Energy and Climate Change 5 (2024) 100152

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

The role of the iron and steel sector in achieving net zero U.S. CO_2 emissions by 2050

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ARTICLE INFO

Keywords:
USA
Iron and steel
Decarbonization
Carbon capture and storage
Hydrogen
Integrated assessment modeling

ABSTRACT

The U.S. steel sector is a hard-to-abate sector because of its heavy dependence on fossil fuels and its high capital requirements. In 2015, the sector was one of the major carbon emitters, contributing 10 % of the U.S. industrial CO_2 emissions. The ability to decarbonize the U.S. iron and steel sector directly affects the ability of the U.S. to achieve economy-wide net zero CO_2 by 2050. In this paper, we use the Global Change Analysis Model (GCAM) to analyze different U.S. steel sector decarbonization pathways under varying technology, policy, and demand futures. These pathways provide insights on how various low-carbon steelmaking technologies such as those using carbon capture and storage (CCS), hydrogen, or scrap could help reduce U.S. steel emissions by mid-century. In our primary decarbonization pathway, we find that nearly all of the conventional fossil-based steelmaking capacity is fully integrated with CCS by 2050. However, without CCS availability, almost all of the conventional fossil-based steelmaking is phased-out by 2050 and is replaced by hydrogen-based production. Scrap-based production continues to remain vital across both of these decarbonization pathways. Furthermore, we find that demand reduction could help reduce the required levels of CCS and hydrogen-based production in the decarbonization pathways. Implementation of advanced energy efficiency measures could help substantially reduce the sector's energy usage. Finally, we observe that addressing the embodied carbon transfer associated with steel imports will be crucial for fully decarbonizing the U.S. steel sector.

1. Introduction

The United States is the fourth largest steel manufacturer in the world, producing about 88 million tons (Mt) of steel in 2019 [1]. The majority of the country's steel (70 %) is produced from scrap-based Electric Arc Furnaces (EAFs), which use recycled steel as their raw material. Most of the remaining steel (26 %) is produced from Blast Furnace-Basic Oxygen Furnaces (BF-BOFs), which first produce pig iron by smelting iron ore in Blast Furnaces and subsequently convert it to steel in Basic Oxygen Furnaces [2]. A small number of U.S. ironmaking facilities produce Direct Reduced Iron (DRI), which is thereafter used in EAF facilities to produce crude steel [3]. Though only four percent of U. S. steel was produced using this process in 2019, the market share of EAF-DRI is expected to grow in the future, largely due to its lower emissions intensity relative to BF-BOF and its greater capability to produce high-quality steel when compared to scrap-based EAF.

The sector is one of the most energy- and emissions-intensive industries in the country, due to its substantial fossil fuel consumption. The major fuels consumed in the sector include natural gas, coal, and electricity [4]. Natural gas and coal constitute the largest portion (80 %) of U.S. iron and steel sector energy use and are employed across all steelmaking processes (BF-BOF, EAF-scrap, EAF-DRI) to provide high-temperature heat. In addition, they are used as precursors for the production of reducing agents across ironmaking processes. While coal is used as a precursor to produce pig iron for the BF-BOF process, natural gas serves the same purpose to produce DRI for the EAF-DRI process. The sector also consumes a significant amount of electricity (20 % of its energy use), which provides the main energy source for EAF steelmaking and is also used in crude steel casting and rolling [5].

In recent years, industrial stakeholders and researchers have identified several low-carbon technologies that have the potential to mitigate carbon emissions from the sector [6,7]. BF-BOFs' emissions can be reduced significantly by substituting coal with biomass-based reductants and partial hydrogen injection [8,9]. Natural gas can be substituted with green hydrogen in DRI production, which when used in an EAF can produce carbon-free steel [10,11]. Retrofitting both BF-BOFs and DRI-based EAFs with carbon capture and storage (CCS) can potentially reduce ninety percent of their process emissions [12,13]. Most of

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https://doi.org/10.1016/j.egycc.2024.100152

Available online 29 August 2024

these low-carbon technologies are currently in the early stages of commercialization, with a few projects deployed globally [14].

Several studies have explored the role of low-carbon technologies and other mitigation measures in decarbonizing the U.S. steel sector [15–19]. Karali et al. (2017) analyzed the contributions of technological transitions on steel sector energy savings [19], Ryan et al. (2020) explored steel sector pathways achieving 70 % emissions reduction by 2050 [18], Pilorgé et al. (2020) estimated the CCS costs for U.S. industries [16], and Worrell et al. (2022) assessed the sector's total emissions abatement potential [15]. These studies together explore different aspects of steel sector decarbonization using bottom-up approaches.

Additional studies have analyzed global steel sector decarbonization alongside economy-wide energy transitions, incorporating the U.S. as a subcomponent of their analysis [20–22]. However, these studies have limited discussion on the country's decarbonization pathways due to their broad scope. They provide key insights on the evolution of the U.S. steel sector, but lack an enhanced focus on the country and do not comprehensively quantify the sector's energy, emissions, physical material flows, and embodied carbon trends.

In this paper, we aim to address this gap. We evaluate the potential future U.S. steel sector decarbonization pathways within the context of the larger U.S. and global energy and economic systems. We examine alternative U.S. steel sector deep decarbonization pathways in the context of a U.S. 2050 net-zero CO_2 emission goal and the global energy system. We explore interactive effects with other U.S. and global energy sectors and the competitive international steel market. We further examine the sensitivity of our results to technology characterization and availability and analyze the embodied carbon transfer trends across the U.S. borders.

The key research questions of this study are as follows: (1) How could the U.S. iron and steel sector evolve in future in which net zero CO_2 emissions are achieved by 2050? (2) To what extent might different low-carbon technologies and fuels contribute to the steel sector's deep decarbonization? (3) How could other mitigation measures (such as demand reduction, energy efficiency, and grid decarbonization) support the abatement of steel sector emissions? (4) How could international steel trade affect U.S. decarbonization efforts?

2. Methodology

In this study, we use the Global Change Analysis Model (GCAM) version 7.0 to model alternative iron and steel sector decarbonization pathways [23]. GCAM is an integrated assessment model that is widely used for assessing the dynamics of and linkages between human and physical Earth-systems for varying energy and emissions futures [24–27]. GCAM models five key human and environmental systems at different levels of spatial resolution and technological complexity [28]. These systems include energy, economy, water, agriculture and land-use, and atmosphere-ocean-climate. In this analysis, we primarily focus on the United States, which is one of GCAM's 32 geopolitical regions. Furthermore, we highlight results from GCAM's energy systems module, which includes the iron and steel sector among other end uses of energy and the connected upstream sectors such as hydrogen production and the power sector.

2.1. GCAM's iron and steel sector

GCAM has a detailed representation of the iron and steel sector (Fig. 1). The sector is categorized into three main subsectors: a) BF-BOF, b) EAF with scrap, and c) EAF with DRI. These subsectors are further categorized into conventional technologies (BF-BOF, EAF with DRI, and EAF with scrap) and developing low-carbon options that use carbon capture and storage (BF-BOF CCS, EAF with DRI CCS) or alternative fuels such as biomass and hydrogen (biomass-based BF-BOF, BF-BOF with hydrogen, H_2-DRI).

Iron and steel energy use is calculated using the future market shares of the different steel-making technologies and their fuel intensities. Energy use is subsequently multiplied by carbon emission factors to determine the total sectoral CO_2 emissions. In GCAM, the new steel-making plant and equipment technologies (i) compete for future market share (S_i) using a logit-based discrete choice model (Eq. (1)). The key inputs to this model include technology costs (c), share weights (α), and a logit exponent (γ).

$$S_i = \frac{\alpha_i c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j c_j^{\gamma}} \tag{1}$$

The technology costs are a calculated as a sum of exogenously

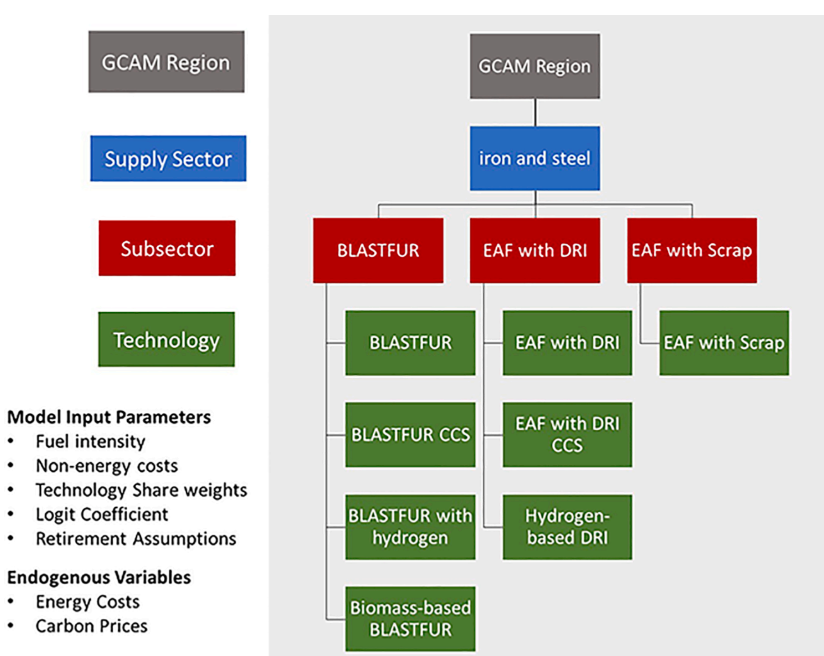

Fig. 1. The structure of the iron and steel sector in GCAM.

specified non-energy costs ($/Mt) and endogenously calculated energy costs. The energy costs are computed by the model based on regional fuel prices ($/EJ) and the input fuel intensities (GJ/Mt) of the technologies. Furthermore, the price of carbon ($/t-$CO_2$) is added to the cost of emissions associated with each technology in constrained emissions scenarios. Meanwhile, the logit exponent (γ) and technology share weights (α) incorporate the impact of non-cost factors on the future market share. While the logit exponent determines the extent to which technology costs determine the market share, the technology share weights capture the impact of non-cost factors such as technology preferences, prevailing infrastructure, and barriers to implementation. Finally, the lifetimes of steel production facilities are also considered when estimating the future market share, and gross steel trade across regions is modelled using a logit-based Armington trade model [29] (see Supplementary Information SI-1 for details).

2.2. Input data, sources, and assumptions

The model is calibrated with historical data from a variety of sources. The data on crude steel production, apparent steel consumption (crude equivalent), imports and exports of semi-finished and finished steel products, and crude steel production by process (BF-BOF and aggregate EAF) are obtained from World Steel Association (WSA) [30,31]. The EAF with DRI steel production is assumed to be equal to the historical DRI consumption (which is estimated using DRI production, imports, and exports data from WSA) [2]. The scrap-based EAF production is calculated by subtracting the calculated EAF with DRI production from the aggregate EAF production reported by WSA.

The total iron and steel energy use (by fuel) is obtained from International Energy Agency's World Energy Balances (flow codes: IRONSTL, EBLASTFUR, TBLASTFUR, ECOKEOVS, and TCOKEOVS) [4]. We use this total energy use data to disaggregate energy use by fuel for the prevailing steel production processes (BF-BOF, EAF with DRI, and EAF with scrap). To do so, we first assume that the BF-BOF process consumes all the coal in the sector. Second, we divide the other fuel consumption (mainly natural gas and electricity) by process using the relative ratios of the process fuel intensity coefficients obtained from literature [32–34]. After the disaggregation we estimate the input process fuel intensities (GJ/t) by dividing the estimated fuel energy use by the steel production for each process.

The steel production non-energy costs are obtained from the Global Steel Cost Tracker (GSCT) database [35]. The GSCT database provides facility-level production cost data for BF-BOF and aggregate EAF technologies. We average these facility-level costs across countries and technologies to estimate the model input costs. Since GSCT does not provide technology capital costs, we add them to the averaged GSCT costs using cost adders determined from the literature [36,37]. Similarly, we also use cost adders for technologies paired with CCS (Section SI-2). Furthermore, we assume that the GSCT aggregate EAF costs are representative of scrap-based EAF and use IEA (2020) global average costs for EAF with DRI technologies [37].

The technology share weights are endogenously calibrated (based on historical market shares and costs) at the model base-year (2015). For EAF with scrap and BF-BOF these share weights are set to their 2015 values for all the future model years. For EAF with DRI they are linearly increased to match EAF with scrap by 2050 in the U.S., representing the gradual removal of implementation barriers and reaching of technological maturity.

3. Scenario framework

In this study, we model the U.S. iron and steel sector decarbonization pathways under different technology, policy, and demand futures (Table 1). We adopt experimental designs developed by the Stanford Energy Modeling Forum Study 37 (EMF37), including experimental protocols adopted by the EMF37 Carbon Management Study Group (CMSG) to provide a standard framework for analysis. These scenarios provide insights on the alternative technological pathways for the U.S. iron and steel sector. In addition, they quantify the impacts of these pathways on the sector's energy demand, fuel mix, emissions, and material demand (primarily scrap use). The six scenarios explored in this study are discussed below in further detail.

Table 1
U.S. iron and steel sector scenarios.

No.	Scenario	Policy	CCS availability	Demand
1	Current Policies 2015	–	–	baseline
2	NZ (net zero) 2050	U.S. + global net zero	yes	baseline
3	NZ 2050 low demand	CO_2 by 2050	yes	low
4	NZ 2050 no CCS		no	baseline
5	NZ 2050 no CCS low demand		no	low
6	NZ 2050 US decarb only	U.S. net zero CO_2 by 2050	yes	baseline

3.1. Current policies (2015) scenario

This scenario represents a "business as usual" future for the US. The population, GDP, and technological assumptions follow an updated "middle of the road" (SSP2) shared socioeconomic pathway (Table SI-4) [38,39]. The non-energy costs and fuel intensities of steel-making technologies are held constant into all the future model years. Furthermore, a "baseline" steel consumption of 330 kg/person for the U.S. is assumed in this scenario. This value is derived from the U.S. average apparent steel consumption (crude equivalent) per capita in the last decade (2010–2020, Figure SI-5). It should be noted that this scenario does not directly model any policies, though the model calibration process implicitly accounts for the policies in force through 2015.

3.2. Net zero CO_2 scenarios

The net zero scenarios model a linear reduction of economy-wide CO_2 emissions to zero from 2020 to 2050 (Fig. 2a). Advanced energy efficiency improvements in the U.S. steel sector are assumed in these scenarios (Fig. 2c). The energy intensities of BF-BOF, EAF-DRI, and EAF-scrap technologies are linearly decreased from 25.5, 22, and 6.1 GJ/t in 2015 to the world best practice values from Worrell et al. (2007) of 14.8, 16.9, and 2.6 GJ/t in 2050, respectively [40]. Advanced green hydrogen cost reductions are also assumed, with a 75 % decrease in installed electrolyser costs attained by 2050 (relative to 2015). Furthermore, the scrap usage (for EAF-scrap and BF-BOF) is constrained to 70 Mt, which is equal to the maximum historically observed new scrap supply available for consumption in the US (Figure SI-6) [41]. This constraint aligns with the regional scrap availability projected by material flow analysis studies in the literature [17,42,43]. The steel demand pathway is exogenously specified and follows either a "baseline" or a "low" demand trajectory based on the scenario (Figure 2b; see Section 3.2.2 for more details). To model the continuation of laws prioritizing domestic steel production, steel imports are fixed at 28 % of the total demand, which is estimated from the average U.S. steel import market share from 2000 to 2020.

To understand the role of steel demand reduction and technological availability in the U.S. iron and steel sector deep decarbonization, we model a combination of net zero scenarios with varying CCS availability and steel demand trajectories (Table 1). These scenarios provide insights on the extent to which demand reduction, CCS, and the usage of low-carbon fuels such as clean electricity, hydrogen, and biomass may contribute to emissions mitigation in the U.S. iron and steel sector.

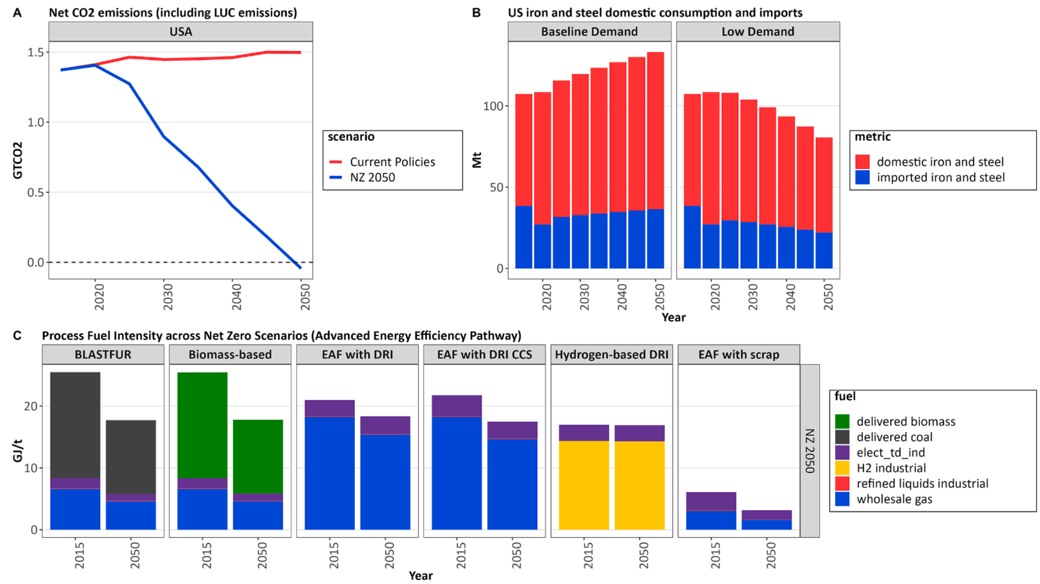

Fig. 2. GCAM modeling input assumptions for the United States: a) net CO_2 emissions across scenarios, b) domestic steel consumption and imports across demand scenarios, and c) evolution of process fuel intensities (2015–2050) for select technologies under advanced energy efficiency assumptions. The process fuel intensities for all the technologies considered in this study are illustrated in Figure SI-3.

3.2.1. Carbon capture and storage

CCS technologies are often recognized as an important mitigation measure for the decarbonization of the global iron and steel sector [44]. These technologies effectively capture the post-combustion CO_2 emissions from the conventional BF and DRI ironmaking processes, and subsequently store the captured CO_2 in a geological storage or utilize it for chemical or fuel production [45].

Although there is strong interest in using CCS technologies for decarbonizing the U.S. steel sector, CCS continues to face commercialization barriers primarily driven by high costs, limited fiscal incentives, regulatory issues, and technical infeasibility pertaining to site suitability and long-term storage uncertainties [46,47]. These barriers could potentially hinder the technology's short- and long-term deployment in the iron and steel sector and beyond. To take this uncertainty into account, in this study we explore iron and steel sector decarbonization pathways with and without CCS.

3.2.2. Steel demand reduction scenario

In 2019, the U.S. was ranked the third largest steel consumer, demanding 88 million tons of steel. Among the end-use markets, the construction (44 %) and automotive (28 %) sectors were the largest steel consumers, followed by machinery and equipment (9 %), energy infrastructure (6 %), and other (13 %) [48]. After a decline in demand during the early years of the pandemic, U.S. steel demand is expected to rebound in the short term, benefiting from the Bipartisan Infrastructure Law and Inflation Reduction Act legislation [49]. In the long term, demand is expected to continue to rise due to the projected growth in the U.S.'s population and GDP.

Demand reduction measures can play an important role in reducing the sector's emissions by combatting the projected growth in steel demand and can be achieved through the implementation of material efficiency strategies. As identified by IEA (2020), the U.S. could benefit from strategies such as material substitution, extended buildings lifetime, improved construction design, automobile light weighting, and enhanced manufacturing yields [37]. The implementation of such strategies could support the restoration and expansion of the country's critical infrastructure with a much lower steel footprint.

Thus, in this study we define a low steel demand pathway consistent with a linear decrease to 200 kg/capita by 2050 (from 330 kg/person in 2019) and analyze its impact on the steel sector transitions in a net-zero CO_2 U.S. economy. The benchmark of 200 kg/capita was selected based on the estimated U.S. demand reduction potential from several studies in the literature [18,20,37].

3.2.3. Embodied carbon and trade

The U.S. is a major net importer of steel and historically has had a considerably higher consumption-based emissions intensity (t-CO_2/t-steel) than production-based emissions intensity. Such discrepancies in consumption- and production-based emissions intensity have led to substantial amounts of embodied carbon transfer across the U.S.'s borders, which has been gaining increasing importance and attention in the context of global climate change mitigation [50,51].

To this end, we explore a sensitivity scenario in which the U.S. achieves net-zero CO_2 by 2050, but the rest of the world follows the current policies (2015) trajectory and examine the resulting embodied carbon transfer trends. This scenario allows for a discussion of the broader implications of carbon leakages for the U.S. and global iron and steel sector decarbonization.

4. Results

U.S. steel production trajectories show substantial variations across scenarios, which are largely influenced by the input steel demand and trade assumptions. The U.S. domestic steel production increases at a rate of 0.67 % per year, in response to growing steel demand assumed across the baseline demand scenarios (current policies, NZ 2050, and NZ 2050 no CCS). In these scenarios, steel production grows from 88 Mt in 2019 to 108 Mt in 2050 (Fig. 3a). Meanwhile, in the low demand scenarios (NZ 2050 low demand, NZ 2050 no CCS low demand), U.S. steel production gradually declines to 66 Mt by 2050, dropping at an annual rate of 1 %.

In the current policies scenario, EAF-based technologies further expand and continue producing the majority of the country's steel through 2050 (Fig. 3a). The growth in EAFs is driven by the increased and extensive use of DRI for steelmaking, which constitutes 20 % of the total production by 2050. Scrap-based EAFs continue to remain a dominant technology due to high domestic scrap availability and produce a large share (52 %) of U.S steel in 2050, with their absolute production maintaining similar levels to those in 2019. Iron and steelmaking from BF-BOF technologies decreases by 13 % when compared to

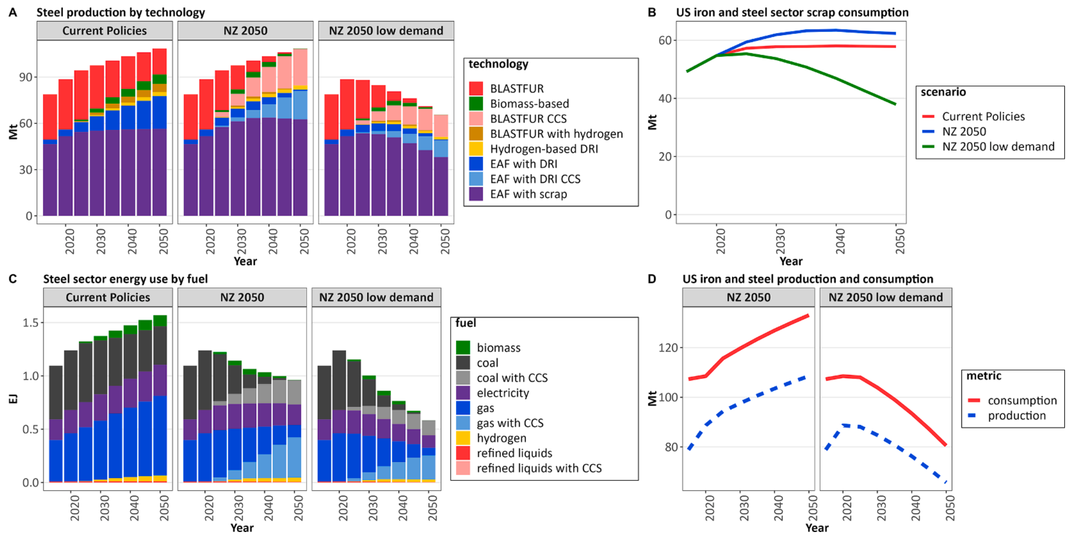

Fig. 3. a) U.S. steel production by technology, b) steel scrap consumption, c) energy use by fuel, and d) steel production and demand across scenarios (current policies 2015, NZ 2050, and NZ 2050 low demand scenarios).

its 2019 production levels, and BF-BOFs using either hydrogen injection or biomass feedstocks gain a notable BF-BOF market share (40 %) by 2050 at the expense of conventional BF-BOFs.

The availability of CCS technologies and additional scrap-based EAFs may be instrumental in achieving the deep decarbonization of the U.S. iron and steel sector. In the NZ 2050 scenario, conventional BF-BOFs are fully coupled with CCS by 2050 (Fig. 3a). The newly added DRI-based EAFs are also nearly fully coupled with CCS by mid-century. CCS integration of these technologies occurs gradually over time, with about 30 % of the BF-BOF and EAF-DRI capacity paired with CCS by 2030. Furthermore, a higher proportion (58 %) of scrap-based EAF is utilized in this net zero CO_2 scenario, thus demanding increased recycled scrap metal when compared to the current policies scenario (Fig. 3b). The consumer steel price in the NZ 2050 scenario is 7 % higher in 2050 relative to the current policies scenario. Meanwhile, the cumulative steel production cost amounts to $2.92 trillion USD from 2025 through 2050 in the NZ 2050 scenario (Figure SI-7).

Demand reduction could help reduce the scale of the required technological transitions. In the NZ 2050 low demand scenario, both BF-BOFs and DRI-based EAFs are still almost fully integrated with CCS by 2050. However, 40 % less CCS-equipped iron and steelmaking capacity in absolute terms is required in this scenario when compared to the NZ 2050 scenario, highlighting one of the key benefits of demand reduction. In addition, the magnitude of steel production from scrap-based EAFs also decreases, reducing the demand for recycled scrap metal to more sustainable levels (Fig. 3b). BF-BOFs with biomass or hydrogen play a very limited role in these net zero scenarios and largely assist in the phase out of unabated BF-BOFs.

Substantial energy savings are attained in the NZ 2050 scenario when compared to the current policies scenario (Fig. 3c). In the NZ 2050 scenario, the total energy use decreases to 0.96 EJ by 2050, down from 1.24 EJ in 2019 and 40 % lower than in the current policy scenario in 2050. The sector's natural gas consumption (with and without CCS) increases only by 9 % through 2050 in the NZ 2050 scenario, which is substantially lower than the 65 % increase observed in the current policies scenario. Furthermore, the sector's electricity consumption decreases by 10 % (0.21 to 0.19 EJ) and its coal consumption decreases by 60 % (0.55 to 0.22 EJ) and is partially replaced by small quantities of hydrogen (0.04 EJ) in the NZ 2050 scenario. These reductions are primarily driven by the advanced energy efficiency improvements assumed across processes, which reduce the sector's cumulative energy use (2025–2050) by 26 % when compared to the current policies scenario. Even larger reductions in energy use are observed in the NZ 2050 low demand scenario, which employs both advanced energy efficiency and demand reduction measures, with the total energy use dropping to 0.58 EJ by 2050 in that scenario.

In the U.S. steel sector decarbonization pathways in which CCS is not available, scrap-based EAFs play a leading role (Fig. 4a). Additionally, other low-carbon steelmaking technologies such as hydrogen-based DRI and biomass-based BF-BOF may become essential in such scenarios. Scrap-based EAFs produce 65 % (70 Mt) of the total U.S. steel by 2050 in the no CCS scenario (NZ 2050 no CCS), demanding the highest levels of recycled scrap when compared to the other scenarios in this study. Hydrogen-based DRIs experience a significant capacity expansion in this scenario, producing 25 Mt (23 %) of the U.S. steel by mid-century, which is nine times larger than the share in the NZ 2050 scenario. Most of this capacity expansion occurs from 2040 – 2050 and is driven by the increasingly stringent emissions constraint and reduced hydrogen costs. These factors also lead to diminished market share of other relatively carbon-intensive steelmaking technologies. Conventional BF-BOFs are fully phased out by 2050 in this scenario. To facilitate immediate carbon emissions reductions, biomass-based BF-BOF and unabated DRI-based EAFs gain a considerable market share in the near term, though this share peaks in 2040 and diminishes thereafter.

The cumulative steel production cost in the NZ 2050 no CCS scenario is 20 % higher than the NZ 2050 scenario and the consumer steel price becomes 64 % higher by mid-century. This largely occurs due to increase in the delivered electricity cost when CCS is not used in the power sector, which increases the levelized cost of the scrap-based EAFs that heavily rely on electricity (Figure SI-7 and SI-8).

The level of hydrogen-based DRI production needed to reach net-zero CO_2 in a no CCS case reduces drastically when demand reduction measures are employed, as scrap-based EAFs are able to provide 90 % (58 Mt) of the US steel production in 2050 in the NZ 2050 no CCS low demand scenario, with a slightly higher steelmaking capacity than the 2019 levels. The remaining steel is largely provided by 5 Mt of new hydrogen-based DRI capacity, which is of smaller magnitude than in the standard NZ 2050 no CCS scenario. The near-term requirements for biomass-based BF-BOF and unabated DRI-based EAFs are also decreased substantially in this low demand scenario.

The sectoral final energy use requirements in the no CCS scenarios are lower than in the CCS scenarios (Fig. 4b). In the NZ 2050 no CCS scenario, the total energy use reduces to 0.88 EJ by 2050, 8 % lower than in the NZ 2050 scenario. This is driven by the increased use of efficient scrap-based EAF and hydrogen-based DRI technologies, which reduce the overall energy use requirements needed to achieve similar emissions

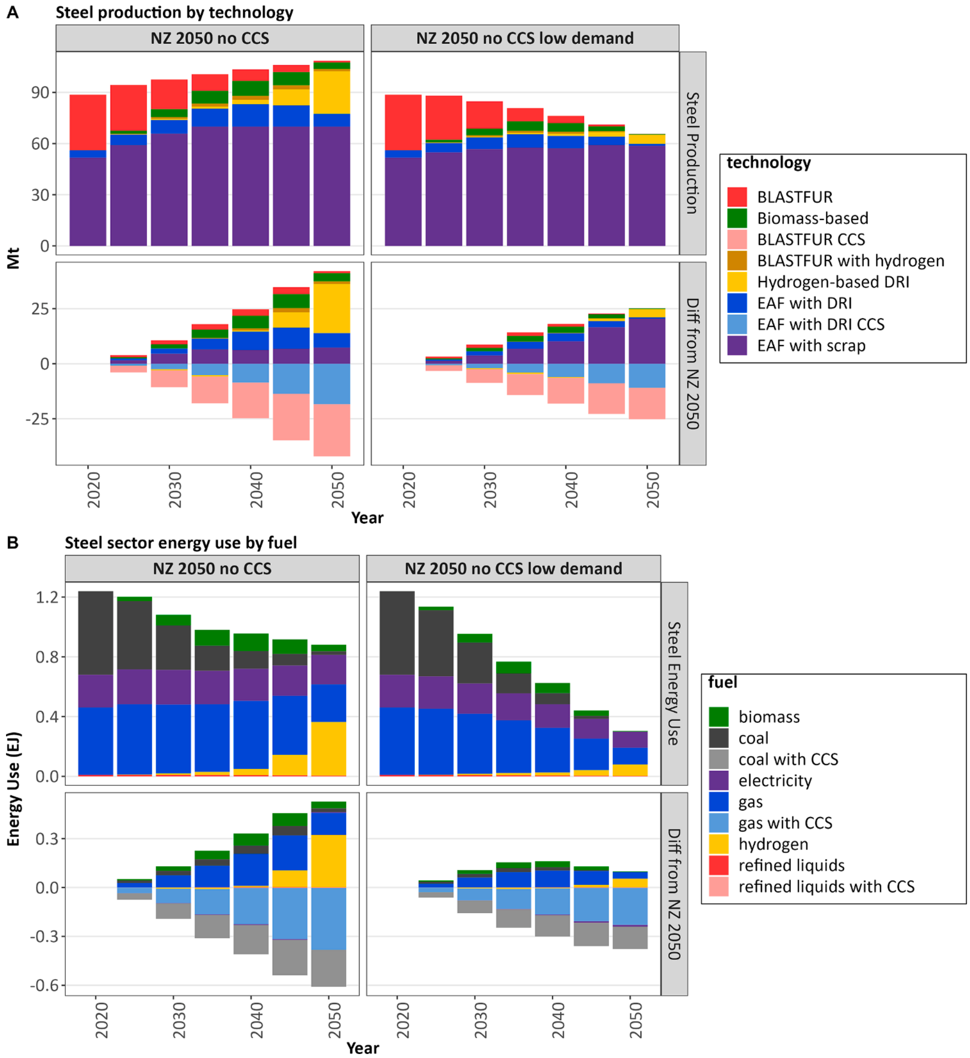

Fig. 4. a) U.S. steel production by technology and b) steel energy use by fuel consumption across NZ 2050 no CCS scenarios. The bottom-most panels in Fig. 4a and b illustrate the temporal difference in the absolute steel production and energy use in the NZ 2050 no CCS and NZ 2050 no CCS low demand scenario relative to the NZ 2050 and NZ 2050 low demand scenario respectively.

outcomes. Hydrogen consumption increases about nine-fold relative to the NZ 2050 scenario, coal consumption drops to near zero, and gas (including both abated and unabated) is consumed at about half the levels as in the NZ 2050 scenario. Furthermore, in the NZ 2050 no CCS low demand scenario, total energy use declines dramatically to just 0.3 EJ by 2050 (Fig. 4b).

Upstream sector transformations enable the U.S. steel sector's deep decarbonization. Indirect steel sector emissions associated with electricity generation contributed 28 % of the sector's total emissions in 2015 (Fig. 5a). To rapidly decrease these indirect emissions by mid-century, the power and hydrogen production sectors need to decarbonize alongside the steel sector. EAF-based steelmaking could particularly benefit from the upstream decarbonization of the grid because of its large future market share and high electricity usage. Meanwhile, hydrogen sector decarbonization is crucial for the viability of hydrogen-based DRI production as a low-carbon ironmaking option.

Though deep decarbonization of the power and hydrogen sectors occurs in all net zero scenarios, the contributions of different technologies to these decarbonized sectors vary between the scenarios (Fig. 5c and d). In all net zero scenarios, low-carbon technologies provide nearly 70 % of electricity by 2030, and the U.S. power grid is fully decarbonized by 2050. Similarly, the hydrogen production sector is also nearly fully decarbonized by 2050. However, in the NZ 2050 no CCS scenario, nuclear-based generation plays a larger role in providing the grid baseload, since fossil-based CCS is unavailable as a mitigation option. Furthermore, hydrogen is primarily produced using renewable electrolysis and thermal splitting processes in the NZ 2050 no CCS scenario, unlike the NZ 2050 scenario in which hydrogen is produced using a diverse mix of technologies also including natural gas reforming with CCS and biomass-H_2 production with CCS.

Deeper steel sector emissions reductions are observed in the NZ 2050 scenario when compared to the NZ 2050 no CCS scenario (Fig. 5a). In the NZ 2050 no CCS scenario, net steel sector emissions drop from 99 $MtCO_2$ in 2015 to 16 $MtCO_2$ in 2050, while in the NZ 2050 scenario they further decrease to 7 $MtCO_2$ by 2050. This leads to an improvement in the U.S. steel production emissions intensity, which gradually drops from 1.25 t-CO_2/t-steel in 2015 to 0.06 and 0.15 t-CO_2/t-steel in 2050 for the NZ 2050 and NZ 2050 no CCS scenarios respectively (Fig. 5b). It is important to highlight that the direct steel sector emissions remain above zero in both of these scenarios. To reach economy-wide net zero CO_2 by 2050, these residual steel emissions are abated by other sectors, which remove carbon from the atmosphere using technologies such as bioenergy with CCS, direct air capture, and other nature-based solutions (Figure SI-11).

To explore the role of international trade in the U.S. steel sector decarbonization efforts and total emissions, we examine the NZ 2050 US decarb only scenario. While the NZ 2050 scenario models all countries,

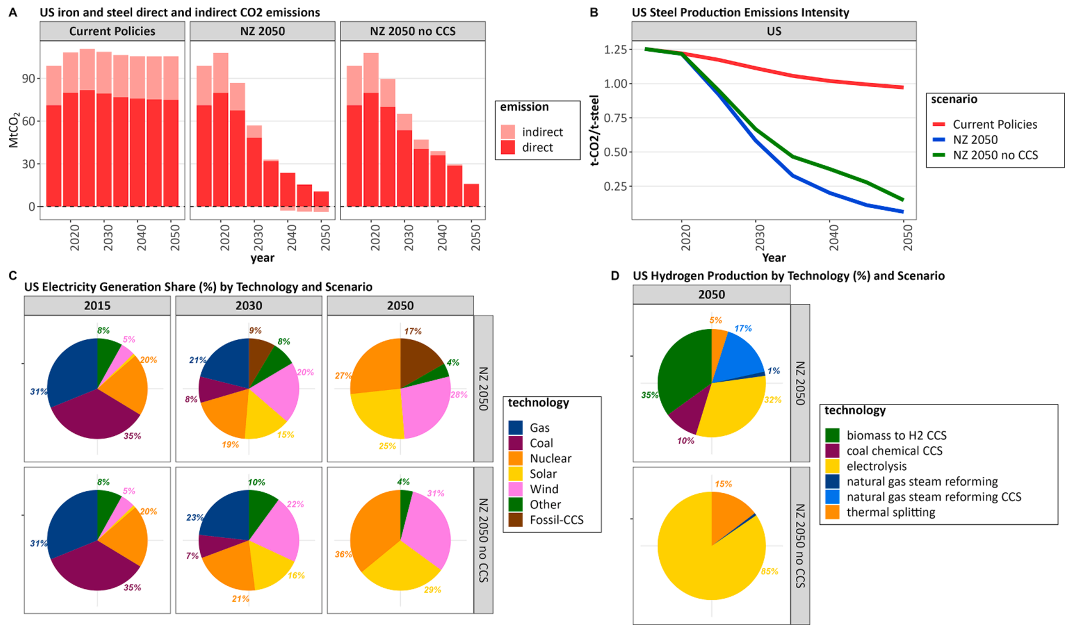

Fig. 5. a) U.S. steel sector direct and indirect CO_2 emissions, b) steel production emissions intensity across scenarios, and c) electricity generation and d) hydrogen production share by technology in NZ 2050 and NZ 2050 no CCS scenarios. The steel production intensity in 4b is estimated using the direct iron and steel sector emissions. The category "other" in 4c aggregates electricity generation from various energy sources including hydropower, biomass, refined liquids, and geothermal.

including the U.S., reaching net zero CO_2 by 2050, the NZ 2050 US decarb only scenario models the net zero target only for the United States. This scenario thus helps us quantify both the production-based and trade-adjusted consumption-based emissions attributed to the U.S. in a hypothetical future in which the global steel sector decarbonization efforts are highly unequal. This scenario directly contrasts with the NZ 2050 scenario, where global alignment in steel sector decarbonization is implicitly assumed (Figure SI-9 and SI-10).

In 2015, the U.S. steel sector's consumption-based emissions were about 1.7 times higher than its production-based emissions (Fig. 6a). This was due to the sourcing of a high volume of steel imports from countries such South Korea, Japan, and Brazil that produce a large share of their steel using the emissions-intensive BF-BOF route. The difference between the consumption- and production-based emissions steadily reduces from 2015 to 2050 in the NZ 2050 scenario. In this scenario, the global steel sector decarbonizes at a comparable rate as to the U.S., thus substantially reducing the emissions intensity of traded steel over time to near zero in 2050 (Fig. 6b). However, in the NZ 2050 US decarb only scenario, the emissions intensity of traded steel remains markedly high causing the U.S.'s consumption-based emissions to be 4.8 times higher than its production-based emissions in 2050. This leads to the transfer of large amounts of embodied carbon, adding a cumulative 1265 $MtCO_2$ to the U.S. steel sector from 2025 to 2050, which is 112 % higher than the cumulative carbon emissions from domestic steel production during the same period.

5. Discussion

An ambitious scale-up of low carbon technologies is important for drastically reducing the U.S. steel sector's emissions by 2050. The extent to which these technologies contribute to the U.S. steel sector's decarbonization will depend on industry-specific factors such as technological maturity, production costs, and raw material availability, and systemic factors such as long-term climate policy, upstream sector transitions, and the evolution of the U.S.'s steel demand.

Across all our scenarios, we find that scrap-based EAFs will be central to decarbonizing the U.S. steel sector. However, the expansion of this technology from current levels will be constrained by the future domestic scrap availability [52]. In this study, we assume that a maximum of 70 Mt recycled scrap is available for annual consumption across

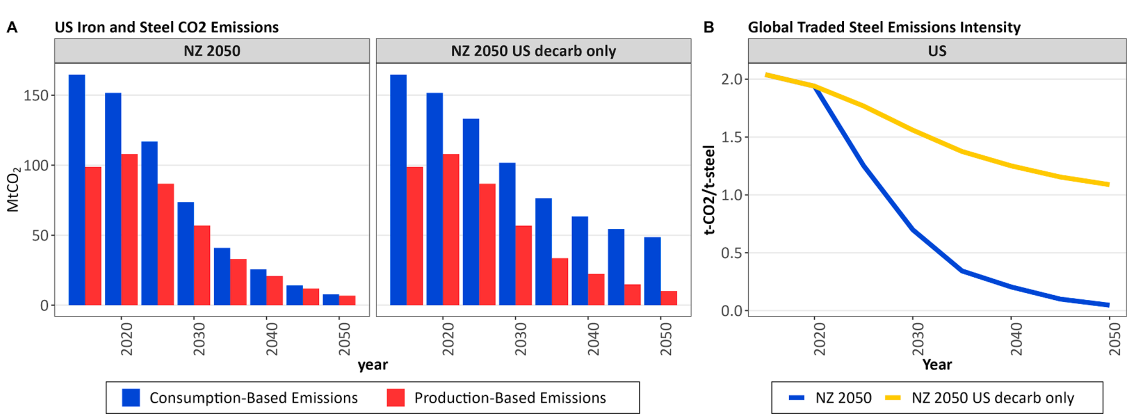

Fig. 6. a) U.S iron and steel sector production- and consumption- based emissions and b) globally traded steel emissions intensity by scenario (NZ 2050 and NZ 2050 US decarb only). The methodology used to estimate the U.S. iron and steel sector production- and consumption- based emissions is elaborated in SI-1.

steelmaking processes. If the future scrap availability is lower than our specified constraint, the expansion of scrap-based EAFs may be limited. This would be notably evident in the NZ 2050 no CCS scenario, which will require additional H_2-DRI and EAF-DRI steelmaking capacity to support the U.S. steel sector decarbonization. Furthermore, issues with scrap quality could also constrain the expansion of scrap-based EAFs. Should the demand for high-grade steel increase particularly for electric vehicle manufacturing and other automotive applications, technological advancements will be needed in scrap preparation processes to further reduce the trace metal content of recycled scrap and elevate its quality to necessary levels [42,53].

To support the continued expansion of scrap-based EAFs, U.S. steel recycling rates will need to gradually increase from the current rates, and the country may need to reduce its scrap exports to support higher domestic utilization. The requirements for domestic scrap could be drastically lowered to more manageable levels if demand reduction measures are implemented across all the end-use steel markets, especially the construction and automotive sectors [54].

Though increased scrap recycling is crucial to U.S. steel decarbonization, it must be paired with other technological transitions to achieve the necessary emissions reductions. In the NZ 2050 scenario, conventional BF-BOFs and DRI-based EAFs coupled with CCS play a significant role in producing low carbon steel. The U.S. is considered the world's leader in CCS deployment, with 14 commercial CCS facilities under operation across the fertilizer, natural gas processing, ethanol, and hydrogen production sectors in 2023 [55]. However, it is broadly agreed that the technology is still in the early stages of commercialization, especially in the iron and steel sector, where only a single CCS project has been proposed in the U.S. to date [56]. In order to be consistent with the primary decarbonization pathway in this study, the U.S. steel sector will require immediate investments supporting the large-scale commercialization of CCS. This could be achieved by retrofitting the existing BF-BOF facilities with CCS and developing new DRI-EAF plants with CCS. Supplementary techno-economic and site suitability analyses will be essential for the potential development of these facilities.

In the absence of large-scale CCS deployment in the U.S. iron and steel sector (NZ 2050 no CCS), H_2-DRI deployment will become even more imperative, highlighting the immediate need for the domestic development and testing of this technology. The provisions in the Inflation Reduction Act (IRA) of 2022 related to climate change, such as the new hydrogen tax credit, carbon sequestration tax credit, and clean energy tax credits, could help catalyze these technological transitions [57]. Additional breakthrough technologies such as Boston Metal's Molten Oxide Electrolysis [58] and ArcelorMittal's Volteron process [59] could also play a potential role in decarbonizing the U.S. iron and steel sector. The role of these technologies is not explored in this study owing to the uncertainties surrounding their large-scale commercialization in the short- and medium-term; this could be a topic for future work to explore.

Finally, it is important to address the embodied carbon transfer associated with the U.S. steel trade. Although the U.S. domestic steel sector mitigates most of its emissions by 2050 in our sensitivity scenario in which only the U.S. meets its decarbonization goals, the country's consumption-based emissions remain elevated. This is largely due to the global steel sector decarbonizing at a slower rate than that of the United States, resulting in high volumes of embodied carbon transfer through steel imports. Such a scenario could occur if steel sector decarbonization lacks multilateral cooperation on a global level in the upcoming decades. Some of the key policy measures that could help address embodied carbon transfer include green steel procurement standards [60], international technology transfer [61], and Carbon Border Adjustment Mechanisms [62,63]. Additional analyses could build on the results of this study by quantifying the impact of such policies on the embodied carbon emissions associated with the U.S.'s steel consumption.

6. Conclusions

The steel sector is often seen as one of the most challenging sectors to decarbonize, due to its reliance on technologies that demand substantial quantities of coal as both a heat source and a reducing agent as well as its capital intensity. In the United States, steel production is one of the largest industrial emitters of CO_2, responsible for about 10 % of total U.S. emissions from industry in 2015. Achieving economy-wide net zero CO_2 emissions by 2050 will thus require an ambitious scale-up of low carbon technologies for iron and steel production.

We used the Global Change Analysis Model (GCAM) to examine this technological shift and evaluate deep decarbonization pathways for the U.S. steel sector. The latest version of GCAM 7.0 includes a detailed technology representation of the iron and steel sector, incorporating existing technologies (BF-BOFs and EAFs with steel scrap or DRI as the main raw material) and emerging low carbon technologies (CCS and H_2-DRI). In addition to technological transitions, we also consider the impact of energy efficiency on emissions reductions from the steel sector. We employ an emissions constraint that facilitates reaching net zero U.S. CO_2 emissions by 2050. We also examine two alternative pathways, one in which CCS is not available in the steel sector and one in which steel demand is substantially reduced. For comparison, we also consider a current policies scenario with no steel sector mitigation measures and no emissions constraint.

In this study, we evaluate alternative technological pathways that could lead to the deep decarbonization of the U.S. iron and steel sector in a net zero CO_2 U.S. economy. In the NZ 2050 scenario, which assumes that CCS technologies are widely available for deployment in the U.S., nearly all the existing BF-BOFs and newly added DRI-based EAFs are fully integrated with CCS, with CCS-equipped technologies producing 40 % of the total steel by 2050. In the scenario in which CCS is not available as a mitigation option, conventional BF-BOFs are fully phased out by 2050. H_2-DRI is used as the primary replacement to replace this lost capacity, producing 23 % of the total steel in 2050. EAF-scrap steel production, which is already dominant in the U.S. in the early-2020s, only increases in its primacy under both these decarbonization scenarios. In the NZ 2050 scenario, EAF-scrap produces 58 % of steel in 2050, whereas in the NZ 2050 no CCS scenario it produces 65 %. Furthermore, simultaneous decarbonization of the electricity generation and hydrogen production sectors occurs in these scenarios, which allows the steel sector to substantially reduce its indirect emissions.

In both these scenarios, the increased use of production technologies with lower energy intensities, alongside advanced energy efficiency improvements, results in a 38–44 % reduction in the U.S. steel sector's energy demand in 2050 when compared to the current policies scenario. In the NZ 2050 scenario, gas with CCS takes the lead as the primary energy source, with electricity and coal with CCS following closely. However, in the NZ 2050 no CCS scenario, hydrogen emerges as the dominant energy source, followed by unabated gas and electricity. Additionally, when demand reduction measures are applied to these net zero scenarios, the total energy demand decreases further, alongside reductions in the required levels of CCS and hydrogen use in the steel sector.

Addressing the embodied carbon transfer associated with steel trade is key for the U.S. and global steel sector decarbonization. In the scenario in which only the U.S. achieves net zero CO_2 by 2050, while the rest of the world follows a business-as-usual pathway, an additional 1265 $MtCO_2$ transfers into the U.S. through steel imports from 2025 through 2050. This analysis highlights the importance of considering technological transitions and decarbonization pathways both within and outside of the U.S. when evaluating the role of the steel sector in meeting the U.S.'s climate goals.

CRediT authorship contribution statement

Siddarth Durga: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Speizer:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Conceptualization. **Jae Edmonds:** Writing – review & editing, Validation, Supervision, Resources, 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.

Acknowledgements

This article was developed based upon funding from the U.S. Department of Energy (DOE), Office of Fossil Energy. PNNL is operated for DOE by Battelle Memorial Institute under contract DE-AC05–76RL01830.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100152.

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