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Technologies to reduce greenhouse gas emissions from automotive steel in the United States and the European Union

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EXECUTIVE SUMMARY

A transition to electric vehicles in parallel with decarbonization of the power sector will help to reduce greenhouse gas (GHG) emissions from transportation. However, to meet climate goals, emissions from vehicle manufacturing also require attention. Steel is the most used material by mass in vehicle manufacturing. The substantial reliance today on fossil fuels, especially coal, in the production of primary steel from mined iron ores highlights the need for new production pathways. Given the automotive industry's substantial steel consumption, automakers may be uniquely suited to drive demand for fossil fuel-free steel and influence the steel industry transition from coal and blast furnaces. Addressing emissions associated with automotive steel manufacturing is thus essential for reducing emissions from both the steel and vehicle industries.

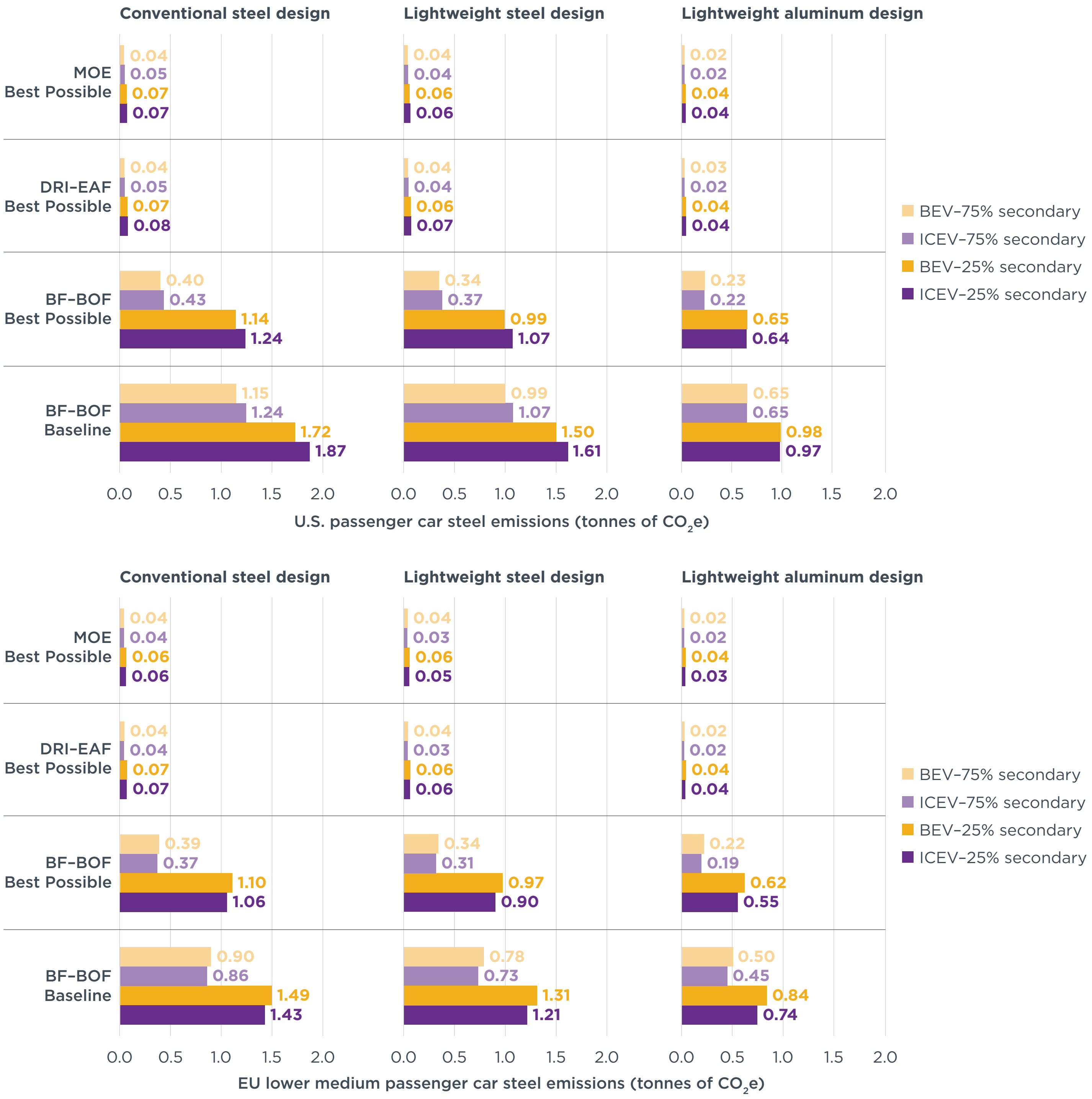
This report examines the technologies and actions available to reduce the emissions associated with automotive steel manufacturing. The report discusses current steel production pathways and their associated GHG emissions. Next, it describes pathways for producing fossil fuel-free steel—interchangeably called "green" steel herein. Other modes for reducing steel-only GHG emissions in the automotive sector are also explored, including increasing the share of secondary steel produced from recycled or scrap steel material and lightweighting. The report then compares the GHG emissions reduction potential of these modes with the status quo for two vehicle types, an internal combustion engine vehicle (ICEV) and a battery electric vehicle (BEV), in the United States and the European Union. The report concludes with an overview of other aspects necessary for the transition to green steel, such as the cost and production timeline, regulatory developments, and opportunities for automakers.

The analysis comparing techniques for decarbonizing steel arrives at the following key results:

Fossil fuel-free steel production technologies can reduce GHG emissions related to vehicle steel by over 95% and reduce vehicle manufacturing emissions overall by up to 27%. For both ICEVs and BEVs, alternative steel production technologies can reduce the GHG emissions from primary steel, which makes up about 75% of the steel used in a typical vehicle today in both the U.S. and EU markets (Figure ES1). Since steel-related emissions can represent up to a quarter of total emissions from vehicle manufacturing, alternative steel production pathways present a major opportunity to reduce these emissions (Figure ES2). Should other materials used in vehicle manufacturing also transition toward green production, vehicle manufacturing emissions are likely to experience further GHG reductions.

Figure ES1

U.S. and EU steel-only vehicle manufacturing GHG emissions for internal combustion engine and battery electric vehicles by steel production pathway



Notes: Production pathways are Baseline blast furnace-basic oxygen furnace (BF-BOF) in 2022; Best Possible scenario of BF-BOF with renewable electricity and more efficient technologies; best possible direct reduced iron (DRI) + electric arc furnace (EAF), which uses green hydrogen and renewable electricity; and best possible molten oxide electrolysis (MOE) using renewable electricity.

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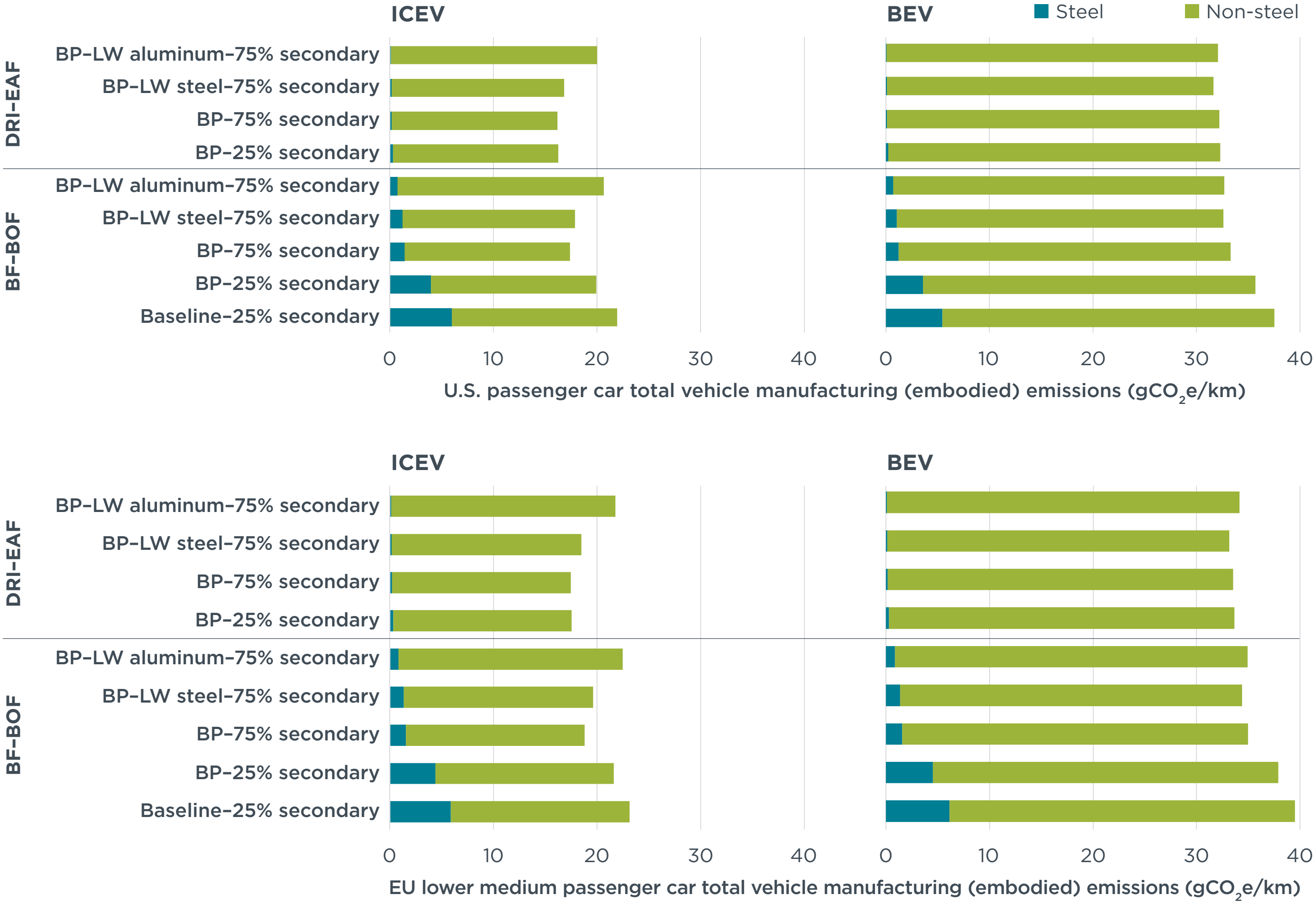
Figure ES2

Total passenger car manufacturing GHG emissions for internal combustion engine and battery electric vehicles



Note: BP = Best Possible; LW = Lightweighting

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Increasing the supply of automotive-grade secondary steel can reduce vehicle manufacturing emissions and raw material demand. The supply of secondary steel with low concentrations of polluting elements, such as copper, is currently limited. Strategies to increase the availability of such high-grade secondary steel for automotive applications include designing vehicles for recycling, ensuring their collection and end-of-life management, and improving the sorting of metal parts during vehicle dismantling and shredding. With realizing an increased supply, a higher secondary steel share in vehicle production could lead to a 35%-65% reduction in steel-related GHG emissions.

Lightweighting could reduce steel-related embodied GHG emissions by 12%–50%, depending on the materials used. Both ICEVs and BEVs rely on steel for use in the body, powertrain, chassis, and other components. By improving component design and substituting mild steel with lighter or stronger materials, total steel mass—and its associated embodied GHG emissions—decreases. Lightweighting with high strength steels can reduce steel-related emissions by 12%–15%. Lightweighting with aluminum can reduce steel-related emissions by up to 50%. Although aluminum-based lightweighting may lead to slightly higher total vehicle manufacturing emissions, the overall mass reduction is greater than lightweighting with steel, resulting in lower emissions from fuel production and consumption during vehicle use.

Using green steel in vehicle production increases cost by $100–$200, or less than 1% of the price of an average new vehicle. Currently, green steel is estimated to cost 20%–30% more than coal-based BF-BOF steel. These costs are expected to decrease as green steel producers increase capacity.

Fossil fuel-free primary steel production technologies already exist and production capacity can increase, but not without commitments from buyers. Automakers can support the transition to decarbonized primary steel production by making purchase agreements with steel producers and investing in those producers directly. Additional actions automakers can take to encourage the development of more fossil fuel-free primary steel production include aggregating demand and joining coalitions with explicit green steel purchase targets. They can also start tracking recycled steel content in vehicles, design and assemble vehicles with the goal of recyclability, and implement lightweight designs to reduce steel quantity.

TABLE OF CONTENTS

LIST OF ACRONYMS

AHSS	Advanced high-strength steel
BEV	Battery electric vehicle
BF	Blast furnace
BOF	Basic oxygen furnace
CCU	Carbon capture and utilization
CCS	Carbon capture and storage
DRI	Direct reduced iron
EAF	Electric arc furnace
EOL	End of life
EU	European Union
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
ICEV	Internal combustion engine vehicle
MOE	Molten oxide electrolysis
SUV	Sport utility vehicle

INTRODUCTION

In light-duty vehicles,[1] steel typically makes up between 50% and 66% of the vehicle mass, depending on the model, segment, and powertrain type (Davis & Boundy, 2022; Ducker Research and Consulting, 2023; Joint Research Centre, 2021). Steel can be found throughout the vehicle, including in the frame, body, engine, transmission, and driveline. The reason for steel's prominence in vehicle manufacturing is manifold: Steel is a low-cost material that can be fine-tuned to provide specific formability and weldability, and its strength is critical for vehicle safety. Due to steel's ubiquity in vehicles, it is a natural candidate for efforts to reduce greenhouse gas (GHG) emissions from vehicle manufacturing.

Iron and steel manufacturing is one of the most energy- and carbon-intensive industries worldwide, emitting approximately 3.6 metric gigatons of carbon dioxide (CO_2) globally in 2019 (Hasanbeigi, 2022). These industries also emit several criteria air pollutants, primarily from the use of coke ovens, sinter plants, and blast furnaces, which can cause a variety of negative health effects related to respiratory and cardiovascular systems, and premature mortality. Industrial manufacturing facilities, including steel plants, are often located close to low-income, disadvantaged communities, subjecting them to high levels of pollution. For example, approximately 50% of the population within a 3-mile radius of a furnace or coke facility in the United States are low-income, compared to the 30% national average for other industrial facilities. In addition, the polluting industrial facilities contribute to reduced property values, hampering social and economic mobility (Hasanbeigi et al., 2022). If these facilities do not swiftly transition away from carbon-intensive methods of steel production, the detrimental effects of local air pollution and economic disadvantages will persist, continuing to burden these communities.

Given the importance of steel decarbonization to reduce the industry's impact on climate and health, and the potential role of automakers in supporting the transition, this paper provides an overview of steel use in the automotive industry and the associated emissions from current steelmaking pathways. It explores the potential of reducing the GHG emissions of automotive steel through three main modes: 1) conversion to primary steel production technologies with lower GHG emissions intensity, and 2) reduction of primary steel demand through the increased use of recycled steel and 3) the decreased use of steel overall through vehicle lightweighting technologies. Argonne National Laboratory's GREET tool is used to estimate the potential of the three modes to reduce the GHG emissions of vehicle manufacturing, and further context is added by the estimation of life-cycle GHG emissions based on earlier ICCT work. We also discuss the potential cost and timeline of steel decarbonization, review potential policy developments, and suggest actions that automakers can take to decarbonize their steel supply chains.

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[1] U.S. light-duty vehicles typically consist of passenger cars, sport utility vehicles, and some pickup truck segments. European Union light-duty vehicles typically consist of passenger cars and sport utility vehicles.

AUTOMOTIVE STEEL OVERVIEW

In 2022, approximately 82 million metric tons (Mt) of steel was produced in the United States. Around 26% of this steel, or about 21 Mt, was used for auto manufacturing, making it the second-largest steel-consuming sector after construction (National Minerals Information Center, 2023). Primary steel, which is produced from mined iron ore, accounted for around 26 Mt, or about 32%, of U.S. steel produced in 2022.[2] About 21 Mt of this steel was from liquid pig iron produced from iron ore in blast furnace–basic oxygen furnace (BF-BOF) integrated mills (World Steel Association, 2023). Direct reduced iron (DRI) made from direct reduction technologies contributed about 5 Mt and was used in both blast furnaces and melted in electric arc furnaces (EAF). The rest of the steel (68%, or 56 Mt) comes from secondary steel produced from recycled scrap.

A variety of sources estimate that at least 75% of steel used in vehicle manufacturing is primary steel (Zhu et al., 2019; BMW Group, 2022b, 2022a; Stellantis, 2024; Volvo Car Group, 2022). Combining the above datapoints, it can be assumed that the U.S. automotive sector requires about 16 Mt of primary steel. With the United States producing 26 Mt of primary steel in 2022, this means that at least 60% of all primary steel produced in the United States is used in auto manufacturing. The remainder of automotive steel consumption (5 Mt) is secondary steel and accounts for close to 9% of the secondary steel produced in the United States.

In the European Union, the steel industry produced 136 Mt of steel in 2022, of which primary steel represented around 52% of total production (71 Mt) (World Steel Association, 2023). The automotive sector represented about 17% of steel consumption in the European Union in 2022 (23 Mt) (European Steel Association, 2023). Due to similar vehicle material requirements and production processes in Europe and the United States, and assuming the same minimum 75% primary steel share in EU vehicles, about 13% (17 Mt) of total EU steel production is primary steel used for automotive manufacturing. This also means that out of the total 71 Mt of primary production in the European Union, the automotive sector consumes around 24%. It is assumed that secondary steel is, at most, 25% of automotive steel in the European Union, or roughly 6 Mt—equivalent to 9% of the region's secondary steel production. These results are shown in Figure 1.

For reference, the global share of steel used for the automotive sector is roughly 12% (226 Mt) (World Steel Association, 2023). Around 76% of the 1,884 Mt produced globally in 2022 was from primary production. Assuming the same 75% share of primary steel is used for automotive applications as in the European Union and United States, global automotive primary steel is estimated to be around 170 Mt, or approximately 12% of total primary production. Conversely, the remaining 25% of automotive steel is secondary, representing about 57 Mt, or 12% of global secondary production.

As depicted in Figure 1, although automotive steel represents a minority of global steel consumption in the United States and the European Union, the sector represents a disproportionately large share of primary steel demand. The figure depicts U.S. and EU steel consumption based on their regional production and excludes imports. Generally, due to specific characteristics required for safety, strength, formability, and other performance criteria, automotive steels have higher prices than other steel grades. As a result of these high prices and the amount of primary steel consumption, the automotive sector has an outsized influence on steelmaker revenues and product portfolios.

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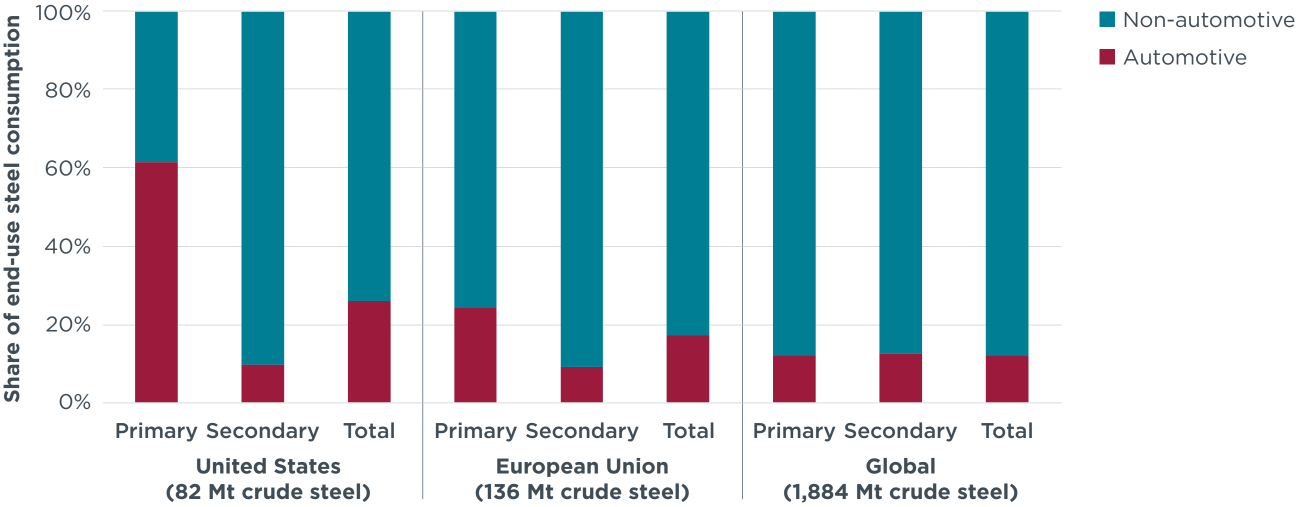
[2] Note that the most common steels are made nearly entirely of iron, with small amounts of other elements often totaling < 5% of total steel mass.

Figure 1

Share of the automotive sector in primary, secondary, and total steel consumption, excluding imports, 2022



Sources: Share of primary and secondary steel in vehicles based on the GREET model (Wang et al., 2022). Total production and shares of primary and secondary steel from World Steel Association; Shares of automotive end-use steel consumption from National Minerals Information Center (2023), World Steel Association (2023), and European Steel Association (2023).

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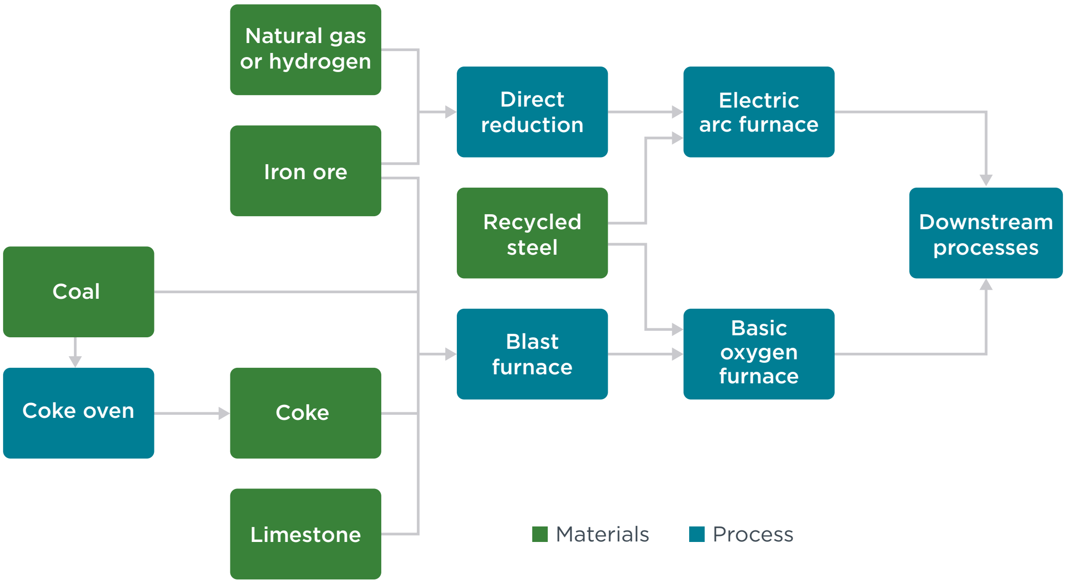
The transition to battery electric vehicles (BEVs) comes with reductions in the emissions associated with the use of the vehicles. Consequently, the relative importance of vehicle manufacturing emissions increases as the market share of BEVs rise. Since steel is a major contributor to vehicle mass, decarbonizing its production can play an important role in reducing GHG emissions from vehicle manufacturing.

CURRENT STEEL PRODUCTION PATHWAYS AND EMISSIONS

Crude steel is the first solid steel product before steel is shaped by other downstream processes to produce primary or secondary steel. Crude steel is produced via two main pathways: blast furnace–basic oxygen furnace (BF-BOF) and electric arc furnace (EAF). In 2023, nearly 72% of the crude steel worldwide was produced via the BF-BOF process, and EAF production accounted for almost 28% (World Steel Association, 2023). These two major pathways are illustrated in Figure 2. Other technological variations of the steelmaking process are discussed later in this section. Figure 2 shows a simplified diagram of the steelmaking pathways: BF-BOF, EAF with direct reduced iron (DRI-EAF) from iron ore, and EAF with recycled or scrap steel.

Figure 2

Producing crude steel through blast furnace-basic oxygen furnace (BF-BOF), direct reduced iron-electric arc furnace (DRI-EAF), and scrap steel-based EAF pathways



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BF-BOF PATHWAY

In the first step of the BF-BOF production pathway, raw materials such as iron ore, coke, and limestone are prepared. For iron ore, sintering converts the ore into coarse lumps (sinter), and pelletizing creates durable marble-sized pellets. Coke, which has a high carbon content and few impurities, is formed from the thermal distillation of metallurgical coal at high temperatures in coke ovens. Limestone, which is high in calcium, is crushed into smaller sizes called fluxes. The iron ore, coke, and limestone are then fed directly into the BF and heated with air that has been preheated in stoves using natural gas. During the ironmaking process, coke is combusted, producing heat and carbon monoxide (CO) gas. The CO then reacts with the iron ore, producing carbon dioxide (CO_2) and molten iron, also called liquid pig iron or hot metal. The limestone combines with impurities in the iron ore and forms slag, a liquid that floats on top of the molten iron, which is skimmed off. Oil, natural gas, or pulverized coal can also be injected into the furnace and combined with coke to reduce cost (American Iron and Steel Institute, n.d).

Following the preparation of the raw materials, the hot metal is put into the BOF. Oxygen is then injected and reacts with the carbon in the hot metal, producing CO_2, to reduce the carbon content of steel. If scrap steel is added to the process, the need for raw materials and primary steel is reduced. Other metals such as manganese, nickel, chromium, or vanadium can be added at the end of this process to adjust the steel's strength, hardness, wear resistance, and other mechanical properties.

DRI-EAF AND SCRAP-BASED EAF PATHWAYS

In the DRI-EAF pathway, iron ore is reduced to iron in a direct reduction process. In the most common method, iron ore is treated with a reducing gas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2). This process transforms iron ore into iron, while producing carbon dioxide (CO_2) and water (H_2O). The reducing gas, which can also serve as the heat source, is typically derived from natural gas or coal. Instead of the mixture of CO and H_2, pure hydrogen can also be used as the reducing gas, which means that only iron and water are formed. There are a variety of direct reduction technologies, such as shaft furnaces, fluidized beds, rotary kilns, and rotary hearths. More details about DRI technologies and their potential in reducing GHG emissions of steel production are discussed later in this paper.

In the steelmaking process, the reduced iron goes into an EAF. Similar to the BOF pathway, scrap steel can be added to the EAF to reduce the need for raw materials, or up to 100% scrap-based steel can be input directly into the EAF to create new steel. In this case, the EAF uses heat generated from a flow of electricity between two electrodes to melt primary iron and scrap steel. Oxygen is blown into the furnace, along with other materials that treat impurities. Similar to the BOF process, the oxygen reacts with the carbon impurities in the hot metal, producing CO_2 and steel. Other metals can be added in the refining process to adjust the properties of the steel composition.

The liquid steel from these steelmaking pathways goes through downstream processes, such as casting, rolling, and stamping, to create finished steel products. These products are referred to as primary or virgin steel if the steel is produced via the BF-BOF or DRI-EAF pathways or secondary steel if produced from the scrap-based EAF pathway. First, the continuous caster forms the semifinished crude steel (e.g., slabs, billets, and blooms), then rolling mills and stamping form the steel's final shapes. Most automotive steel comes from hot-rolled and cold-rolled steel strips. Hot rolling shapes or rolls steel at a high temperature to make larger sizes. This steel can then go through several other refining processes tailored to customer needs before going to stamping. Cold rolling is an additional step that processes the hot-rolled steel, increasing its strength. Finally, stamping or pressing shapes steel products into a variety of designs.

GREENHOUSE GAS EMISSIONS OF STEEL COMPANIES

The total energy and material used in the iron- and steel-making industry has increased with the increased demand for steel (International Energy Agency, 2020). The sector accounts for about 8% of global energy demand. Coke alone accounted for about 872 million tonnes of coal equivalent in 2019, or 16% of global coal demand, with the steel sector accounting for almost all use of coke. In the same year, the steel industry constituted 2.5% (90 billion cubic meters) of global natural gas demand and 5.5% (1,230 terawatt hours) of global electricity demand.

In 2019, the steel industry emitted approximately 3.6 metric gigatons of CO_2 globally, with 86% from the BF-BOF pathway and 14% from scrap-based EAF and DRI-EAF pathways (Hasanbeigi, 2022). Close to 75% of the CO_2 emissions from the BF-BOF pathway are associated with coke combustion in the blast furnaces (Fan & Friedmann, 2021; Nimbalkar, 2022).

Steel companies' total GHG emissions, or the GHG emission intensity per tonne of steel, can be found through company reports and public data sources. The emission intensity in these sources is expressed in CO_2 or CO_2-equivalent (CO_2e), depending on whether other GHGs in addition to CO_2, such as methane (CH_4), nitrous oxide (N_2O), or fluorinated gas, are included in the reporting. The types of steel production reported also vary from crude steel to final steel products. Table 1 shows the GHG emission values from select steel companies, available information on steel production pathways, and the scope of emissions included. Scope 1 emissions include direct emissions from a company's facilities. Scope 2 emissions include emissions from electricity and any other energy sources used to run the facilities. Scope 3 emissions include all other emissions associated with the company's supply chain, such as the production of purchased goods and transportation.

Table 1

Greenhouse gas emissions intensity of select steel companies by production pathway

Headquarters	Company	Steel pathway	Year	Scope	GHG emissions	Source
United States	**Cleveland-Cliffs**	BF-BOF	2022	1 and 2	1.6 t CO_2e/t of crude steel	Cleveland-Cliffs Inc. (2023)
		EAF		1 and 2	1.04 t CO_2e/t of crude steel	
	U.S. Steel	BF-BOF	2022	1 and 2	2.05 t CO_2e/t of crude steel	United States Steel Corporation (2023a)
		EAF		1 and 2	0.41 t CO_2e/t of crude steel	
	Nucor	EAF	2022	1 and 2	0.44 t CO_2e/t of steel produced (0.76, including Scope 3)	Nucor Corporation (2023)
Europe	**ArcelorMittal**	Unknown	2022	1,2, and limited 3	1.98 t CO_2e/t of crude steel	ArcelorMittal (2023a)
	thyssenkrupp	Unknown	Fiscal Year 2022–2023	1 and 2	23.9 Mt CO_2e	thyssenkrupp (2024)
	voestalpine	Unknown	2022	1,2, and 3	24.5 Mt CO_2e	voestalpine (2023)

Hasanbeigi (2022) estimated that the average CO_2 emissions of steel plants differ among regions. For example, the average CO_2 emission intensity of an integrated BF-BOF steel mill process in the United States is estimated to be 1.8 t CO_2/t of crude steel in 2019. For the EAF pathway, the U.S. average is close to 0.6 t CO_2/t of crude steel. For Europe, the BF-BOF CO_2 emission intensity is higher, closer to 1.9 t CO_2/t, and for EAF, it is lower, closer to 0.5 t CO_2/t. Note that these regional average emissions only correspond to CO_2 emissions, not CO_2e, as they do not cover the impact of other GHG emissions.

DECARBONIZATION OF PRIMARY STEEL PRODUCTION

There are many technologies and production pathways that have the potential to decrease GHG emissions from steelmaking processes. Kim et al. (2022) classified 86 options by their technology-readiness level, including those that are commercially available but not widely utilized, those with working prototypes as of 2020, and experimental technologies likely available only after 2025. He and Wang (2017) identified 158 different technologies with some overlaps with Kim et al., and provided the fuel, energy savings, capital cost, and payback period where data was available. This section highlights some technologies with high decarbonization potentials that can replace BF-BOF pathways in the upcoming years. It also provides a note on mass balancing strategy and its role in steel decarbonization.

HYDROGEN-BASED DIRECT REDUCTION

In 2022, more than 127 million tonnes of iron by direct reduction process were produced globally. Most of this production occurred in India (43.6 mil lion tonnes) and Iran (32.9 million tonnes), which together accounted for more than 60% of global production (Midrex Technologies Inc., 2022). There are several suppliers of DRI, each using slightly different production processes, with 57.8% of DRI in 2022 produced using MIDREX technology, 12.1% using the HYL process, and 2.2% using the PERED process. Rotary kilns were used to produce 27.9% of DRI.

As of 2023, the reducing gas used in the direct reduction process commonly comes from fossil resources, such as natural gas or coal. The carbon monoxide (CO) and hydrogen from these sources combine with the oxygen in iron ore, producing metallic iron, CO_2, and water (H_2O). However, it is possible to use solely hydrogen instead of a mixture of CO and hydrogen to reduce iron, thereby producing only metallic iron and water. By substituting the mixture of CO and hydrogen produced from fossil fuels with hydrogen made from renewable electricity, this ironmaking pathway has close to zero GHG emissions. However, hydrogen from electrolysis represented less than 1% of total hydrogen production in 2022 (International Energy Agency, n.d).

MOLTEN OXIDE ELECTROLYSIS AND ELECTROWINNING

Molten oxide electrolysis (MOE) is an electrochemical process developed by Boston Metal that applies the main production process of aluminum to steelmaking. Here, iron oxide is dispersed in a molten oxide electrolyte at high temperatures (up to 1600 °C) and electricity is applied to reduce iron ore to iron. The result is the formation of liquid iron at the cathode with oxygen gas produced as a by-product at the anode. This liquid metal can be sent directly for downstream processes, where the chemical composition is adjusted with alloys and final steel products are produced. The GHG emissions intensity of the process mainly depends on the source of electricity. Boston Metal estimates the process requires 4 MWh of electrical energy per tonne of steel, compared to 5.5 MWh of coal energy for the BF-BOF process (Boston Metal, 2021, n.d.).

Electrowinning is a process widely used in copper production and is currently being tested on a pilot scale for application in ironmaking. Similar to MOE, this process applies electricity to reduce iron ore to iron at the cathode, while forming oxygen gas at the anode. In the case of electrowinning, however, the iron ore is dissolved in an aqueous alkaline electrolyte at room temperature instead of a hot molten oxide solution. The produced iron is then sent to an EAF for steelmaking (Junjie, 2018; Popov et al., 2002; Siderwin, n.d.). Like MOE, the total process primarily relies on the electricity mix used and can become fossil fuel-free when using solely renewable energy.

CARBON CAPTURE AND UTILIZATION OR STORAGE

Carbon capture and utilization (CCU) and carbon capture and storage (CCS) are not steelmaking pathways but are two technology options that can be used to treat the carbon emissions produced from conventional steelmaking. The technologies do not allow for the full decarbonization of conventional iron and steelmaking. Instead, the technologies capture part of the carbon emissions from the exhaust stream of industrial processes and either use them in other industries or store them underground. The use of CCU usually implies the emission of carbon at a later stage, and thus does not eliminate emissions. For example, at LanzaTech commercial steel plants, CO emissions are captured, converted into ethanol, and later burned as a sustainable aviation fuel (LanzaTech, n.d). In the case of CCS, carbon emissions are permanently stored, but safe storage capacity is limited and there are near- and long-term risks of carbon emissions leakage. Only a limited share of the emitted carbon is captured by both technologies. For example, the current capture rate of CO_2 emissions in natural gas-based hydrogen production facilities is about 55% (Zhou et al., 2021). These technology options can be integrated into life-cycle analyses to determine if the steel produced is “near zero-emission,” as defined by the International Energy Agency and other voluntary initiatives such as First Movers Coalition and SteelZero (Climate Group, 2023; First Movers Coalition, 2024; International Energy Agency, 2022). More information about these initiatives can be found in the section on opportunities for automakers.

MASS BALANCING

Mass balancing is not an alternative steel production method, but instead involves allocating the effect of emission reduction measures to single products. Several steelmakers currently offer low- or reduced-CO_2 emission steel products that are based on mass balancing. In this concept, the companies reduce CO_2 emissions from existing plants by energy efficiency improvements, utilizing CCS or CCU, or making changes to BF feedstocks. Rather than equally allocating the remaining emissions across all products of the plant, the emissions are assigned to only a proportion of the products while assigning lower or no emissions to other products. This concept is widely used in steel industry and other sectors, and is considered in the ResponsibleSteel certification which scores steel sites based on their environmental and social operations (ResponsibleSteel, 2024). Because mass balancing allows producers sell low CO_2 emission steel products without scaling up low CO_2 emissions steel production processes, it may blur the continued reliance on coal in steel production, such as in blast furnaces.

REDUCING PRIMARY STEEL DEMAND

The following sections explore how the demand in primary steel can be reduced through increasing the use of secondary steel and through reducing the overall demand of steel on a per vehicle basis. Strategies at individual vehicle, manufacturer, and industry-wide levels that can reduce primary steel demand are discussed. Although the timeframe of realized demand reduction varies, manufacturers and policymakers can begin incorporating these options today.

INCREASED RECYCLED STEEL SHARE

Most of the steel used to build new vehicles is primary steel made from iron ore through the BF-BOF and DRI-EAF pathways (Sullivan et al., 1998). However, secondary steel made via EAF from prompt scrap, that is, pre-consumer (manufacturing) scrap, can also be suitable for automotive applications. This scrap is collected from the factory floor and immediately returned to the steelmaker for remelting. Consequently, quantities of prompt scrap are inherently limited and are decreasing as manufacturers improve manufacturing efficiency, wasting less steel per part. Post-consumer scrap steel, which is collected when the vehicle is dismantled at its end-of-life, typically contains higher amounts of contaminants such as copper, which reduce the steel's quality. Better separation of different metal parts upon recycling can reduce this contamination, and thereby improve the quality of post-consumer scrap. Further, ongoing research is investigating how the removal of contaminants in metallurgical post-processing can become economical, though major challenges remain (Material Economics, 2019). For the time being, post-consumption scrap is combined with primary iron to dilute the concentration of contaminating elements.

A main benefit of secondary steel is that it has a lower average GHG emissions intensity than primary steel (Hasanbeigi, 2022). Moreover, since secondary steel is produced in EAFs, its emission intensity will decrease over time as local electricity grids use more low-carbon energy sources. Thus, increasing the fraction of secondary steel used in automotive production can lead to reduced steel-related emissions.

Numerous automakers have disclosed the percentages of secondary steel used in their products. BMW shared that there is an average of 25% secondary steel content in its vehicles; the company plans to increase this percentage to 50% by 2030 (BMW Group, 2022b, 2022a; Shen et al., 2023). Renault Group estimated that the secondary steel content in its vehicles ranged from 17% for flat steel to more than 90% for steel bars and cast iron in 2022 (Renault Group, 2023). Stellantis reported using up to 30% recycled steel, including both pre- and post-consumer scrap steel (Stellantis, 2024). Volvo reported using 15% recycled steel in its vehicles in 2022, with the aim to increase this to 25% by 2025 (Volvo Car Group, 2022).

Recent announcements of partnerships between automakers and steelmakers indicate a trend towards increased utilization of secondary steel in vehicles. General Motors announced an agreement with ArcelorMittal for steel made via the EAF pathway containing 70%–90% recycled steel (ArcelorMittal, 2023b). The company also signed an agreement with U.S. Steel to procure steel made of 90% recycled content (United States Steel, 2023b). Mercedes reported that sheet steel procured from Steel Dynamics Inc. (SDI) has a recycled steel content of at least 70% and is used in all Mercedes Benz models produced in Tuscaloosa, Alabama (Mercedes-Benz Group, 2023).

VEHICLE LIGHTWEIGHTING

Lightweighting is achieved by vehicle designs that reduce the mass of steel needed by using stronger steel alloys and lighter materials, most commonly aluminum. Lightweighting can be incorporated when automakers design new vehicle models or redesign existing ones.

Advanced high-strength steel (AHSS) generally has higher tensile strength than conventional steel grades (WorldAutoSteel, 2021), which enables parts made from AHSS to use less steel overall in vehicle components. Ducker (2023) found that AHSS constituted 12% of the mass of the average North American vehicle in 2022, while conventional steel accounted for 25%, other steels for 13%, and iron for 6%. Data from vehicles in Europe in 2020 show that the average mass shares of steel and iron are broadly similar to those in North America (Joint Research Centre, 2021).

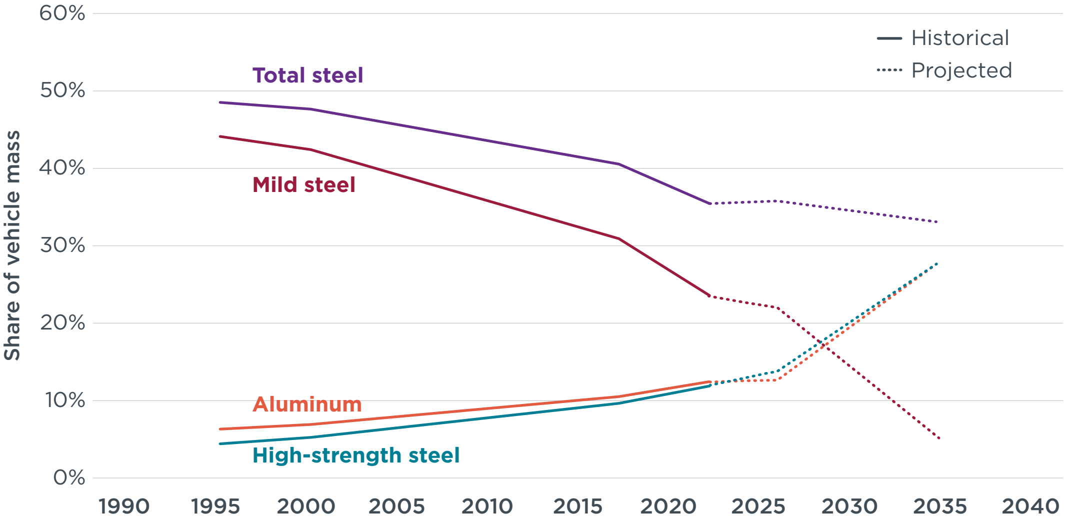
There remains significant opportunity for continued lightweighting through the use of lighter, stronger steels (Abraham, 2019). Several vehicles have higher-than-average AHSS and ultra-high strength steel content, the latter of which is the strongest AHSS grade with minimum tensile strengths of 1,000–1,200 megapascals. The use of structural adhesives also enables thinner steel gauges (Visnic & Brooke, 2019). Studies indicate that mass reduction by using stronger steels and improved design can reduce component mass by up to 50%, body and frame mass by up to 17%, and overall vehicle mass by 2%–6% with no or low additional material cost (Bailo et al., 2020; Malen et al., 2017; Isenstadt & German, 2017).

Ducker (2023) identified that lightweighting with aluminum is more prevalent in BEVs than in ICEVs. This is likely because weight reduction enables lower energy consumption, and thus a smaller, cheaper battery pack can be used to achieve the same electric range. When aluminum is used instead of steel in the body and closures, mass can be reduced by up to 35% (Malen et al., 2017). Overall, substituting mild (low-carbon) steel with aluminum can achieve roughly double the vehicle mass reduction than is achievable by reducing the amount of steel alone, albeit at a slightly higher cost (Alumobility, 2022; Bailo et al., 2020).

Automakers are pursuing multi-material strategies that employ lightweighting through the use of more HSS and aluminum. Figure 3 shows the historical and projected average shares of HSS and aluminum content in vehicles in North America. As shown, the historical trend of increasing shares of aluminum and HSS is expected to continue, with a simultaneous decrease in the share of mild steel. These trends reflect the fleet-average content per vehicle, and thus consider increased market shares of BEVs as well as the use of stronger and lighter metals to meet fuel efficiency and performance expectations. Note that this figure does not depict iron or electrical steel. Iron not used in steelmaking represents under 10% of vehicle mass in both U.S. and EU vehicles (Ducker, 2023; Joint Research Centre, 2021). As BEVs gain in market share, the percentage of iron in vehicle mass is expected to continue to fall.

Figure 3

Historical and projected steel and aluminum mass share per vehicle in North America



Sources: Historical data from Ducker (2023) and Davis & Boundy, (2022). Projections are based on Ducker (2023) through 2026 and the 2030–2035 premium and mass market vehicles scenarios in Bailo et al. (2020).

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IMPACT OF STEEL ON VEHICLE LIFE-CYCLE GHG EMISSIONS

This section assesses the impact of the pathways for reducing GHG emissions from steel production described above. The methods and results are discussed below.

METHODOLOGY

As described earlier, the three main modes for steel decarbonization in the automotive sector are: (1) reducing the GHG emissions of primary steel production and reducing primary steel demand through (2) lightweighting, and (3) increasing recycled steel content. For this study, we utilize the Argonne National Laboratory's GREET model to assess the impact these pathways have on GHG emissions (Wang et al., 2022). We first adjust some of the baseline input parameters of the GREET model due to the improved efficiencies of some technologies, and then use the model to estimate the impact of these strategies on reducing the GHG emissions from vehicle manufacturing. Finally, we build on Bieker (2021) to add the GHG emissions from fuel or electricity production and fuel consumption. Due to the importance of vehicle operation on the total life-cycle GHG emissions of a vehicle, the emissions are presented per vehicle-kilometers traveled (VKT) over a vehicle lifetime. The total manufacturing emissions are converted to VKT considering the average lifetime mileage for U.S. and EU vehicles as described by Bieker (2021). The GREET model default utilizes vehicle mileage traveled, which is converted to VKT to accommodate both the U.S. and EU market analyses.

Vehicle manufacturing emissions

In this study, embodied vehicle manufacturing emissions are those associated with steel, other material, and battery production, as well as vehicle assembly. For steel, the embodied GHG emissions include the direct emissions from the iron ore mining, iron and steel production plants, as well as methane leakage from coal mining and natural gas extraction and transport, and emissions from electricity consumption during the ironmaking and steelmaking processes. The GREET model generally covers a broader scope of emissions than some of the comparable literature, including certain process emissions such as iron ore mining and final stamping or methane emissions from coal mining (Hasanbeigi, 2022; Synapse Energy Economics, 2023). Therefore, the GHG emissions of the BF-BOF pathway may be higher than those in some other studies but align with studies that consider a similar scope of emissions (Swalec & Grigsby-Schulte, 2023).

For this analysis, the baseline vehicle mass and battery capacity specifications in the GREET tool were adjusted to represent average 2022 vehicles in the United States and the European Union. For the United States, we consider sales-weighted average characteristics of ICEVs and BEVs in the passenger car, sport utility vehicle (SUV), and pickup segments. For the European Union, we consider passenger cars in the lower medium segment and SUVs. Information on vehicle mass is based on the U.S. Environmental Protection Agency Automotive Trends Report and the ICCT European Vehicle Market Statistics Pocketbook (U.S. Environmental Protection Agency [U.S. EPA], 2023; International Council on Clean Transportation [ICCT], 2024). Battery capacities for U.S. vehicles were sourced from the EV-Volumes database at ev-volumes.com. Capacities for EU segment-average vehicles were derived by combining sales data from the European Environment Agency (European Environment Agency, 2023) and vehicle specifications data from the Allgemeiner Deutscher Automobil-Club (ADAC) (ADAC, n.d.).

For the steel production emissions, we applied the 2022 U.S. and EU electricity grid mix from the International Energy Agency's World Energy Outlook (International Energy Agency, 2023). Further, the inputs for steelmaking through the BF-BOF pathway were adjusted to reflect slight improvements in energy efficiencies in the United States and the European Union (U.S. Department of Energy, 2017, 2015). These updates include reduced coke production, improved coke oven gas and blast furnace gas recovery, blast furnace controls, and blast furnace heat recovery.

The GREET model includes an option for steel production via natural gas-based DRI in combination with an EAF. To estimate the emissions of fossil-fuel free DRI plants, the emissions of using renewable electricity-based hydrogen instead of a natural gas-based reducing gas are considered, and some process input values were adjusted to reflect more energy-efficient mining, pelletizing, iron reduction, and EAFs (Allen, 2021; Cappel, 2021; Duarte et al., 2008; He & Wang, 2017). Additionally, all other processes for fossil-fuel free DRI are considered to use renewable electricity. For instance, hydrogen-produced DRI would have 0% carbon content instead of the usual 2%–4%. Any additional measures required to adjust these DRI to the desired carbon content could be carried out using fossil-free methods, such as incorporating biochar produced through renewable energy into the process (Chevrier, 2020; Hornby, 2021). While technical difficulties are not anticipated, the effectiveness of these adjustments warrants experimental confirmation (Patisson & Mirgaux, 2020).

To estimate the GHG emissions of ironmaking via MOE, the GREET inputs are altered to reflect the relevant energy consumption and process steps. These include heating the molten oxide bath to 1600 °C and the electric energy consumption of electrolysis (Boston Metal, n.d).

To estimate the GHG emissions effect of lightweighting, it is assumed that most of the mass reduction occurs due to changes in materials (substitution of steel with higher strength steel or aluminum) and design of the body and closures, with additional secondary mass savings throughout the vehicle due to powertrain downsizing (Bailo et al., 2020). Consistent with prior lightweighting studies, mass is added back to the vehicle at a rate of 4%–5% to account for safety, performance, and consumer features (Bailo et al., 2020). Additionally, we assume ICEV efficiency improves at a rate of 6% for every 10% reduction in vehicle mass, and BEV efficiency improves at a rate of 4% for every 10% reduction in vehicle mass (Del Pero et al., 2020). For BEV lightweighting, battery size also decreases to maintain the same range, resulting in reduced battery production emissions (an output calculated in GREET).

When lightweighting with steel, unibody vehicles (passenger cars and SUVs) are assumed to have 20% lighter bodies, with overall vehicle mass reductions ranging between 5% and 6% depending on powertrain type (ICEV or BEV) and segment. Pickups, as body-on-frame vehicles, are assumed to have 15% lighter bodies and 10% lighter frames, resulting in a net mass reduction of 7%–8% depending on powertrain type. These reductions in mass are typical when utilizing high-strength steels, although greater reductions may be possible (Malen et al., 2017; Palazzo & Geyer, 2019). As a result of lightweighting with steel, total steel mass decreases by 12%–15% depending on vehicle type and powertrain. Since AHSS is produced the same way as other primary steel, albeit with additional steps to add more strength, these processes could be performed using electricity.

When lightweighting with aluminum, unibody vehicles have a 30% reduction in body and closure mass (Alumobility, 2022). When combined with secondary mass reduction and mass add-back, the net vehicle mass reduction is 13%–15%, dependent on powertrain and vehicle type. Pickup bodies are assumed to have a 25% mass reduction. Pickup frames are assumed to continue to rely on steel but, due to lighter bodies and the use of advanced steels, have a mass reduction of 15%. Lightweighting with aluminum leads to steel mass reductions of 35%–50%, depending on vehicle type and powertrain. Overall, pickup mass reduction is about 15%.

Lastly, the default GREET secondary steel content is approximately 25%. To model the effects of increased rates of secondary steel, the default value was changed to 75%. This value was determined based on statements from ArcelorMittal (2023c) and Nucor (2021) showing recycled steel content of automotive steel between 60% and 75%.

Usage phase emissions

For the vehicle usage phase, this analysis considers the GHG emissions from the production and delivery of fuel and electricity to the vehicle (well-to-tank emissions), and the emissions of fuel consumption in the vehicle (tank-to-wheel emissions). Using the methodology and data described in Bieker (2021), the fuel and electricity production emissions take into account the average fuel and electricity mix over an 18-year vehicle lifetime. The development of the average electricity mix between 2024 and 2041 is based on the Stated Policy Scenario in the International Energy Agency's World Energy Outlook (International Energy Agency, 2023).

The fuel and electricity consumption by vehicle mass and battery size correspond to 2022 segment-average vehicles, based on the U.S. EPA Automotive Trends Report and the ICCT European Vehicle Market Statistics Pocketbook (U.S. EPA, 2023; ICCT, 2024). To reflect improvements in vehicle efficiency due to lightweighting, these values are adjusted as described above.

RESULTS AND DISCUSSION

This section shows the steel-only results for total vehicle manufacturing, including steel and non-steel components, and vehicle life-cycle emissions for average new U.S. passenger cars and EU medium-sized cars. In the steel production emissions section, we model different production pathway, electricity mix, recycling, light-weighting scenarios, and compare the emissions by two vehicle types, BEVs and ICEVs. Further results for U.S. SUVs, U.S. pickups, and EU SUVs follow similar trends to cars and are shown in the Appendix.

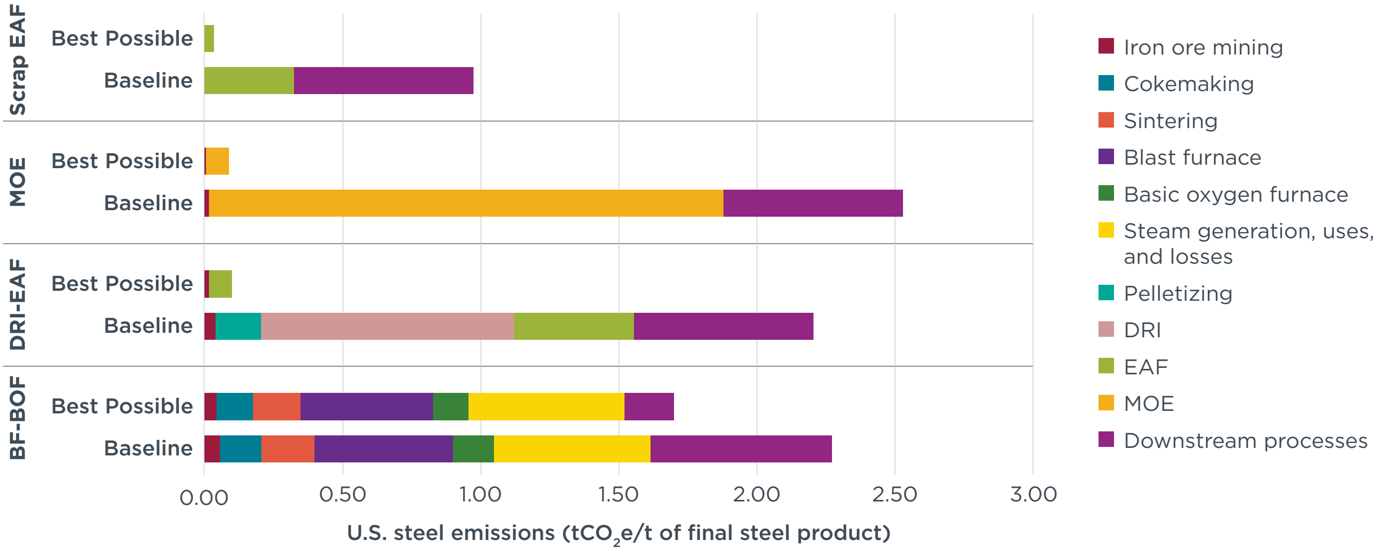
Steel production emissions

First, we calculate the GHG emissions intensity of the different steel production pathways. The analysis includes primary steel produced via the BF-BOF, DRI-EAF, and MOE pathways, as well as secondary steel from scrap-based EAF. Figure 4 and Figure 5 show the GHG emissions intensity of the pathways in two scenarios for steel production in the United States and in the European Union, respectively, in tonnes of CO_2e per tonne (tCO_2e/t) of final steel product. For each of the pathways, the Baseline scenario—which uses the 2022 average GHG emissions intensity of the grid mix and current fossil fuel inputs—is compared to a Best Possible scenario using best available technology, solely renewable electricity, and, in the case of DRI-EAF, renewable electricity-based hydrogen instead of natural gas. In all scenarios, we do not consider the incorporation of CCU and CCS technology.

The figures also display the GHG emissions contribution of the individual steps in steel production. The BF-BOF steps generally consist of iron ore mining (including extraction and processing), cokemaking, sintering, blast furnace, basic oxygen furnace, and on-site generation of steam supply for other processes, such as hot air use in the blast furnace, heat for downstream processes, or electricity generation (denoted as steam generation, uses, and losses). The DRI-EAF pathway steps consist of iron ore mining, pelletizing, DRI processes that include reducing gas production and iron ore reduction, and EAF processes that mainly use electricity to induce chemical reactions. In the results shown in the figures, we consider the mined ore values from GREET and exclude the addition of scrap steel in the BF-BOF, DRI-EAF, and MOE processes. The MOE and scrap-based EAF pathways mostly consume electricity. The EAF emissions from the DRI-EAF pathway can be slightly higher than the scrap-EAF pathway due to the higher melting point and the combustion of iron ore, and lime. All pathways generally have similar downstream processes, which can include hot rolling, cold rolling, galvanizing, and stamping, and might differ depending on the type of final steel product.

Figure 4

Greenhouse gas emissions intensity of steelmaking pathway scenarios in the United States



Source: GREET model (Wang et al., 2022)

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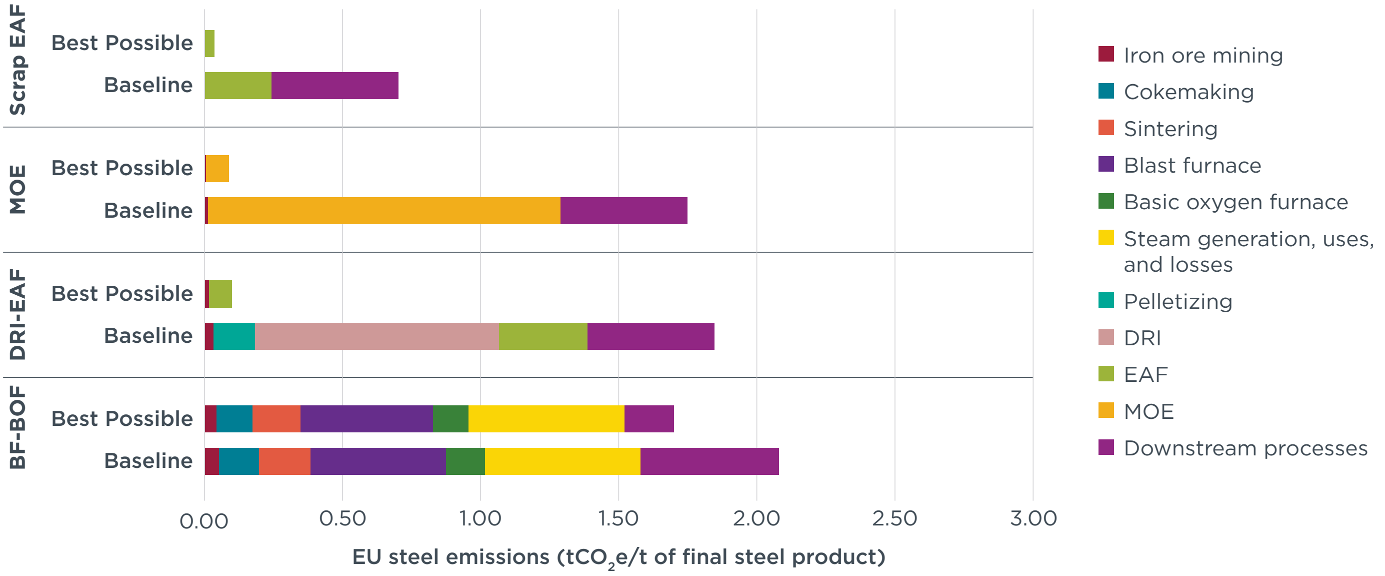
Figure 5

Greenhouse gas emissions intensity of steelmaking pathway scenarios in the European Union



Source: GREET model (Wang et al., 2022).

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For each pathway, the Baseline scenarios have the highest emission intensity, while the Best Possible scenarios have the lowest emissions. The MOE Baseline pathway has the highest emissions intensity among scenarios in the United States, at around 2.5 t CO_2e/t of final steel product, due to the high amount of fossil fuels in the 2022 electricity grid mix. In the European Union, the BF-BOF Baseline pathway has the highest emissions at 2.1 t CO_2e/t of finished steel. The three pathways with the lowest emission intensities are all Best Possible scenarios and are the same in both the United States and the European Union, including Scrap EAF at 0.03 t, MOE at 0.09 t, and DRI-EAF at 0.10 t CO_2e/t of final steel product.

Emissions decrease at a slower rate under the BF-BOF pathway than other steelmaking pathways. In the BF-BOF Best Possible scenario, emissions decrease by 25% in the United States and 18% in the European Union compared to the Baseline scenario. The emission reductions for the DRI-EAF and MOE pathways are 87% and 97%, respectively, in the United States and 83% and 95% in the European Union. This comparatively lower reduction rate for the BF-BOF pathway can mainly be attributed to ongoing fuel combustion emissions, which account for more than 90% of emissions in the BF-BOF pathway, as well as emissions which are the result of chemical reactions rather than combustion—such as CO combining with an oxygen-rich atmosphere to produce CO_2—and a small amount from the degradation of graphite electrodes (Pisciotta et al., 2022). The other two pathways in the Best Possible scenarios mainly produce non-combustion emissions as the electricity mix becomes fossil-fuel free.

Emissions by processes generally vary based on pathways, but also share some similarities. The downstream processes emit about the same amount in each Baseline scenario and is zero for all Best Possible scenarios, except for BF-BOF. This is due to the BF gas by-product and coke oven gas that can still be utilized as a fuel source, resulting in some GHG emissions.

Vehicle manufacturing emissions

Steel emissions from vehicle manufacturing can vary depending on the ratio of primary and secondary steel used. Figure 6 and Figure 7 show the emissions in t CO_2e/t of final steel product of several U.S. and EU steelmaking pathways and recycling scenarios. The steel pathways include BF-BOF, DRI-EAF, and MOE, and the scenarios are based on the grid mix (Baseline and Best Possible) and secondary steel content (25% or 75%). In all pathways, the combination of the 2022 baseline grid and 25% secondary steel content results in the highest emissions intensity, while the Best Possible–75% secondary steel scenarios have the lowest emissions intensity. The figure also shows the Baseline–75% secondary steel scenarios have around two thirds the emissions of the Baseline–25% secondary steel scenario. The emissions of the steel production pathway scenarios are the same for SUVs and pickup trucks.

Figure 6

GHG emission intensities of steelmaking pathway scenarios with different amounts of secondary steel in the Unites States

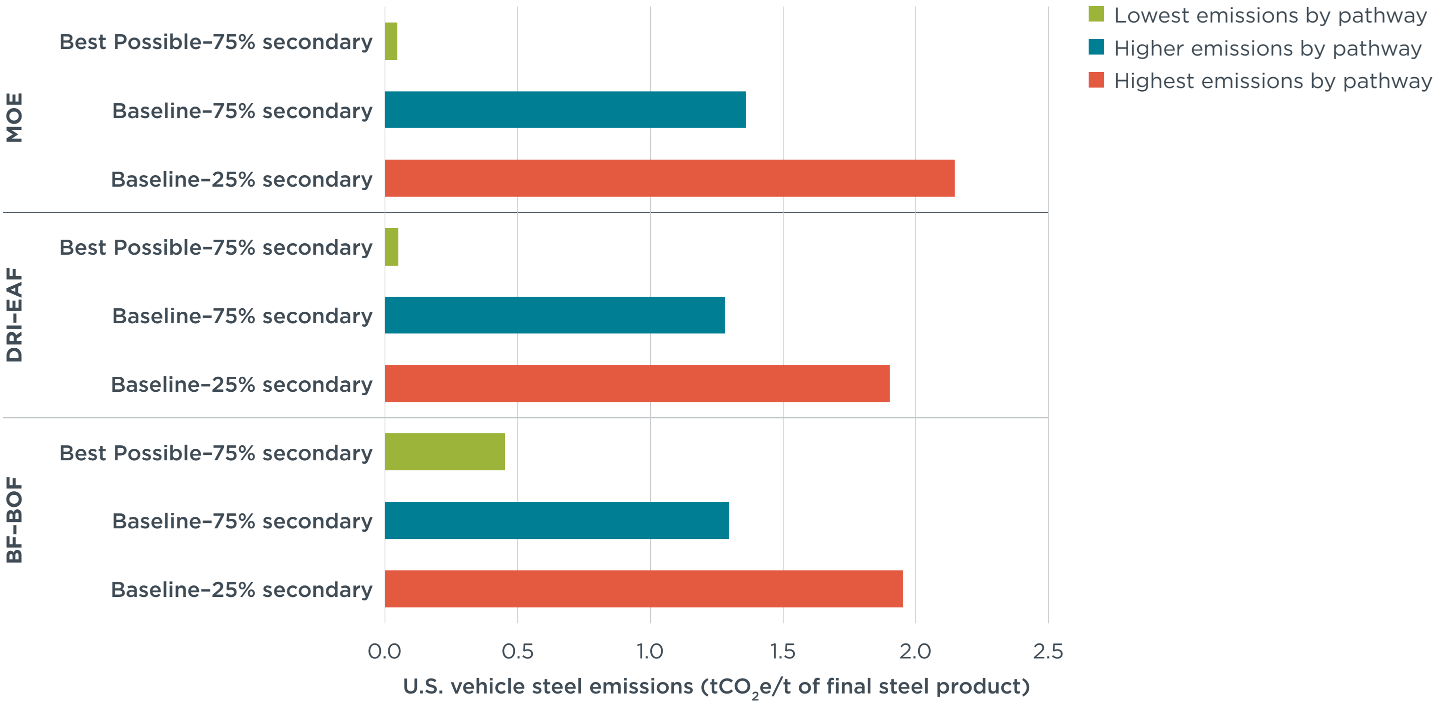

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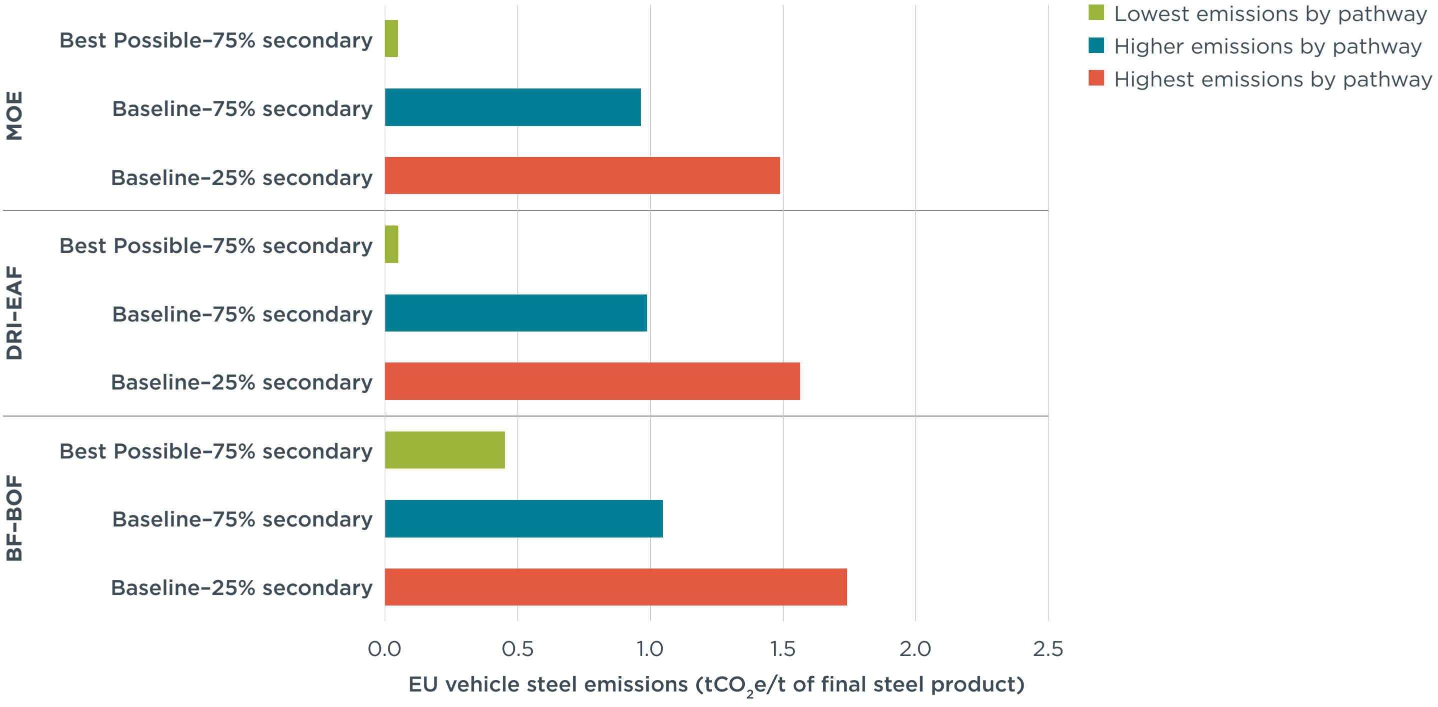
Figure 7

GHG emission intensities of steelmaking pathway scenarios with different amounts of secondary steel in the European Union



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Despite using only renewable electricity and the best available technology in the Best Possible scenario, the BF-BOF production pathway has the highest emissions among all steelmaking pathways. The BF-BOF Best Possible–75% secondary steel scenario emits approximately 0.45 t CO_2e/t of final steel product. This is more than 9 times the emissions of the lowest emission scenarios, DRI-EAF Best Possible–75% secondary and MOE Best Possible–75% secondary, which produce emissions of around 0.05 t CO_2e/t of final steel product.

We also compare the emissions from steel production for the manufacturing of an ICEV and a BEV. Figure 8 and Figure 9 illustrate the steel emissions in tonnes of CO_2e for U.S. passenger and EU lower-medium passenger BEVs and ICEVs, based on steelmaking pathway, share of recycled content, and lightweighting scenarios. Similar figures for SUVs and pickup trucks can be found in the Appendix. For each scenario, the steel production pathway is combined with one of the two recycled content options (25% secondary or 75% secondary steel). All the scenarios, except for the Baseline BF-BOF scenario, assume the best possible technology. The figures also show the results of adding lightweighting with steel or aluminum to each scenario.

Figure 8 shows that the U.S. steelmaking emissions are the highest for the BF-BOF Baseline–25% secondary scenario with conventional steel design for an ICEV at 1.87 t CO_2e, followed by the same scenario for the BEV at 1.72 t CO_2e. The lowest emissions are from the MOE Best Possible–75% secondary scenario with lightweighting aluminum design for the ICEV and BEV, at around 0.02 t CO_2e, although there is minimal difference between lightweighting with aluminum or steel. The steel manufacturing emissions are higher for the ICEV than the BEV in most scenarios because the volume of steel is higher in the ICEV. In scenarios with aluminum lightweighting included, the steel mass decreases more drastically for the ICEV, leading to ICEV steel-only emissions almost equal to these of the BEV.

Figure 8

Steel manufacturing GHG emissions for a U.S. passenger BEV and ICEV by steelmaking scenario

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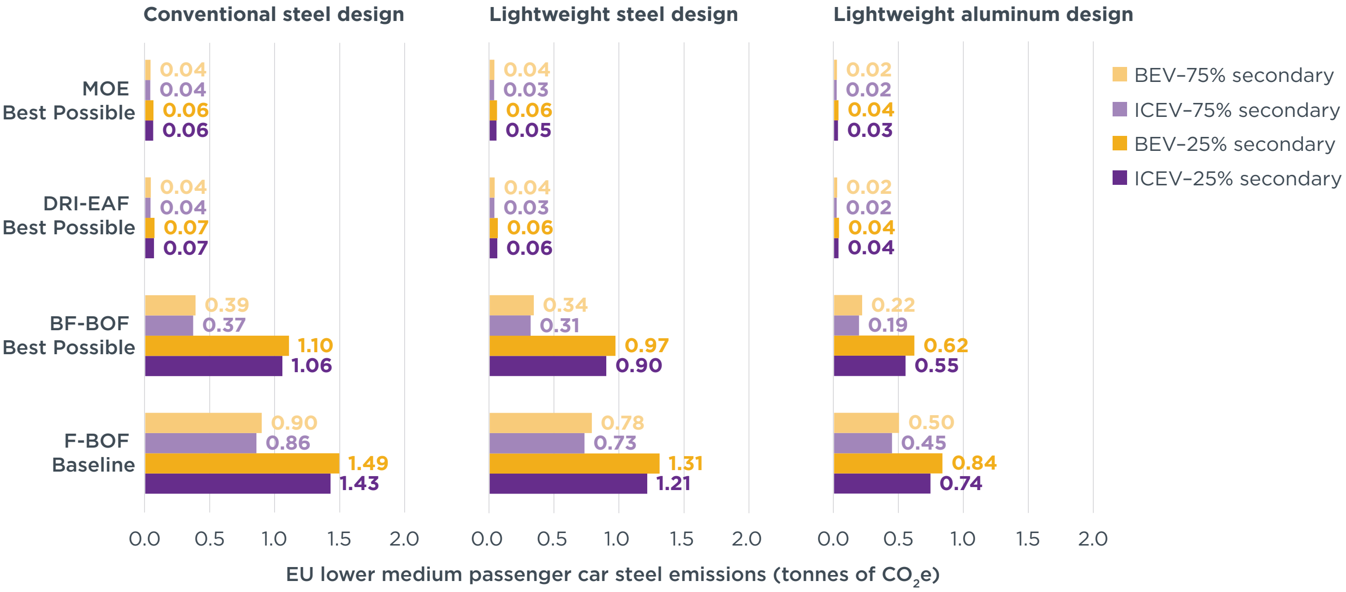
Figure 9 shows that the steel emissions from the production of a lower medium passenger car in the European Union are highest for BF-BOF Baseline–primary 75% scenario without lightweighting for the BEV at 1.49 t CO_2e, followed by the ICEV at

1.43 t CO_2e. Similar to the United States, the lowest emissions come from MOE Best Possible–75% secondary scenario for the ICEV and BEV at around 0.02 t CO_2e. In contrast, steel manufacturing emissions are generally higher for the BEV than for the ICEV in all scenarios as steel volume is higher in the EU lower medium passenger BEV than in the ICEV. This outcome is likely an artifact of different average masses of ICEVs and BEVs in the United States and the European Union.

Figure 9

Steel manufacturing GHG emissions for EU lower medium passenger BEVs and ICEVs by steelmaking scenario



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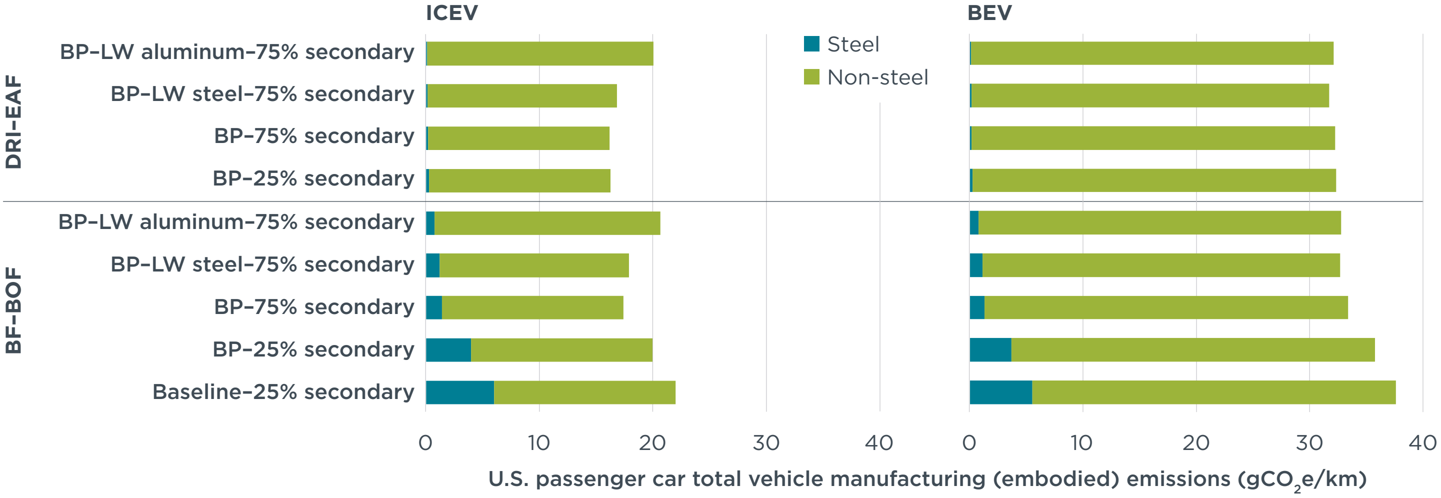
Both figures show potential GHG emission reductions of 95%–99%, depending on the decarbonization strategy or combination of strategies: fossil fuel-free steel production, a decrease in the use of primary steel, and lightweighting. With the U.S. and EU electrical grids transitioning to be fossil fuel-free, all other steelmaking pathways that can operate primarily on electricity are estimated to have 95% lower emissions than the BF-BOF Baseline pathway. Reductions of primary steel use alone can lead to a 35%–65% reduction in GHG emissions from vehicle steel manufacturing. Lightweighting with high-strength steels can reduce steel emissions by 12%–15%, and lightweighting with aluminum can reduce steel emissions by up to 50%.

Steel constitutes a portion of the embodied vehicle manufacturing emissions calculated based on emissions per lifetime distance traveled (gCO_2e/km). Figure 10 and Figure 11 show the embodied emissions of U.S. and EU passenger vehicles by steel and non-steel components for the Best Possible BF-BOF and DRI-EAF scenarios. The MOE pathway, though not showed, generally has slightly lower steel and non-steel emissions than the DRI-EAF pathway. For this analysis, we assume that the production pathways for non-steel components remain unchanged across all steelmaking scenarios for each vehicle type. However, the emissions vary when lightweighting is included due to the changing vehicle mass. Non-steel components with more aluminum generally have slightly higher emissions due to the aluminum production process having higher emission intensity in the GREET model. If the production of other materials also transitions from the use of fossil fuels, the embodied emissions are likely to experience further reductions. Similar figures for U.S. and EU SUVs, and U.S. pickup trucks can be found in the Appendix.

Figure 10 shows that the embodied emissions of a U.S passenger BEV, in general, are almost 2 times higher than an ICEV. The BEV's embodied emissions range from 32–38 g CO_2e/km, while the range is 17–22 g CO_2e/km for an ICEV. The steel-related emissions range from minimal to up to 15% of embodied emissions of a BEV and 27% of embodied emissions of an ICEV. The emissions from BEV battery manufacturing make up more than half of the non-steel emissions. The figure also shows that steel and aluminum lightweighting can result in higher non-steel emissions compared to other scenarios because of the higher emission intensity of the production of other materials substituting for steel.

Figure 10

Embodied emissions of a U.S. passenger BEV and ICEV under different steel production pathway scenarios



Note: BP = Best Possible; LW = Lightweighting

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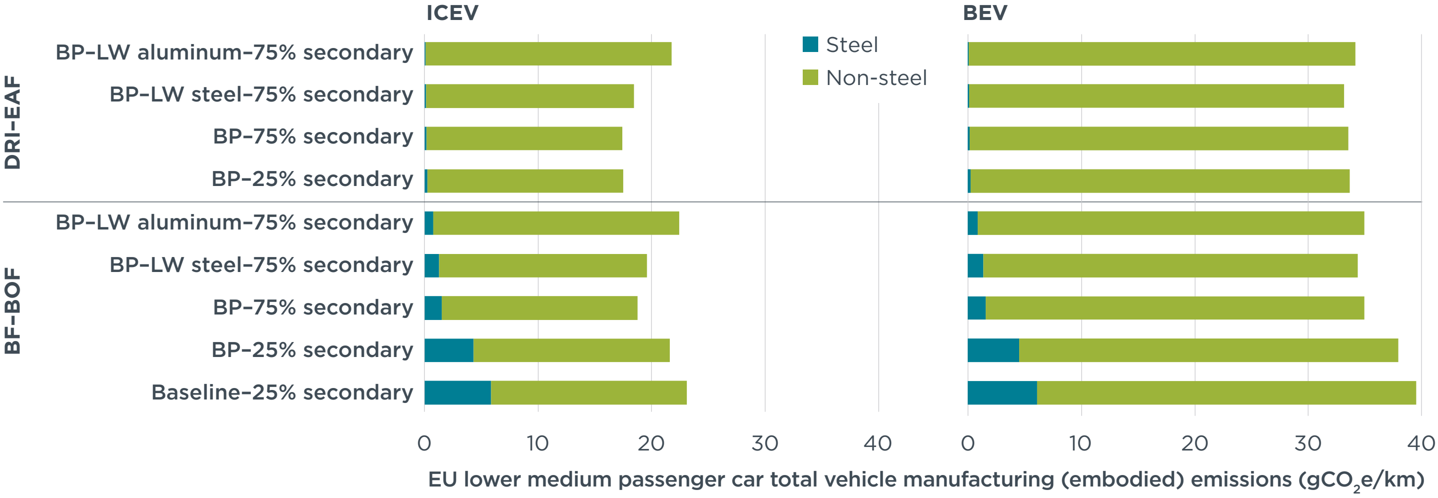
Figure 11 shows the embodied emissions of an EU lower medium passenger car. Similar to the United States, the BEV's embodied emissions is around two times higher than the ICEV. The BEV's embodied emissions range from 33 to 40 g CO_2e/km, while the range is 17 to 23 g CO_2e/km for an ICEV. The steel-related emissions are up to 16% of the embodied emissions of a BEV and 25% of an ICEV.

Figure 11

Embodied emissions of a lower medium passenger EU BEV and ICEV under different steel pathway scenarios



Note: BP = Best Possible; LW = Lightweighting

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As the grid transitions to become fossil fuel free, embodied emissions will become an increasingly large share of a vehicle's total life-cycle emissions. The higher embodied emissions of a BEV compared to an ICEV highlights the growing need to reduce electric vehicle manufacturing emissions.

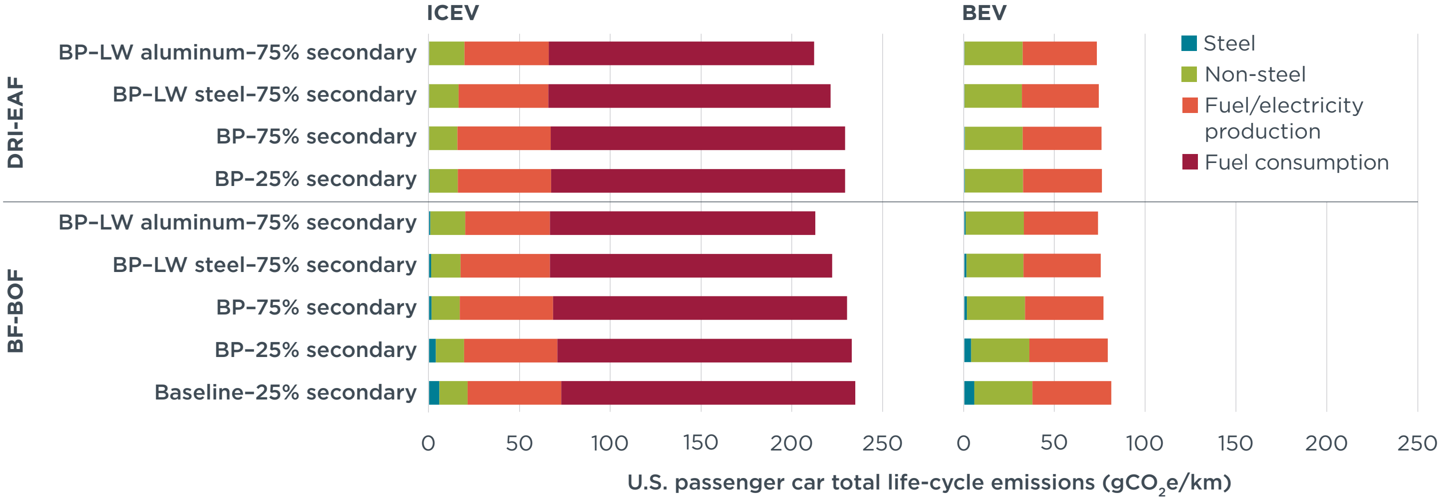
Vehicle life-cycle emissions

Vehicle manufacturing emissions are only a part of the total life-cycle emission of a vehicle. When electricity production and consumption are included, the total emissions of a BEV are significantly lower than an ICEV, as shown in Figure 12 and Figure 13.

Figure 12 shows the total life-cycle GHG emissions of a U.S. passenger BEV and ICEV, broken down by steel production, non-steel production, fuel and electricity production, and fuel consumption emissions. The scenarios include Baseline BF-BOF, Best Possible BF-BOF and Best Possible DRI-EAF, combined with steel recycling and lightweighting options. The figure shows that an ICEV's total life-cycle emissions are about 3 times higher than a BEV's. Based on the projected average 2024–2041 grid mix, the BEV has lower electricity production emissions than ICEV fuel production emissions. The BEV also produces no tailpipe emissions. The lowest ICEV total life-cycle emissions of a ICEV are from the DRI-EAF Best Possible–LW aluminum–75% secondary scenario at more than 218 g CO_2e/km, three times more than the BEV's emissions under the same pathway, at 73 g CO_2e/km. Lightweighting technologies lead to higher fuel efficiency, thus reducing GHG emissions from fuel/electricity production and fuel consumption.

Figure 12

Vehicle life-cycle GHG emissions of a U.S. passenger BEV and ICEV by steel production pathway scenario



Note: BP = Best Possible; LW = Lightweighting

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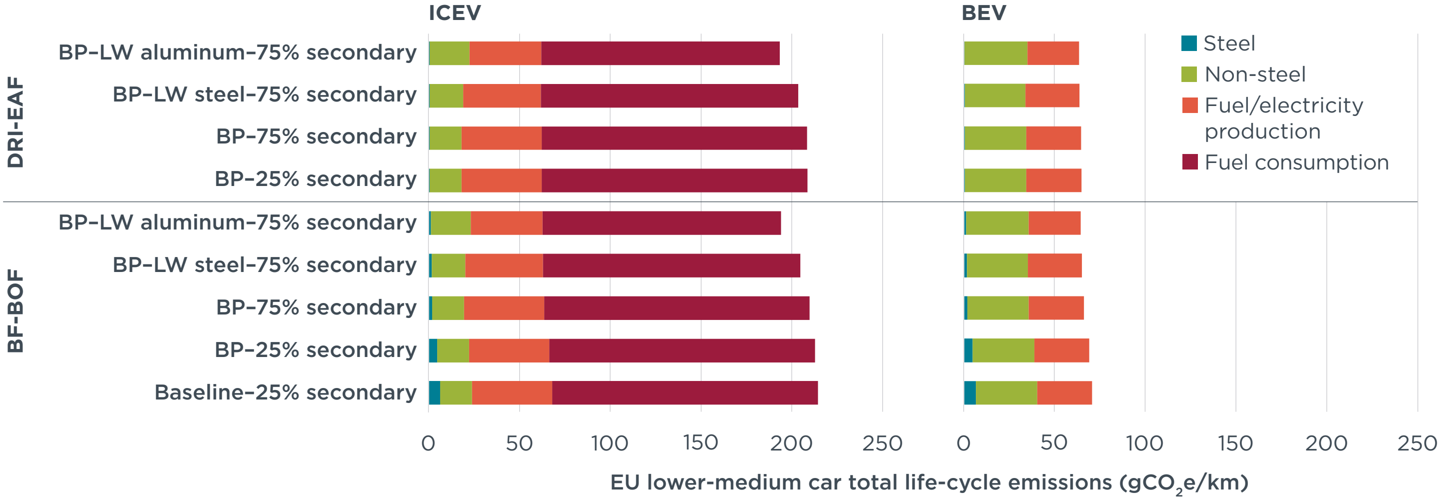
Similarly, Figure 13 shows that the total life-cycle emissions of an EU lower medium passenger ICEV are more than three times higher than a BEV. The lowest ICEV total life-cycle emissions come from the DRI-EAF Best Possible–LW aluminum–recycled 75% scenario, at about 190 g CO_2e/km, compared with the BEV's lowest emissions from the same pathway, at 62 g CO_2e/km.

Figure 13

Vehicle life-cycle emissions of an EU lower medium passenger BEV and ICEV by steel production pathway scenario



Note: BP = Best Possible; LW = Lightweighting

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As shown in the figures above, the emissions exclusively associated with embodied steel constitute a relatively small factor within the overall calculation of a vehicle's total life-cycle emissions. The highest percentage of steel-only emissions are 7% for a BEV and 2% for an ICEV under the BF-BOF Baseline scenario. These emissions are minimal in the other steelmaking scenarios. Emissions from an ICEV stem primarily from tailpipe emissions, constituting approximately 70% of the total life-cycle emissions. In contrast, for a BEV, approximately 55% (United States) and 45% (European Union) of emissions are from electricity production, and there are no tailpipe emissions. Nevertheless, greening steelmaking plants, including both iron and steelmaking processes that produce more than automotive steel, could have a large GHG impact economy wide.

REVIEW OF COST ESTIMATES

The cost associated with the transition from the use of fossil fuels in production is a major focus for steelmakers. There is a range of price differences between the traditional BF-BOF production pathways and other low-GHG emission technologies. As of April 2024, U.S. hot-rolled steel bands cost about $920 per tonne and cold-rolled coils cost about $1,140 per tonne. Between 2013 and April 2024, the price per tonne ranged from $400 to $2,100 (World Steel Dynamics, 2024). Terry et al. (2023) found the conversion of BF-BOF production to DRI-EAF technology—initially using natural gas before switching to green hydrogen in 2030—can potentially lead to a levelized cost of hot-rolled band production to around $555 per tonne. In addition, steel from a new integrated DRI-EAF that uses 100% green hydrogen would cost around $635 per tonne. Another study suggests that low-GHG steel is likely to be more expensive to produce than conventional steel in 2030, projecting that the average cost of steel produced via BF-BOF in 2030 can be less than $400 per tonne, while the levelized cost of using other technologies range from $430 to $840 per tonne (Mission Possible Partnership, 2022). H2 Green Steel, which has a plant under construction in Sweden, announced in September 2023 that higher upfront costs will make the price of steel produced with green hydrogen 20%–30% more than conventional steel (St. John, 2023). At this price point, the use of this steel would add $100–$200 (or less than 1%) to the average vehicle price (Farge, 2023; Hasanbeigi et al., 2024). As the cost of green steel decreases, this price premium should diminish.

The cost of secondary steel will likely be less than produced steel produced via BF-BOF in the future. As of April 2024, scrap steel price ranges from $335 to $414 per tonne, depending on the type of scrap used. For example, busheling, which is new sheet steel scrap that is likely to be recycled for automotive-grade steel, cost $414 per tonne (World Steel Dynamics, 2024). It does not necessarily bear the same premium as primary green steel since recycled steelmaking is a well-established technology. Thus, future pricing likely depends on the price of scrap, which has seen less drastic fluctuation compared to primary steel over the past ten years. Between 2013 and April 2024, U.S. iron and steel scrap prices ranged from around $150 per tonne to around $850 per tonne (World Steel Dynamics, 2024).

Assuming an average 40-year asset life span of steelmaking plants, investment decisions made in the 2020s will significantly impact technology compositions in the 2050s and 2060s (Mission Possible Partnership, 2022). The average BOF plant in the United States is close to 50 years old as of 2023 (Association for Iron & Steel Technology, 2023). At the global level, ironmaking production equipment is relatively young. Blast furnaces are only about 13 years old, on average, counting the last major refurbishment (International Energy Agency, 2020). Relining, or replacing the refractory brickwork on blast furnaces, could add another 15 to 20 years of service to the plant (Agora Industry et al., 2021). Before 2030, 97% of blast furnaces in the United States will need relining, as will 70%–80% of those in China, Europe, Japan, and South Korea (Agora Industry et al., 2021). Relining these furnaces in the near future could hinder many countries aiming to achieve net zero targets by 2050 (Mission Possible Partnership, 2022).

One study shows that reinvestment occurring between 2021 and 2030—which combines blast furnace relining, plant overcapacity reduction, and conversion to scrap-based EAF and DRI-EAF pathways—would lead to 90% of existing blast furnaces being phased out without premature shutdown by 2040 (Agora Industry & Wuppertal Institute, 2023).

Many fossil fuel-free technology pathways are currently under development and have commercially available timelines similar to the best BF-BOF low-carbon pathway. For example, integrated DRI-EAF that uses 100% green hydrogen is expected to be commercially available around 2026. Deployment of the BF-BOF pathway that uses hydrogen in combination with pulverized coal injection is expected in 2025, and the same pathway combined with CCS or CCU in 2028. (Mission Possible Partnership, 2022). Boston Metal announced that it is on track to reach MOE commercialization by 2026 (Boston Metal, n.d.).

STEEL DECARBONIZATION POLICY DEVELOPMENT

Several policies can be leveraged to reduce primary steel use and incentivize more fossil fuel-free primary steel production. Policies that encourage lightweighting could reduce the amount of steel consumed by the automotive sector. Strong corporate average fuel efficiency or CO_2 emission standards motivate both the use of lightweighting and higher sales of BEVs, which already use less steel. Vehicle safety agencies could also incentivize lighter vehicles by awarding lower safety ratings to heavier vehicles that could significantly damage vehicles in another class. States, municipalities, and local governments could also set registration fees or other financial measures based on vehicle mass, potentially specific to the powertrain type. For example, Paris introduced parking fees that are three times the normal rate in February 2024 for vehicles that weigh above a certain threshold (EU Urban Mobility Observatory, 2024). Governments can promote increased use of recycled steel in vehicles by regulating embodied emissions of vehicles and establishing standards for end of life (EOL) recovery/design and recycling (EU Urban Mobility Observatory, 2024). Governments can also financially support further metallurgical research.

EUROPEAN UNION

In the European Union, several policy developments could support steel decarbonization. These include the EU's Emissions Trading System (ETS) in combination with the Carbon Border Adjustment Mechanism (CBAM), the proposed Regulation on Circularity Requirements for Vehicle Design and on Management of End-of-Life Vehicles, the proposed Ecodesign for Sustainable Products Regulation, and the recently adopted Corporate Sustainability Due Diligence Directive.

The EU's ETS is a market mechanism that sets a cap on the amount of CO_2 emissions that the companies operating in covered industries, including the steel and power sectors, are allowed to release into the atmosphere. The emissions cap, which is reduced annually, is matched by a number of allowances, each of which gives permission to emit one tonne of CO_2. For each year, companies must surrender allowances equal to their emissions or pay a fine. These allowances can be traded among companies on the EU carbon market. Since 2005, the EU ETS has contributed to reducing emissions from the energy sector and manufacturing industry plants by 37%. (European Commission, n.d.-b). To avoid the risk of carbon leakage, where companies relocate production to outside the European Union to avoid paying emissions allowances, the European Union has granted free allowances to sectors considered a particularly high risk, including the steel sector. It is estimated that, between 2008 and 2019, the steel sector has received about 2.3 billion free emission allowances. As a consequence, emissions in the steel sector have remained at consistent levels, as opposed to decreasing (Carbon Market Watch, 2022). Measures included in the revision of the EU ETS and the EU CBAM, which entered into force on October 1, 2023, are intended promote emission reductions in the EU steel sector (European Commission, n.d.-a). The CBAM will progressively apply a carbon price to imported steel goods to mitigate the risk of carbon leakage, and at the same time the free allowances will be gradually eliminated in the period 2026–2034.

In July 2023, the European Commission published a proposal for a new regulation on Circularity Requirements for Vehicle Design and on Management of End-of Life Vehicles (Directorate-General for Environment, 2023). The proposal foresees an assessment on the feasibility, costs, and benefits of setting minimum recycled steel content requirements for the production of new vehicles. Further, new vehicle types would have to be made up of a minimum of 85% reusable or recyclable material by mass, and 95% of the vehicle materials would have to be reusable or recoverable. Further, this proposal would cover more vehicle types and tighten current enforcement provisions to increase the number of end-of-life (EOL) vehicles being treated within the European Union. This proposed regulation tackles vehicle production emissions from two standpoints. Better EOL treatment of vehicles would ensure that materials are handled correctly and could be used to promote the recovery of higher quality steel. In addition, vehicle design is crucial in ensuring that steel is not mixed with other materials, which lowers its quality and affects EOL treatment.

The Ecodesign for Sustainable Products Regulation (ESPR) proposed by the European Commission aims to establish a broad framework for setting ecodesign requirements for sustainable products (European Commission, n.d.-c). Among the proposed tools is the creation of a digital product passport for information sharing and the establishment of ecodesign criteria such as durability and reliability, reusability, upgradability, reparability, the possibility of maintenance and refurbishment, presence of the substance of concern, energy and resource efficiency, and recycled content. The ESPR includes iron and steel products in the priority product groups identified but does not specifically include vehicles. A preparatory study to assess the feasibility of the regulation will include a market analysis and review of existing international initiatives on low- and zero-emissions steel (European Commission, n.d.-c). It will also identify potential performance and information requirements applicable to iron and crude steel, in addition to semifinished and finished steel products of steel, for a possible future delegated act.

The Corporate Sustainability Due Diligence Directive sets obligations for companies to identify and address adverse human rights and environmental impacts of their own operations, their subsidiaries and business partners along the supply chain. This includes an obligation to adopt a transition plan to reach climate neutrality by 2050, aligned with the Paris Agreement and the European Climate Law. The final text was adopted in May 2024 by the European Parliament and Member States (European Commission, 2024). The directive carries significant implications for steelmakers and the automotive industry, as it necessitates increased transparency and reduction of GHG emissions-generated activities in their supply chain.

UNITED STATES

In the United States, the GHG regulatory landscape is much more barren. Although Section 111 of the Clean Air Act provides authority to the U.S. EPA to regulate GHG emissions from integrated steel mills, the agency has not promulgated a comprehensive regulation (Congressional Research Service, 2022). EPA has issued national emission standards for hazardous air pollutants for integrated iron and steel manufacturing facilities, but these do not cover GHG emissions. It remains unclear whether embodied emissions of vehicles will be regulated in the future. Thus, there is significant opportunity for EPA to develop GHG standards for iron and steel facilities.

OPPORTUNITIES FOR AUTOMAKERS

As explained earlier in this study, the automotive sector is responsible for a large share of demand for primary steel, and thus has an outsized influence on steelmaker revenues and product portfolios. As such, there are many actions automakers could take to encourage the transition to fossil fuel-free steel. Such actions include committing to purchase green steel in individual supply agreements with steel companies, or also jointly through an aggregated purchase pool, such as the Rocky Mountain Institute's Sustainable Steel Buyers Platform (Rocky Mountain Institute, 2023), and joining initiatives promoting the transition to fossil fuel-free steel production. For example, the SteelZero initiative requires members to target purchasing 50% "low embodied carbon steel" by 2030, and 100% "net zero steel" by 2050 (Climate Group, 2023). As of April 2024, Volvo is the only automaker that has signed on to the initiative. The First Movers Coalition requires members to set a target of at least 10% of steel purchased annually to be "near-zero emissions" by 2030. As of April, 2024, Ford, General Motors, and Volvo have joined this coalition (First Movers Coalition, 2024).

Automakers can take also several steps to increase the quantities of secondary steel in vehicle manufacturing. Tracking quantities of pre- and post-consumer scrap contained within purchased steel and creating policies and procedures to facilitate steel, aluminum, and copper separation at the vehicle's EOL could help to increase the availability of automotive-grade steel scrap that can be infinitely recycled without downgrading. To hasten improved vehicle recyclability in the long term, manufacturers could design their vehicles with disassembly in mind. Additionally, manufacturers could invest in or create alliances with scrappage facilities to improve the separation of steel from contaminants (McKinsey & Company, 2020).

Automakers could take several additional actions to reduce the climate impacts of steel and their vehicles overall, including: directly investing in companies developing green steel, increasing lightweighting designs to reduce the quantity of steel in a vehicle, and securing lightweight material supply chains that will also be fossil fuel free.

CONCLUSIONS

Due to the heavy use of fossil fuels—especially coal—in primary steel production today, new steel production pathways are necessary for the steel industry to contribute to national and global climate goals. The automotive industry is one of the largest purchasers of steel in the United States and the European Union and, due to quality requirements, is an outsized consumer of primary steel. Therefore, automakers may be uniquely suited to drive demand for fossil fuel-free steel and drive the steel industry to transition away from coal and blast furnaces. With this goal in mind, the following conclusions can be drawn from the foregoing discussion:

Fossil fuel-free steel production technologies can reduce GHG emissions related to vehicle steel by over 95% and reduce vehicle manufacturing emissions overall by up to 27%. For ICEVs and BEVs, new steel production technologies can reduce the embodied emissions of vehicle steel by over 95%. Since these emissions represent up to a quarter of total vehicle embodied emissions, new steel production pathways present a major opportunity. As the transition to battery electric vehicles progresses, and as the electricity grid mix continues to decarbonize, reducing embodied emissions becomes increasingly important. Should other materials used in vehicle manufacturing also transition towards green production, vehicle manufacturing emissions are likely to experience further GHG reductions.

Secondary steel can play an important role in reducing automotive steel's climate impact. The supply of secondary steel with low concentrations of polluting elements, such as copper, is currently limited. Strategies to increase the availability of such high-grade secondary steel for automotive applications include designing vehicles for recycling, ensuring their collection and end-of-life management, and improving the sorting of metal parts during vehicle dismantling and shredding. With realizing an increased supply, a higher secondary steel share in vehicle production could lead to a 35%-65% reduction in steel-related GHG emissions.

Lightweighting can reduce the embodied emissions from steel by 12%–50%, depending on the materials used. Both ICEVs and BEVs rely on steel in the body, powertrain, chassis, and elsewhere. By improving component design and substituting mild steel with lighter or stronger materials, total steel mass—and its associated embodied emissions—decreases. The most common materials used to substitute for mild steel are higher strength steels and aluminum. Lightweighting with high-strength steels reduces steel emissions by 12%–15% depending on vehicle segment and powertrain. Lightweighting with aluminum reduces steel emissions by up to 50%. Although aluminum-based lightweighting may lead to slightly higher total vehicle manufacturing (embodied) emissions, the overall mass reduction is greater than lightweighting with steel, resulting in lower emissions from fuel production and consumption during vehicle usage phase.

Switching to fossil fuel-free steel can be cost-effective. Green steel premiums are on the order of 20%–30% today. This increased cost translates to about $100–$200 per vehicle, which in generally is less than 1% of the average price of a new vehicle. These costs are expected to decrease as green steel producers increase capacity in response to demand commitments.

Primary production technologies for fossil fuel-free steel already exist and production capacity can increase, but not without commitments from automakers. Automakers can support the transition to decarbonized primary steel by making purchase agreements with fossil fuel-free steel producers and investing in those producers directly. Additionally, automakers can signal to steelmakers the strong demand for fossil fuel-free steel by aggregating and joining coalitions with explicit green steel purchase targets. They can also start tracking recycled content in vehicles, design and assemble vehicles with the goal of recyclability, and implement lightweight designs to reduce steel quantity.

When comparing the U.S. and the EU markets, similar opportunities and challenges exist in the transition to automotive green steel. Both regions have significant steel consumption by the automotive sector, providing opportunities for automakers and steelmakers to drive demand for fossil fuel-free steel. Differences in regulatory frameworks, market structures, and industrial landscapes may influence the pace and approach of the transition in each region. Nevertheless, concerted efforts and commitments from the auto and steel industries, combined with the governmental urgency to address climate change, will help accelerate the adoption of green steel. This will reduce emissions associated with vehicle manufacturing, mitigate adverse air quality and health impacts of steel production, and increase both industries' contribution to global climate change mitigation efforts.

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APPENDIX: GREENHOUSE GAS EMISSIONS FOR ADDITIONAL VEHICLE TYPES

Figure A1

Steel manufacturing GHG emissions for a U.S. sport utility BEV and ICEV by steelmaking scenario

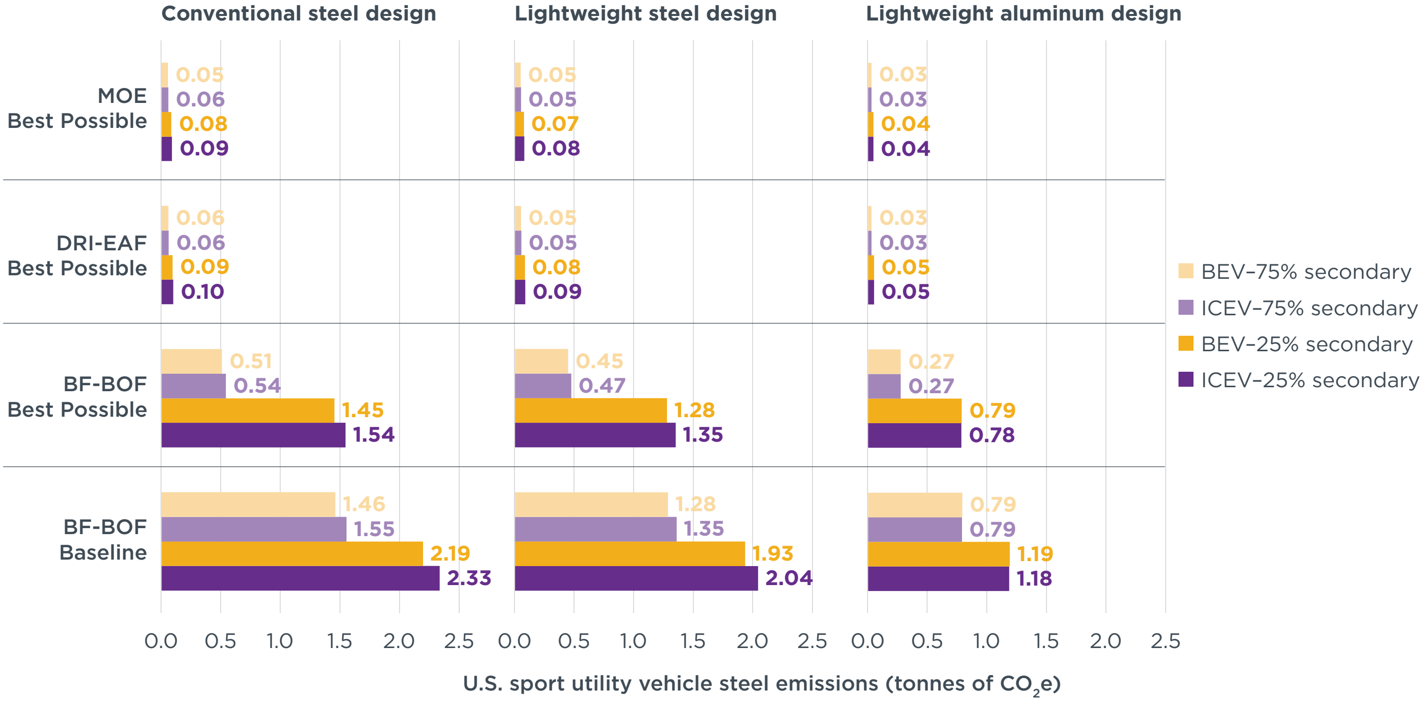

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Figure A2

Steel manufacturing GHG emissions for a EU sport utility BEV and ICEV by steelmaking scenario

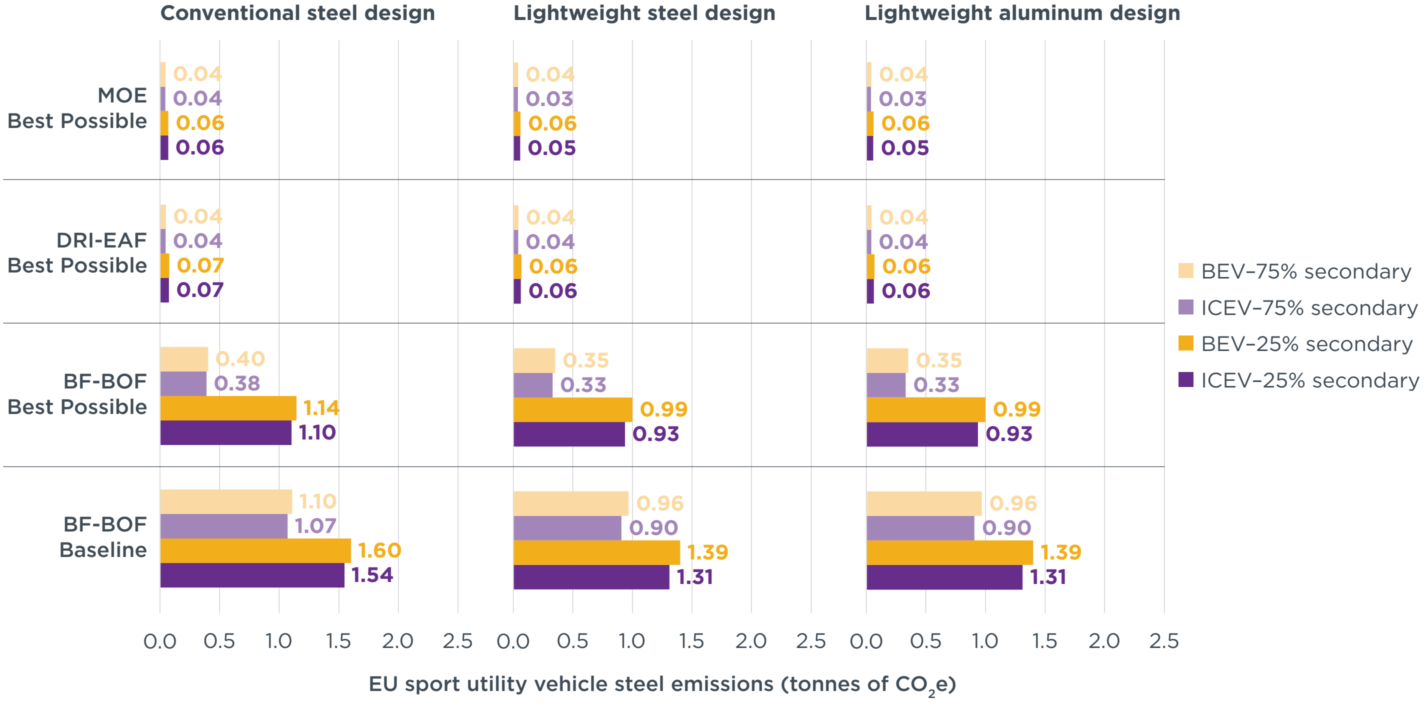

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Figure A3

Steel manufacturing GHG emissions for a U.S. pickup BEV and ICEV by steelmaking scenario

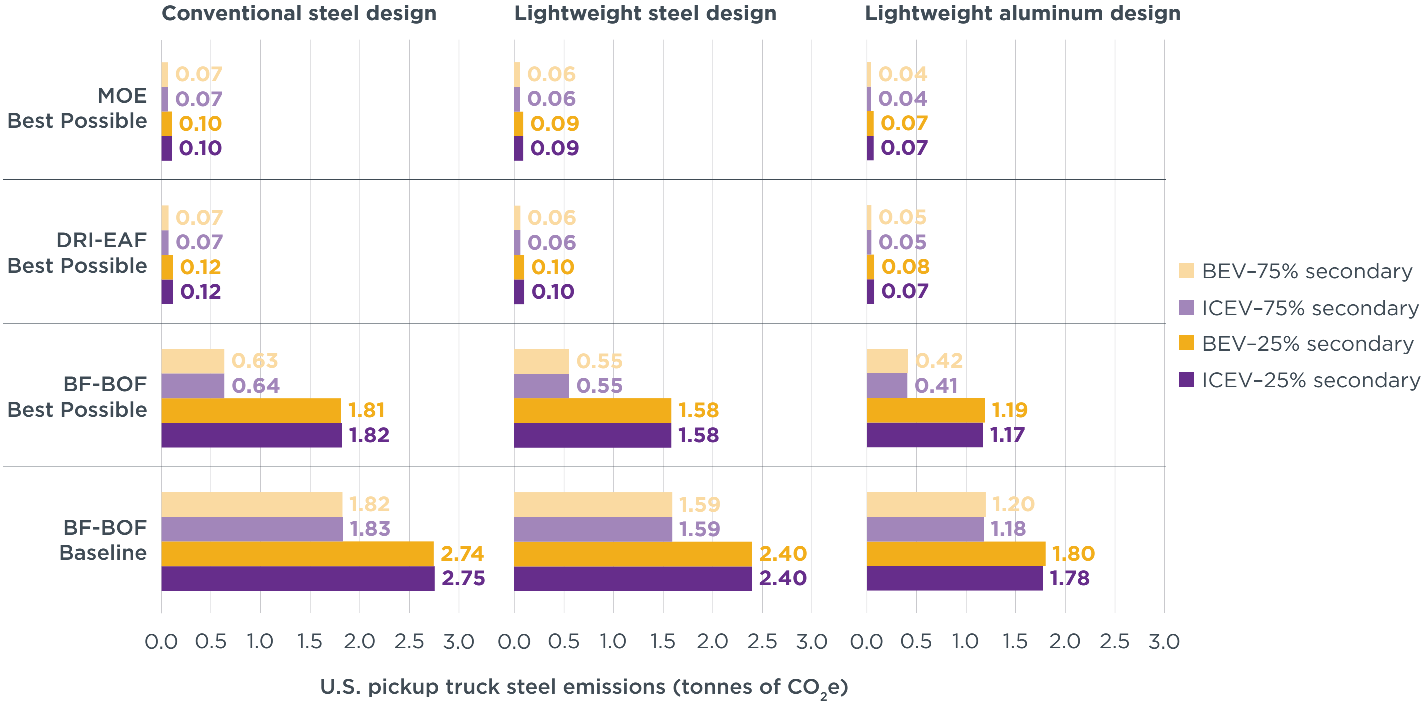

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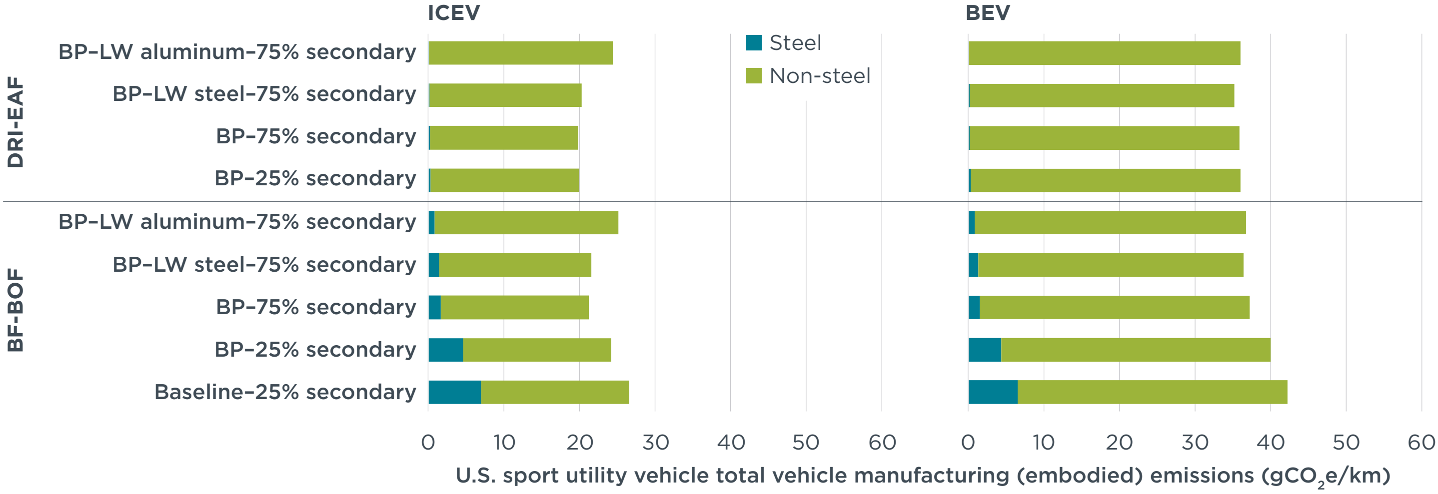
Figure A4

Embodied vehicle manufacturing emissions of a U.S. sport utility BEV and ICEV under different steel production pathway scenarios



Note: BP = Best Possible; LW = Lightweighting

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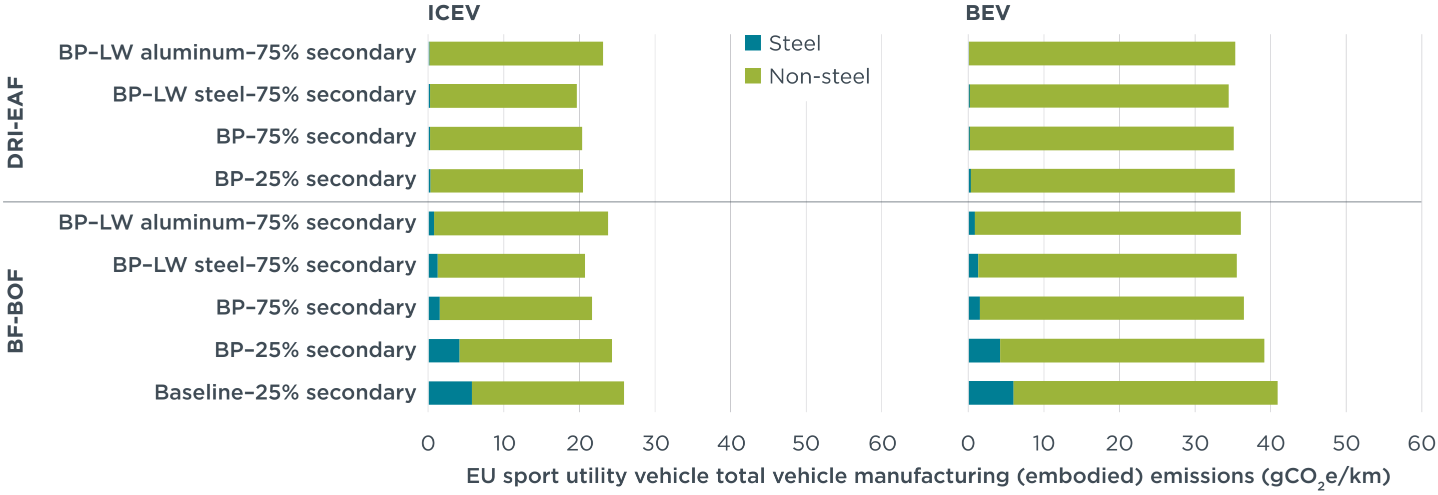
Figure A5

Embodied emissions of an EU sport utility BEV and ICEV under different steel production pathway scenarios



Note: BP = Best Possible; LW = Lightweighting

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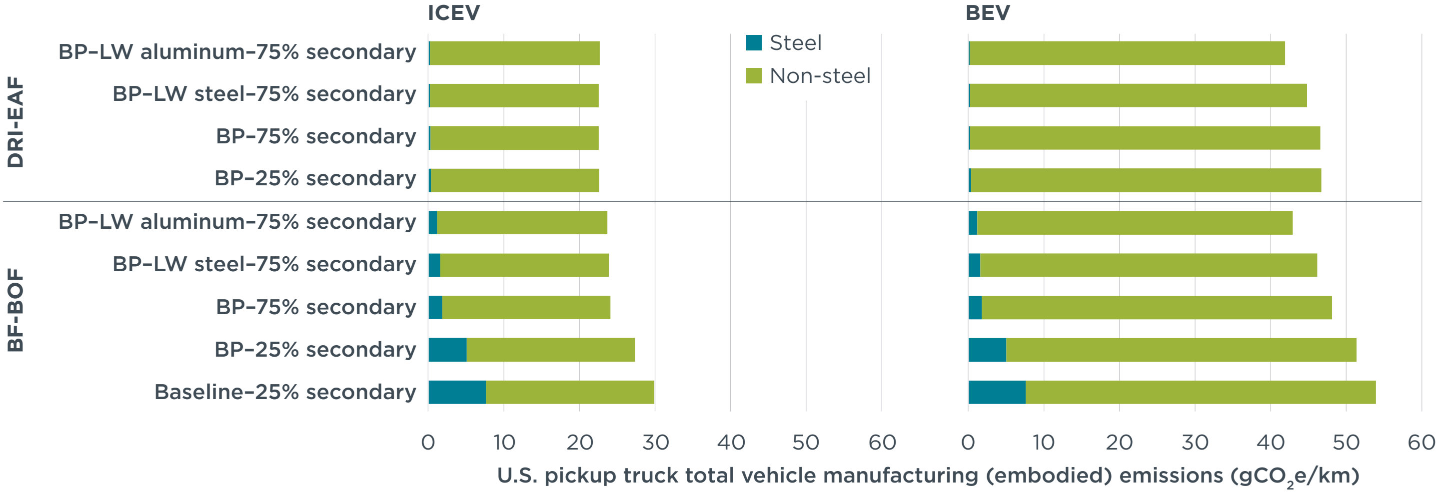
Figure A6
Embodied emissions of a U.S. pickup BEV and ICEV under different steel production pathway scenarios



Note: BP = Best Possible; LW = Lightweighting

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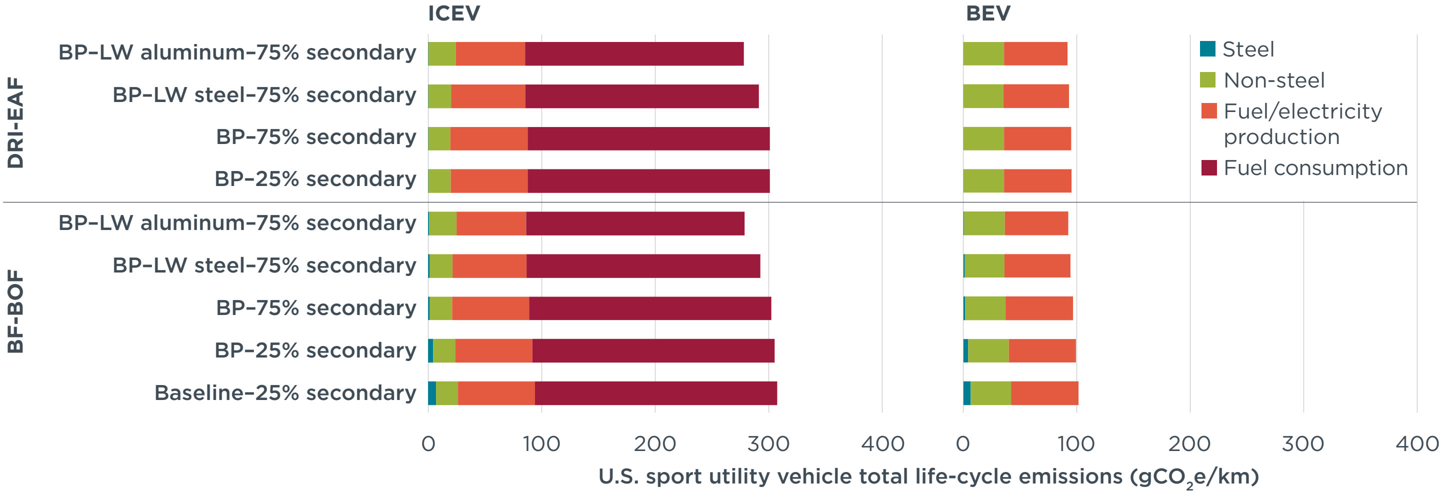
Figure A7
Vehicle life-cycle GHG emissions of a U.S. sport utility BEV and ICEV by steel production pathway scenario



Note: BP = Best Possible; LW = Lightweighting

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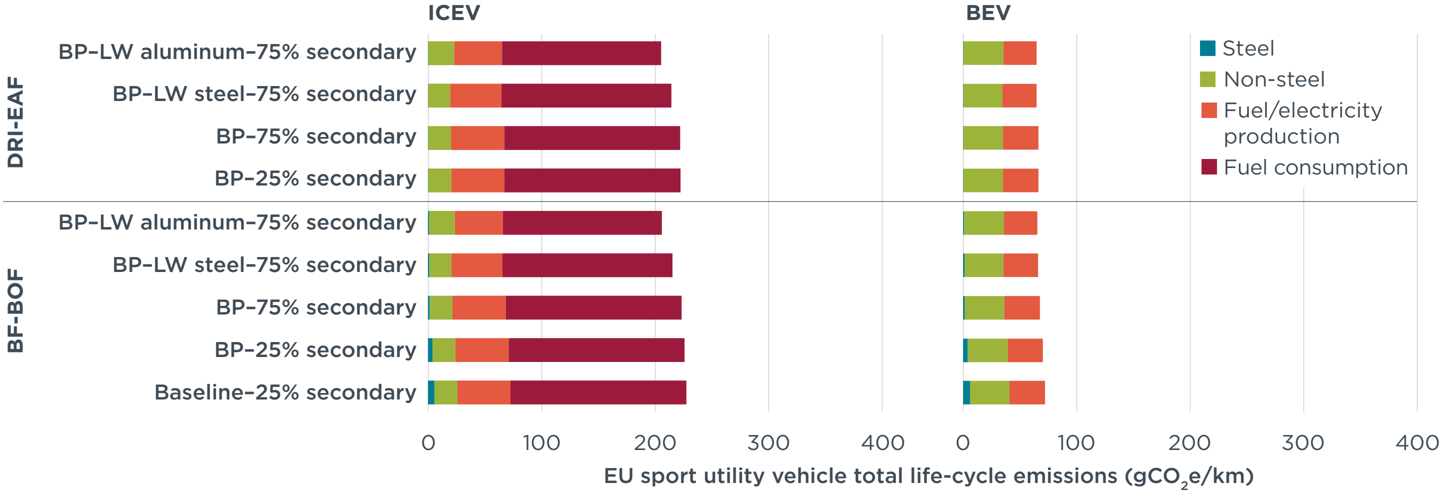
Figure A8

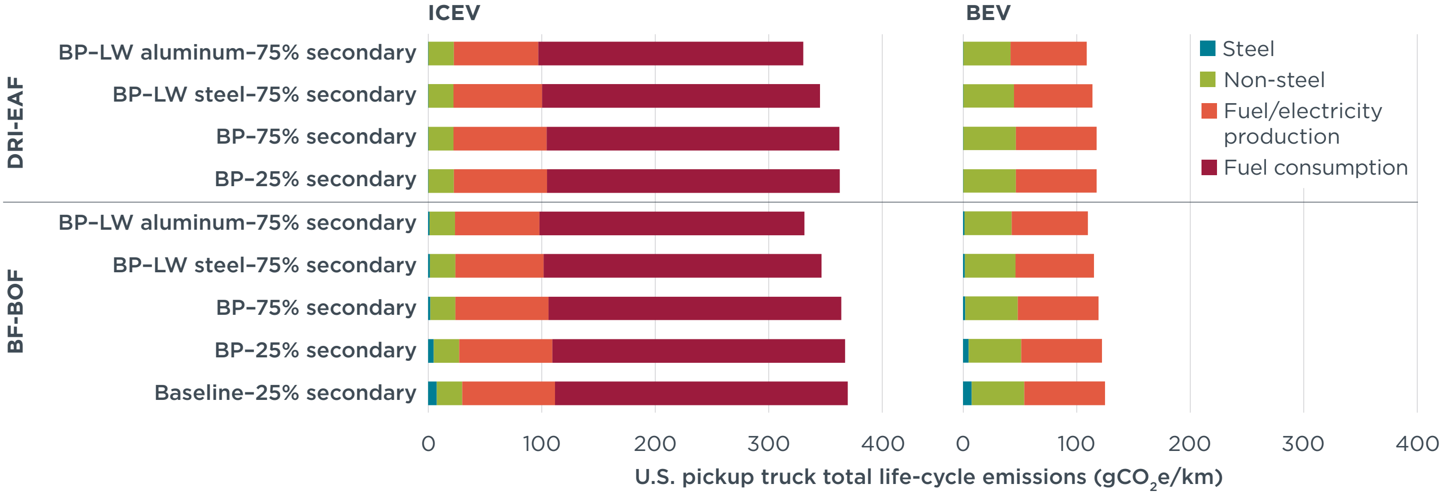
Vehicle life-cycle GHG emissions of an EU sport utility BEV and ICEV by steel production pathway scenario



Note: BP = Best Possible; LW = Lightweighting

Figure A9

Vehicle life-cycle GHG emissions of a U.S. pickup truck BEV and ICEV by steel production pathway scenario



Note: BP = Best Possible; LW = Lightweighting

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