSA	MEA-based amine scrubbing	VPSA	MEA-based amine scrubbing
CO_2 Capture Rate[2]	90%	90%	90%	90%	90%	90%
Electricity Demand	136 kWh	172 kWh	127 kWh	136 kWh	Included[3]	136 kWh
Heat Demand	3.0 GJ	0	0	3.0 GJ	Included[3]	3.0 GJ
Monoethanolamine demand	1.0 kg	n.a.	n.a.	1.0 kg	Included[3]	1.0 kg
Data Source	IEAGHG (2013)	Ho et al. (2013)	Ho et al. (2013)	IEAGHG (2013)	Sikstrom (2013)	IEAGHG (2013)

[1] : In the high-capture case, streams of lower-concentration CO_2 from auxiliary processes (e.g. the coke oven, lime kilns, and charcoal production) were modeled to be processed using MEA-based amine scrubbing, with the same parameters as that of BF-BOF flue gas assumed. For biosyngas production, VPSA was assumed.

[2] : Percentage of CO_2 in flue gas that is captured.

[3] : VPSA already integrated into ULCORED process, so no additional energy use is required.

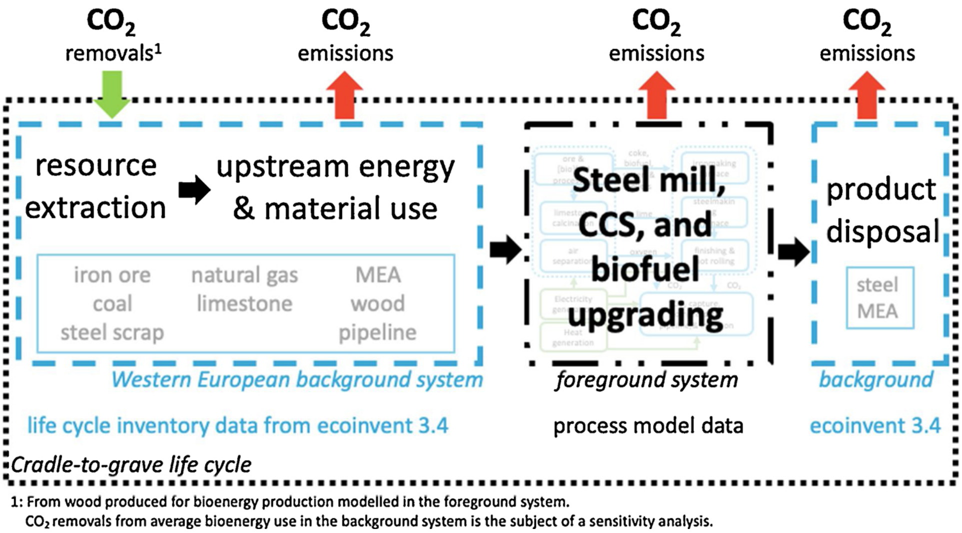


Fig. 3. LCA System Boundaries.

to explore the influence of CO_2 transport distances.

2.3. Life cycle CO_2 emissions

The process models described above were used to estimate the direct CO_2 emissions of the steel mill, as well as CO_2 capture and bioenergy upgrading. Additionally, the emissions of upstream and downstream supply chains were estimated for the system summarized in Fig. 3. The CO_2 emissions of the background system were estimated using life cycle inventory data from ecoinvent 3.5 (Wernet et al., 2016).

This study included the emissions of CO_2 from fossil and biogenic sources and CO_2 emissions attributed to land transformation. Removals of CO_2 from the atmosphere were also included for biomass production. Table 9 summarizes the main upstream CO_2 inventory data used for this study. The influence of CH_4 emissions was considered in a sensitivity analysis, as was the impact of delayed carbon reuptake for biogenic CO_2 emissions, so called carbon debt. These and a number of other sensitivity analyses explore the influence of the configuration assumptions in the outcomes of this study.

3. Results

This study modeled the life cycle CO_2 balances of two commercialized and three emerging steelmaking technologies considering different cases of bioenergy use and carbon capture with permanent storage. The main results, using the initial model parameters are presented first, follow by the sensitivity analyses. Numerical results of CO_2 production, emissions, removals, and storage for all cases are available in the supplemental information.

For clarity, only net life cycle CO_2 balances are presented in t CO_2/t HRC. All other quantities are presented in kg CO_2. All quantities are rounded to the nearest 100 kg (0.1 t) to maintain a consistent level of detail.

Table 9
Upstream LCI data, from ecoinvent 3.5 (Wernet et al., 2016).

Substance	CO_2 Emissions
iron ore	63 kg CO_2/t iron ore
$CaCO_3$	5 kg CO_2/t $CaCO_3$
steel scrap	121 kg CO_2/t steel scrap
hot rolled coil, disposal	9 kg CO_2/t hot rolled coil
coal, bituminous	201 kg CO_2/t coal
coal, coking	241 kg CO_2/t coal
natural gas	356 kg CO_2/t natural gas
wood chips[1]	38 kg CO_2/t wood (dry)
dry cleft timber[1]	33 kg CO_2/t wood (dry)
monoethanolamine	4581 kg CO_2/t MEA
CO_2 transport[2]	0.1 kg CO_2/tkm
Substance	**Atmospheric CO_2 Removals**
wood chips	1810 kg CO_2/t wood (dry)
dry cleft timber	1810 kg CO_2/t wood (dry)

1: Excludes carbon debt

3.1. Overall results

Fig. 4 presents the estimated life cycle CO_2 balances for each case of technology, bioenergy, and CCS modeled using our base assumptions. Without any bioenergy use or CCS, BF-BOF steelmaking has estimated life cycle emissions of 2.4 t CO_2/t HRC, of which 1400 kg/t HRC are from the blast furnace. The addition of TGR to the BF-BOF model decreased estimated furnace emissions to 1100 kg CO_2/t HRC and life cycle emissions to 2.0 t CO_2/t HRC. For HIsarna-BOF, which has fewer auxiliary processes, life cycle emissions are 2.1 t CO_2/t HRC, of which 1500 kg/t HRC are furnace emissions.

For DRI-EAF steelmaking, estimated life cycle CO_2 emissions without bioenergy or CCS are 1.5 and 1.3 t CO_2/t HRC for Midrex and ULCORED. Ironmaking furnace emissions account for 500–600 kg CO_2/t HRC. In both cases, approximately 400 kg CO_2/t HRC resulted from electricity use, primarily for the electric arc furnace. Overall, electricity use was 1150 kWh/t HRC in DRI-EAF, compared to 300–400 kWh/t HRC for smelt reduction technologies.

For all technologies, upstream emissions are between 200–300 kg CO_2/t HRC, accounting for approximately 15% of the life cycle emissions of smelt reduction steelmaking and 20% for DRI steelmaking. Fuel production is responsible for roughly half of upstream emissions in all cases.

The CO_2 emissions for the baseline cases are within 85–99% accordance with the reference literature, when considered from the same system boundaries, despite having a coarser level of detail. Most of the difference is attributable to the use of harmonized emission factors and auxiliary process efficiencies, which may differ slightly from the reference literature. A comparison of the results of this study with the reference literature and an explanation of the differences are available in the supplemental information.

Next, we considered cases of CCS use without bioenergy. CCS alone results in permanent CO_2 storage, but without the removal of atmospheric carbon cannot result in negative emissions. In smelt reduction steelmaking, the limited CCS cases only captured CO_2 from the

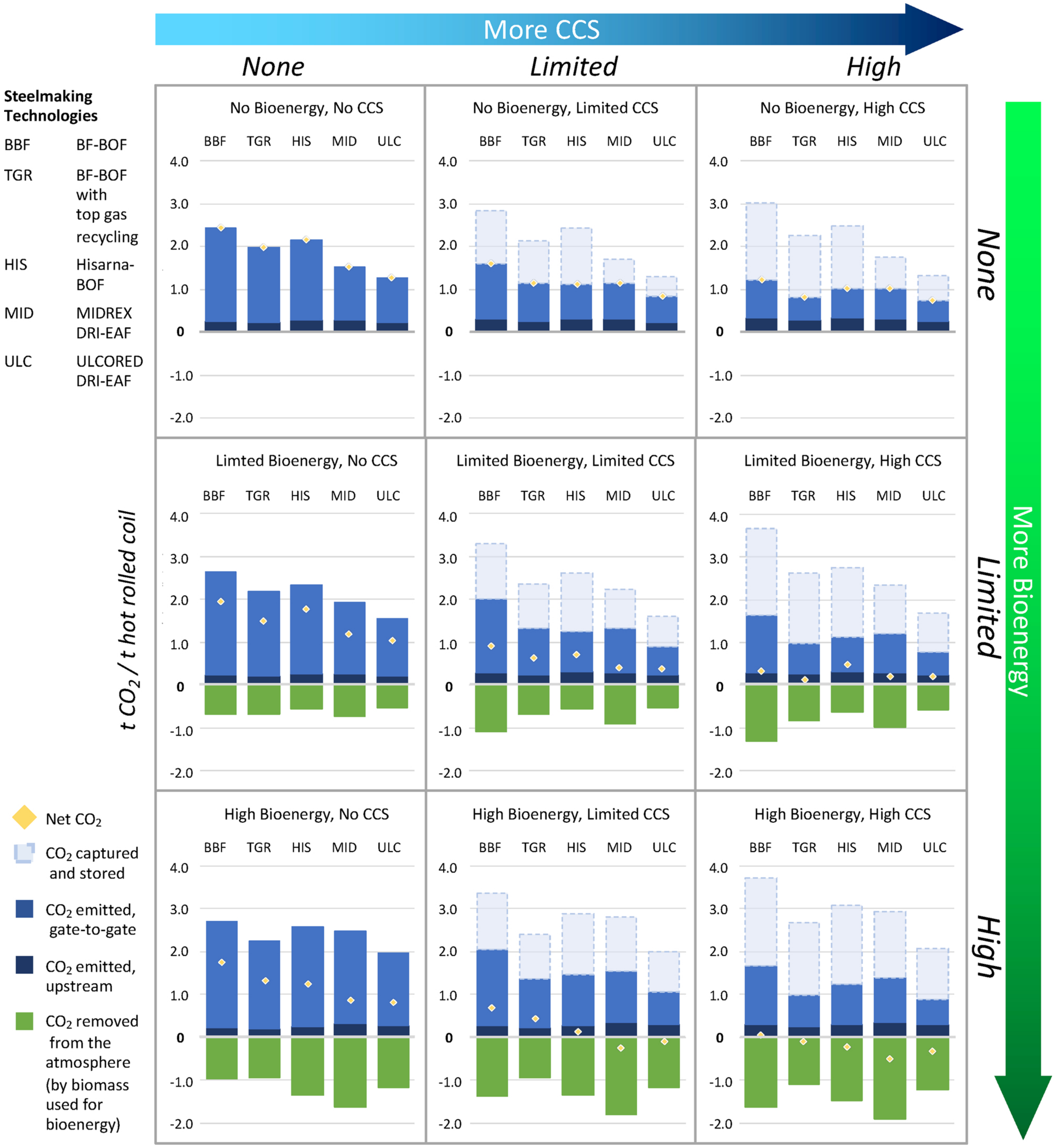


Fig. 4. Estimated life cycle CO_2 of steelmaking by technology and case of bioenergy use and CCS use.

ironmaking furnace and resulted in 1000–1300 kg CO_2/t HRC sent to permanent storage. However, CO_2 production increased by 10% from the baseline case, due to the energy demand of CCS. The net result is 35–50% lower life cycle CO_2 to 1.6 t CO_2/t HRC for BF-BOF and 1.1–1.2 t CO_2/t HRC for BF-BOF with TGR and HIsarna-BOF. For DRI-EAF steelmaking, approximately 500 kg CO_2/t HRC was captured and stored, with total CO_2 production increasing 1–3% and life cycle CO_2 emissions decreasing 25–35% to around 1.0 t CO_2/t HRC.

The high CCS cases applied CO_2 capture to all flue gas streams except steam and electricity production. The additional CCS use, without bioenergy, only further reduced the net life cycle CO_2 significantly for BF-BOF steelmaking, which decreased to 1.2 t CO_2/t HRC without TGR and to 0.8 t CO_2/t HRC with TGR. In all other cases, life cycle CO_2 did not decrease more than 100 kg CO_2/t HRC compared to the limited CCS case. The energy demand of CCS accounts for approximately 90% of additional CO_2 produced. The remaining sources of increased CO_2 production include the transport and storage of CO_2 and the production and disposal of MEA. Overall, the high CCS cases show a 5% increase in CO_2 production for ULCORED steelmaking, a 15% increase MIDREX DRI, BF-BOF with TGR, and HIsarna steelmaking, and a 25% increase for BF-BOF steelmaking; all directly correlated with the throughput of the CO_2 capture unit. Overall, the full integration of CCS into the steel mills reduced estimated gate-to-gate CO_2 emissions by 40–70%, with total life cycle CO_2 emissions decreasing 30–40% for DRI steelmaking and 50–60% for smelt reduction.

In the cases of bioenergy use alone, CO_2 is removed from the

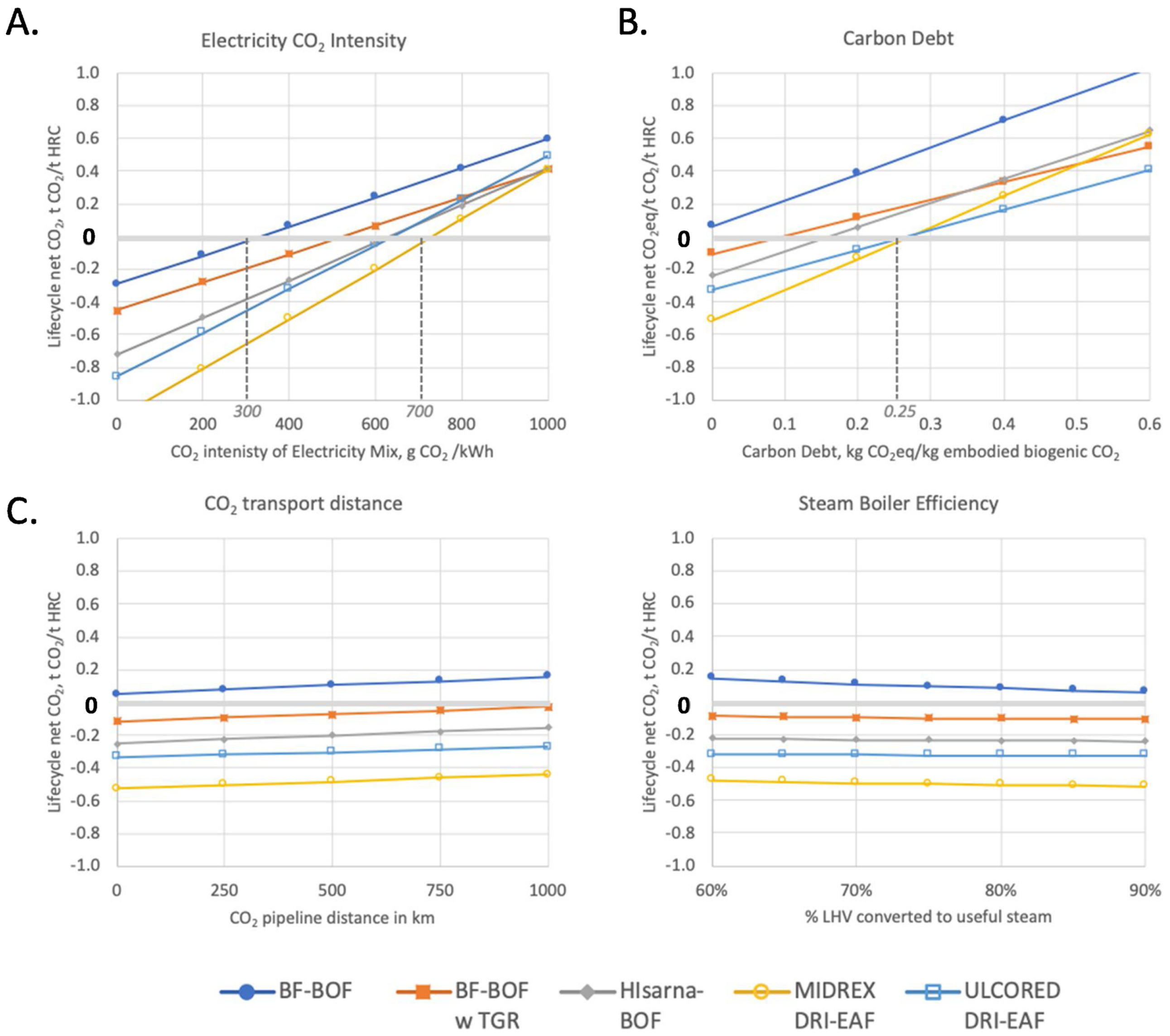


Fig. 5. Sensitivity analysis of electricity carbon intensity (A), biomass carbon debt (B), CO_2 transport distance (C), and steam boiler efficiency (D) in the cases of high bioenergy and high CCS use for all technologies.

atmosphere via the photosynthesis of biomass, but that CO_2 is returned to the atmosphere after the biomass is combusted. Thus, bioenergy use alone can reduce CO_2 emissions but cannot result in negative emissions. Without CCS, the limited bioenergy cases resulted in 20–25% reduction in net life cycle CO_2 from the baseline (BF-BOF: 2.0, TGR: 1.5, HIsarna: 1.8, Midrex: 1.2, ULCORED: 1.0 t CO_2/t HRC) and 30–40% reduction in the "high" cases (BF-BOF: 1.7, TGR: 1.3, HIsarna: 1.3, Midrex: 0.9, ULCORED: 0.8 t CO_2/t HRC). Total CO_2 emitted increased $100-500$ kg CO_2/t HRC for smelt reduction steelmaking and $300-1000$ kg CO_2/t HRC for DRI steelmaking. In all cases, the increase in CO_2 production resulted primarily from the transformation of raw biomass (wood) into a high-energy biofuel: charcoal for smelt reduction and biosyngas for DRI.

BECCS combines atmospheric CO_2 removal and permanent CO_2 storage and can theoretically result in negative emissions, if the amount of atmospheric carbon removed and stored is higher than the amount of CO_2 emitted across the complete life cycle systems of steel, bioenergy, and CCS. In all cases, BECCS led to both higher total CO_2 generation and lower net CO_2 than the use of bioenergy or CCS alone. Within the assumptions and boundaries in this model, six cases were estimated to be carbon neutral or carbon negative. Additionally, for all five technologies, the "limited bioenergy, limited CCS" case resulted in lower net CO_2 than either the "no bioenergy, high CCS" or "high bioenergy, no CCS" cases. For both bioenergy use and CCS, the limited uses cases include interventions at the iron furnace, which is the largest point source of carbon in all cases. Therefore, the high use cases see small marginal reductions in CO_2, compared to the limited use cases.

For BF-BOF steelmaking, with and without TGR, the net CO_2 estimates for the "limited bioenergy, high CCS" case is 300–400 kg/t HRC lower than the "high bioenergy, limited CCS" cases, due to the stricter limits on bioenergy use in the blast furnace arising from the need to maintain the mechanical properties of the fuel. In the "limited bioenergy, high CCS" case, BF-BOF with TGR approaches carbon neutrality (0.1 t CO_2/t HRC). This is in contrast HIsarna and DRI steelmaking, all of which are near or below carbon-neutral (–0.3 to 0.1 t CO_2/t HRC) in the "high bioenergy, limited CCS" case, but at $0.2-0.5$ t CO_2/t HRC in the "limited bioenergy, high CCS" case. The HIsarna and DRI pathways have fewer point sources of emissions, as well as higher potentials for bioenergy use, thus allowing for higher marginal decarbonization estimates from bioenergy use in the ironmaking furnace.

In the "high biomass, high CCS" case, the estimated CO_2 balance of all technologies approach or exceed net carbon neutrality, with CO_2

production between 2000–4000 kg/t HRC, CO_2 emissions of 900–1700 kg/t HRC, and CO_2 removal between 1100–1700 kg/t HRC. Only BF-BOF steelmaking remainscarbon-positive at 0.1 t CO_2/t HRC. The net CO_2 of BF-BOF with TGR is only slightly lower, at −0.1 t CO_2/t HRC, but the reduced fuel consumption resulted in 1000 kg/t HRC less CO_2 produced than in BF-BOF alone.

For DRI-EAF steelmaking, the life cycle CO_2 emissions in the "high biomass, high CCS" case are net negative, estimated at −0.5 t CO_2/t HRC for Midrex and −0.3 t CO_2/t HRC for ULCORED. In DRI steelmaking, CO_2 captured from biosyngas production is over half of the total CO_2 captured. In comparison, charcoal CO_2 accounts for 20–30% of CO_2 captured from smelt reduction technologies.

3.2. *Sensitivity analyses*

The above results consider the use of BECCS in different steelmaking technologies under a specific set of assumptions of technological configuration, emission accounting, and the efficiency of background systems. Below, we explore the impact of some of these assumptions, including the carbon intensity of electricity, CO_2 transport distance, steam boiler efficiency, methane emissions, charcoal kiln efficiency, carbon debt, and the use of alloying metals. The supplemental information contains the numerical results of the sensitivity analysis as well as the results of sensitivity analyses that had little impact on the results, including the inclusion of upstream emissions of factory and equipment use; atmospheric CO_2 removal in the background supply chain; and the HIsarna burden composition.

3.2.1. *Electricity production*

The base model assumed that all electricity was generated using natural gas, with an electricity emission factor of approximately 400 g CO_2/kWh. However, if electricity is produced from coal, the carbon intensity can reach 850–1020 g CO_2/kWh (IEA, 2019) Conversely, decarbonization of electricity is a central component the EU's ambition to be carbon-neutral by 2050 (European Commission, 2018). Fig. 5(A) shows the impact of a CO_2 emission factor of electricity between 0–1000 g CO_2/kWh in the "high bioenergy, high CCS" cases, as the high BECCS cases are those with the highest electricity demand, and thus highest sensitivity to its emission factor.

Without bioenergy or CCS, the reduction of electricity's carbon intensity from 400 g CO_2/kWh to 0 g CO_2/kWh results in 100–200 kg/t HRC less CO_2 for smelt reduction steelmaking and 500 kg t/HRC less CO_2 for DRI-EAF steelmaking. The use of bioenergy has little impact on electricity use, and the difference in electricity demand between the baseline and high BECCS case results almost entirely from CCS.

At a CO_2 intensity of around 700 g CO_2/kWh, slightly above the average carbon intensity of electricity production in China in 2017 (IEA, 2019), net CO_2 estimates are positive for all technologies. At 300 g CO_2/kWh, similar to that of the EU grid in 2018 (IEA, 2019), all high BECCS net CO_2 balances were negative. Full decarbonization of electricity decreases the net CO_2 of the high BECCS cases by 400 kg CO_2/t HRC for smelt reduction steelmaking and 600 kg CO_2/t HRC for the more electricity-intensive DRI-EAF steelmaking.

3.2.2. *Boiler efficiency*

In the baseline model, a 90% boiler efficiency is assumed for the provision of heat for CO_2 capture. Depending on size and configuration, boiler efficiency may be lower, particularly for high-moisture fuels, such as wood chips. Overall, boiler efficiency has a noticeable yet limited impact on net CO_2. As shown in Fig. 5(D) for the high BECCS cases, a 30% decrease in boiler efficiency increased the net CO_2 of any case by no more than 100 kg CO_2/t HRC.

3.2.3. *CO_2 transport distance*

In the baseline case, a CO_2 transport distance of 100 km is assumed. Mandova et al. (2019) identified CO_2 pipeline routes between 30 steel plants and off-shore storage aquifers, with pipeline distances ranging from 1 to 799 km. Therefore, our sensitivity analysis considered pipeline distances of 0–1000 km, as shown in Fig. 5(C) for the high BECCS cases. For all technologies, increasing the transport distance from 100 km to 1000 km increases net life cycle CO_2 emission by less than 100 kg CO_2/t HRC.

3.2.4. *Carbon debt*

CO_2 from bioenergy combustion is emitted all at once, but the equivalent (re-)uptake of atmospheric CO_2 by biomass takes a number of years dependent on the rotation period of the crop. Even when the biomass is sustainably grown, with attention to replanting and land use change, as is assumed in our model, the delay in CO_2 reuptake and changes in soil carbon, bacterial activity, and albedo occurring as a response to biomass harvest increase the global warming potential of biogenic CO_2 emissions (Cherubini and Strømman, 2011). These factors, collectively known as the "carbon debt" of biomass, represent the greenhouse gas emission reduction that the use of biofuel must provide to be carbon neutral (Fargione et al., 2008). The "carbon debt" is independent of other CO_2 emissions in the biomass supply chain, such as those from fertilizer use or equipment and energy use in harvest and transport.

Guest et al. (2013) calculated "GWP_{bio}" factors, estimating the global warming potential of these processes in kg CO_2-eq per kg of biogenic CO_2 emitted. These factors are relative to the rotation period of the biomass and the time horizon of the study. At the 100-year time horizon, annual crops having a negligible GWP_{bio} factors (0.003 kg CO_2eq/kg biogenic CO_2), but long-rotation crops, such as hardwood timber with a 100-year rotation period are estimated to have a GWP_{bio} factor of 0.44 kg CO_2eq/kg biogenic CO_2.

Fig. 5(B) shows the impact of these GWP_{bio} factors on the net CO_2 emissions of the high bioenergy cases. At a GWP_{bio} factor of 0.25 (on a 100-year time horizon), corresponding to a rotation period of roughly 60 years, all technologies have a net-positive CO_2 balance.

3.2.5. *Methane emissions*

The base model only considered CO_2, which is responsible for 90% of the global warming potential of steel production (World Steel Association, 2011). A full greenhouse gas accounting was outside the scope of this paper, but Fig. 6 shows the influence of including the estimated methane emissions of charcoal production in the hot tail kilns and the methane emissions of upstream processes from ecoinvent.

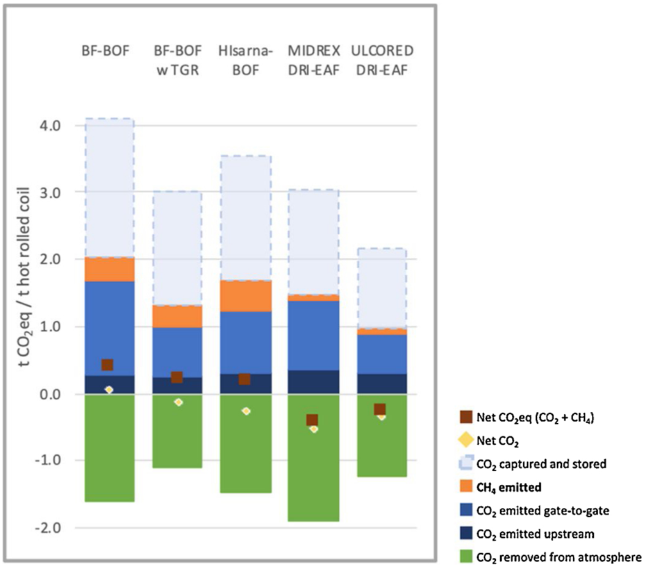


Fig. 6. Estimated impact of CH_4 emissions from charcoal production and background systems on life cycle CO_2-eq (100-year time horizon).

Methane emission data was not available for the biosyngas production. As in the base model, all fuel carbon used for steelmaking is assumed to be fully combusted.

For cases without charcoal use, methane emissions add 100–200 kg CO_2eq/t HRC, over 90% of which is from fossil fuel supply chains. In the high biomass cases for smelt reduction, methane produced for charcoal add an additional 200 kg CO_2eq/t HRC, leading their net life cycle CO_2-eq estimates to increase to a net positive $0.2 - 0.4$ t CO_2eq/t HRC.

While outside the scope of this study, methane leakage could play an important role in the greenhouse gas balance of steelmaking, due to its high global warming potential and the formation of methane in both the steelmaking gases and the energy supply chains. For the high BECCS case of Midrex DRI-EAF, which had the lowest net CO_2, only 20 kg/t HRC of methane leakage are necessary anywhere in the supply chains of steel, bioenergy, and/or CCS for the system to have a net positive global warming potential (on a 100-year time horizon).

3.2.6. Charcoal production

The base model assumed that charcoal was produced in industrial hot tail kilns with CO_2 emissions of 1400 kg CO_2/t charcoal. Hot tail kilns are used to produce charcoal for the steel industry in Brazil. However, they are less efficient than Missouri kilns, which can have CO_2 emissions between 400–700 kg CO_2/t charcoal (Pennise et al., 2001). Without CCS, the use of a highly efficient kiln with CO_2 emissions of 500 kg CO_2/t charcoal reduced the estimated net $CO_2$by 200 kg CO_2/t HRC. In the high BECCS cases, CO_2 capture is assumed to be applied to charcoal production, so while CO_2 production is reduced by a similar amount, net CO_2 emissions decrease by less than 100 kg CO_2/t HRC as compared to the high BECCS case with hot tail kilns. Further results of the charcoal kiln efficiency analysis are available in the supplemental information, including for less efficient kilns, although these are unlikely to be used on an industrial scale.

3.2.7. Alloying metals

The base model assumed the production of unalloyed carbon steel. Using data from ecoinvent (Wernet et al., 2016), the use of the small amounts of nickel, chromium, and magnesium in “low alloyed” steel add 500 kg CO_2/t HRC to the life cycle net CO_2 in all cases. The sourcing of the large amounts of chromium and nickel in 18/8 stainless steel add an additional 3600 kg CO_2/t HRC to life cycle net CO_2, requiring that any possibility of carbon negative stainless steel address the CO_2 emissions of the chromium supply chain. The decarbonization of the chromium supply chain is outside the scope of this study, but as the steel industry is the primary consumer of chromium (Singerling et al., 2018), it is an aspect that requires further attention.

4. Discussion

This study considered a “tomorrow’s technology today” scenario where current and emerging steelmaking technologies were considered on an equally commercialized basis, as they might exist in 20–40 years’ time, while using present-day CO_2 emission data for the background supply chains. This reduced the uncertainty in the model and limited the changes in net CO_2 to changes in the steelmaking supply chain. However, the data quality is thus inherently unequal between the different technologies and is more uncertain particularly for HIsarna-BOF and ULCORED DRI-EAF steelmaking.

In the base BF-BOF model, which most closely represents the current dominant steelmaking technology, over 80% of life cycle CO_2 production resulted directly from the steelmaking process. However, in the high BECCS case, CO_2 from steelmaking increases slightly, but it’s relative share drops to 60% of life cycle CO_2 production, as CO_2 from bioenergy production and CCS energy use increase. Similarly, for DRI-EAF, direct emissions from steelmaking represent 50% of life cycle CO_2 production in the base case and 30% in the high BECCS case. In a BECCS-in-steel system, the carbon intensity of the background sectors, particularly for energy sourcing including biomass production, fossil fuel extraction, and electricity generation, become more important, and therefore require greater rigor when estimating the CO_2 balance of a specific BECCS-in-steel implementation. The influence of the composition of the steel, including both recycled scrap content and alloying metals (see Section 3.2.7) also deserve great attention.

It is important to emphasize that negative CO_2 emissions do necessarily imply negative global warming potential. Though CO_2 is responsible for over 90% of steelmaking’s global warming potential (World Steel Association, 2011) the impact of additional greenhouse gases, such as methane, dinitrogen oxide, and fluorocarbons, are not accounted for in this study, though the impact of methane from charcoal productions was briefly discussed (Section 3.2.5).

Below, we briefly address some further considerations of BECCS-in-steel beyond our model, including the practicality of implementation, inefficient negative emissions, and resource use.

4.1. Implementation considerations

The CO_2 emissions of steel production are dominated by those emitted during the steelmaking process, with the ironmaking furnace being the single largest source of CO_2 emissions for all technologies. The choice of ironmaking method affects not only the CO_2 emissions in the baseline case, but also the effectiveness of BECCS.

4.1.1. Bioenergy use

In BF-BOF steelmaking, the replacement of coal with charcoal is limited by the need to maintain the mechanical properties of the fuel to maintain consistent furnace parameters, and therefore maintain the quality of the iron. In DRI-EAF steelmaking, the use of a gas fuel theoretically allows for complete replacement with biosyngas, and in this model showed a greater potential for negative emissions than BF-BOF steelmaking. However, there is current commercial use of charcoal in blast furnaces, but no commercial DRI plant currently uses biosyngas. The production of charcoal is also an established commercialized process that produces a homogenous end product, whereas the production of high-quality biosyngas is an emerging industry with heterogenous feedstocks and products. This lack of experience may prove a greater hurdle to widespread bioenergy use in DRI-EAF than in BF-BOF steelmaking, even if the decarbonization potential for bioenergy in DRI-EAF steelmaking is greater.

The bioenergy supply chain has complex impacts on global warming, as captured partially in carbon debt factors in 3.2.4, related to land use change, albedo, soil carbon disruption, and the delay between CO_2 (re)uptake and biomass combustion. Wood-based bioenergy is of particular concern for European biomass production, as spruce and pine can have rotation periods as long as 100–150 years northern European countries (Bauhus et al., 2010), with a carbon debt factor of 0.4 kg CO_2eq/kg biogenic CO_2 (Guest et al., 2013). In contrast, eucalyptus in equatorial regions can have a rotation period as short as 5–10 years (Bauhus et al., 2010), implying a carbon debt factor of < 0.1 (Guest et al., 2013). However, if used in European steelmaking, equatorial biomass adds the additional complexities of long distance transport and multiregional supply chain governance. In our model, biosyngas was assumed to be produced from wood, but biosyngas can also be produced from annual crops (e.g. Swanson et al. (2010); Carpenter et al. (2010)), which could substantially decrease the carbon debt burden.

4.1.2. CO_2 capture

In contrast, CO_2 capture has been commercially applied to DRI-EAF steelmaking, where gas cleaning and reforming is an integrated process. In BF-BOF steelmaking, which produces offgases with more contaminants, CO_2 capture is not yet commercialized.

Top gas recycling theoretically allows for easier CO_2 capture at a blast furnace by increasing to the CO_2 concentration of the offgases, but this technology is still under development. Top gas recycling can also increase the fuel efficiency of iron production, but it reduces the available energy from the blast furnace offgases, so if less energy is then available for the previous use of the offgases (e.g. heat in other steelmaking processes or electricity export), additional energy may be needed to satisfy those processes, thus potentially generating additional CO_2 emissions elsewhere.

In the high CCS cases, we assumed that all flue gases were processed for CO_2 capture, except those of electricity and steam generation. While technologically possible, this may prove economically or spatially impractical, requiring extensive ductwork, and tradeoffs between combining and transporting flue gases of different pressures, temperatures, and CO_2 concentration, or CO_2 capture, units at multiple point sources (Hurst and Walker, 2005). However, integrated steel mills typically extensively redirect combustible off gases, and therefore are likely to have the expertise necessary to design gas transport solutions for CO_2 capture.

4.2. *"Inefficient" negative emissions*

The lower net CO_2 emissions of HIsarna over BF-BOF with TGR and of Midrex DRI-EAF over ULCORED DRI-EAF in the high BECCS case illustrate a counterintuitive phenomenon wherein a BECCS system with lower energy efficiency can result in lower net CO_2 than a BECCS system with a higher energy efficiency. This is due to the larger quantity of CO_2 that is removed from the atmosphere to supply bioenergy and then is subsequently captured and permanently stored, resulting in more negative CO_2 emissions. In the more efficient systems, the lower bioenergy demand leads to less CO_2 removal from the atmosphere and subsequently less storage of removed atmospheric CO_2.

Such "inefficient" systems can generate more negative CO_2 emissions by using more resources (e.g. wood, electricity) for the same quantity of steel production. However, this necessarily increases costs, as well as competition for limited resources. Unless negative emissions are themselves sufficiently economically valued, the "inefficient" generation of negative emission will not be appealing. This concept of inefficient production to increase negative emissions has been explored for power generation in Mac Dowell and Fajardy (2017).

4.3. *Resource demand*

The change in demand for energy resources—biomass, fossil fuels, and electricity— from the baseline cases to the high BECCS case is summarized in Table 10. While the high BECCS cases decrease net CO_2 by 1500–2400 kg CO_2/t HRC from the baseline cases, it increases total primary energy demand by an average of 6 GJ/t HRC including an average of 500 kWh of final electricity demand and 800 kg (dry mass) of wood per tonne of steel.

A first estimate suggests that if all blast furnace steel production in Europe (100 Mt/year) was fitted with top gas recycling and implemented the high BECCS cases, annual European steel industry CO_2 emissions would decrease by 260 Mt, and the net CO_2 balance of European BF-BOF steelmaking would be −10 Mt CO_2/year, under the assumptions and system boundaries here considered. This case also requires an addition 52 Mt/year of dry wood, which is approximately 25% of the total European forestry harvest (Eurostat, 2019; Fonseca and Task Force Members, 2010), as well as an additional 50 TW h/year of electricity, increasing European industrial electricity usage by 5%. This increased demand is also expected to compete with the electrification and decarbonization efforts in other industries and the power sector, compounding pressure on available renewable energy resources.

5. Conclusions

In this paper, 45 cases of steelmaking technology, bioenergy use, and CCS use were modeled to explore the impact of BECCS on the net life cycle CO_2 of steelmaking. Each case was modelled using a fixed-ratio input-output process model for the production of steel, auxiliary inputs, bioenergy, and CCS, at a commercial-scale modern integrated steel mill in Western Europe. The results of the process model were used to estimate the emissions of the upstream and downstream supply chains. As this study focused on exploratory work, the systems were not optimized, and a number of parameters were explored in non-stochastic sensitivity analyses.

In our model, the use of CCS alone resulted in higher net CO_2 reductions than the use of bioenergy alone, but the combination of bioenergy and CCS resulted in greater net CO_2 reductions than the sum of separate interventions. In particular, the use of both bioenergy and CCS at the ironmaking furnace showed greater decarbonization potential than site-wide deployment of either bioenergy or CCS alone. Aggressive deployment of both bioenergy and CCS in the high BECCS case resulted in estimates of near-neutral net CO_2 for BF-BOF steelmaking with and without top gas recycling (0 ± 0.1 t CO_2/t HRC), and slightly negative net CO_2 (−0.2 to −0.5 t CO_2/t HRC) for HIsarna-BOF, Midrex DRI-EAF, and ULCORED DRI-EAF. This required the use of bioenergy both for ironmaking and some auxiliary processes, as well as CO_2 capture on all flue gases from steelmaking and bioenergy production, followed by permanent storage.

A series of non-stochastic sensitivity analyses explored the role of the carbon intensity of electricity, CO_2 transport distance, steam boiler efficiency, methane emissions, charcoal kiln efficiency, carbon debt, and the use of alloying metals on the life cycle CO_2 estimates. Net CO_2

Table 10
Resource use of BECCS (High bioenergy, high CCS case compared to base case).

	UNIT	BF-BOF ONLY	BF-BOF WITH TGR	HISARNA-BOF	MIDREX DRI-EAF	ULCORED DRI-EAF
Net CO_2	t / t HRC	0.1	−0.1	−0.3	−0.5	−0.3
(change from base case[1])		*(−2.3)*	*(−2.1)*	*(−2.5)*	*(−2.0)*	*(−1.6)*
Primary energy demand[2]	GJ / t HRC	28	20	26	27	20
(change from base case[1])		*(+10)*	*(+6)*	*(+7)*	*(+5)*	*(+2)*
Biomass demand[3]	kg dry wood / t HRC	890	600	820	1030	660
Coal	kg / t HRC	460	340	350	0	0
(change from base case[1])		*(−210)*	*(−200)*	*(−290)*	*(0)*	*(0)*
Natural gas[4]	kg / t HRC	0	0	0	130	120
(change from base case[1])		*(0)*	*(0)*	*(0)*	*(−140)*	*(−170)*
Electricity[5]	kWh / t HRC	890	860	1200	1530	1360
(change from base case[1])		*(+520)*	*(+550)*	*(+790)*	*(+390)*	*(+220)*

[1] : Without bioenergy or CCS.
[2] : Including fossil fuel and biofuel used in steel making, auxiliary processes, and electricity generation. Includes losses.
[3] : There is no biomass demand in the base case.
[4] : Excluding for electricity generation.
[5] : Final electricity demand. Excludes losses.

estimates were particularly sensitive to the carbon intensity of electricity, the use of alloying metals, and the role of biomass carbon debt. In this study, a decarbonized electricity sector was shown to reduce net CO_2 by approximately 500 kg CO_2/t HRC in the high BECCS cases. However, the high BECCS cases also increases electricity use by approximately 500 kWh/t HRC, primarily from the CO_2 capture system.

Furthermore, this study assumed that the biomass was sustainably harvested and regrown, but the delay in carbon reuptake, along with other impacts of biomass production, can increase the global warming potential of biogenic CO_2, which is highly dependent on the rotation period of the biomass. Slow-growing tree species, such as Norwegian spruce or Scots pine could have additional global warming impacts that negate the carbon removal benefit of bioenergy use, when considered within a 100-year time horizon. Emissions of biogenic methane from bioenergy production, nitrogen emissions from biomass production, and other greenhouse gases, also deserve further attention, to better estimate whether negative CO_2 steel production results in negative global warming potential.

It is our initial assessment that negative life cycle CO_2 emissions in the production of carbon steel are possible through aggressive use of bioenergy paired with the capture and permanent storage of CO_2 from both steelmaking and bioenergy production, if rigorous attention is paid to ensure the sustainability of the energy and biomass supply chains. The use of decarbonized electricity, short-rotation biomass, and efficient bioenergy production increase the likelihood of a net negative CO_2 balance. Real-world implementation of BECCS in steelmaking requires a thorough life cycle assessment for the specific technological configuration and supply chain choices to determine if negative emissions can be achieved.

CRediT authorship contribution statement

Samantha Eleanor Tanzer: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Kornelis Blok:** Writing - review & editing, Supervision. **Andrea Ramírez:** Conceptualization, Writing - review & editing, Supervision.

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.

Appendix A. Supplementary data

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