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Ryan N, Miller SA, Skerlos S, Cooper D. Reducing CO<sub>2</sub> emissions from US steel consumption by 70% by 2050, *Environmental Science & Technology*, 2020, 54 (22): 14598-608.  
<https://doi.org/10.1021/acs.est.0c04321>

## **Reducing CO<sub>2</sub> emissions from U.S. steel consumption by 70% by 2050**

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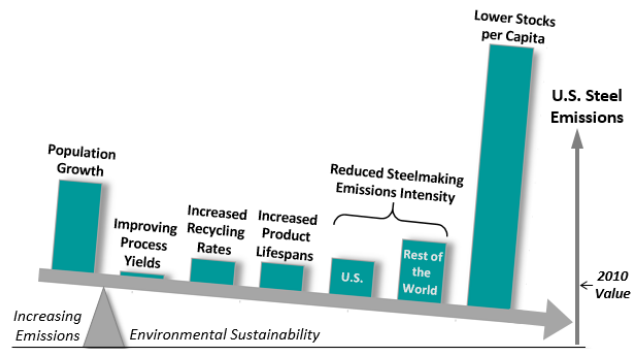
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## Abstract Art



## Abstract

The steel sector emits 25% of global industrial greenhouse gases and the U.S. is the world's second-largest steel consumer. In this article, we determine how CO<sub>2</sub> emissions attributable to U.S. steel consumption can be cut by 70% by 2050. We vary four key steel cycle parameters (U.S. steel stocks per capita, recycling rate, product lifespan, and manufacturing yield) in a dynamic material flow analysis to determine annual steel demand and the scrap available for recycling. We combine these data with steelmaking technology and trade scenarios to calculate potential U.S. steel sector emissions in each year to 2050. Only 20% of the pathways we modeled for the U.S. steel sector achieved the emissions target. Emissions in 2050 are most sensitive to the CO<sub>2</sub> released per kilogram of steel produced and the steel stocks per capita. Deployment of emerging low carbon steelmaking technology alone is insufficient to achieve the emissions cut; conversely, reducing stocks per capita from the current ~11 tons/capita toward levels in the U.K. and France, ~8 tons/capita, would enable the emissions cut to be achieved under a range of foreseeable steelmaking technology scenarios and steel cycle parameters. If action to reduce per capita steel stocks is delayed by more than five years then it is likely infeasible for the U.S. steel sector to stay within its 2050 CO<sub>2</sub> budget because of the increased demand for emissions-intensive steel made from iron ore.

## 1. Introduction

All sectors of the economy will need to decarbonize significantly in order to stabilize the global temperature and prevent the most extreme consequences of climate change.<sup>1</sup> The Intergovernmental Panel on Climate Change (IPCC) recommends a cut in greenhouse gas (GHG) emissions of 41-72% by 2050 from 2010 levels in order to ‘likely’ stay below a 2°C temperature increase.<sup>2</sup> In 2017, the industrial sector, which produces materials, products, fuels and chemicals, accounted for 21% of the world’s anthropogenic GHG emissions.<sup>3</sup> This percentage has likely shifted slightly since 2017 and has the potential to shift with changing economies. The production of a few key materials makeup the majority of industry emissions. Steel production alone accounted for 25% of global industry emissions in 2017,<sup>4</sup> and global steel demand is projected to double by 2050.<sup>5</sup> Wesseling et al. (2017) assert that energy-intensive processing industries, like steel, will need to have zero emissions before 2070 to meet the “well below 2°C” target.<sup>6</sup> However, despite industry’s significant contribution to global GHG emissions, most decarbonization roadmaps (e.g., Rockström et al. (2017)) present little guidance for the industrial sector, and even less for the steel sector specifically, on how to achieve the necessary emissions cut.<sup>1,6-8</sup> Supekar and Skerlos (2017) outline how the U.S. could meet IPCC goals in the automotive and energy sectors,<sup>9</sup> but no analysis has been completed for the U.S. steel sector. This work seeks to fill that gap by determining pathways that reduce U.S. steel sector emissions by combining options to deploy emerging steelmaking technology with options for reducing steel demand. The U.S. is the world’s second-largest consumer of steel behind China.<sup>10</sup> Therefore, the emissions attributable to the U.S. steel sector account for a significant portion of global steel sector emissions.

Steel sector emissions predominantly depend on the mass of steel consumed and the emissions released per kilogram of steel produced, which we term the emissions intensity (EI) of

production. Several studies have sought to predict the mass of future steel flows. Yin and Chen (2013) use a stock-based dynamic material flow analysis model with stock forecasts based on relationships such as floor space per capita versus GDP.<sup>11</sup> Toi and Sato (1998), Hatayama et al. (2010), and Pauliuk (2012, 2013a) also predict future flows using stock-driven dynamic material flow analysis models. They model stock saturation by extrapolating logistic curves fitted to historical data of stocks per capita against time or GDP for select sectors.<sup>12–15</sup> Pauliuk et al. (2013a)’s global steel demand prediction (2008-2018) had only a 6% error in annual demand and a 1% error in cumulative demand when compared to recorded World Steel Association values.<sup>14,16</sup> These papers make strides in predicting steel demand and highlight the use of stock-driven predictions of future steel flows. However, none of the above articles focus on the U.S. nor do they discuss the emissions implications of the predicted flows, which requires knowing what the production EIs are now and what they could be in the future.

The energy intensities of widely used steelmaking technologies are well documented in seminal works such as Cairns et al. (1998) and Worrell et al. (2007). Both include detailed data on the current process energy consumption of commercialized steelmaking technologies as well as potential reductions through best available technologies.<sup>17,18</sup> These energy intensities have been converted to EIs that can be found in academic publications<sup>19–22</sup> and grey literature.<sup>17,23,24</sup> Currently, there are no economically competitive low carbon primary steelmaking technologies. The technologies that show the greatest potential to reduce CO<sub>2</sub> emissions (e.g., electrolysis and hydrogen direct reduction) rely on expensive electrical energy and are currently 4 to 6 times more electricity intensive than the electric arc furnaces used to recycle scrap steel (Supporting Information (SI) Section 4).

A few researchers have combined estimates of future steel flows (e.g., demand) and steelmaking EIs to predict future steel sector emissions; however, none have conducted a parametric study that reveals the options for how the sector needs to evolve over time in order to meet an emissions goal. Most studies do not consider potential changes to the demand trajectory,<sup>21,25–30</sup> and only a small subset consider changes to steelmaking technology.<sup>4,31</sup> Milford et al. (2013)’s global analysis is the most comprehensive found in the literature. Their analysis includes both supply (e.g., electrolysis deployment) and demand (e.g., more intense material use) emission reduction options. Globally, the effect on emissions of improving supply-side technology is negated by increasing demand for emissions-intensive primary steel to build-up societal stocks in the developing world. Subsequently, Milford et al. find that even aggressive deployment of supply-side efficiency measures can only reduce global steel sector emissions by 20% by 2050.<sup>20</sup> In contrast, U.S. steel consumption per capita has plateaued since the 1980s.<sup>32</sup> Without a U.S. focused study, it is unclear whether supply-side measures alone are sufficient for the U.S. steel sector to meet the emissions target.

## 1.2 Scope of this Work

The goal of this study is to define pathways that cut CO<sub>2</sub> emissions attributable to U.S. steel consumption by 70% from a 2010 baseline by 2050, which is close to the maximum reduction recommended by the IPCC.<sup>2</sup> We focus on CO<sub>2</sub> emissions because it accounts for 93% of the GHG emissions from primary and secondary steel production.<sup>33</sup>

Each pathway defined in this analysis is a unique combination of *steelmaking technology scenarios*, *trade scenarios*, and *steel cycle parameters*, together representing a comprehensive suite of options for reducing emissions. Therefore, this analysis informs an evaluation of the

efficacies and trade-offs between a supply-side technology driven and/or demand driven emissions reduction strategy for the steel sector. The *steelmaking technology scenarios* determine the EI of primary and secondary steelmaking in the U.S. and the rest of the world (ROW). The *trade scenarios* determine the percentage of U.S. steel consumption that is produced overseas. This analysis focuses on emissions attributable to U.S. steel consumption and therefore includes emissions released outside of the U.S. in order to make steel for U.S. consumption. The four *steel cycle parameters* (U.S. steel stocks per capita, recycling rate, steel lifespan, and manufacturing yield) determine future steel demand and the availability of scrap for recycling. Policy interventions (e.g., to increase *recycling rates*) could be made, or societal or commercial shifts (e.g., towards longer product *lifespans*) could be realized that reduce future steel demand. Therefore, a range of values is modeled for each steel cycle parameter in 2050. A business as usual (BAU) pathway is defined as equal to the base case *steelmaking technology* and *trade scenario* and base case set of *steel cycle parameters* (see *Methodology*).

This article is intended to be useful to a broad audience, including industry, policymakers, and researchers. Each of these stakeholders has the potential to take action that could shift the steel sector towards a lower emissions pathway.

## 2. Methodology

The methods section explains how the annual and cumulative CO<sub>2</sub> emissions were calculated for each simulated pathway of the future U.S. steel sector (2.1), and how the *steelmaking technology scenarios* (2.2), *trade scenarios* (2.3), and *steel cycle parameters* (2.3) were defined and combined.

### 2.1 Calculating U.S. steel sector emissions and targets

The annual CO<sub>2</sub> emissions attributable to U.S steel consumption, *Annual emissions*<sub>*t,i*</sub> in year *t* (2020-2050) under simulated pathway *i*, were calculated using eqn. 1:

$$Annual\ emissions_{t,i} = \sum_{tech} (prod_{t,i,tech}^{U.S.} \times EI_{t,i,tech}^{U.S.}) + \sum_{tech} (prod_{t,i,tech}^{ROW} \times EI_{t,i,tech}^{ROW}), \quad (1)$$

where  $prod_{t,i,tech}^{U.S.}$  and  $prod_{t,i,tech}^{ROW}$  are the masses of steel produced for U.S. consumption by each steelmaking technology in the U.S and the ROW respectively; and,  $EI_{t,i,tech}^{U.S.}$ , and  $EI_{t,i,tech}^{ROW}$  are the EIs of those steelmaking technologies in the U.S. and the ROW respectively. This research focused on direct and indirect emissions released from steelmaking (i.e., the conversion of iron ore to steel or the melting of scrap), which accounts for 70-77% of the CO<sub>2</sub> emissions released during the production of a steel part.<sup>33</sup> The majority of remaining emissions after the steelmaking process are indirect emissions from the generation of electricity used to power manufacturing processes.<sup>34</sup>

The IPCC emissions targets are in reference to 2010. As with pathway emissions (eqn. 1), 2010 emissions are dependent on steel flows (collected from World Steel Statistical Yearbook)<sup>16</sup> and production EIs (SI Section 6).

## 2.2 The emissions intensity of production: Steelmaking technology scenarios

Four *steelmaking technology scenarios* determine the EIs used in eqn. 1. Each scenario defines the mix of primary steelmaking technologies and the EI of the electricity grid for each year (2020-2050) in the U.S. and the ROW. The scenarios were defined by identifying emerging steelmaking technologies (section 2.2.1); calculating the EI of the steelmaking technologies (section 2.2.2); and, then determining their feasible market share by 2050 (section 2.2.3). All the *steelmaking technology scenarios* are equal in 2020. After 2020, they begin to diverge as the

market share of emerging technologies increases at a constant rate ultimately matching the unique scenario values in 2050.

### 2.2.1 Identifying emerging steelmaking technologies

Most primary steelmaking facilities in the U.S. and the ROW currently include a **Blast Furnace (BF)** that converts iron ore, coke and sinter to pig iron, and a **Basic Oxygen Furnace (BOF)** that converts pig iron to raw steel. The BF is the most emissions intensive step in conventional primary steelmaking, driven by indirect emissions from the coking process and direct emissions from fuel burning and reduction of the iron ore. Therefore, for the EI of primary steelmaking to reduce significantly the conventional BF must be improved or superseded. Alternative commercial and emerging steelmaking technologies were identified through a literature review<sup>35–39</sup> and interviews with industry experts.<sup>40–42</sup>

An adaptation of the conventional BF that lowers the EI is **BF top-gas recycling** where the CO from the BF off gases is fed back into the furnace. The returned CO acts as a reductant and displaces the use of coke. Direct reduction (DR) can decrease emissions further by reducing iron ore to direct reduced iron (DRI) without the emissions intensive coking process. DRI is a sponge iron that must go through an EAF or a BOF to produce steel. DR can use a variety of fuels. **Coal-DR** and **NG-DR** (natural gas-DR) are commercialized steelmaking technologies, but globally produce less than 5% of all primary steel. **H-DR** (hydrogen-DR) is an emerging steelmaking technology and could release near to zero emissions if the hydrogen were produced using electrolysis powered by a renewable electricity source. **Smelt reduction (SR)** and **steel electrolysis** are both emerging primary steelmaking technologies that also eliminate the coking process. SR reduces pelletized iron ore or fines in a two-step process with coal gasification. Steel

electrolysis is electricity intensive (2,692 kWh/t steel) but could greatly reduce the EI of steelmaking if powered by decarbonized electricity (SI Section 4).

Recycling steel scrap in the U.S. and the ROW currently occurs either in an EAF (secondary steelmaking) or in the BOF, where it **absorbs the heat that results from the conversion of carbon to carbon monoxide**. For secondary steelmaking, we identified no rival technologies to the EAF. Approximately 73% of EAF emissions are from electricity generation (SI Section 4); however, some direct emissions are released from burning natural gas within the furnace, which provides up to 30% of the energy.<sup>43</sup>

Other steelmaking processes considered in this study but excluded from the *steelmaking technology scenarios* include the paired straight hearth furnace (**PSH**), hydrogen flash ironmaking technology (**FIT**), and carbon capture and storage (**CCS**) (SI Section 4). PSH is an emerging technology that uses coal to produce DRI but is more emissions intensive than commercially available NG-DR. FIT is an emerging steelmaking technology similar to DR but requires almost twice as much hydrogen as H-DR.<sup>19,44</sup> CCS could remove CO<sub>2</sub> from the BF exhaust gas but has a limited potential to reduce emissions: a European Steel Association analysis found that equipping all BFs in the E.U. with CCS by 2050 would lower annual emissions by only 60% compared to 1990.<sup>45</sup> CCS is also expensive (200 to 500 USD/tCO<sub>2</sub>),<sup>4</sup> and it is unproven at an industrial scale.<sup>45</sup>

## **2.2.2 Calculating the emissions intensity of steelmaking technology**

Figure 1 shows the EIs of the steelmaking technologies included in the *steelmaking technology scenarios* at different electricity EIs. The EI of each steelmaking technology includes the direct emissions from burning fuels (e.g., coke in the BF), and indirect emissions from electricity generation and the production of feedstocks (e.g., sinter in smelt reduction). For most

commercial steelmaking technologies, direct emissions, feedstock and electricity requirements were found in academic publications<sup>19–22</sup> and grey literature.<sup>17,26,45</sup> However, the EIs of emerging steelmaking technologies, which have yet to see commercial use (e.g., electrolysis), are less well reported. They were derived from data sources that publish anticipated reductions in emissions compared to existing technologies; e.g., the European Steel Associations Low Carbon Roadmap (2013) reported that making steel using electrolysis can reduce CO<sub>2</sub> emissions by 98% compared to using a BF (SI Section 4).<sup>45,46</sup> Figure 1, illustrates the importance of grid decarbonization in each technologies' EI. Those with the greatest percent indirect emissions have the greatest potential for decarbonization (e.g., electrolysis) but are therefore limited by the grid's EI.

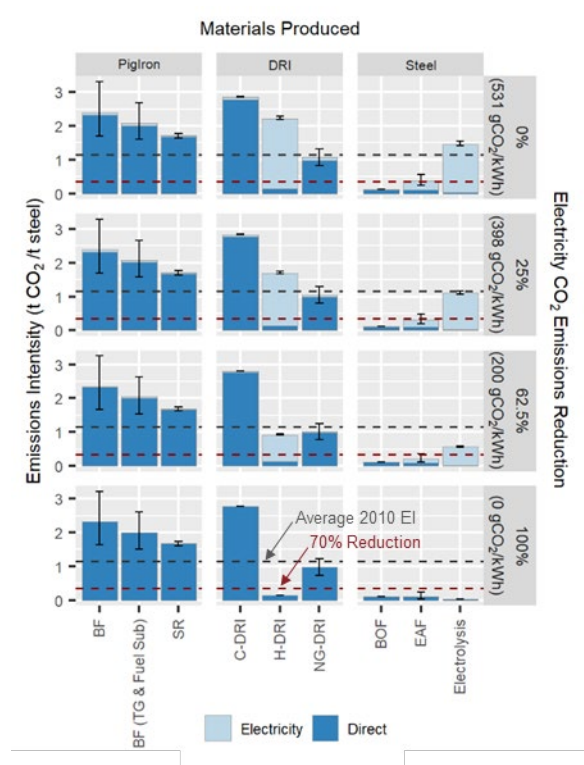


Figure 1, Steelmaking technology CO<sub>2</sub> emissions intensity (EI) at different levels of electricity decarbonization. Pig Iron and direct reduced iron (DRI) must also go through either the BOF or the EAF to become steel. 2010 U.S. electricity EI = 531 gCO<sub>2</sub>/kWh. BF = blast furnace, TG = top gas recycling, SR = smelt reduction, C = coal, H = hydrogen, NG = natural gas, EAF = electric arc furnace

### 2.2.3 Market share of low carbon technology by 2050

Table 1 defines the four *steelmaking technology scenarios* used in this analysis. In the base case scenario (highest emissions), the market share of each steelmaking technology and the EI of the electricity grid is the same in 2050 as it was in 2020 (421 g CO<sub>2</sub>/kWh). The three other *scenarios* represent increasingly aggressive steelmaking decarbonization (decreasing EIs).

Figure 1 shows that the greatest potential to reduce steelmaking emissions is rapid deployment of H-DR and steel electrolysis coupled with a decarbonizing electricity grid. However, Fishedick et al. (2014) and Wyns et al. (2016), in comprehensive reviews of the potential for deep decarbonization in primary steelmaking, predict that H-DR and steel electrolysis will not be fully commercialized until 2030 and 2040 respectively because they are uneconomical at current electricity prices without subsidies.<sup>35,47</sup> Therefore, even in the low emissions *steelmaking technology scenario*, H-DR and steel electrolysis were limited to a 20% and 15% market share by 2050 respectively (SI Section 4).

SR is also not anticipated to be fully commercialized until 2030 or later<sup>37,45</sup> and has a limited potential to reduce emissions compared to the BF (Figure 1) and was therefore kept at a 5% market share by 2050 in each scenario.

NG-DR is already used at a commercial scale; therefore, it is expected that its market share could grow significantly by 2050. However, because the EI of NG-DR is still greater than 50% of the BF/BOF route, NG-DR was limited in the scenarios to a 40% market share to leave a share for cleaner technologies (e.g., steel electrolysis).

The BF remains a significant source of primary steel in all the scenarios. BF top gas recycling and fuel substitution only offers a small reduction in the BF EI. However, BF top gas recycling and fuel substitution is assumed to be widely deployed by 2050 in the high, medium,

and low *steelmaking technology scenarios* because it is a (relatively simple) retrofit to existing BF facilities (Table 1).

The EI of the electricity grid was varied across the *steelmaking technology scenarios*, because it has a significant effect on the overall steelmaking EI (Figure 1). In 2018, electricity generation from low carbon resources accounted for only 17% of the supply in the U.S.<sup>48</sup> and 26% globally.<sup>49</sup> Many studies have shown that 80-100% renewable grids are feasible.<sup>50–53</sup> Therefore, in the low emissions *steelmaking technology scenario*, a 100% reduction in electricity emissions is assumed by 2050 (Table 1).

Table 1, Steelmaking technology scenarios

| Technology Scenarios                                    |                                           |  |                       |                         |                      |      |
|---------------------------------------------------------|-------------------------------------------|--|-----------------------|-------------------------|----------------------|------|
|                                                         | Base Case (highest Emissions (2020-2050)* |  | High Emissions (2050) | Medium Emissions (2050) | Low Emissions (2050) |      |
| Primary EI                                              |                                           |  |                       |                         |                      |      |
| U.S. (t CO <sub>2</sub> /t steel)                       | 2.25                                      |  | 1.77                  | 1.40                    | 0.970                |      |
| ROW (t CO <sub>2</sub> /t steel)                        | 2.31                                      |  | 1.81                  | 1.42                    | 0.970                |      |
| Secondary EI                                            |                                           |  |                       |                         |                      |      |
| U.S. (t CO <sub>2</sub> /t steel)                       | 0.313                                     |  | 0.260                 | 0.180                   | 0.100                |      |
| ROW (t CO <sub>2</sub> /t steel)                        | 0.346                                     |  | 0.285                 | 0.192                   | 0.100                |      |
| Electricity Grid Emissions                              |                                           |  |                       |                         |                      |      |
| % Electricity Emissions Reduction                       | 0%                                        |  | 25%                   | 62.5%                   | 100%                 |      |
| U.S. Electricity EI (g CO <sub>2</sub> /kWh)            | 421 <sup>54</sup>                         |  | 316                   | 158                     | 0.00                 |      |
| ROW Electricity EI (g CO <sub>2</sub> /kWh)             | 485 <sup>54</sup>                         |  | 364                   | 182                     | 0.00                 |      |
| Primary Steelmaking Market Share 2050                   | U.S. <sup>16,55,56</sup>                  |  | ROW <sup>16,56</sup>  | U.S. & ROW              |                      |      |
| Electrolysis                                            | 0%                                        |  | 0%                    | 10%                     | 12.5%                | 15%  |
| Coal-DR                                                 | 0%                                        |  | 1%                    | 0%                      | 0%                   | 0%   |
| NG-DR                                                   | 10%                                       |  | 6%                    | 20%                     | 30%                  | 40%  |
| H-DR                                                    | 0%                                        |  | 0%                    | 5%                      | 12.5%                | 20%  |
| Smelt Reduction                                         | 0%                                        |  | <1%                   | 5%                      | 5%                   | 5%   |
| Blast Furnace                                           | 90%                                       |  | 93%                   | 60%                     | 40%                  | 20%  |
| Top Gas Recycling as fuel substitution % of BFs in 2050 | 0% <sup>57</sup>                          |  | 0% <sup>57</sup>      | 80%                     | 90%                  | 100% |
| Secondary Steelmaking Market Share                      |                                           |  |                       |                         |                      |      |
| EAF                                                     | 100%                                      |  | 100%                  | 100%                    | 100%                 |      |

\* The Base Case values are representative of 2020 and do not change between 2020 and 2050.

## 2.3 Mass of steel produced by each steelmaking technology

The mass of steel produced each year by each steelmaking technology in the U.S. and the ROW (needed in eqn. 1) was calculated by:

- First, using the *steel cycle parameters* to determine the annual steel demand and scrap available for secondary steelmaking (section 2.3.1);
- Second, using the *trade scenario* to determine the amount of that steel demand that will be produced in the ROW and the amount of scrap that will be exported (section 2.3.2);
- Third, using an annual mass flow analysis to combine the steel demand, available scrap, imports/exports, and steelmaking technology mix to calculate the annual mass of steel produced by each steelmaking technology (section 2.3.3).

### 2.3.1 Calculating U.S. steel demand and scrap availability (SI Section 2)

Annual steel demand and scrap availability depend on the *steel cycle parameters*: the quantity of steel *stocks per capita* needed to provide material services (e.g., infrastructure); the *lifespan* of steel that determines how often it needs to be replaced; the *recycling rate* that determines the percentage of available scrap from discarded products collected for U.S. recycling or export; and, the *manufacturing process yield* that determines the steel required per kilogram of finished steel product. These four parameters were selected so that the steel consumption and losses occurring at each stage of the material cycle could be adjusted: production, use, and disposal. The steel parameters represent a top down approach and do not prescribe specific policy mechanisms. Previous literature has used lightweighting or intensity of use rather than adjusting stock per capita or demand for example,<sup>20</sup> however, the goal of this work is not to test specific policy options but outline the required changes in each parameter a policy would need to achieve. This analysis simulated changes to the *steel cycle parameters* at a constant rate from their values in 2020 to a range of feasible values in 2050 (Table S1).

A dynamic material flow analysis (DMFA) was used to calculate the annual scrap availability and steel consumption. Based on when a material enters use (i.e., stock), a DMFA uses a *lifespan* distribution to predict when it leaves use as scrap. Not all steel products have the same *lifespan*; therefore, steel flows were disaggregated into four demand sectors (construction, transport, machinery, and products) and assigned unique *lifespan* distributions taken from the literature (Table S6).<sup>164–167</sup> The annual scrap availability,  $Scrap_{t,s,i}$ , in demand sector  $s$  under simulated pathway  $i$ , was calculated using eqn. 2 for  $t = 2020, 2021, \dots, 2050$ :

$$Scrap_{t,s,i} = \sum_{t_o=1880}^t Consumption_{t_o,s,i} L_{t-t_o}(\mu_{t_o,s,i}, \sigma_{t_o,s,i}), \quad (2)$$

where  $Consumption_{t_o,s,i}$  is the annual consumption of steel products in demand sector  $s$  in year  $t_o$  (dating back to 1880) under pathway  $i$ , and  $L_{t-t_o}$  is the discrete *lifespan* normal distribution of steel with a mean *lifespan* of  $\mu$  years and a standard deviation of  $\sigma$  years.  $L_{t-t_o}$  determines the probability that steel entering use in year  $t_o$  will leave use as scrap in year  $t$ . Increasing the product *lifespan* delays when a product will be scrapped, reducing annual scrap availability (eqn. 2), replacement rate, and consumption (eqn. 3). Steel sector pathways were simulated for steel *lifespan*s ( $\mu$  and  $\sigma$ ) that in 2050 are +/- 30% of the 2020 values (Table S6). Base case *lifespan*s are kept at 2020 values. One set of analyses simulated the effect of changing the *lifespan* of only new products (non retrofit case; eqn. 2), and another set of analyses simulated the effect of changing the *lifespan* of both new and existing products (retrofit case; SI Section 2stock.3). The base case simulated unchanged product *lifespan*s between 2020 and 2050.

The annual steel consumption ( $Consumption_{t,s,i}$ ) in demand sector  $s$  in future year  $t$  was calculated using eqn. 3 (a stock-driven DMFA).

$$Consumption_{t,s,i} = (STC_{t,s,i}Pop_{t,i} - STC_{t-1,s,i}Pop_{t-1,i}) + Scrap_{t,s,i}, \quad (3)$$

where  $STC_{t,s,i}$  is the *stocks per capita* in demand sector  $s$  in year  $t$  under pathway  $i$ , and  $Pop_{t,i}$  is the U.S. population in year  $t$ . Consumption is modeled as a function of stocks because it is the demand for material services (e.g., commercial real estate) provided by the in-use stock that drives the material cycle for materials with long product *lifespans* (e.g., steel).<sup>58,59</sup> By connecting stocks and consumption, we can begin to understand how the design and use of steel products will have to change in order to reduce consumption.

The U.S. steel *stock per capita* in 2020 was estimated to be 10.7 tons/capita using methods from Cooper et al. (2020) (SI Section 2.1).<sup>32</sup> The range of simulated *stocks per capita* values in 2050 was based on the range of *stocks per capita* saturation values found in the literature for developed countries (8-14 tons/capita).<sup>60</sup> In the BAU pathway, the *stocks per capita* followed a logistic saturation curve as a function of time (SI Section 2.3.1), rising from 10.7 tons/capita in 2020 to 11.4 tons/capita in 2050. Otherwise, the *stocks per capita* was simulated at a constant rate of change between 2020 and 2050. The base case U.S. population is modeled at 331 million in 2020 and 389 million in 2050, as predicted by the U.S. Census Bureau.<sup>61</sup> In order to account for the uncertainty in this population projection (eqn. 3), we modeled steel emissions for a range of population growth rates (Table S1); from no population growth to a population of 452 million by 2050 (similar to the U.S. Census Bureau's high migration scenario).<sup>62</sup>

The DMFA calculated the future annual U.S. steel consumption of finished goods. However, this is not equal to the quantity of steel that must be produced (the steel demand) because scrap is generated in manufacturing between the production of intermediate steel goods (e.g.,

slabs) and finished steel components (e.g., car doors). The ratio by mass of finished to intermediate goods is called the *manufacturing process yield* and was used to calculate the annual steel demand. Globally, the mean *manufacturing process yield* is 78%.<sup>5</sup> Many researchers have advocated improving this yield,<sup>5</sup> which could reduce manufacturers' material costs.<sup>16</sup> Therefore, alongside a base case process yield value of 78% (unchanged between 2020-2050), we also simulated the case of *manufacturing process yields* increasing at a constant rate from 78% in 2020 to 88% in 2050.

The DMFA calculated the future annual generation of scrap from discarded products but not all of the scrap produced is recycled (secondary production). The percentage of this scrap collected for domestic recycling or export is equal to the *recycling rate*. The aggregate recycling rate in 2020 was 79% (Table S7).<sup>30,63,64</sup> In the base case, *recycling rates* remained unchanged between 2020 and 2050. There is scope for *recycling rates* to increase but there are also pressures that could reduce *recycling rates* (e.g., due to a decrease in demand for low quality recycled steel products (Cooper et al. 2020)); therefore, we modeled a range of *recycling rates* in 2050 that are +/-10% compared to the 2020 values.

### 2.3.2 Calculating steel imports and scrap exports: Trade Scenarios (SI Section 3)

International trade of steel and steel scrap must be tracked because the U.S. and the ROW currently use different steelmaking technology, have a different ratio of primary to secondary steelmaking, and have different electricity EIs. Three *trade scenarios* (high, medium, zero; Table S8) were simulated in this analysis to encompass the range of possible foreign policy effects on iron ore, steel, and scrap trade. The scenarios define the percentage of U.S. steel consumption provided by imports and the percentage of collected U.S. scrap that is exported. All the trade scenarios model a constant rate of change over time from 2020 to 2050. The highest trade scenario

reflects an extension of the free trade seen before the imposition of the 2018 U.S. steel import tariffs.<sup>65</sup> The base case is the medium *trade scenario*.

This study used the recycled content method<sup>66</sup> to account for emissions attributable to trade. No credit (i.e., negative emissions) was assigned to U.S. scrap exports but the recycled content of imports was included in the EI of the ROW steelmaking.

### **2.3.3 Annual mass flow analysis: calculating production routes (SI Section 5)**

An annual mass flow analysis was used to calculate the mass of steel produced by each steelmaking technology in the U.S. and ROW in each year of the simulated steel sector pathways. The annual mass flow analysis combined the simulated steel demand, scrap collection, steel imports, and scrap exports with the steelmaking technology mix. The mass flow (Figure S30) was made determinant by using a linear optimization, with the masses of steel produced by domestic steelmaking technologies as decision variables. The optimization minimized domestic primary steelmaking subject to scrap supply and steel demand constraints. In turn, this maximized the use of scrap in secondary steelmaking. The optimization objective function is reflective of real-world practice because secondary steelmaking is cheaper than primary steelmaking.

The mass of steel produced using each steelmaking technology in the ROW was determined by the U.S. steel consumption, the *trade scenario*, the predicted ratio of primary to secondary steelmaking in the ROW 2020-2050 from Pauliuk et al. (2013),<sup>14</sup> and the technology mix in each simulated *steelmaking technology scenario* (Table 1).

## **3. Results and Discussion**

In this analysis, we simulated 329,284 distinct pathways for the future of the U.S. steel sector (Table S1, 3 *trade scenarios*, 16 *steelmaking technology scenarios*, 7 stocks per capita levels x 14 product lifespans, 5 recycling rates, 7 population projections, and 2 manufacturing yields). The BAU pathway results in annual emissions of 129 Mt CO<sub>2</sub> in 2050 and 3.4 Gt of cumulative CO<sub>2</sub> emissions (2020-2050): 278% and 58% above the annual, 34 Mt, and cumulative, 1.7 Gt, emissions target respectively. The BAU pathway is defined as base case *steelmaking technology* and *trade scenarios*, 2020 values for product lifespans, recycling rates and manufacturing yields, a stocks per capita of 11.4 tons/capita, and population equaling U.S. Census Bureau 2050 predictions. Only 1 in 5 of the pathways successfully meet the requirement that CO<sub>2</sub> emissions attributable to U.S. steel consumption are reduced by 70% by 2050. Figure 2 illustrates the sensitivity of meeting the CO<sub>2</sub> emissions targets to the *steelmaking technology scenario*, *trade scenario*, and *steel cycle parameters*. Figure 2 shows how the percentage of pathways that meet the targets changes when switching between extreme scenarios and 2050 *steel cycle parameter* values. However, these percentages and others presented in the results should not be interpreted as probabilities. They are used to describe the impact a parameter has on sector emissions rather than their likelihood of occurrence.

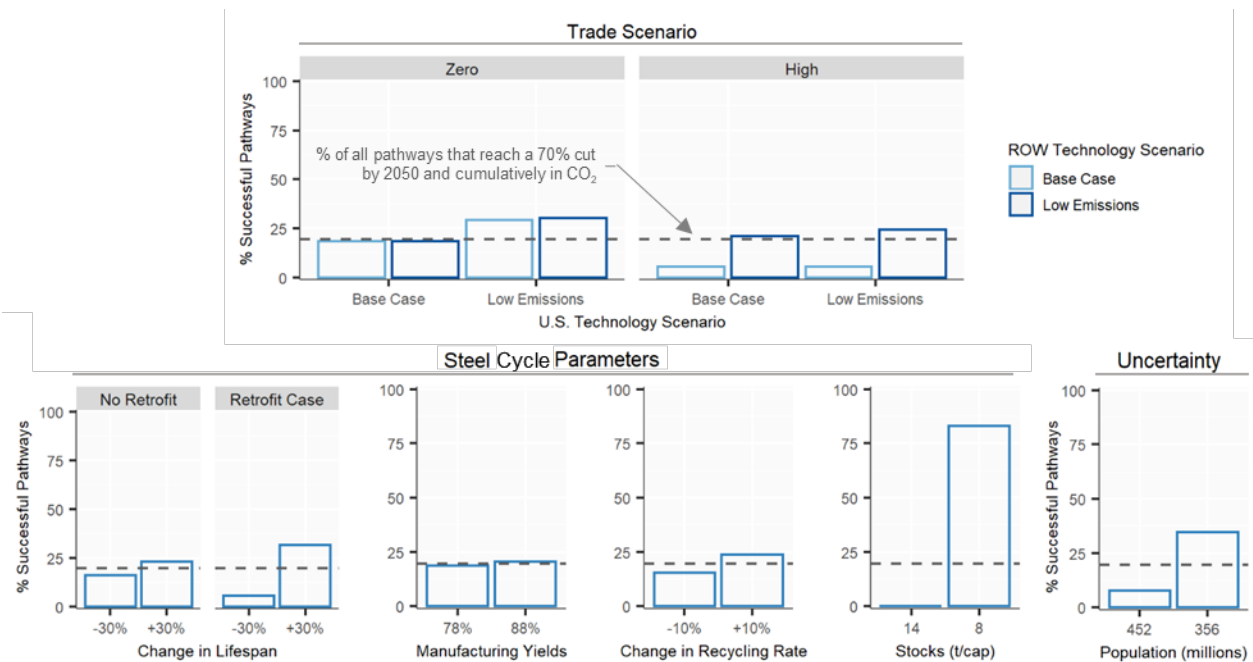


Figure 2, The percentage of pathways that meet the 2050 annual and cumulative CO<sub>2</sub> emissions targets (i.e., a successful pathway) for extreme trade scenarios (top), steelmaking technology scenarios (top), steel cycle parameters in 2050 (bottom), and values for the U.S. population in 2050 (bottom-right). The Base Case steelmaking technology scenario (Table 1) is the highest emissions steelmaking scenario. The percentage changes in recycling rate and lifespan represent changes from the base case values listed in Table S7 and Table S4. ROW = Rest of World

Figure 2 shows that U.S. emissions are most sensitive to the *steelmaking technology scenario*, *stocks per capita*, *product lifespan*, and *population*. Figure 3 shows how these *steelmaking technology scenarios* and *steel cycle parameters* combine to determine the annual emissions in 2050, and which combinations stay within the emissions limits. SI Section 8 includes results figures for all 329,284 simulated pathways.

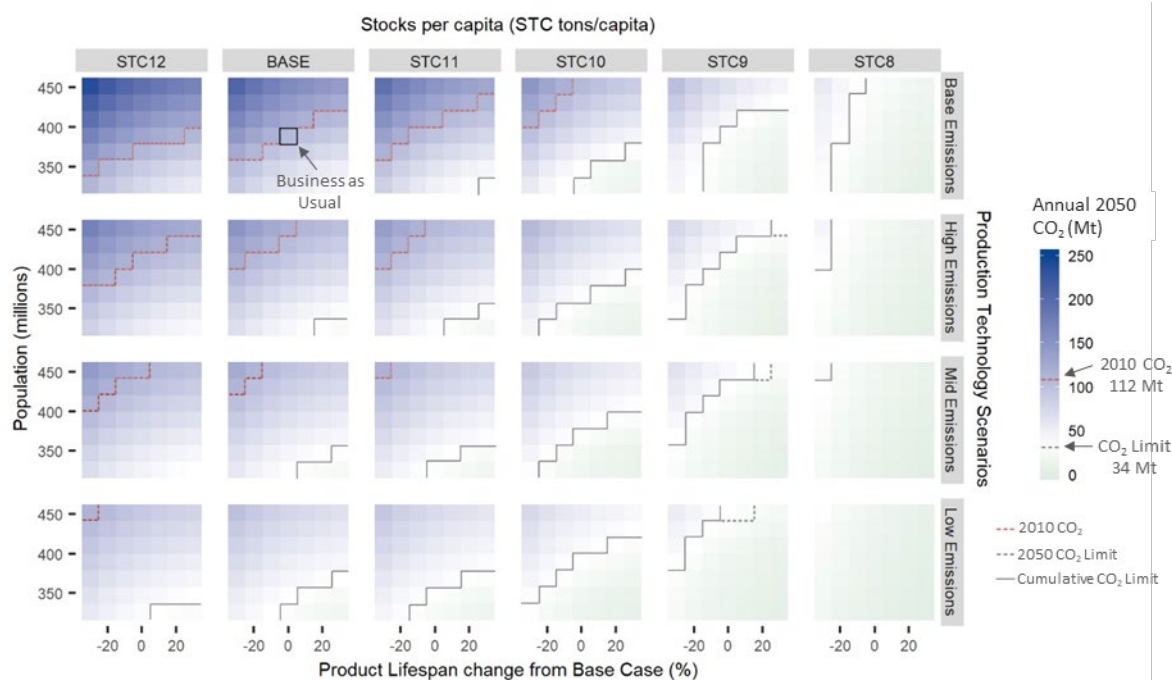


Figure 3, Annual emissions attributable to U.S. steel consumption in 2050. The gray lines mark the divisions between pathways that do (green) and do not (blue) achieve the emission targets. Results generated for the base case *trade scenario*, *recycling rate*, *manufacturing process yield*, and *product lifespan* under the retrofit case. The expected U.S. population in 2050 is 389 million people (middle row in each facet)

All of the pathways that meet the emissions targets represent a significant departure from BAU steelmaking and steel demand; extraordinary action is likely required by industry and government to sufficiently reduce emissions. Figure 3 shows that reducing the EIs of steel production and the steel *stocks per capita* will have the greatest impact on emissions, and are discussed in sections 3.1 and 3.2 respectively. Section 3.3 discusses the effect on emissions of varying *product lifespans*, *recycling rates*, and the *manufacturing process yield*. Section 3.4 addresses the effect of delaying action on the feasibility of meeting the cumulative CO<sub>2</sub> emissions target.

### 3.1 Changes Needed in Steelmaking Technology

If the steel sector continues to use its current technology, drastic reductions primary steel are required to meet the emissions target. Figure 3 shows that only 4% of pathways with the base

case *steelmaking technology scenario* stay within the CO<sub>2</sub> emissions limits. This 4% of pathways represented an average reduction in domestic primary production of 94% between 2019 and 2050. Additionally, Figure 3 shows that even under the lowest emissions *steelmaking technology scenario*, the emissions targets can only be met if there has also been a reduction in *stocks per capita*, a reduction in expected *population* growth, or an increase in *product lifespans* by 2050. Meaning, less carbon intensive steelmaking does not guarantee that the emissions targets will be met.

Figure 4 shows the relationship between reductions in *stocks per capita* and the deployment of low carbon steelmaking technologies. For any level of *stocks per capita* in 2050, there exists a theoretical range (shaded in green) of primary and secondary steelmaking EIs that would allow the U.S. to succeed in meeting the 2050 annual emissions cut. However, even under the low emissions *steelmaking technology scenario*, the *stocks per capita* must be reduced to at least 10 tons/capita by 2050 for the emissions targets to be achieved.

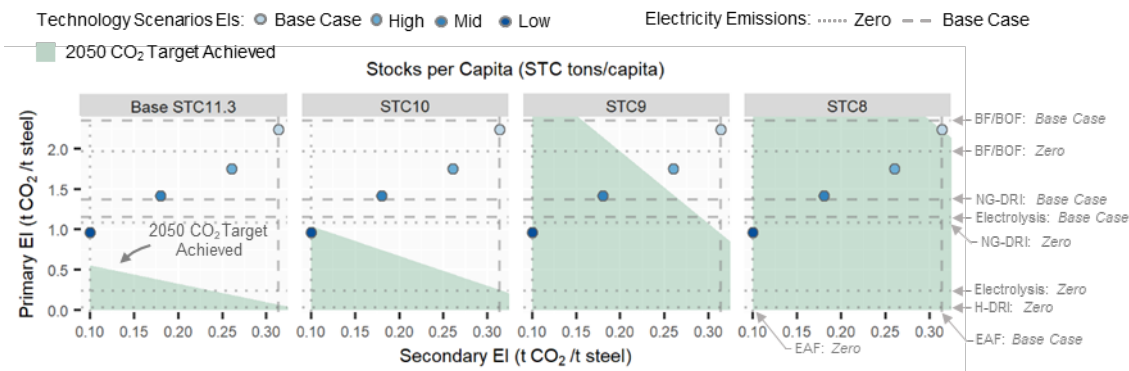


Figure 4, Primary and secondary steelmaking EIs needed by 2050 to achieve a 70% cut in annual emissions from 2010 levels under varying *stocks per capita* (STC) values in 2050 (green regions) compared to *technology scenario* emissions intensities (EIs). The data plotted is for the base case *trade scenario*, *recycling rate*, and *manufacturing process yield*

The primary steelmaking EI is the main barrier to the emissions targets being met (Figure 4). Unfortunately, low carbon primary steelmaking technologies (H-DRI and electrolysis) are not expected to be fully commercialized for another 10 to 20 years. Additionally, the grid's EI has the potential to limit their decarbonization ability. Furthermore, Figure 4 shows the emissions target is unachievable with today's electricity EI irrespective of the steelmaking technology if not accompanied by a reduction in *stocks per capita* to at least 9 tons/capita.

Hazardous Air Pollutant standards,<sup>67</sup> which exclude GHGs, are currently the only air emissions regulations on U.S. steelmaking plants. The U.S. government could attempt to motivate the development of H-DRI and electrolysis by introducing GHG regulations; however, given low carbon technologies are currently uneconomical the increased costs could cause a shift to greater international production. The U.S. government could also provide research and development grants aimed at reducing the operation costs of H-DRI and electrolysis, and production and investment tax credits to motivate the construction of low emissions steelmaking plants in the U.S. However, given the short time frame for action, these actions would likely be insufficient to meet the emissions target. Additionally, Figure 2 shows that high levels of trade limit the ability to decarbonize U.S. consumption through domestic action alone. This is because imported steel has a lower recycled content than domestically sourced steel. The U.S. could try to use the advancement of low emissions technologies and foreign policy to help motivate a shift to using low emissions steelmaking technology in the ROW. Barriers to implementing low emissions steelmaking technology will vary depending on a country's current production capacity, facility ages, and demand. Countries with growing demand and limited capacity will have fewer barriers to implementation.

### 3.2 Options to reduce U.S. steel stocks per capita

Of the *steel cycle parameters*, changing the *stocks per capita* has the greatest effect on emissions. Figure 2 shows that a reduction to 8 tons/capita by 2050 increases the percentage of pathways that stay within the emissions limits to above 83%. Figure 4 shows that at 8 tons/capita the emissions targets are likely to be achieved even without a change in steelmaking technology. 8 tons/capita is equal to the saturated *stocks per capita* in the U.K. and France,<sup>168</sup> illustrating that a high standard of living can be maintained at a lower *stocks per capita* value.

U.S. *stocks per capita* can be reduced by either decreasing steel consumption (i.e., any additions to stock) or prematurely discarding, recycling, and not replacing existing steel products (e.g., demolishing a functioning building). Given 64% of the steel stocks that will exist in 2050 have yet to be built (Figure S39), there is significant scope for reducing *stocks per capita* by reducing additions to stock and there is no need to discard steel prematurely in order to reduce in-use stocks. If all new U.S. steel consumption between 2020-2050 is used at an intensity of 8 tons/capita (i.e., steel is replaced using the ratio of 8 tons/capita to the value of existing stocks/capita) then aggregate U.S. stocks will have reduced to 9.7 tons/capita by 2050; thus, enabling the emissions targets to be met without extreme steelmaking decarbonization (Figure S39).

Reducing additions to stock can be achieved by making products that contain less steel (i.e., lightweighting) or by making fewer products. The first option (lightweighting) is perhaps the most attractive politically as its effects are largely invisible to the final user. Carruth et al. (2011) found that most new steel products could be 30% lighter<sup>68</sup> without a loss in performance. If all steel products made between 2020 and 2050 are 30% lighter than equivalent products today then aggregate U.S. stocks will be 9.9 tons/capita by 2050. The second option, making fewer steel products, could occur without government intervention if the U.S. economy continues to shift

toward online shopping and remote working. If the expected steel demand (2020-2050) for new office buildings, commercial real estate, and transport is halved then aggregate U.S. stocks will be 9.3 tons/capita by 2050.

A reduction in stocks per capita is simply a reduction of the steel currently in use. A transition to lower *stocks per capita* could be supported by building sector policies, for example, incorporating steel utilization targets<sup>69</sup> into green building rating systems (e.g., LEED)<sup>70</sup>, transportation sector policies, like mandating that new infrastructure be bikeable and walkable, or increased funding for public transportation, as well as more general policies like consideration of steel intensity in infrastructure bills. All of the above would reduce the steel required to supply a given service. Government could also act as an exemplar in the construction of new lightweight government buildings and remote working practices. Examining the connection between societal characteristics (e.g., population density, transportation infrastructure, location of commercial areas etc.) and steel stocks (particularly in the U.K. and France versus U.S.) could reveal other methods of reducing U.S. steel *stocks per capita*.

Reducing *stocks per capita* decreases the annual steel consumption. For the pathways simulated in this study that successfully meet the emissions requirement, the average quantity of steel produced domestically in 2050 by primary and secondary steelmaking is 3.2 Mt and 58 Mt respectively. Compared to 2019, this represents an 86% cut in primary steelmaking but only a 6.4% cut secondary steelmaking. This means that most of the eight BF facilities currently operating in the U.S. would likely need to close by 2050.<sup>71,72</sup> The consequent job losses could have significant impacts due to the concentration of BFs in the Midwest. The significant reduction in primary steelmaking in these pathways is in part due to the amount of scrap available as *stocks per capita* is decreasing. Once the *stocks per capita* have been level for the lifespan of a steel product

sector the available scrap will also level off and the primary steel demand will become dependent on the *recycling rate*, and the population growth. With no population growth and the highest *recycling rate* we modeled, 10% of demand would still need to be supplied by primary once this leveling off has occurred. The goal however, is for the reduction in *stocks per capita* to provide the industry time to develop and deploy the low carbon technology options discussed e.g., H-DRI, electrolysis and for the grid to further decarbonize.

### 3.3 Product lifespans, Recycling rates, and Process yields

Of the other *steel cycle parameters*, changing the *lifespan* (retrofit case) has the greatest impact on emissions. However, increasing the *lifespan* of only new products (Figure 2: product lifespan non-retrofit), potentially through more durable or modular designs, will result in a negligible decrease in emissions across 2020-2050 because the mean steel product lifespan is already 44 years (Figure 2). On the other hand, increasing the lifespan of both new and existing products by 30% (Figure 3: product lifespans, retrofit case) increases the number of pathways that meet the emissions requirement by 25%. Lifespan extension could be promoted by reducing value added taxes on repairs and remanufacturing, as implemented by Sweden in 2016.<sup>73</sup>

Figure 2 shows that increasing the *recycling rate* or the *manufacturing process yield* causes a minimal increase to the percentage of pathways that achieve the emissions targets. Increasing the recycling rate changes the ratio of primary to secondary steelmaking but does not affect the aggregate steel demand. The effect of generating manufacturing process scrap is only to add an industry recycling loop, which generates minimal emissions. Additionally, improving process yields can reduce a manufacturer's material costs, meaning that the profit motive alone should increase yields.

### 3.4 Time frame for action

Immediate and significant action is required to meet the emissions targets. These actions, shifting towards low carbon steelmaking and reducing *stocks per capita*, will take time to implement. However, the U.S. does not have long before the cumulative target is no longer feasible. Figure 5 shows that if no action is taken (BAU) then the cumulative U.S. steel sector CO<sub>2</sub> budget for 2020-2050 will run out in 2031. If action to reduce *stocks per capita* and steelmaking *emissions* is delayed by more than 5 years then it is likely infeasible for the U.S. steel sector to stay within the budget allotted for 2020-2050. However, immediate action towards low carbon steelmaking and a reduction in *stocks per capita* towards 8 tons/capita by 2050 will achieve the emissions target with over one-fifth of the emissions budget remaining in 2050.

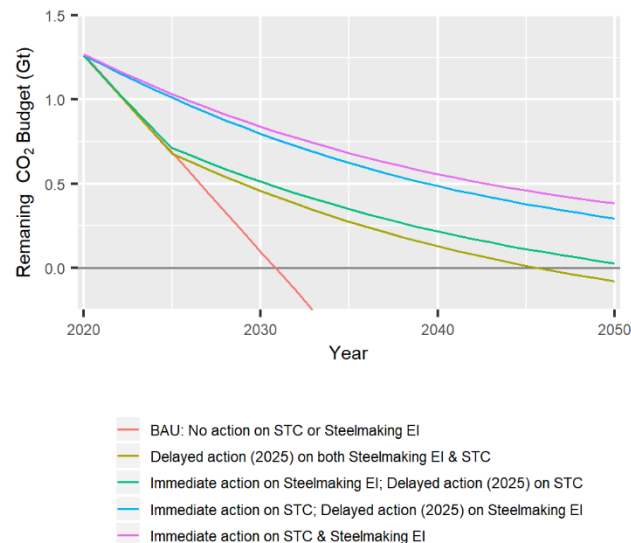


Figure 5, The remaining U.S. steel sector cumulative CO<sub>2</sub> budget 2020-2050 under different pathways. Modeled for the base case *trade scenario*, *steel lifespans*, *manufacturing yield*, *recycling rate*, and expected population. Action on STC: a constant decrease in STC at -0.11 t/cap/year. If not delayed, would reach 8 t/cap in 2050. Action on steelmaking EI: a constant decrease in primary (-46 kgCO<sub>2</sub>/t steel/year) and secondary steelmaking EI (9 kgCO<sub>2</sub>/t steel/year). If not delayed, would reach the values for the low emissions technology scenario (Table 1) by 2050.

### Supporting Information

The supporting information contains data sources, assumptions, and the mathematical formulations used to calculate historical and future steel flows, and steelmaking CO<sub>2</sub> emissions, as well as, results figures encompassing data from each steel industry pathway.

## Acknowledgements

N.A. Ryan acknowledges the support of the School for Environment and Sustainability doctoral fellowship at the University of Michigan. The authors thank all the industry experts who assisted in this study by being interviewed.

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