The use of Green Steel in the Automotive Industry

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EXECUTIVE SUMMARY

Steel is a vital component of the automotive sector, accounting for approximately 12% of global steel demand and 17% of EU steel demand (EUROFER, 2023), and it accounts for a high share of the overall material content in road vehicles, and therefore contributes also to a significant share of the manufacturing GHG emissions impacts of new vehicles. So-called 'Green Steel' is seen as a key route to achieving Europe's wider decarbonisation goals and by OEMs as a key component of their strategies to reduce their impacts from vehicle production.

Transport & Environment (T&E) commissioned Ricardo to conduct an analysis of the potential impacts (on GHG emissions and costs) from the potential future use of 'green steel' in the EU automotive sector. The objectives of this study were to:

- Develop a market outlook for the present and future of the green steel with the focus on the automotive sector.
- Provide an estimate and compare the CO_2 footprint of cars built with conventional steel and "green steel" (via a life cycle assessment, LCA).
- Provide an estimate of the production costs of green steel (along the most common production pathways as defined by automakers today) and compare it with the production costs of conventional steel.
- Model scenarios for the demand and supply (production capacity) of "green steel" in the automotive industry in Europe in the upcoming years for a baseline and ambitious uptake scenario.
- Provide a summary and conclusions on the basis of the findings.

During this project, Ricardo characterised the current and future market for green steel within the automotive sector, quantifying the potential impacts on projected supply and demand of green steel on the sector's decarbonisation targets.

The first part of our assessment concerned first the characterisation of the options for steel decarbonisation (compared to the current blast furnace/basic oxygen furnace – BF/BOF, and electric arc furnace – EAF – processes) and their feasibility and likelihood of application in the automotive sector, to inform the development of the scenarios for analysis. The primary option that is emerging as the most likely process to be used to achieve long-term decarbonisation steel production is the Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) production process, using green hydrogen and electricity from either the energy grid mix or renewable sources. 'Green H-DR' is the term often used to refer to this when the hydrogen is produced from renewable electricity. This option offers the potential for up to 98% reduction in emissions from primary steel production compared to conventional steel production using the blast furnace/basic oxygen furnace (BF-BOF). In addition to the 'Green H-DR' production process, a number of other novel options are being developed for primary steel decarbonisation. However, our analysis suggests that these options seem unlikely for widespread adoption for decarbonisation of steel in the automotive sector, based on their potential for commercial scalability and GHG emission reductions, and their lack of inclusion in publicly available announcements of automotive OEM decarbonisation strategies.

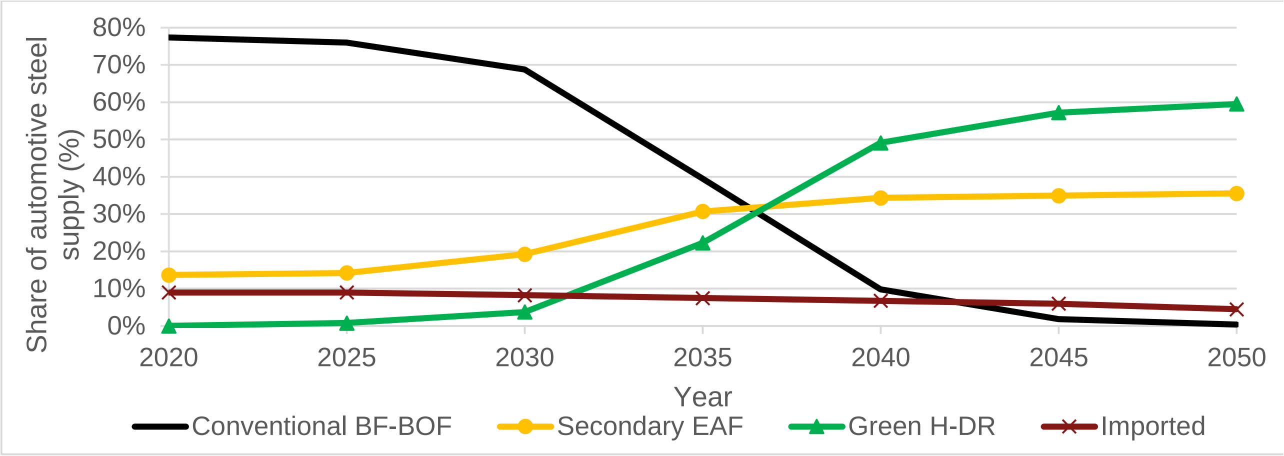
For example, examination of another option, NG-DRI (natural gas DRI) "grey" steel, suggested that despite it offering the potential for up to 50% emission reductions, this option raises some concerns regarding the low-carbon status of fossil gas due to fugitive (accidental) and non-fugitive (operational) methane emissions. In addition, H2-DRI "Blue" steel hinges on 'blue' hydrogen produced from gas with Carbon Capture and Storage (CCS), which currently lacks a definitive regulatory framework, amidst ongoing apprehensions surrounding fossil gas and uncertainties regarding CCS. For this option, CCS equipment has to be applied to all the emission sources, which makes achieving a high level of overall CO_2 reduction rate using CCS technology extremely difficult.

In the course of the work it was therefore concluded that (in addition to EAF with renewable electricity for secondary steel production) **H2-DRI "Green" steel is emerging as the most promising alternative that is likely to be applied for automotive primary steel decarbonisation**, albeit with reservations regarding its cost-competitiveness and the accessibility of green hydrogen. It is important to note the central role of expanding electrolyser capacity and integrating renewable energy for electrolysis, albeit constrained by challenges such as grid connection availability and capacity, as well as the absence of low-cost renewable energy and hydrogen transport infrastructure in certain regions.

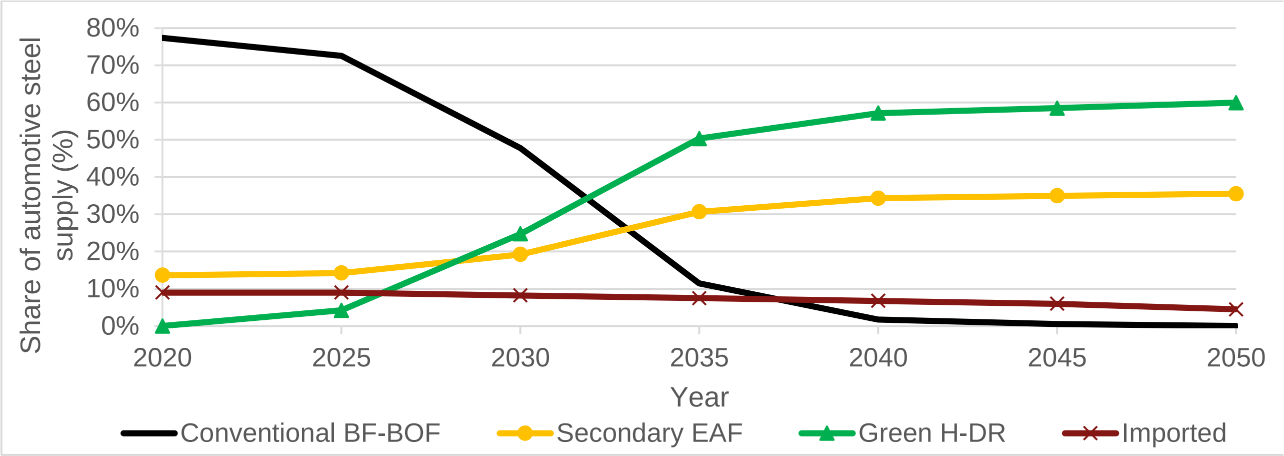
In the second part of our assessment, two scenarios for deploying lower-carbon steel pathways were developed (Figure ES1): a Baseline scenario matching current automotive demand, informed by automotive OEM supply announcements; and an Ambitious scenario aligned with the highest decarbonisation targets announced by carmakers, aiming to achieve 50% lower-carbon steel by 2030. These two lower-carbon steel scenarios were compared to each other and a Conventional scenario assuming no change from production technologies for automotive steel in 2020.

Figure ES1: Baseline and Ambitious lower-carbon steel scenarios, 2020-2050 (EU27)

Baseline Scenario



Ambitious Scenario



Source: Ricardo analysis (2024).

Notes: BF-BOF = steel produced using the current predominant blast furnace/basic oxygen furnace process technology; Secondary EAF = recycled steel using the electric arc furnace process, 'Green H-DR' = steel production using the novel Hydrogen Direct Reduced Iron/EAF process. Imported = imported steel produced outside of the EU.

To reflect a range of potential impacts from lower-carbon steel consumption, sensitivities were added to the model allowing further analysis in addition to the Default model inputs. Particularly, low and high GWP ranges and a high cost range (reflecting the high range of projected electricity and hydrogen production costs) of all steel production technologies, as well as low and high projections for future automotive steel demand from Secondary EAF technology and Imported sources.

Both lower-carbon steel scenarios provide significant GWP savings compared to the current automotive steel supply, achieving a **93% GWP reduction by 2050 compared to the 2020 automotive steel GWP**. The Ambitious scenario achieves annual emission reductions compared to the Baseline scenario of 7 MtCO2e (23% reduction) by 2030, 8.5 MtCO2e (47% reduction) by 2035, and 2 MtCO2e (29% reduction) by 2040, before the two scenarios converge to the same annual GWP by 2050. Compared to the total automotive steel GWP across the EU27 in 2020, the Ambitious scenario achieves an emission reduction of 46% by 2030, 78% by 2035, 89% by 2040, and 93% by 2050. **100 MtCO2e is the total amount of CO2e emissions saved by 2050 from using the higher amount of green steel under the Ambitious scenario compared to the**

Baseline scenario, representing a 16% cumulative reduction in total automotive emissions between 2020-2050.

While overall GWP savings are significant from the fleet and vehicle steel production perspective, it can be seen that **from a vehicle lifecycle perspective, the improvements are relatively small in proportion to the entire footprint over a vehicle's operation lifetime**. This is due to a combination of steel production being a smaller share compared to other lifecycle impacts (but a larger share for BEVs).

Greater automotive demand for lower-carbon steel is projected to **increase the cost of steel content in vehicles in the short term before becoming more affordable by 2040** as lower-carbon steel infrastructure becomes widely available and costs for key feedstocks for lower-carbon steel (such as renewable electricity and hydrogen) reduce. For passenger cars with Default cost sensitivity, steel cost under the Baseline and Ambitious scenarios reaches a peak in 2030 and declines thereafter due to the decline in steel content in passenger cars. The Ambitious scenario has a peak in steel content costs of €462 per vehicle in 2030, representing a 13% increase on 2020 steel costs, before falling to around €165 per vehicle by 2050. The Baseline scenario shows a small increase from Conventional steel costs between 2025 and 2030, reaching a peak steel cost of €443 per vehicle in 2025 before declining in line with the Ambitious scenario to around €165 of total steel content cost per vehicle by 2050. For an average passenger car using 100% steel from the green H-DR-EAF pathway, the steel content cost is higher than both the Baseline and Ambitious scenarios between 2020-2050, with a total cost of steel content of €524 per vehicle (23% increase compared to the Baseline) in 2030 and total cost of steel content of €284 per vehicle (3% decrease compared to the Baseline) in 2040.

An additional sensitivity on the future projected steel content in the vehicle was also conducted, assuming that this remains constant in the future (instead of an anticipated decrease in the future due to actions taken to reduce new vehicle mass to improve operational efficiency). This analysis highlights the significant impact of the expected trend of vehicle lightweighting on both emissions and costs. In terms of GHG emissions, the highest disparity is observed in 2035 when, under the assumption of constant steel content, emissions are nearly 50% higher compared to the default scenario accounting for lightweighting. Moreover, when considering constant steel content, the potential for GHG reduction from green steel in the ambitious scenario surpasses that of the default mass assumptions based on lightweighting trends, exceeding by double by 2035 (with further reductions in subsequent periods). Additionally, we observe how vehicle lightweighting influences the cost of steel components. Assuming constant steel content, the overall cost of steel content for the entire fleet increases until 2040 (and hence the cost and GHG impacts of green steel use is amplified), before subsequently declining. With the anticipation of vehicle lightweighting, the cost of steel content for the entire fleet begins to decrease in 2025.

On an individual vehicle level, the impact of all lower-carbon steel scenarios on the retail price paid by consumers for vehicles is limited to less than a 1% rise in early years and a slight reduction in later years due to a reduction in lower-carbon steel prices relative to the Conventional scenario. Comparing the abatement cost of pursuing the Ambitious scenario as opposed to the Baseline is €270 per tCO_2e in 2025, reducing rapidly to €155 per tCO_2e in 2030, €85 per tCO_2e in 2035 and near-zero by 2040. Between 2040-2050, it is more economically beneficial and cost competitive to pursue the Ambitious scenario than the Baseline. **Ensuring a carbon price above €150 per tCO2e (or around €200 per tCO2e under High costs) would allow the Ambitious scenario to be cost-competitive with the Baseline**, incentivising European steel producers and automotive OEM consumers to pursue the faster steel decarbonisation pathway.

In conclusion, **pursuing a high-uptake lower-carbon steel scenario compared to the current automotive demand would require minimal initial cost in the short-term while achieving a significant reduction in the GWP** from automotive steel consumption. As such, the Ambitious scenario for lower-carbon automotive steel supply developed in this project would help ensure that the automotive sector decarbonises **in line with the EU's Fit for 55 and net zero targets for 2030 and 2050**, while securing a strong green steel industry in Europe to support the automotive sector and wider economy in the future**. Some policy interventions, such as increased carbon pricing for steel and mandated minimum targets for lower-carbon steel in the automotive sector, may be required** to ensure an ambitious demand and supply of lower-carbon steel to the automotive sector.

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1. INTRODUCTION, PROBLEM DEFINITION AND OBJECTIVES OF THE STUDY

1.1 INTRODUCTION AND PROBLEM DEFINITION

Steel is a vital component of the automotive sector, accounting for approximately 12% of global steel consumption and 17% of EU steel demand (EUROFER, 2023). This makes the automotive industry the second largest consumer of steel in Europe, behind the construction sector. Its widespread use in the industry is attributed to its unmatched combination of strength, durability, affordability, and sustainability. Moreover, steel plays a pivotal role in the circular economy due to its high durability, reusability, and recyclability, extending the lifespan of products and facilitating recycling processes[1].

Nevertheless, steelmaking is a very energy intensive process, and the current dominant technology pathways mostly based on coal. As countries and industries globally strive to achieve ambitious net-zero targets by curbing carbon emissions, steel production takes centre stage. Currently, approximately 75% of worldwide steel is predominantly manufactured in coal-fired blast furnaces, releasing substantial carbon dioxide into the atmosphere. For the EU, this figure reaches 57% of crude steel production. The process demands extensive energy, with Blast Furnaces (BF) reaching temperatures exceeding 1,000°C. In total, steel production contributes to roughly 8% of the world's emissions. The remaining worldwide supply is mostly provided by electric arc furnaces (EAF) using steel scrap (i.e. recycled steel), which results in much lower impacts, and Direct Reduced Iron (DRI) using natural gas. Addressing this significant industrial source of CO_2 pollution is pivotal in the fight against climate change.

As global steel demand is projected to surge by more than a third by 2050, innovative and efficient lower-carbon technologies are imperative to aid iron and steel producers in reducing energy consumption and greenhouse gas emissions. This reduction is essential to meet global sustainability targets and enhance the competitiveness of the industry. Among automotive structural materials, steel production boasts the lowest carbon footprint, making it a key player in achieving lower-carbon travel. However, to further enhance its environmental benefits, there is a pressing need to develop "green steel."

The concept of "green steel" is gaining prominence, especially in the context of decarbonising heavy industry. Europe, in particular, is committed to becoming climate neutral by 2050, driving initiatives to produce steel with significantly reduced environmental impact. Various projects focused on manufacturing "green steel" are underway, albeit at different stages of maturity and commercialization. Government funding, especially in the European Union, is on the rise to support such endeavours. For instance, the EU has allocated substantial funding for hydrogen technologies in steel and chemical industries, aiming to accelerate the transition to sustainable steel production. One notable example of progress in this domain is the Swedish steelmaker H2 Green Steel, which will start producing by 2025 "green steel" using renewable hydrogen instead of coal (Green Steel World, 2023), marking a significant step towards sustainable steel manufacturing.

However, the terminology surrounding "green steel" is not standardised, leading to varying definitions ranging from steel produced without coke in the manufacturing process to existing scrap steel melted in electric arc furnaces (EAF), as well as more novel technologies (including also BF with carbon capture and storage). Consequently, there is a lack of comprehensive data on the adoption of "green steel" in the automotive sector, as well as a standardised definition accepted by automakers. Moreover, a comparative analysis of the carbon footprints of vehicles constructed with conventional steel versus those built with "green steel" is missing, adding to the existing knowledge gaps.

Economic questions surround and potentially further complicate the transition to "green steel." Currently, the additional costs associated with producing this material are not well-defined, although they are believed to represent a relatively small fraction of the final vehicle costs. On average, "green steel" production costs are estimated to be approximately 40% higher than unabated production costs today (BloombergNEF, 2023). However, there is optimism that these costs could decrease significantly by 2050, potentially making "green steel", potentially even more cost-effective than fossil-based routes. It is expected that the most significant impact on production costs will come from the CO_2 and energy prices. Considering that carbon prices in EU

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[1] Unlike some materials that degrade during recycling, steel can be recycled indefinitely without losing its inherent properties. The recycling process does not weaken the steel, and it retains its strength and durability. Additionally, recycling steel requires significantly less energy compared to producing it from raw materials.

will rise, estimations of GMK centre indicate that difference in production costs and prices of DRI-EAF green and conventional producers in 2030 will not be significant (GMK Centre, 2023).

Considering these challenges and opportunities, some leading players in the automotive sector have made significant commitments to accelerate the adoption of "green steel." Companies like Mercedes-Benz have entered into binding agreements with suppliers like H2 Green Steel to source substantial quantities of lower-carbon steel annually, demonstrating a growing industry-wide commitment towards sustainable steel sourcing. Similarly, Volvo achieved a milestone by delivering electric trucks constructed with fossil-free steel to customers, marking a significant advancement in the commercial use of environmentally friendly steel in the automotive sector. Starting in 2026, Porsche and several direct suppliers of production materials for Porsche will receive nearly zero-emission steel from H2 Green Steel. This marks the second agreement between H2 Green Steel and a Volkswagen Group company, with the first being with Scania, announced earlier in 2023 (Green Steel World, 2023).

The adoption of "green steel" in the automotive industry holds immense potential in reducing the sector's carbon footprint, aligning with global sustainability goals, and fostering a more circular economy. However, addressing definitional ambiguities, gathering comprehensive data, and navigating economic challenges are crucial steps in realising the full benefits of this innovative material. As key stakeholders in the automotive sector continue to make strategic commitments, the path towards a sustainable future for steel production in the industry becomes increasingly tangible.

1.2 OBJECTIVES OF THE STUDY

The objectives of this study are to:

- Develop a market outlook for the present and future of the green steel with the focus on the automotive sector.
- Provide an estimate and compare the CO_2 footprint of cars built with conventional steel and “green steel” (via a life cycle assessment, LCA). This comparison should include scrap and material referred to as lower-carbon by automakers.
- Provide an estimate of the production costs of green steel (along the most common production pathways as defined by automakers today) and compare it with the production costs of conventional steel. Provide a comparison for the price difference at vehicle level.
- Model scenarios for the demand and supply (production capacity) of “green steel” in the automotive industry in Europe in the upcoming years. The scenarios should include a Business-as-usual scenario without additional policy intervention and an Accelerated-Green-Steel in line with most ambitious automakers’ commitments to date.
- Provide a summary and conclusions on the basis of the findings.

2. CHARACTERISATION FON THE MARKET FOR 'GREEN STEEL' IN THE EUROPEAN AUTOMOTIVE SECTOR

2.1 CURRENT AND PROJECTED STEEL DEMAND

In 2022, **automotive steel consumption**[2] within the European Union (EU) reached **35.7 Mt per year**. The total automotive finished steel demand in the EU reached **23.7 Mt** and represented **17%** of total steel demand, with an increase of 3.88% compared to 2021 demand (EUROFER, 2023). This makes the automotive industry the second largest consumer of steel in Europe, behind the construction sector. Total annual steel consumption was almost 148 million metric tonnes in 2022, whilst European steel demand (or apparent consumption) for 2022 was nearly 140 million metric tonnes (EUROFER, 2023). 56.3% of total EU steel production in 2022 followed the Blast Furnace – Basic Oxygen furnace (BF-BOF) primary route, whilst 43.3% was fully electrified using an Electric Arc Furnace (EAF) following the secondary route (EUROFER, 2023).

The EU **imported 28.9 Mt** of finished steel products in 2022, with the majority from Asia (14.9 Mt) and Europe excluding the EU27 (11.3 Mt), and **exported 16.6 metric Mt** of finished steel products in 2022, with the majority to Europe excluding the EU27 (8.4 Mt) and North/Central America (3.9 Mt) (EUROFER, 2023).
Hence, the EU27 was a net importer of 12.3 Mt primary steel products in 2022.

Globally, steel use reached 1,760 million metric tonnes in 2022, with 12% of global steel consumption from the automotive sector (Worldsteel, 2023).

Key trends which are expected to influence future demand for automotive steel include lightweighting, and an increased focus on lifecycle emissions and sustainability of materials used in vehicles. Automotive lightweighting involves reducing the weight of vehicle components through design and material innovations, whilst maintaining or enhancing their safety and performance. Lightweighting improves the lifecycle impact of a vehicle by reducing the emissions from the vehicle's use phase and reducing the amount of material used per vehicle. Light alloys and composites, such as aluminium and carbon fibre, are potential lightweight alternatives to steel in passenger vehicles. However, these alternatives have higher production emission intensity (7 tCO_2e/t primary aluminium (ALUPRO, 2023) and 45.4 tCO_2e/t carbon fibre reinforced polymer (Ansini, 2023)) due to their energy intensive production processes, affecting their overall lifecycle emissions and sustainability credentials relative to steel.

For Heavy Duty Vehicles (HDVs), replacing primary steel with aluminium currently only delivers small environmental benefits after a long use-phase, due to the amount of steel content used in trucks and the higher carbon intensity for primary aluminium production versus lightweighting during the use-phase (Palazzo, J., Geyer, R., 2019). However, this does preclude that decarbonisation efforts in other foundation material industries, including aluminium, may lower embedded emissions from material production in the medium-term, through improvements in energy efficiency and low carbon processes. Also, the increasing demand for high load-bearing capacity in HDVs will limit the extent to which lightweighting materials can replace steel components without compromising structural integrity or safety (Muslemani, H., et. al., 2022).

As Original Equipment Manufacturers (OEMs) continue to transition production towards Battery electric Vehicles (BEVs), vehicle design innovation is expected to balance three factors: (1) the cost of the battery (i.e. with lightweighting reducing the size of the battery required to meet range objectives); (2) the costs of lightweighting efforts and materials; and (3) the vehicle's CO_2 footprint, which includes production and End-of-Life (EoL) emissions (Automotive World, 2022)[3]. Hence, future availability of green, affordable and lightweight steel materials, such as advanced- and ultra- high-strength steel, will determine the balance of demand for steel and alternative lightweighting materials, such as aluminium and synthetic composites.

As outlined above, one of the key factors influencing automotive demand for green steel is its cost competitiveness to conventional steel and alternative lightweighting materials. The European steel sector is subject to carbon pricing within the EU Emission Trading System (ETS), which incentivises a shift towards lower-carbon production through the capping and trading of emission allowances. However, whilst the conventional integrated BF-BOF route continues to remain cheaper than the primary green steel pathways

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[2] Steel consumption is the actual amount of steel consumed and may not necessarily be equal to steel demand, as companies may use steel inventories as part of total steel demand or consumption in a given year. The difference in steel demand and consumption is the change in steel inventories over a given period.

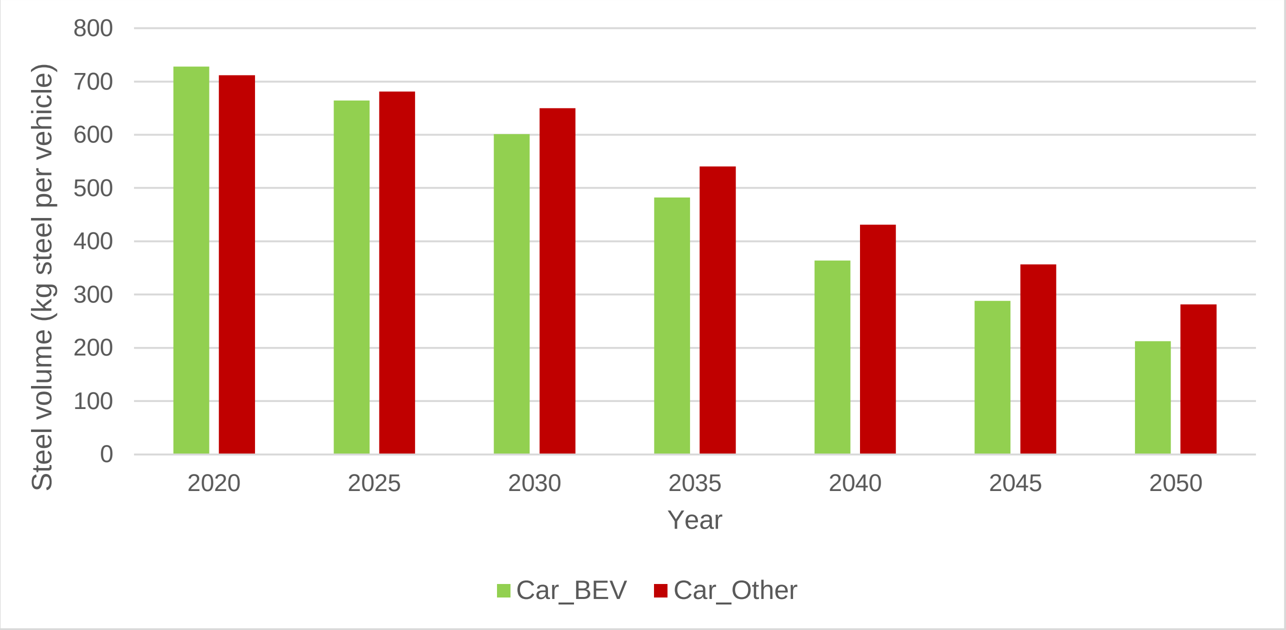
[3] EoL emissions refer to the greenhouse gas emissions or pollutants released during the disposal, recycling, or treatment of a product at the end of its useful life.

(see Section 3.1.1), there is a risk of carbon leakage where cheaper, imported steel from low-regulation regions with a higher carbon intensity replaces lower-carbon, but expensive, domestic supply. To address this, the EU Carbon Border Adjustment Mechanism (CBAM) was introduced in 2021, with a transitional period of reporting beginning in 2023. From 2026, free emission allowances granted to EU producers will be replaced by paid allowances in a phased-in approach (European Commission, 2023). As such, initially, non-EU steel producers will be required to report both direct and indirect emissions and, from 2026, will need to purchase CBAM certificates to cover the GHG emissions associated with their production of imported steel products (Shearman & Sterling, 2021). Therefore, the EU CBAM is a key market-based framework designed to prevent non-EU countries with cheaper and more carbon-intensive steel benefitting from an unfair advantage compared to European domestic production during the decarbonisation of steel supplied to the automotive and other sectors.

However, CBAM does not apply to most finished or assembled products, such as vehicles (European Commission, 2023). As such, low-cost EVs with high embedded emissions from non-EU countries risk outcompeting vehicles produced in the EU on price, leading to a decline in the European automotive sector and associated (green) steel demand. Future extensions of the CBAM to include products within sectors important to the EU economy, such as automotive manufacturing, would ensure fair competition for green steel producers (SteelGuru, 2023).

Considering these factors, it is projected that the steel content of an average[4] battery electric passenger car will reduce from 35% of total weight in 2020 to 17% in 2050 under a 1.5°C scenario, see Figure A1. This corresponds to a reduction in steel volume from over 700 kg in 2020 to under 240 kg by 2050, see Figure 2-1. Likewise, HGV steel demand is projected to reduce from 40% of total vehicle weight in 2020 to 12% by 2050 for a 40 tonne articulated BEV lorry, see Figure A2 (Ricardo, 2015a), (Ricardo, 2015b), (Ricardo, 2020). Therefore, for an articulated lorry, the steel volume is expected to reduce from nearly 10,000 kg in 2020 to around 2,000 kg by 2050, see Figure 2-2Figure 2-2.

Figure 2-1 – Average steel content projections for passenger car, 2020-2050



Source: Calculated based on Ricardo LCA modelling data and projected future European passenger car production

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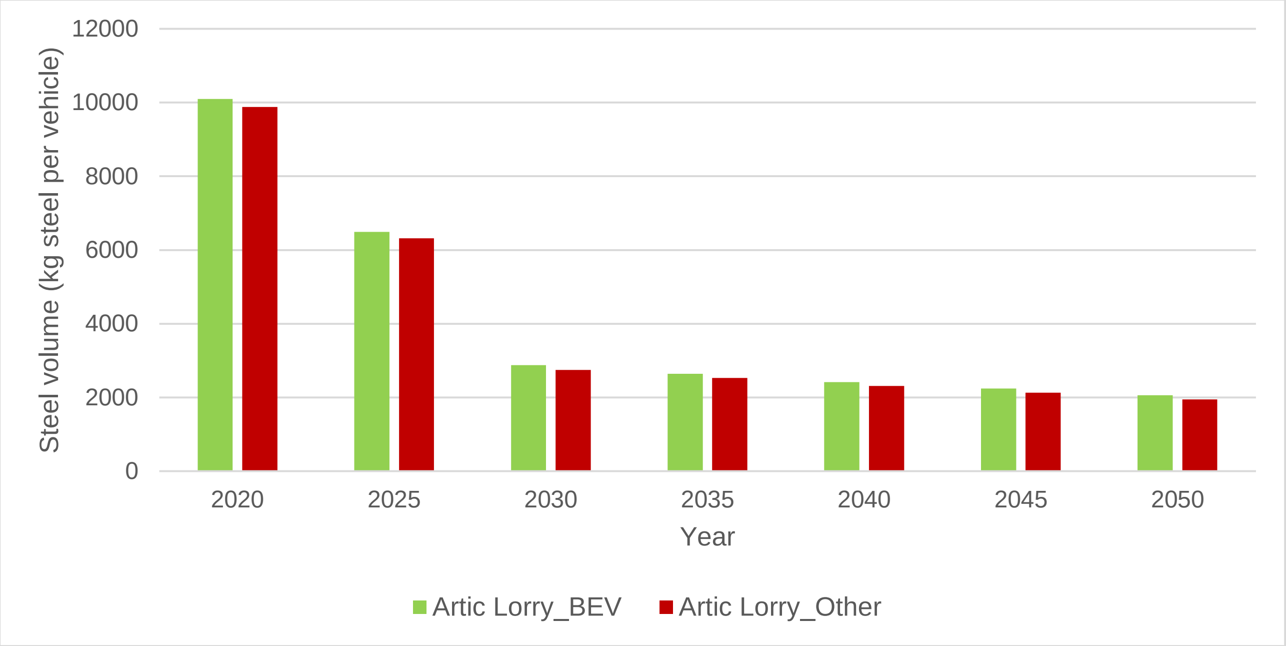
[4] An average passenger car's steel content is defined as the average steel content of the lower-medium and SUV car segments.

Figure 2-2 - Steel content projections for articulated lorry, 2020-2050.



Source: Calculated based on Ricardo LCA modelling data and projected future European passenger car production

2.2 CIRCULAR ECONOMY

The EU has a production capacity of 190 million metric tonnes of steel per year, spread over 198 steelmaking facilities (EUROFER, 2021). Around 54% of steel production uses the “primary” integrated Blast Furnace-Basic Oxygen Furnace (BF-BOF) route to produce virgin steel, whilst around 46% of production capacity processes steel scrap into recycled steel in the “secondary” route using electric arc furnaces (EAFs), see Section 3. In 2022, actual steel production in Europe reached 136 million metric tonnes, split between 56% from the BF-BOF route and 44% from the Secondary EAF route (Worldsteel, 2023). European supply of scrap steel from EoL and production waste consistently exceeds recycled steel demand in the EU. In 2022, the EU was a net exporter of scrap steel by 13.78 Mt, and consumed 79.34 Mt of scrap steel domestically (EUROFER, 2023)

The use of recycled steel in the automotive sector from the Secondary EAF production route is currently limited by the requirement for low levels of impurities in the steel used for performance-critical vehicle components, such as body panels and the chassis. Although there is no technical limit to using recycled steel in vehicles, typical scrap steel sorting and processing methods leads to “downcycling”, where high-quality steel is mixed with lower grades with greater impurities. For example, automotive-grade steel typically requires a maximum copper content of 0.06%, whilst the current steel scrap average in the OECD is between 0.2-0.25% (WEF, 2023a). However, the use of existing production processes such as Vacuum Induction Melting (VIM), Vacuum Arc Remelted (VAR), and Electro-Slag Re-melted (ESR) steel enable the production of high-quality steels via. the EAF. Upgrading production sites may be necessary to facilitate the manufacturing of high-volume, high-quality recycled steel. Although the use of recycled steel from Secondary EAF production is currently limited in the automotive sector, around 10% of total production of high-grade steels is produced in an EAF and roughly 15% of steel used in the automotive industry comes from the Secondary EAF route (Watari, T., et. al., 2023). In addition, between 15-20% of primary steel used in vehicle components comes from scrap steel added into the blast furnace as a coolant agent during primary BF-BOF production (WEF, 2023a). Similarly, WorldAutoSteel estimates that the overall recycled steel content in automobile bodies alone is around 25% on average, with even higher shares in some internal components (WorldAutoSteel, 2021).

There are several incentives for automotive manufacturers to increase the use of recycled steel in vehicles. Production of recycled steel via the secondary-EAF route emits around 85% less CO_2 than the primary BF-BOF route, and uses existing infrastructure and production process, requiring minimal investment in infrastructure and cost competitiveness with primary steel (see Section 3.1.2). Furthermore, the EU has an abundance of steel scrap, with high automotive steel recycling rates of around 90% (WorldAutoSteel, 2021) and scrap availability in the EU expected to reach 128 million tonnes per year in 2030 and 173 million tonnes in 2050 (Material Economics, 2019). EoL HDVs typically contain over €10,000 in scrap metal content and reusable parts, with the economic value of EoL HDVs incentivising high recycling rather than the subsequent environmental benefits (Muslemani, H., et. al., 2022).

European regulations to improve material circularity will also provide pressure for OEMs to consider the EoL stage of materials. In particular, the EU proposal for the revised End-of-Life Vehicle (ELV) Regulation requires the recycling and recovery of materials from ELVs (European Commission, 2023). As such, automotive manufacturers must consider the full lifecycle of materials, with an increased focus on recycling to deliver circular production.

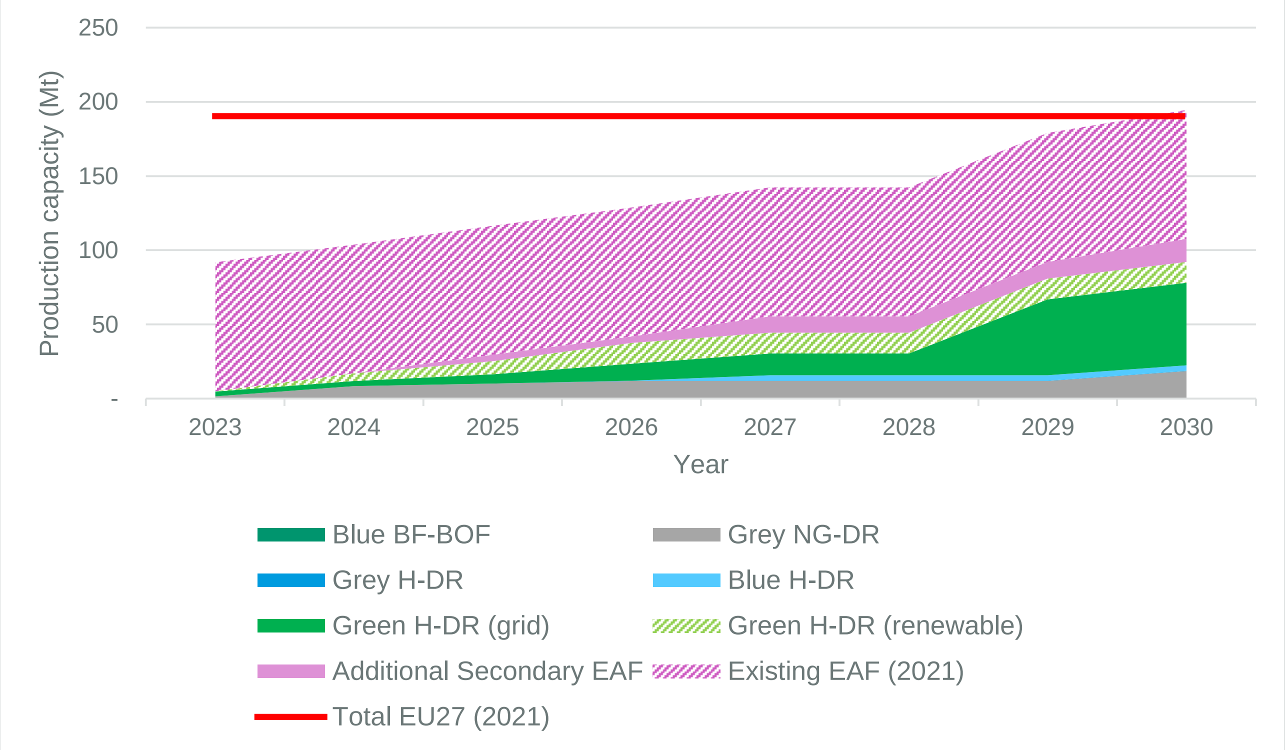
As such, although current use of recycled steel is limited, improved scrap sorting of grades and voluntary OEM targets and mandatory recycled content targets hold potential for recycled steel from EAFs to play a key role in the decarbonisation of automotive steel. Volvo has committed to use 25% recycled steel by 2025, BMW plans to use 50% scrap steel by 2030 (ibid), with Mercedes-Benz and BMW signing agreements with H2 Green Steel to establish a steel scrap supply chain (H2green steel, 2023b) (BMW, 2022).

2.3 ANNOUNCEMENTS, TARGETS AND ACTIONS BY OEMS

2.3.1 Outlook for "green" steel production in Europe

To date, there have been new lower-carbon steel production announcements totalling 107 Mt of production capacity by 2030 across 33 different plants in Europe.[5] The majority (65%, or 70 Mt) of newly announced capacity are from the "green" Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) production process, using green hydrogen and electricity from either the energy grid mix or renewable sources. Combining newly announced lower-carbon steel production capacity with the existing Secondary EAF production capacity of 87 Mt, total lower-carbon steel production capacity is projected to reach 194 Mt by 2030, exceeding the 2021 production capacity, see Figure 2-3 and Figure 2-4 (EUROFER, 2021).

Figure 2-3 The cumulative European lower-carbon steel production capacity between 2023 and 2030, relative to the total European production capacity in 2022.



Source: Ricardo analysis using data collected by the Green Steel Tracker and internal calculations: [Green Steel Tracker - Leadership Group for Industry Transition]

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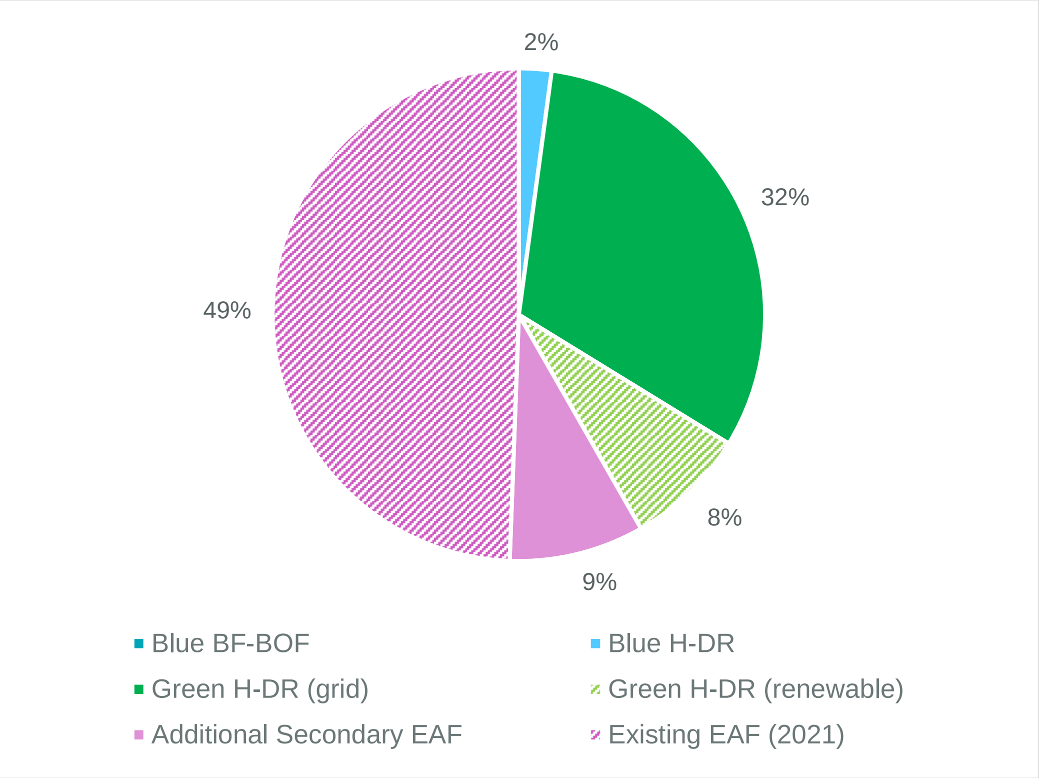
[5] Ricardo analysis using data collected by the Green Steel Tracker and internal calculations. Source: Green Steel Tracker - Leadership Group for Industry TransitionSource: Green Steel Tracker - Leadership Group for Industry Transition

Figure 2-4: Estimated share of green steel production in 2030 (%, from announcements and 2021 capacity)



Source: Ricardo analysis using data collected by the Green Steel Tracker and internal calculations: Green Steel Tracker - Leadership Group for Industry Transition

2.3.2 Outlook for "green" steel demand in Europe from the automotive industry

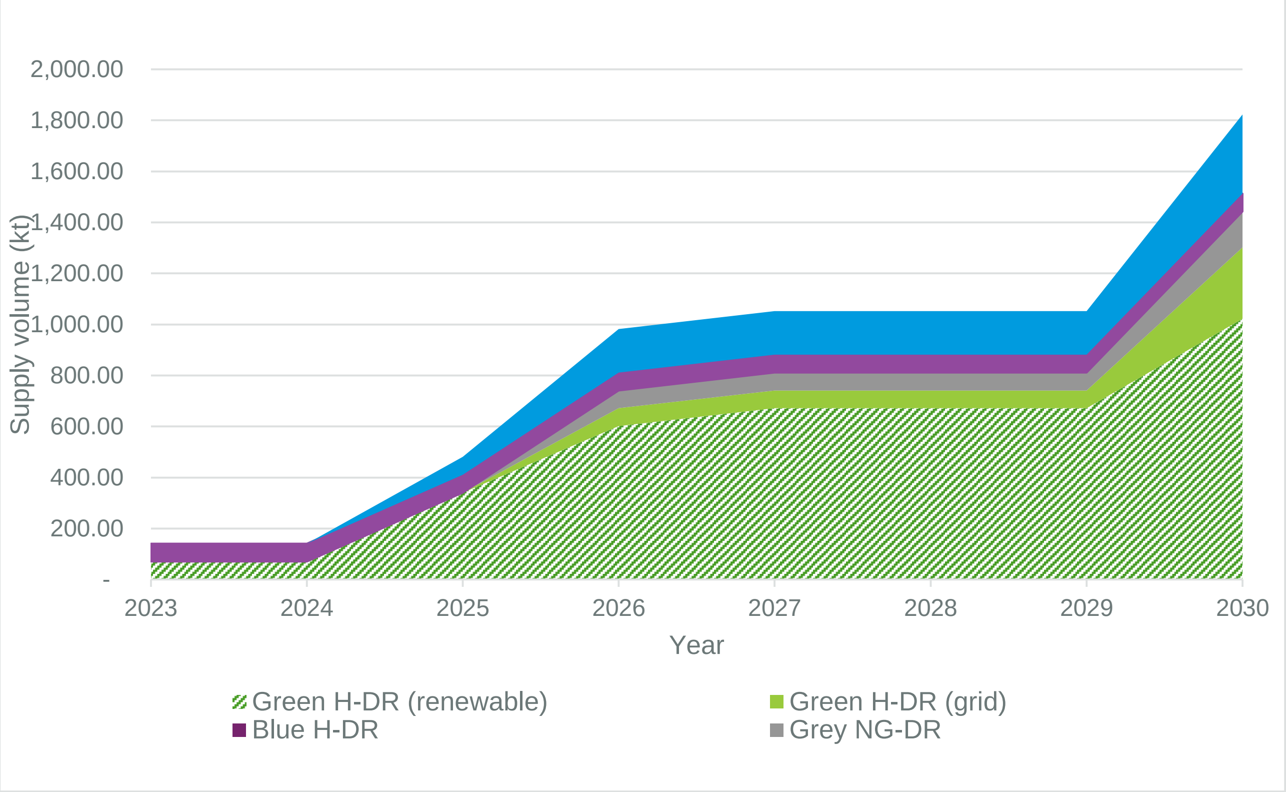
So far, demand for green steel from the automotive sector outstrips other sectors. In 2021, of the 48 global supply agreements for green steel, the automotive sector accounted for 22 (46%) (BNEF, 2021). The different announcements of transition by automotive firms and date of announcement can be seen in the Appendix 1 – Announcements made by automotive OEMs.

The automotive sector benefits from a less complex supply chain with fewer market participants relative to the construction sector (Muslemani, H., et. al., 2022), (Sichali, 2017). Moreover, the automotive sector has greater incentive to decarbonise steel than the construction sector due to the potential introduction of lifecycle emissions reporting for automotive OEMs, their use of LCA to support corporate reporting of (Scope 3) carbon emissions, and a higher proportion of steel found in vehicles than buildings (Muslemani, H., et. al., 2021).

Also, the demand for green steel from the automotive sector will be influenced by consumer willingness to pay (WTP) the "green premium" for vehicles using lower-carbon steel; and the degree of cost increases likely for green steel components (Muslemani, H., et. al., 2022). The expected increase in cost for a passenger vehicle from use of green steel ranges from 0.3% of TCO (total cost of ownership) for the NG-DRI route to 0.7% for the H2-DRI route, representing around a €200 increase (BCG, 2022), (Muslemani, H., et. al., 2021). JRC has also estimated that the impact of the use of green steel in the final price of a passenger car could be around 1+% (JRC, 2022). However, consumer WTP for green steel use in LDVs (i.e., passenger cars) may be lower than for improved fuel economy and electric vehicles due to a lack of communication about the impacts of production emissions on total vehicle lifecycle impact (Muslemani, H., et. al., 2022). In addition, industry focus for HDVs has been on reducing fuel consumption and transitioning to electric powertrains (either battery electric or fuel-cell electric trucks), rather than addressing production emissions (Lee, D. Y., Thomas, V. M., 2017), due to their greater overall impact currently. With both light- and heavy- duty alternative-fuel vehicles already carrying an "environmental label" for energy-efficient and low-emission engines, additional value derived from the utilisation of lower-carbon steel may be difficult to incorporate within current economic incentives (Muslemani, H., et. al., 2022).

So far, there have been 26 European OEM supply agreements with lower-carbon steel producers, securing a total 1.8 Mt of lower-carbon steel by 2030, see Figure 2-5[6]. This represents only 9% of total automotive steel demand in 2030. However, there is projected to be sufficient overall lower-carbon steel supply from EU27 production to meet demand from the automotive sector, with the estimated automotive steel demand in 2030 of around 21 Mt[7] representing only 11% of total lower-carbon steel production capacity (see Section 2.3.1). The majority of demand of lower-carbon steel from the automotive sector is currently from the H-DR route using green hydrogen from renewable electricity. The combined steel supply from the green H-DR route using either grid or renewable electricity is anticipated to reach 1.3 Mt (72% of total supply) by 2030.

Figure 2-5 Cumulative European OEM lower-carbon steel supply agreements between 2023 and 2030



Source: Estimated by Ricardo based on OEM supply agreements (see Appendix A1)

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[6] Ricardo analysis of publicly announced supply agreements for green steel and assumptions.

[7] Total automotive steel demand in 2030 was calculated through Ricardo modelling analysis as part of this project, informed by assumptions on future vehicle steel content and vehicle categories considered during this project. See Section 4 for further details.

3. TECHNOLOGY PATHWAYS FOR EU STEEL PRODUCTION

3.1 DEFINITION OF DIFFERENT TECHNOLOGY ROUTES

3.1.1 Conventional: Blast Furnace-Basic Oxygen Furnace

3.1.1.1 Description

The most established and dominant method for primary steel production is the blast furnace-basic oxygen furnace (BF-BOF) pathway (also often referred to as the "integrated" route), producing around 71% of global crude steel (CGEP, 2021) and 56% of European crude steel in 2020. (JRC, 2022)

The main feedstock for the BF-BOF pathway is mined iron ore (Fe_2O_3), which is first pre-processed into sinter or pellets at dedicated plants at temperatures between 1,200-1,500 °C (JRC, 2022). Coke, used in the BF to refine the iron ore, is made in a separate coke plant from heating coking coal to 1,000 °C. The pellets or sinter of iron ore are then reduced in the blast furnace (BF) at around 1,500 °C, using injected coke to remove the oxygen and produce pure (pig) iron (Fe) (Eurofer, 2020). To produce one tonne of pig iron in the BF, between 1.4-1.6 tonnes of iron ore and around 500 kg of coke are needed.

Limestone is also added to the BF and BOF as a lime fluxing agent to remove impurities such as sulphur, phosphorus and silica, producing CO_2 process emissions and a secondary by-product called slag (the combination of the non-iron content of the iron ore with the lime flux). The iron and steel industry are a major consumer of lime in the EU, consuming some 40% of total lime demand in the EU. (Manocha, 2018) Around 250 kg of limestone or dolomite is needed, and 400 kg of slag is produced for every tonne of steel via the BF-BOF pathway.

The molten pig iron is then poured into the basic oxygen furnace (BOF), where oxygen is blown into the liquid iron to reduce the carbon content of the metal from around 4% to steel grade level of below 1%. At this stage, steel scrap and directly reduced iron (DRI) can also optionally be fed into the BOF as additional metallic inputs. The crude steel from the BOF is then cast into different intermediary steel products through various hot-and cold-rolling downstream processes. Between 1.05-1.20 tonnes of pig iron is required to produce a tonne of crude steel (IEA, 2020b).

3.1.1.2 Associated emissions

Producing one tonne of crude steel via the BF-BOF production pathway creates approximately 1.2 tonnes of CO_2 from direct emission sources, namely through the consumption of coke and lime flux in the chemical reduction of the ore. Indirect emissions from the production of consumed reagents, electricity and heat in each stage of production results in roughly 1.0 additional tonnes of CO_2 per tonne of steel (IEA, 2020b). As such, **the BF-BOF production pathway produces between 1.8 and 2.2 tCO_2e/t steel**, compared to the current global average of 1.7 tCO_2e/t steel produced by all methods combined (BHP, 2020), (Lopez, Galimova, & Fasihi, 2023), (Sasian Conde A., 2022), see Table 3.1.

Table 3.1: CO2e emissions from BF-BOF steel according to different sources

CO_2e emissions per tonne of BF-BOF steel	Grid mix for calculation	Source
1.8 tCO_2e /t	N/A (BF-BOF route)	Conde et al., 2022
Average 2.0 tCO_2e /t	N/A (BF-BOF route)	BHP, 2020
2.25 tCO_2e /t	N/A (BF-BOF route)	Lopez et al., 2023

In terms of the breakdown between the three stages of the process, the largest source of CO_2 emissions from the BF-BOF pathway is the initial processing of raw iron ore into pig iron in the BF, responsible for approximately 1.2 tCO_2e/t steel, or over 50% of total CO_2 emissions of the final product (JRC, 2022). As already mentioned, this stage produces direct process emissions from the use of coke and lime flux, as well as indirect emissions from fossil fuel combustion to maintain the high (1,500°C) furnace temperatures. The production of the raw materials (coke, sinter and pellets) inputted to the BF produces between 0.3-0.4 tCO_2e/t steel, mainly from the combustion of fossil fuels to reach the high processing temperatures.

The BOF stage then produces additional 0.2 tCO_2e/t steel, from both fossil fuel combustion and the use of lime flux.

The final stage of casting and processing the crude steel from the BOF ranges from 0.1 to 0.3 tCO_2e/t steel, depending on the use of electricity or fossil fuels as energy inputs.

3.1.1.3 Associated costs of production

Between 2015 and 2020, the average cost of crude steel from integrated BF-BOF production was €436/tonne of steel[8]. The integrated BF-BOF cost per tonne of steel is projected to remain the cheapest amongst potential primary steel production pathways until the late 2020s, with BF-BOF currently costing around €540 per tonne of steel and other production routes costing between 20-100% above this.[9] However, with renewable electricity costs anticipated to fall and CO_2 emissions prices expected to increase, the BF-BOF pathway is projected to no longer be cost-competitive compared to innovative production processes by 2040.

The largest source of CAPEX for a BF-BOF pathway facility is the initial installation cost for a BF, estimated at between €190-280 per tonne of production capacity (IEA, 2020b). Due to extreme temperatures and chemical reactions taking place in the BF, the internal refractory lining must be replaced after roughly 25 years of operation, with the relining costing around half of the initial BF investment (€90-140 per tonne of production capacity). Relining existing BFs is a far more affordable option for steel producers compared to retiring the BF and replacing it with a new innovative steelmaking facility, which is estimated to cost €3.7 billion (BHP, 2020). The CAPEX of all equipment associated with the BF-BOF pathway, including BF and pellet/sinter plants, coke ovens etc., is around €900-1,400 per tonne of steel (IEA, 2020b), (Steel Technology, 2023).

At present, the OPEX for the current BF-BOF pathway of €415/t steel is also significantly lower than for other more innovative primary production pathways, like e.g., the H2-DRI-EAF pathway (see Section 3.1.6 below) costing €624/t steel for 2019 electricity prices (Mayer, Bachner, & Steininger, 2019).

3.1.1.4 Favourable aspects for the automotive industry

The main attraction of the BF-BOF pathway for the automotive sector is the economic competitiveness of the crude steel produced from this process, and the established infrastructure.

Europe currently has 56 BOFs, most of which follow the integrated BF-BOF pathway, producing 114 Mt of crude steel per year. In comparison, there are currently 148 EAFs in Europe, with a total capacity of 90 Mt of crude steel. In addition, several full-scale DRI-EAF facilities (see Sections 3.1.4, 3.1.5, and 3.1.6) have been announced, with operation of the first plants using hydrogen as the main energy input planned for 2026.

Steel producers will be left with significant stranded assets if they proceed with investment to cleaner steel production pathways, due to the large initial investments required for an integrated BF-BOF plant and long operational lifetimes of around 40 years. China and India have a particularly young BF fleet, with the potential for 20 to 30 more years of production before the facilities are retired, retrofitted, or refurbished (IEA, 2020b). As such, supply of crude steel from the BF-BOF pathway to the automotive sector is expected to remain relevant for the next several decades.

3.1.1.5 Limitations

Compared to the alternative innovation pathways explored in the next sections, the BF-BOF pathway is the most carbon intensive by far (e.g., the green H2-DRI-EAF pathway offers up to 98% CO_2 emission reduction (JRC, 2022), see Section 3.1.6). The current integrated BF-BOF plants already maximises energy efficiency at close to the optimum limit, with retrofitting technologies to further lower the CO_2 emissions of this pathway (e.g., CCS, hydrogen injection into the BF) remaining so far unaffordable and limited outside of small-scale projects.

As such, **continued reliance on the BF-BOF production pathway will present a significant barrier to achieving either the steel sector target of reducing CO_2 emissions from 1990 levels by 80-95% by 2050** (European Environment Agency, 2011)**, or the more ambitious target of reaching climate neutrality by 2050 in line with the European sector-wide economy** (EC, 2019)**.**

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[8] €460/t for the BF-BOF pathway, using the average exchange rate during the five-year period of USD 1 to EUR 0.89: Steel – Breakthrough Agenda Report 2023 – Analysis - IEASteel – Breakthrough Agenda Report 2023 – Analysis - IEA

[9] Adjusted for inflation and informed by Ricardo assumptions and 2020 data from (EPRS, 2021).

As automotive manufacturers begin to decarbonise their supply chains in order to reach net zero production emissions by 2050, the environmental benefits of steel produced using innovative pathways will begin to outweigh the premium cost necessary to adopt materials produced using these technologies. Policy and regulatory support, coupled with an increase in CO_2 emission prices and a reduction in the cost of renewable electricity, are expected to help to make innovative steel production pathways economically and strategically attractive for investment by the steel industry and automotive sector.

3.1.2 Secondary (scrap) Electric Arc Furnace Steel

3.1.2.1 Description

Electric Arc Furnace (EAF) refers to a furnace that uses electric arcs to generate heat[10]. Scrap steel is collected from sources like end-of-life vehicles and machinery. After removing contaminants, recycled scrap is melted in an EAF at 1600 ℃ to produce liquid steel that can be cast into various forms. While electricity is the main energy input, natural gas or a small amount of coal or coke are also used to melt the scrap or to improve energy efficiency. Secondary steel produced via the EAF route requires around 2.5-3 GJ/t of crude steel output.

Secondary scrap EAF steel is a highly utilized method. Around 30% of the global steel production is from scrap steel. In Europe, secondary EAF steel is more widely produced with a share of 40% (JRC, 2022).

3.1.2.2 Potential decarbonisation vs BAU

Secondary scrap EAF steel is an environmentally lower impact method compared to BAU route, with a reduction of around 80-85% of GHG emissions compared to the conventional route, at present. In addition to preventing recycled materials from being wasted, one tonne of scrap EAF steel creates only around 0.4t of CO_2 emission (exact figure depending on the carbon intensity of the electricity used to power the EAF), see Table 3.2.

Table 3.2: CO_2 Emissions from Secondary (scrap) EAF Steel

Decarbonisation potential compared to BF-BOF[11]	Grid mix for calculation	Source
85%	EAF using EU grid mix at 300gCO_2e/kWh	JRC, 2022
80% (0.04t of direct CO_2e emission and 0.3t of indirect emission)	EAF using global average grid mix at 538gCO_2e/kWh	IEA, 2020

This large difference is mainly due to the avoided reduction process, as the iron in scrap steel is already present in its metallic (Fe^0) chemical form. As mentioned in section 1.1, the largest source of CO_2 emissions from the BF-BOF pathway is the processing of raw iron ore into pig iron. It produces direct emissions through the chemical reaction of iron ore and coal.

CO_2 emissions in secondary scrap EAF steel production are primarily due to electricity generation. A typical EAF consumes around 500 kWh of electricity per tonne of steel. This equates to around 0.2-0.3tCO_2e/t steel (depending on grid mix).

However, there are also small amounts of natural gas and coal used to provide additional heat to process scrap steel. This contributes to 0.06-0.1tCO_2e/t steel of direct emissions (Echterhof, 2021).

Essentially, at present, **secondary EAF steel can reduce around 80-85% of carbon emissions**, which is around 1.5 tonnes of CO_2 per tonne of steel; these figures are then **expected to improve further as electricity grid mixes in Europe and globally continue to be de-carbonized**. Additionally, scrap steel avoids the consumption of 1.4 tonnes of iron ore, 740kg of coal and 120kg of limestones (World Steel, 2022a).

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[10] In an EAF, when an electric current passes through two carbon electrodes, it creates a high-temperature arc of electricity between them. The intense heat of the arc breaks down the chemical bonds in the metal, causing it to melt and become molten.

[11] Considering the range of estimates from Table 3.1: CO2e emissions from BF-BOF steel, BAU (BF-BOF steel) emission in this report is assumed to be 2.0t/t.

3.1.2.3 Levelised costs vs BAU

In 2019, the average cost of producing scrap-based EAF steel was between €320-460/t[12], which is comparable to or slightly lower than the cost for primary BF-BOF steel. Annualised CAPEX was €32-54/t and OPEX was €29-50/t. The scrap steel itself costs €190-280/t (IEA, 2020b). Consistent with ESTEP, scrap steel comprises around 60% of the cost of the EAF steelmaking process. (ESTEP, 2019) While further de-carbonization of the electricity mix used for EAF steel production is desirable, there is uncertainty in terms of the sheer availability of renewable electricity in the future, which is currently assumed to cost between €28-84/MWh.

Overall, the cost of production is competitive compared to other lower-carbon steel options.

3.1.2.4 Favourable aspects for the automotive industry

The main attraction of the secondary scrap EAF route is the **cost competitiveness**. Compared to its decarbonisation potential of around 80-85%, there is no significant cost difference with the BF-BOF route in future years, and a very low premium in the near-term. Not only is it affordable, but this route is already established with considerable production capacity. Comprising around 30% of the global crude steel production and 40% of the European steel production, there is no huge investment required for this route. As mentioned above, there are 148 EAFs in Europe, with a capacity of 90 MT of crude steel. Additionally, existing EAFs can be used in various other ways even if scrap steel is not used (see Sections 3.1.4, 3.1.5, and 3.1.6).

Further, using secondary scrap makes it easier to meet any future regulations on use of recycled content in new vehicles. In the current directive of End-of-Life vehicles there are no targets for recycled content and the new proposal, yet to be adopted as law, only includes mandatory targets for recycled plastics, with steel due to be assessed at a later date. Beyond this, producing steel via the secondary scrap EAF route encourages the demand for scrap steel, thereby disincentivizing vehicles from being disposed of illegally. According to the End-of-life vehicle directive report, 3.5 million vehicles are disappearing from the EU road without trace each year.[13] Increasing demand for scrap steel will ensure these vehicles are collected for recycling, preventing carbon leakage to third countries/regions.

3.1.2.5 Limitations

Secondary EAF steel is currently not directly applicable for some automotive applications which require high-quality grades. Although there is no technical limit to using recycled steel in vehicles, typical scrap steel sorting and processing methods leads to “downcycling”, where high-quality steel is mixed with lower grades with greater impurities. For example, automotive-grade steel typically requires a maximum copper content of 0.06%, whilst the current steel scrap average in the OECD is between 0.2-0.25% (WEF, 2023a). Therefore, Secondary EAF steel is currently mostly used in applications where lower-quality steel grades are allowed (JRC, 2022). Improvements in the sorting and recycling process are needed to ensure high-quality grades are captured and maintained through the Secondary EAF process.

As the cost for scrap steel represents 60% of the total Secondary EAF production cost, the production of secondary recycled steel is highly dependent on the price and availability of steel scrap. Also, there is simply not enough scrap, especially high-quality scrap, to meet the global steel demand out of secondary steel. In fact, it has been estimated that, due to its limited availability, around half of the world’s steel will still need to be made from primary iron ore even in 2050 (Mission Possible Partnership, 2021). Such a shortage adds the risk of cost volatility of the scrap as well.

Because of the mentioned concerns regarding purity, and limitations in the amounts of steel scrap available, secondary EAF steel is unlikely to entirely meet the steel demand of the automotive sector, and will need to be complemented with primary steel supply.

3.1.3 BF-BOF “Blue” steel

3.1.3.1 Description

Carbon capture and storage (CCS) technology refers to the method of capturing CO_2 emission at the production site and then permanently storing it in a location that prevents it from being re-emitted (JRC, 2022). The most widely used capture technologies are chemical absorption and physical separation. Chemical absorption uses a chemical reaction between CO_2 and a chemical solvent. Physical separation involves a few

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[12] This figure was originally in USD ($). All values in this report are converted to Euro (€) using the average 2023 exchange rate of $1 = €0.93 unless specified otherwise. Please be aware that exchange rates may vary.

[13] https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles/end-life-vehicles-regulation_en

different ways such as using a solid surface, liquid solvent, adsorbent and temperature. There are technologies like membranes and looping cycles as well. The chosen technology depends on factors like operating pressure, temperature and cost considerations (IEA, 2020a).

The conventional BF-BOF route can theoretically implement these technologies to reduce CO_2 emissions (Global CCS Institute, 2017). For instance, in the blue BOF steelmaking process, CO_2 can be captured as it is emitted in blast furnaces. Captured CO_2 would then have to be transported by means of trucks, rail, ships or even pipelines. Then, it would be stored in locations like underground reservoirs. There are several types of such reservoirs, such as deep saline formations and depleted oil and gas reservoirs (IEA, 2020a).

Starting from the 2004 ULCOS (Ultra Low CO_2 Steelmaking) programme funded by the European Commission, major steelmakers like ArcelorMittal, Thyssenkrupp and Tata Steel have been attempting to develop large-scale projects.

However, **CCS is still far from being adopted at scale in the iron and steel industry, and a lot of uncertainty remains on its ultimate viability**. More specifically:

- CO_2 capture by amine solvents is mature (high Technological Readiness Level) and already commercialized in natural gas or fertilizers processing plants. Nevertheless, no large-scale project has been found in the literature regarding post-combustion capture with chemical absorption in the Iron & Steel industry;
- CO_2 capture using membranes is a relatively cost-effective *emerging* technology (low TRL) for carbon capture in power plants and energy intensive industries. However, so far, only few theoretical works have been published in the literature related to the Iron & Steel industry (Perpinan, 2023).

3.1.3.2 Potential decarbonisation vs BAU

The decarbonisation potential of the BF-BOF route with CCS technology is very uncertain. Estimates range from 20% to 80% according to different studies, see Table 3.3.

Table 3.3 CO_2 Emissions from BF-BOF "Blue" Steel

Decarbonisation potential compared to BF-BOF	Grid mix for calculation	Source
80% (**theoretical**)	N/A (BF-BOF route)	Roland Berger, 2021
20%	N/A (BF-BOF route)	Hydrogen Europe, 2022
Approximately 50% (Ranging from 40% to 75% by type of CO_2e capture technology: post-combustion; calcium looping; SEWGS)	N/A (BF-BOF route)	JRC, 2022

The amount of reduction depends on the amount of CO_2 that can be captured out of the BF-BOF route in Section 3.1.1. There are several CO_2 emission sources in the BF-BOF integrated route. Any CO_2 that is not captured circulates within the plant and is emitted at different points. To achieve a high level of decarbonisation, CCS equipment has to be applied to all the emission sources, which makes achieving a high level of overall CO_2 reduction rate using CCS technology extremely difficult (Onarheim, 2015).

Due to that, most projects aim to retrofit CCS technologies to the blast furnace only, where more than 50% of CO_2 originates from the blast furnace, where large quantities of carbon in the form of coke and coal are processed as a reductant and a fuel (JRC, 2022). For instance, ArcelorMittal is developing a pilot project to capture CO_2 by capturing waste gases from the blast furnace and reforming it to syngas (carbon monoxide and hydrogen), which can be injected back into the blast furnace as reducing gases. Additionally, at its Dunkirk site, ArcelorMittal is spearheading the development of a 3D pilot project that employs novel amine-based technology to capture 0.5 tons of CO_2 per hour from the blast furnace, with a target completion date set for 2030 (JRC, 2022).

Finally, carbon capture and utilisation (CCU) technology is not included in this report because it raises a major issue of allocation and potential double-counting, since any fossil carbon that is captured and then utilized to produce other products is then susceptible to the risk of delayed emission, whenever such products are then disposed of or burnt (if they are fuels).

3.1.3.3 *Levelised costs vs BAU*

A STOA research in Europe (Ledari, 2023) forecasts the expected evolution of the cost of the BF-BOF route using CCS technology over time. In 2020, it was 30% more expensive than the conventional unabated BF-BOF integrated route, at around €550 per tonne of steel. This price difference is however expected to be reversed in 2050 due to the rising cost of CO_2 emission.

If the cost is split by its use, the estimated cost of the CCS application is around €100 per tonne of steel (Ledari, 2023). This is consistent with another study that estimated the cost of capturing one tonne of CO_2 as €47, which would equate to assuming 2 tonnes of CO_2 emissions per tonne of steel (Global CCS Institute, 2021). However, in fact, like its decarbonisation potential, CCS cost estimates vary a lot according to different studies. BNEF estimated 20% (BloombergNEF, 2021) and Agora estimated around 60-120% higher costs compared to the conventional integrated route (Agora Energiewende and Guidehouse, 2021).

The gap between the two methods will reflect the CAPEX required to retrofit existing BF plants and apply CCS technology. Roland Berger has estimated that €31bn of investment is required to meet capacity to achieve 2030 target using the BF-BOF with CCS route (Roland Berger, 2021). OPEX to capture and store carbon will be required as well (JRC, 2022).

However, the actual cost might not be as significant in the long term. Assuming a CO_2 price of €85/ton, CCS is cheaper than the conventional route without CCS (ING, 2023).

3.1.3.4 *Favourable aspects for the automotive industry*

Deploying CCS in conjunction with otherwise conventional BF-BOF steel production would have the benefit of maintaining the existing production facilities. Producers would not need to find new suppliers and customers as the quantity and quality required would be maintained.

3.1.3.5 *Limitations*

The main and foremost limitation of the BF-BOF route with CCS is that, overall, it is still an unproven technology with low TRL and very large uncertainties on both ultimate achievable decarbonization potential, and cost.

BF-BOF route with CCS requires investment to retrofit the current integrated route. This is estimated to result in higher costs by 2050 compared to other decarbonisation routes (JRC, 2022). Besides, despite the high cost expected, the decarbonisation potential is uncertain. As shown above, it varies a lot by study due to different types of technology and their suitability. Therefore, **it does not appear to be realistic to decarbonise automotive steel to a significant extent using just CCS technologies applied to BF-BOF steel production.**

3.1.4 NG-DRI “grey” steel

3.1.4.1 *Description*

NG-DRI steel is another commercially established method of steel production. Currently, DRI only accounts for around 5% of global steel production (IEA, 2020b), but there are more than 16 plants announced to be built. This accounts for 25 million metric tonnes of capacity (McKinsey and Company, 2022).

While the integrated route reduces primary iron ore using blast furnaces (BF), Direct Reduced Iron (DRI), also known as sponge iron, is produced in fluidized bed reduction (FBR) furnaces. Before being fed to the FBR furnace, the iron ore needs to be pelletized and pre-heated (Franklin Templeton Institute, 2023).

Then, the iron ore is mixed with a reducing agent, which triggers a chemical reaction that separates oxygen from the iron ore (JRC, 2022). This reducing agent can be either a gas or a solid. Natural gas is one common option for the reduction gas. Iron ore is converted into DRI as oxygen combines with natural gas, generating water and carbon dioxide as by-products.

The DRI thus produced is then used as a feedstock for EAFs for steel production, in a similar fashion as described in Section 3.1.2 when talking about secondary EAF steel production from scrap.

3.1.4.2 *Potential decarbonisation vs BAU*

Although it will vary depending on the electricity sources used to power the EAF, **NG-DRI steel has a decarbonisation potential of around 50% compared to “integrated” BF-BOF steel**. This equates to around 1 tonne of GHG emission per tonne of NG-DRI steel production, see Table 3.4

Table 3.4 CO_2 Emissions from NG-DRI "Grey" Steel

Decarbonisation potential compared to BF-BOF	Grid mix for calculation	Source
50%	EAF using unspecified grid mix	Roland Berger, 2021
55%	EAF using EU grid mix at 300gCO_2e/kWh	JRC, 2022
67%	EAF using 100%RE	JRC, 2022
40%	EAF using global average grid mix at 538gCO_2e/kWh	IEA, 2020
35%	EAF using grid mix at 386gCO_2e/kWh	Rosner et al., 2023

The main source of emission is the direct CO_2 from the DRI process. Around 40% of the emissions arise from the chemical reaction when reducing the iron ore. This is significantly less than the emissions from the BF route. The second largest source of emissions is the iron ore pelletizing stage, which accounts for 20% of the total emissions. Thirdly, 17% of emissions are from the EAF stage, which is amenable to further reduction as the grid mixes decarbonise.

3.1.4.3 Levelised costs vs BAU

NG-DRI steel costs around €671/t, which is higher than the average cost for the conventional integrated BF-BOF route. This includes €74 of CAPEX and €98 of OPEX. The NG-DRI route will need investment to expand the existing DRI-EAF infrastructure. For instance, €42bn of CAPEX is required to expand the capacity to meet the 2030 target (Roland Berger, 2021). OPEX will include factors like renewable electricity cost, which have experienced an increase between 2020-2023 and impacted the total cost of steel from this technology.

Resource costs also significantly affect the total cost of production. In particular, natural gas costs €95 per tonne of steel produced, which is around 18% of the total cost (Rosner, 2023) and hence the cost of NG-DRI steel production is subject to volatility in natural gas prices.

3.1.4.4 Favourable aspects for the automotive industry

One strength of NG-DRI "grey" steel is that it is already commercially available. It is the only DRI route that is commercialised at present (World steel, 2022b). It can be produced on a large scale and has cost competitiveness if using cheap natural gas. It is also proven that high-quality products can be produced via this route (McKinsey and Company, 2020).

Besides, **DRI-EAF facilities can be converted easily to produce green H2 DRI-EAF steel (see Sections 3.1.5 and 3.1.6). In other words, NG-DRI "grey" steel can function as a "bridge" technology to start implementing the DRI route while the cost of green H_2 in particular decreases** (Conde, Rechberger, Spanlang, Wolfmeir, & Harris, 2021).

3.1.4.5 Limitations

Compared to the secondary EAF route (Section 3.1.2) or other hydrogen-based DRI routes (Sections 3.1.5 and 3.1.6), NG-DRI steel has limited decarbonisation potential. As the direct carbon emission from the chemical reaction is inevitable, its CO_2 reduction is not sufficient to meet the Net Zero pathway. Besides, during the production of natural gas, there is a **risk of fugitive methane gas emissions** (which is a significant concern, since each tonne of methane has 25 times the global warming potential of one tonne of CO_2).

Another limitation would be relevant to the price of natural gas, which represents around 18% of the total cost, thus making NG-DRI steel dependent on the price and availability of natural gas. For instance, most shaft furnace DRI plants are located in natural gas-rich countries these days (JRC, 2022), (McKinsey and Company, 2022). Considering the major natural gas production countries are not located in the EU, the construction and operation of the plants might not be efficient.

Moreover, unlike the BF-BOF route with input flexibility, high-quality DRI pellets are required for the DRI-EAF route (IEA, 2020b), (Franklin Templeton Institute, 2023). Higher-purity iron ore grades are traded with an average 20% premium to lower grades, with represents an added cost (Franklin Templeton Institute, 2023).

This problem with high-quality iron ore is likely to continue, as conventional BF-BOF routes are gradually expected to be replaced by DRI-EAF routes.

3.1.5 H2-DRI "Blue" steel

3.1.5.1 Description

H2-DRI "blue" steel refers to steel that is produced with DRI using "blue" H_2 as a reducing agent. The method goes through the same production route as other DRI-EAF steel routes (as described in Section 3.1.4). The primary ore is reduced in a fluidized bed reduction (FBR) furnace into DRI. It is then used to produce steel. But since in H2-DRI blue steel, the reductant is blue H_2 (instead of natural gas), this causes a chemical reaction that only generates water as a by-product when separating oxygen from iron ore. DRI is then used as a feedstock for EAFs for steel production.

"Blue" hydrogen refers to hydrogen gas produced via conventional reforming of fossil fuels (commonly, natural gas), but where the carbon emitted from its production is captured via CCS technologies.

It is important to note that, although blue hydrogen is categorized as lower-carbon hydrogen, it is in fact not zero-carbon hydrogen. Studies suggest that around 10-20% of the carbon emitted to produce hydrogen via natural gas reforming cannot be captured (Giovanninni, 2020), (IRENA, 2020).

Shell's Quest project and Air Products' port Arthur facility are examples of blue hydrogen production.

3.1.5.2 Potential decarbonisation vs BAU

A recent peer-reviewed scientific study compared "blue" H_2 to "grey" H_2 and natural gas, and found that "blue" H_2 could, at best, only achieve a modest 40% reduction in life-cycle GHG emission intensity per MJ, when compared to the straight use of natural gas (Massarweh, 2023), see Table 3.5.

As a consequence, **H2-DRI "blue" steel can only be expected to achieve partial decarbonisation vs. the conventional "integrated" BF-BOF route**.

Table 3.5 CO_2e Emissions from H2-DRI "Blue" Steel

Decarbonisation potential compared to BF-BOF	Grid mix for calculation	Source
Approximately 60%	EAF using unspecified grid mix	Own calculation, based on literature sources for NG-DRI "grey" steel (Section 3.1.4) and (Massarweh, 2023).

Even so, the H2-DRI "blue" route may still be of some relevance in the early stages of the transition from conventional BF-BOF steel to lower-carbon steel, essentially because it is part of the DRI "family" of processes, and it could be used as a stepping stone towards H2-DRI "green" steel (Section 3.1.6), i.e., moving from H2-DRI "grey" to H2-DRI "blue" to H2-DRI "green" steel, while retaining the same DRI-EAF infrastructure. Also, like for H2-DRI "grey" (Section 3.1.4), the EAF step of the chain is amenable to further modest GHG reductions via the decarbonization of the electricity grid mix.

3.1.5.3 Levelised costs vs BAU

The cost of producing blue H2-based DRI steel is expected to be higher than other routes. The cost is uncertain due to the price of blue hydrogen and renewable electricity. These are the main variables of OPEX of steel. (JRC, 2022)

Assuming €85 per tonne of CO_2 emitted, H2-DRI "blue" steel is expected to cost €870 per tonne of steel produced. This is 70% higher than the integrated route (ING, 2023). This would be due to the high cost of blue hydrogen and the investment required to construct DRI-EAF facilities. The current levelized cost of blue hydrogen production is between €2.6-3.3/kg. Considering the production of one tonne of steel requires 70-90kg of hydrogen, it adds €190-280 more per tonne. In addition, €21bn CAPEX is required to expand the H2 DRI-EAF capacity to meet the 2030 target (Roland Berger, 2021).

It is also important to note that the relative costs of "blue" vs "green" H_2, and consequently of H2-DRI "blue" steel vs. H2-DRI "green" steel (Section 3.1.6), depend on multiple key economic factors: the cost of natural gas (for “blue” H2 production), the cost of CCS (for “blue” H2 production), the electrolyser (for “green” H2 production) and the cost of renewable electricity (for “green” H2 production). Among these, it was found that the cost of natural gas is likely to be the most important factor by far to eventually determine the economic competitiveness of the “blue” vs “green” options in the coming decades in Europe. More specifically, “blue” H2 (and hence H2-DRI “blue” steel) may come to dominate the overall market for H2-DRI steel in a scenario where the cost of natural gas increases linearly from a historical cost of 29 €/MWh in 2020 to 39 €/MWh in 2050. However, natural gas sprice in Europe increased sharply in 2022, and prices around 100 €/MWh have been observed in the first half of 2022, whereupon the prices increased further in the second half of the year. Hence, according to (Durakovic, 2023), *“The results presented here suggest that* ***if the natural gas prices observed in 2022 are representative of the future gas prices in Europe, then blue hydrogen will likely not be an economical way to produce large quantities of hydrogen****.”*

3.1.5.4 Favourable aspects for the automotive industry

The primary advantage of H2-DRI "blue" steel lies in its compatibility with existing processes. In the short term, transitioning from "grey" H2 to "blue" H2 may be more feasible, given that this gas shows larger availability, despite its limited decarbonization potential. This approach could be more viable than switching to "green" H2, especially considering that the majority of hydrogen production currently relies on fossil fuel reforming methods *(IRENA, 2020)*. Blue hydrogen could utilize this current grey hydrogen infrastructure by installing CO_2 capturing equipment, which may initially be less expensive than building new electrolysers.

3.1.5.5 Limitations

H2-DRI “blue” steel shares some of the same limitations as BF-BOF “blue” steel (Section 3.1.3), related to **lingering uncertainty both in terms of decarbonisation potential and costs; overall, it does not appear to be realistic to decarbonise automotive steel to a significant extent using just CCS technologies applied to H2-DRI steel production.**

This route is also not commercially ready yet. If the steel industry wanted to switch to blue hydrogen-based steel today, it would require 130% of the total current supply (Franklin Templeton Institute, 2023). In the long term, by 2050, blue hydrogen capacity could be expanded to about 5-6 times the current capacity; however, **there is no blue hydrogen plant tested at a commercial scale yet** (Institute for Energy Economics and Financial Analysis, 2023). There are ongoing projects, but most of them are at the pilot or demonstration stage (JRC, 2022). Also, the long-distance transportation of hydrogen would require significant infrastructure. It has sometimes been argued that existing pipes to deliver natural gas could potentially be converted to deliver hydrogen, however, the practical feasibility of doing so remains untested (hydrogen is even more prone to leakage than methane, and it also leads to embrittlement of the pipelines). Recent scientific evidence has also shown that the

More generally speaking, H2-DRI “blue” steel also shares the limitations of other DRI-based steels (see Sections 3.1.4 and 3.1.6), in particular relating to the need for higher-grade iron ore for the fluidized bed reduction process (Franklin Templeton Institute, 2023).

3.1.6 H2-DRI “Green” steel

3.1.6.1 Description

H2-DRI “green” steel refers to the steel that is produced based on the same DRI process described in Sections 3.1.4 and 3.1.5 above; specifically, the only difference between H2-DRI “Blue” steel and H2-DRI “Green” steel lies in how the hydrogen is produced. In H2-DRI “green” steel, “green” H_2 is used as the reducing agent, i.e. hydrogen produced by splitting water in an electrolyser, with the electricity used to power the electrolyser being sourced by renewable energy (thus benefiting from very low “embodied” GHG emissions).

H2-DRI “green” steel is not commercialised yet on a large scale (World steel, 2022b). However, there are several announced production facilities in Europe, with the first full-scale green H-DR-EAF plant in Boden, Sweden run by H2GS set to come online by the end of 2025, ramping up to full-scale commercial production of 5 Mt steel production capacity by 2026 (H2GS, 2023). H2GS also plan to jointly operate a Spanish DR plant with Iberdrola by 2026, with an initial capacity of 2 Mt of green DRI and potential for an integrated EAF to produce green steel on-site (H2GS, 2021). Also, ArcelorMittal have announced plans to replace the conventional BF and BOF infrastructure at their sites in Gijon and Sestao with a DR plant and EAFs to produce “green” steel through a phase-in of green hydrogen from 2025 (ArcelorMittal, 2021a), (ArcelorMittal, 2021b).

3.1.6.2 Potential decarbonisation vs BAU

Green H_2 can be almost fully decarbonised along with the electricity grid, see Table 3.6.

Table 3.6: CO_2e Emissions from H2-DRI "Green" Steel

Decarbonisation potential compared to BF-BOF	Grid mix for calculation	Source
98%	EAF using 100% renewable energy	Roland Berger, 2021
99%	EAF using 100% renewable energy	RMI, 2019
97.2% (Unavoidable CO2 emission of 53kg)	EAF using 100% renewable energy	Vogl et al., 2018

The break-even grid emission intensity that would equalize GHG emissions from conventional “integrated” BF-BOF steel and electrolyser-H2-DRI steel has been calculated to be 532CO_2e/kWh. Given the global average grid mix carbon intensity of 538CO_2e/kWh, the BF-BOF route still emits very marginally less than the electrolyser-H2 DRI route today. However, even modest further grid decarbonisation will suffice to make electrolyser-H2-DRI steel the better option globally (Vogl, 2018); for many world regions such as Europe (average grid mix carbon intensity of 300gCO_2e/kWh), electrolyser-H2-DRI steel is already a clear winner. Certain countries, such as Sweden and France, boast highly carbon-efficient grids even at present. Sweden has grid mix carbon intensity of 7gCO_2e/kWh, while it reaches 68 gCO_2e/kWh for France. EU27 is expected to reach around 110gCO_2e/kWh by 2030.

While most of the processes in the H2-DRI “green” steel route can be decarbonised, there is still a small amount of CO_2 emissions of around 53kg per tonne of steel (Vogl, 2018) embedded in the extraction of iron ore and other feedstocks, which require additional actions such as electrification of mining equipment.

3.1.6.3 Levelised costs vs BAU

Table 3.7: H2-DRI Steel Cost of Production

H2-DRI cost compared to BAU route	Source
10%~60% higher (Europe)	JRC, 2022
30%~120% higher (World)	JRC, 2022
60% higher	Ledari et al., 2023
36% higher	Conde et al., 2021
20% higher	Lopez et al., 2023; Hydrogen Europe, 2022

The current cost estimates of producing H2-DRI “green” steel are all over €560 per tonne of steel (Ledari, 2023), (Conde, Rechberger, Spanlang, Wolfmeir, & Harris, 2021), (Mayer, Bachner, & Steininger, 2019); these costs are relatively higher than the “integrated” BF-BOF route, thereby holding back its immediate introduction. However, there is considerable scatter due to differences in location and access to inexpensive renewable energy, with e.g., only a +20-30% cost penalty at present vs. BF-BOF steel when using hydropower in Sweden (Financial Times, 2023).

The price difference is highly dependent on the price of green hydrogen and renewable electricity (JRC, 2022). However, the price of green hydrogen is expected to decrease globally over time. It has been estimated that it will go below that of “grey” hydrogen in 2030, along with lower renewable electricity costs (McKinsey and Company, 2020). **If these projections are realised, then eventually H2-DRI “green” steel would become cheaper than conventional BF-BOF steel in the future**. However, uncertainties remain, and cost estimates for “green” H_2 in 2050 range between 1 €/kg to over 5 €/kg[14], leading to H2-DRI “green” steel in Europe

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[14] Real world costs of green hydrogen in 2030 are expected to be more likely in the range of €4–7/kg

potentially being cheaper or 60% more expensive than today's steelmaking costs (JRC, 2022), (McKinsey and Company, 2022), (Ledari, 2023).

CAPEX related to green H2 steel is estimated to be 574 €per tonne of steel. It includes 160 €per tonne for the electrolyser construction, 230 €for the direct reduction shaft, and 184 €for EAF (Vogl, 2018). Another study suggests €320 of shaft investment per tonne of steel, requiring €504 per tonne of crude steel (Hydrogen Europe, 2022).

3.1.6.4 Favourable aspects for the automotive industry

H2-DRI "green" steel appears to be the most promising option for the decarbonisation of primary steel production for the automotive sector in the long term at scale. This process can produce high-quality steel that is suitable for the automotive industry, utilizing primary ore. The H2-DRI "green" route has sufficient decarbonisation potential that satisfies the net zero goal, which will be completed as the electricity grid further decarbonizes. Its production scale is also not limited by the shortage of input, unlike secondary scrap steel. Although the current cost of production is relatively high, this will be mitigated as the cost of producing green hydrogen drops and as the electricity grid decarbonizes.

Besides, as it is possible to switch gradually from the NG-DRI "grey" route to the H2-DRI "green" route; the construction of new DRI-EAF facilities can begin now, eventually minimizing the issue with stranded assets.

3.1.6.5 Limitations

The largest concern about H2-DRI "green" steel is the supply of green hydrogen. If the steel industry switched to hydrogen-based steel today, it would require 130% of the total current supply (Franklin Templeton Institute, 2023). In the long term, by 2050, hydrogen capacity should be expanded to 530m/t which is about 5-6 times of current capacity. Besides, most of the hydrogen produced these days (95%) is grey hydrogen produced from coal or natural gas, emitting GHG. Thus, expanding electrolyser capacity and renewable energy to power the electrolyser is crucial. However, building electrolysis is subject to constraints like grid connection availability and capacity. Some areas may not have low-cost renewable energy or hydrogen transportation infrastructure.

These concerns tend to dampen early adoption of the H2-DRI "green" steel route. Until production is ramped up, H2-DRI "green" steel is unlikely to be cost competitive. Due to these capacity and price issues, sourcing green hydrogen leaves high uncertainty in terms of production cost as discussed above. Currently, H2-DRI costs are higher than the market clearing price (Ricky Mountain Institute, 2019). However, (Ledari, 2023) estimated that the cost differential between H2-DRI "green" steel and conventional "integrated" BF-BOF steel will be reversed by 2050.

Finally, H2-DRI "green" steel shares the same technical limitation of other DRI-based steels, i.e., a higher-grade iron ore is required for the fluidized bed reduction process (Franklin Templeton Institute, 2023)

3.1.7 Emerging Technologies: Iron Ore Electrolysis

Along with the 2H-DRI green steel production, other technologies are expected to replace existing steel production processes in terms of decarbonisation. The iron ore electrolysis technology is one of them, already widely used for metals like zinc and aluminium. Replacing the iron ore reduction stage, it produces liquid iron to be fed into the electric arc furnaces. Its fundamental concept is that electric current passes through iron ore in an electrolyte. Positively charged iron ore ions move towards the negatively charged cathode, and they undergo reduction. Negatively charged oxygen ions are released from the solution (Cavaliere, 2019). Electricity is the only energy requirement for reduction and does not produce direct CO2 emissions. Thus, **when 100% renewable electricity is used, it is possible to achieve 100% carbon reduction**. It can also avoid the upstream stages like H2 production (Hydrogen Europe, 2022).

Iron ore electrolysis can be achieved in either low or high temperatures. The technology at low temperature refers to electrowinning. Iron ore grains are reduced in the solid state at 60 to 110 degrees (Canary media, 2023) (JRC, 2022). In the EU, the focus is more on the low-temperature electrolysis (JRC, 2022). An example is the Siderwin project led by ArcelorMittal, which aimed to validate the technology at Technology Readiness Level (TRL) 6 by 2023. It has been completed successfully, with the approval for the next step (ArcelorMittal, 2023). The other is molten oxide electrolysis (MOE) at high temperatures. Liquid iron oxide electrolyte melted at 1600 degrees is reduced into liquid iron. MOE has higher productivity than other electrolytic processes. However, it is relatively inflexible as it requires constant electricity. This may cause a grid congestion problem (Hydrogen Europe, 2022).

For both routes, low TRL is the major barrier. Building on the current TRL 6, electrowinning is expected to be commercially available in 2050 (JRC, 2022). MOE has an even lower TRL. Due to the early stage of technological readiness, its usefulness in the EU steel industry before 2050 is unclear. In the same context, the cost of steel production via iron ore electrolysis (both electrowinning and MOE) is highly uncertain. Early results indicate that steel production would require similar amounts of electricity as the hydrogen DRI route (JRC, 2022). The cost will be highly dependent on the cost of renewable electricity and other variables such as CAPEX required for the equipment.

3.2 TIMING AND PRACTICAL LIMITATIONS FOR SHIFTING SUPPLY TOWARDS GREEN STEEL

Shifting to green steel production requires significant investments in new technologies and infrastructure. Some new and innovative steelmaking methods will require new infrastructure networks to function effectively. This infrastructure is essential both upstream (to provide hydrogen and electricity as required) and downstream of the steel production process (for example, to gather and transport CO_2 to a suitable storage location). This timing aspect involves aligning investment schedules with the automotive industry's production cycles and budgetary constraints. Rapidly converting existing facilities to accommodate green steel production without disrupting current operations poses a challenge.

There are also persistent concerns regarding lock-in risks within the steel industry. When companies heavily invest in traditional steel production methods, they often become locked into established technologies and processes. Moving away from these investments carries risks; it may mean forfeiting the value of existing infrastructure and potentially incurring write-offs or losses if the transition happens abruptly or prematurely. Yet, considering that 2050 is only one investment cycle away, the sector urgently needs to introduce and adopt new, low-CO_2 technologies in this decade to avoid the risk of having stranded assets. Given that the blast furnace-based production route is significantly CO_2-intensive and that EU mills are already operating at close to peak efficiency, the industry seems to be prioritising hydrogen-based steelmaking. Simultaneously, exploration into carbon capture, storage, and utilization technologies is ongoing to mitigate emissions in the interim. The pressing call for action is evident not just in the European Commission's revised 2020 Industrial Strategy (European Commission, 2021a) and its accompanying Staff Working Document on Steel (European Commission, 2021b), but also in the evaluations conducted by the steel industry itself (Eurofer, 2020).

3.2.1 Technological readiness and market readiness

Green steel production methods, such as hydrogen-based direct reduction or electric arc furnaces powered by renewable energy, are promising alternatives. However, these technologies may still be in the developmental or scaling-up phase. Implementing them on an industrial scale while ensuring cost-effectiveness and maintaining quality standards poses a technological challenge. Other technologies are identified in a very early stage of readiness and, thus, there is not sufficient data on expectations nor projections to facilitate its inclusion in the modelling of future scenarios. This is the case of iron ore electrolysis, which has a more extensive journey ahead before reaching market introduction. However, it possesses several characteristics that could expedite its innovation timeline compared to certain other technologies. These opportunities encompass the possibility of reduced risk during the scaling process, given its modular traits, knowledge transfer from other electrolysis technologies, standardised and repetitive manufacturing, and the potential to provide grid balancing services. Knowledge spill overs in design, operation and materials might be expected to flow from aluminium to steel electrolysis since both projects have many points in common. Iron electrolysis is believed to use 15-30% less electricity for each tonne of steel compared to the hydrogen-based DRI route. This can help reduce pressure on electricity grids, which is increasing with a higher reliance on renewable energy, whose availability is limited so far. This advantage could be really helpful as society moves to try to make the entire energy system move faster towards zero emissions.

The readiness of technology and market acceptance greatly relies on the specific resources and regional circumstances. Choosing the right steel production technologies, particularly for primary steel production, depends on several factors. Key among these factors are the availability of different energy sources in the area, energy costs, access to necessary resources and infrastructure, and the age and scale of existing assets in that region. Additionally, factors like public approval and local regulations also play a significant role in determining the feasibility of adopting a particular technology, such as CCUS technologies in specific regions.

Europe has a well-established blast furnace fleet with an extended history, considering the years since their initial installation (with an average active fleet age of 50 years). However, this average age significantly decreases when factoring in recent upgrades and refurbishments (averaging around 10 years). This aspect, coupled with the European steel industry's strong dedication to various research and demonstration projects for low-emission steelmaking technologies, positions the region to embrace a diverse array of options. These options include both carbon avoidance and carbon management techniques. Hydrogen plays a central role, building upon ongoing projects integrating hydrogen into existing blast furnaces and DRI units, facilitated by a supportive policy landscape for this technology. Results suggest that the high costs of hydrogen transportation make a European steelmaking supply chain cost competitive compared to steel produced with imported hydrogen.

Another interesting point conditioning market readiness is the availability of green steel to meet the demand of the automotive sector. The availability and scalability of green steel might not currently meet the automotive industry's entire demands. Supply chain readiness, including sourcing raw materials and logistics, needs to align with the industry's production requirements. Ensuring a consistent supply of green steel at a competitive price is crucial for widespread adoption.

The timing is crucial for these advancements. **Considering the urgency for action and timeframes for innovation and steel plant investment cycles, it is vital to establish reliable policies, support systems, and early-stage planning initiatives for long-term success**.

Regulatory frameworks, standards, and incentives play a vital role in encouraging and facilitating the transition to green steel. Collaborations between automotive manufacturers, steel producers, and policymakers are essential to overcome these challenges and drive the successful integration of sustainable steel in automotive production. The timing of these policies is vital to send the right signal to industry players. For example, it will likely be more advantageous from both a commercial and climate perspective to delay the retirement of an aging plant until it can be substituted with a much lower-emission one, rather than replacing it with a conventional plant that might operate for several decades with incentives to do so (IEA, 2020b).

4. POTENTIAL IMPACTS FROM DIFFERENT TECHNOLOGICAL AND POLICY SCENARIOS FOR ADOPTION OF 'GREEN STEEL' IN THE AUTOMOTIVE SECTOR.

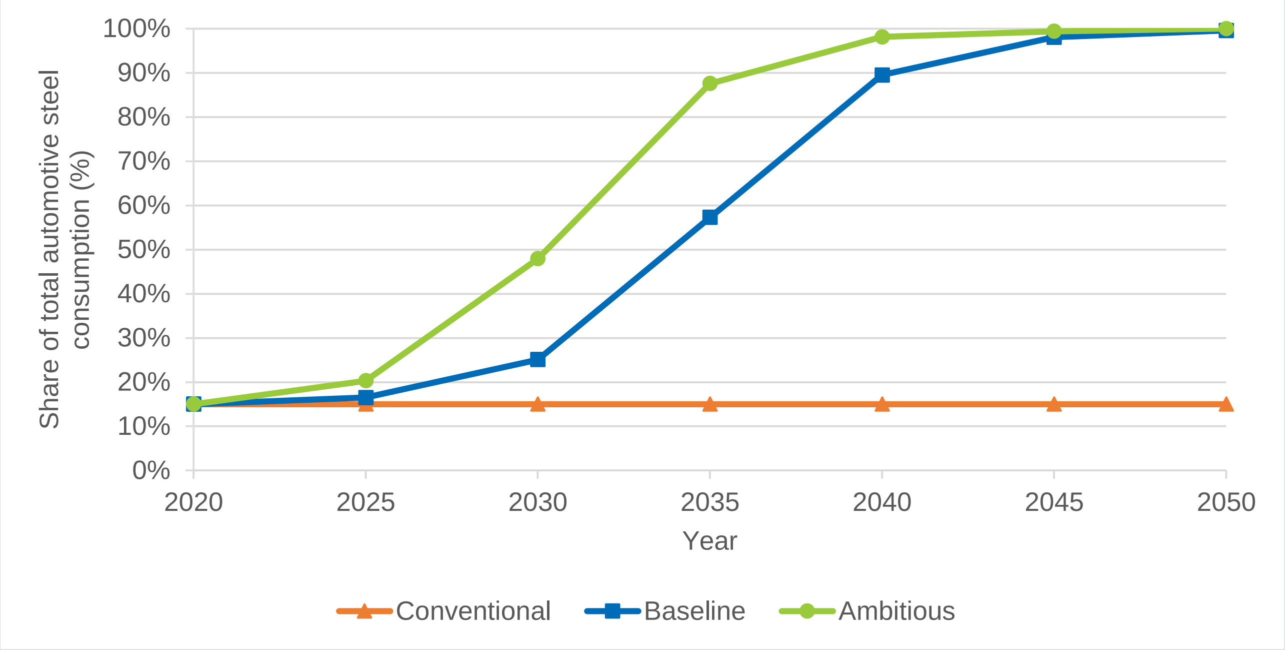
4.1 AUTOMOTIVE LOWER-CARBON STEEL DEMAND SCENARIOS

In order to model the impacts of varying lower-carbon steel uptake within the automotive sector, Baseline and Ambitious green steel scenarios were developed, see Figure 4-1.

The "Baseline" scenario is informed by publicly available automotive OEM targets for lower-carbon steel supply and wider decarbonisation of production supply chains. As such, the Baseline scenario has a gradual increase of lower-carbon steel from an initial share of 15% of total domestic steel demand[15] in 2020 (from an initial Secondary EAF share) to 100% by 2050, reaching 25% and 57% lower-carbon steel shares by 2030 and 2035 respectively. The "Ambitious" scenario is in line with the highest announced proposed uptake of green steel in the automotive sector by OEMs, with lower-carbon production pathways reaching roughly 50% of total steel demand by 2030, 88% by 2035, near-100% by 2040, and 100% by 2050.

In addition, to compare the impact on emissions and costs of the two scenarios, a "Conventional" scenario was developed assuming that the share of automotive steel produced from primary BF-BOF and secondary EAF production technologies remain constant between 2020 and 2050 at 85% and 15% respectively.

Figure 4-1: Conventional, Baseline and Ambitious lower-carbon steel projections for domestic automotive steel consumption



The lower-carbon steel shares in the Baseline and Ambitious scenarios are split between the technological routes introduced in Section 3, with the uptake of each steel production technology discussed in further detail below.

Secondary EAF is assumed to comprise 15% of the domestic automotive steel demand in 2020, see Section 2.2. Under the Default sensitivity for secondary steel uptake, it is assumed that, by 2050, all scrap steel from the automotive sector is reprocessed in an EAF to produce recycled steel, satisfying 37% of total automotive steel demand by 2050[16]. Also, low and high recycled steel sensitivities were developed for the Secondary EAF pathway, see Section 4.1.1.

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[15] Domestic steel refers to steel produced in the EU27, with total steel consumption met by both domestic and imported supply.

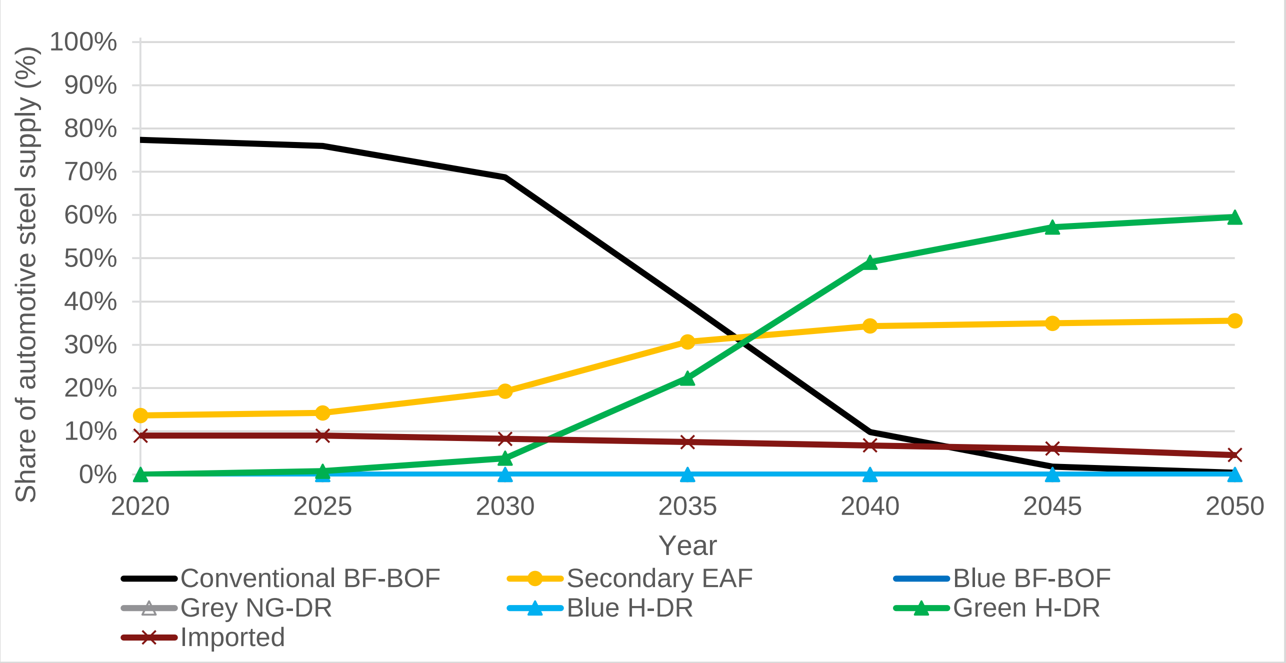
[16] Calculated from the number of vehicles removed from the fleet in Europe from the E3M PRIMES-TREMOVE model and Ricardo LCA data on vehicle steel content.

Primary lower-carbon steel production shares for each scenario are informed by the projected volumes of lower-carbon steel demand from the automotive sector from publicly announced OEM supply agreements. Green H-DR is expected to be the dominant lower-carbon steel production pathway, making up around 80% of currently announced automotive steel demand by 2030.[17] The Grey NG-DR production pathway is assumed to not contribute to lower-carbon automotive steel as this technology: has limited automotive demand (8% of announced volume by 2030); is broadly viewed as a transition technology between current production and Green H-DR; and has variable emission reduction potential (see Section 3.1.4). As no automotive OEM supply announcements indicate demand for the use of CCS technology in combination with either the BF-BOF pathway (Blue BF-BOF) or the hydrogen DR-EAF (Blue HDR) pathway, these technologies also do not feature in the automotive steel demand scenarios between 2020-2050.

In 2022, imported steel made up 9% of total European steel consumption. As the majority of announced lower-carbon steel production capacity and automotive steel supply agreements are concentrated within Europe, it is assumed that imported steel from outside the EU27 continues to be dominantly produced via the primary BF-BOF route up to 2050. Due to the introduction of the EU Carbon Border Adjustment Mechanism (CBAM) in 2026, demand for imported steel with a higher carbon intensity is expected to decline. As such, the Default imported steel projection assumes that the automotive sector reduces its representative imported share of 9% in 2020 by half to 4.5% in 2050. A High imported sensitivity assumes a constant share of 9% between 2020-2050, see Section 4.1.1.

Figure 4-2 and Figure 4-3 show the Baseline and Ambitious lower-carbon steel scenarios split between Conventional BF-BOF, Secondary EAF, Imported, and primary lower-carbon steel production pathways.

Figure 4-2: Baseline lower-carbon steel scenario, 2020-2050 (EU27)



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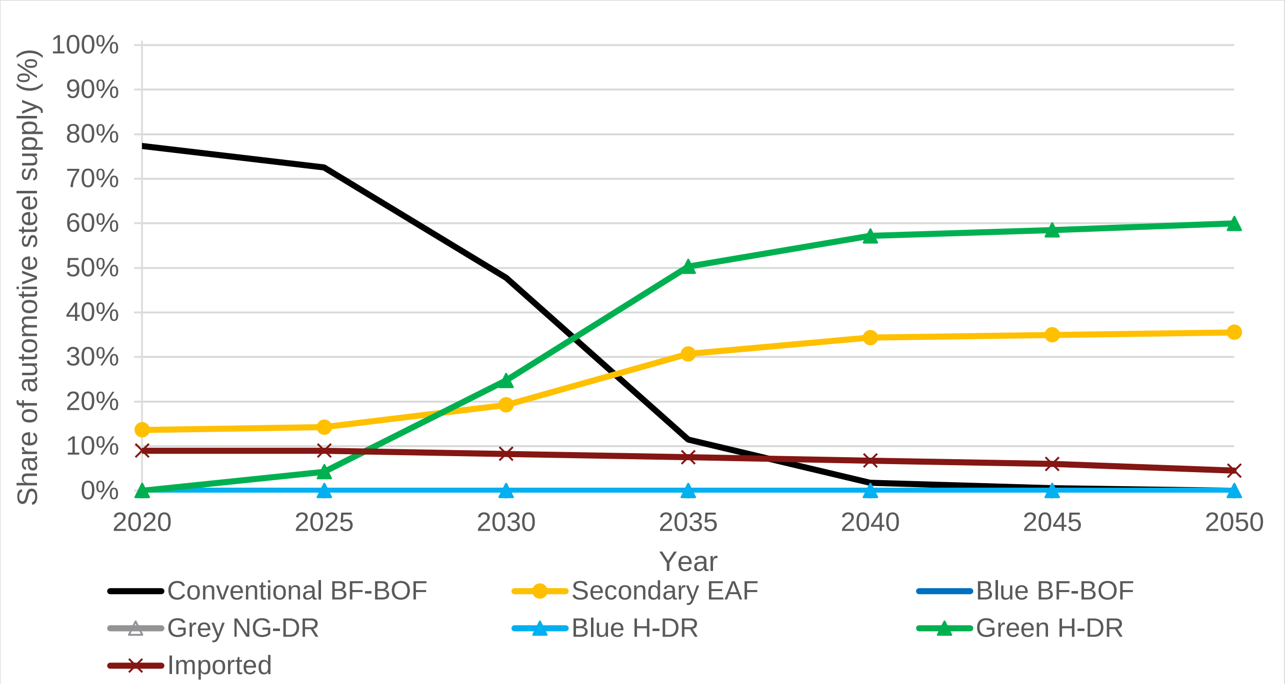
[17] Ricardo analysis of publicly announced OEM supply agreements.

Figure 4-3: Ambitious lower-carbon steel scenario, 2020-2050 (EU27)



4.1.1 Model sensitivities

In order to reflect a range of potential impacts from lower-carbon steel automotive consumption, sensitivities[18] were added to the model to allow for further analysis and comparison of the impacts of a range of input data. In particular, sensitivities were provided for the GWP (low, default and high) and cost sensitivities (default and high) of all steel production technologies; low, default and high projections for automotive steel demand from Secondary EAF technology; and default and high projections for Imported steel share. Although not analysed in this report, a mass sensitivity was included to compare the Default mass (assuming a reduction in vehicle steel content between 2020-2050, see Section 2.1) with a constant vehicle steel content. Unless otherwise specified, this report analyses the impact of the lower-carbon steel scenarios under Default sensitivities.

4.1.1.1 Steel cost and GWP sensitivities

The Default costs for Conventional BF-BOF and primary lower-carbon steel production pathways between 2020-2050 were adapted from data used by a 2020 study by the European Parliament (European Parliment, 2021). As Imported steel consumed by the automotive sector is assumed to be predominantly produced through the primary BF-BOF route, the cost is assumed to be the same as for domestically produced primary BF-BOF steel. Currently, steel from Secondary EAF has a marginal cost premium of 10.5% compared to primary BF-BOF (WEF, 2023b), with increases in costs between 2020-2025 driven by electricity price changes before reaching cost competitiveness with BF-BOF steel by 2028 and continuing to reduce between 2030-2050.

In addition, electricity prices and levelized costs between 2020-2023 were used to reflect the impact of electricity price increases between 2020-2023 on steel production costs in the near-term (IEA, 2023), (IRENA, 2023). High cost sensitivities for all steel technology costs, excluding H-DR, project a 25% increase in electricity costs from the Default sensitivity costs.

H2 production costs and cost projections have been revised upwards since 2020 due to rising CAPEX and renewable electricity costs. As such, the cost contributions to the total H-DR steel unit cost associated with producing green hydrogen (namely the cost of electricity used in the production of H2 and the CAPEX attributable to the electrolyser) were inflated by comparing the EPRS hydrogen costs to revised actual and projected hydrogen costs. In particular, a hydrogen cost of 6.8 per kgH2 in 2022 (European Hydrogen Observatory, 2023), 4.0 per kgH2 by 2030 (IEA, 2023) and 1.5 per kgH2by 2050 (IRENA, 2020b) were used

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[18] Sensitivities in a forecasting model refer to the variations or changes in the model's output resulting from adjustments made to certain input variables or assumptions.

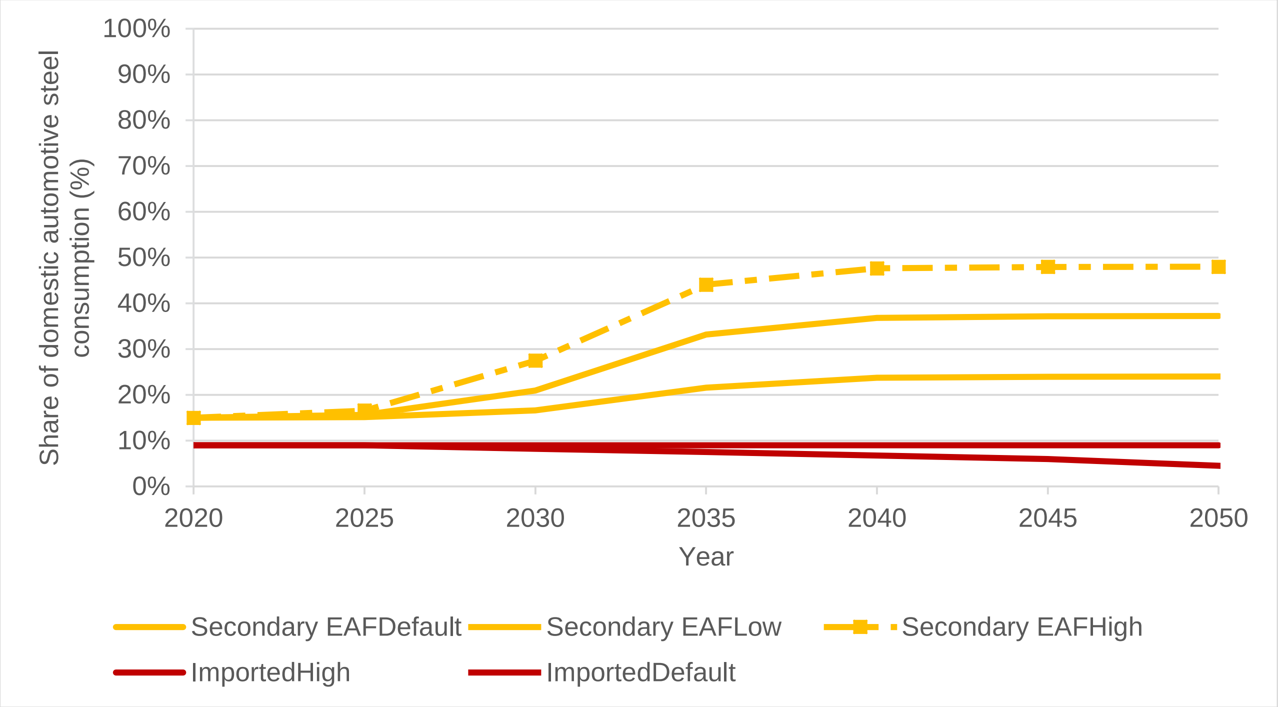
in the project. A High cost sensitivity for the H-DR steel technology pathway was produced by considering the high range of hydrogen production costs from the above sources.

The GWP projections for lower-carbon steel technologies were presented relative to the current emission factor for the primary BF-BOF pathway, taken to be 1.8 tCO_2e/t steel in 2020 (Ecoinvent, 2023). Using the emission factors available from the literature and Ricardo internal analysis, a low, default and high emission reduction for each steel technology was projected from 2020-2050.

4.1.1.2 *Secondary EAF and Imported steel sensitivities*

In addition, Low, Default and High sensitivities for Secondary EAF and Imported (excluding low) steel projections were provided in the model. For Secondary EAF steel, the Default share sensitivity increases from the initial value of 15% in 2020 to 37% of domestic steel production in 2050, corresponding to the volume of steel available from vehicle removals by 2050.[19] The high Secondary EAF uptake trajectory assumes that automotive demand reaches 48% by 2050, representative of the current Secondary EAF share of European steel production capacity, and a low trajectory assumes half (24%) of this uptake, see Figure 4-4. For Imported steel shares, the Default sensitivity assumes that the automotive sector halves from an industry-wide representative imported share of 9% total automotive steel demand in 2020 to 4.5% in 2050, with the High imported steel share sensitivity maintaining a constant 9% share between 2020-2050, see Figure 4-4.

Figure 4-4: Default, Low and High model sensitivities for Secondary EAF and Imported steel domestic automotive demand projections, 2020-2050 (EU27)



4.1.1.3 *Mass sensitivities*

Under the Default mass sensitivity, the steel content across all vehicle types is projected to reduce between 2020-2050 due to the effects of vehicle lightweighting, such as the replacement of heavier steel components with lighter alloy or polymer composite alternatives and an overall reduction in vehicle weight, see Section 2.1. An additional Constant mass sensitivity was developed to allow analysis of the impacts of the lower-carbon steel scenarios with no change in vehicle steel content from 2020 levels between 2020-2050. Figure 4-5 shows the Default and Constant mass sensitivities for an average BEV and non-BEV passenger car between 2020-2050.

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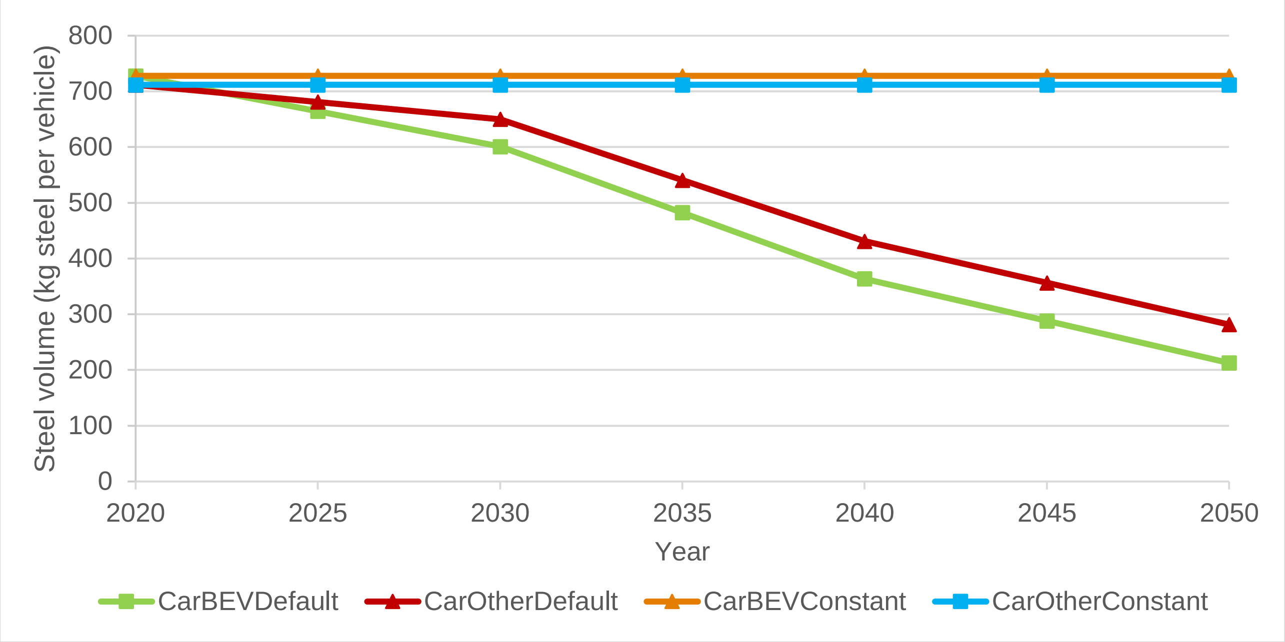
[19] The Default recycled sensitivity is based off the amount of steel available from EoL vehicles, which assumes that: (1) 100% of scrap steel from EoL vehicles will be recovered and reused in the automotive sector by 2050, which is realistic but ambitious due to current inefficiencies in the recovery and recycling; (2) there will be increased competition from other industrial and non-industrial sectors for recycled steel as the steel industry as a whole decarbonises, limiting the amount of recycled steel from other scrap sources that is available for the automotive sector.

Figure 4-5: Default and Constant mass sensitivities for an average BEV and non-BEV passenger car between 2020-2050



4.2 IMPACTS ON EMISSIONS

4.2.1 Total automotive steel emissions

Both lower-carbon steel scenarios provide significant GWP savings compared to the current automotive steel supply, achieving a 95% reduction by 2050 compared to the 2020 automotive steel GWP. The Ambitious scenario delivers larger annual GWP reductions earlier in the study period compared to the Baseline scenario, due to faster uptake of lower-carbon steel in EU27 vehicle production between 2025 and 2035. For total automotive steel from all new vehicle[20] production across the EU27, the Ambitious scenario achieves an emission reduction of 46% by 2030, 78% by 2035, 89% by 2040, and 93% by 2050, compared to the initial 2020 value. The Ambitious scenario achieves an annual emission reduction compared to the Baseline scenario of 7 $MtCO_2e$ (23% reduction) by 2030, 8.5 $MtCO_2e$ (47% reduction) by 2035, and 2 $MtCO_2e$ (29% reduction) by 2040, before the two scenarios converge to the same annual GWP by 2050, see Figure 4-6.

If as an alternative we consider a constant steel content for vehicles (although lightweighting is the anticipated trend), the two scenarios reveal a notable disparity in emissions between 2025 and 2040, gradually converging thereafter. In this case the potential for GHG reduction resulting from green steel in the ambitious scenario is significantly greater than for the default assumptions – more than double by 2035 (reducing in later periods).

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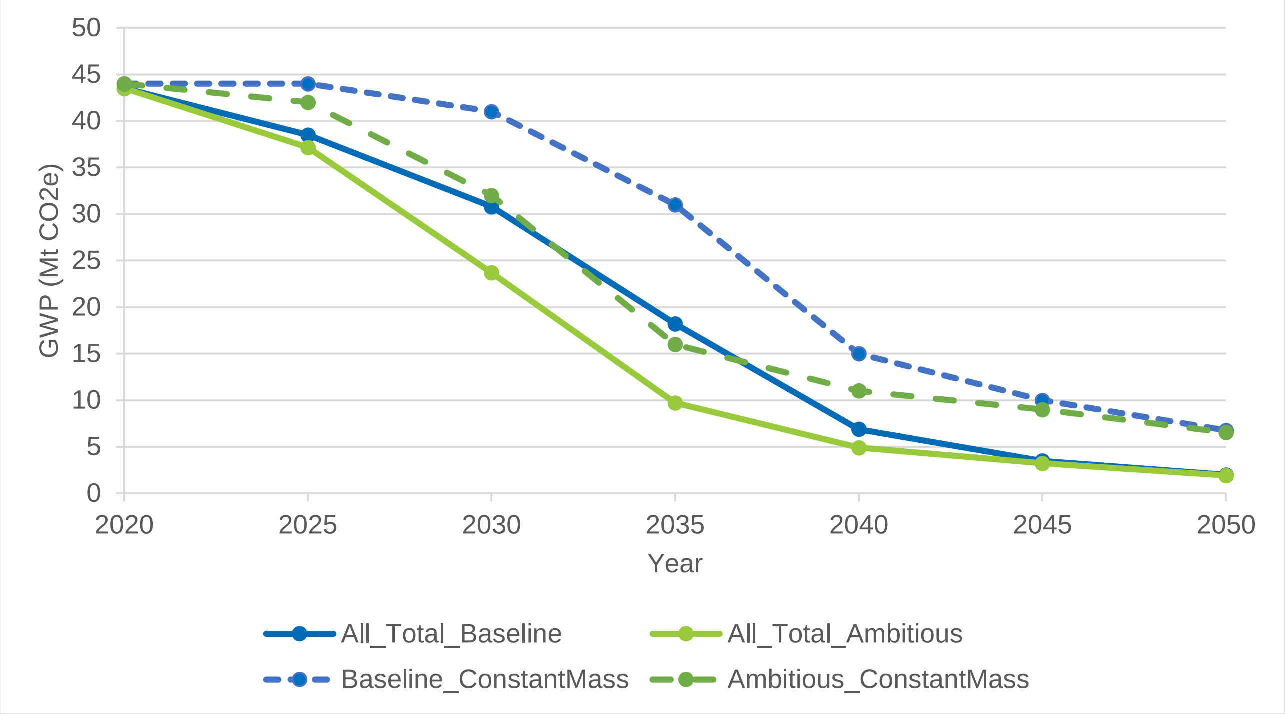
[20] The vehicles covered within the scope of this project are passenger cars, vans, rigid lorries, articulated lorries (tractor-trailers), buses and coaches, with indicative segments used for each vehicle type. In the case of the passenger car, the steel content is averaged between lower medium and SUV segments to better reflect the vehicle's average steel content.

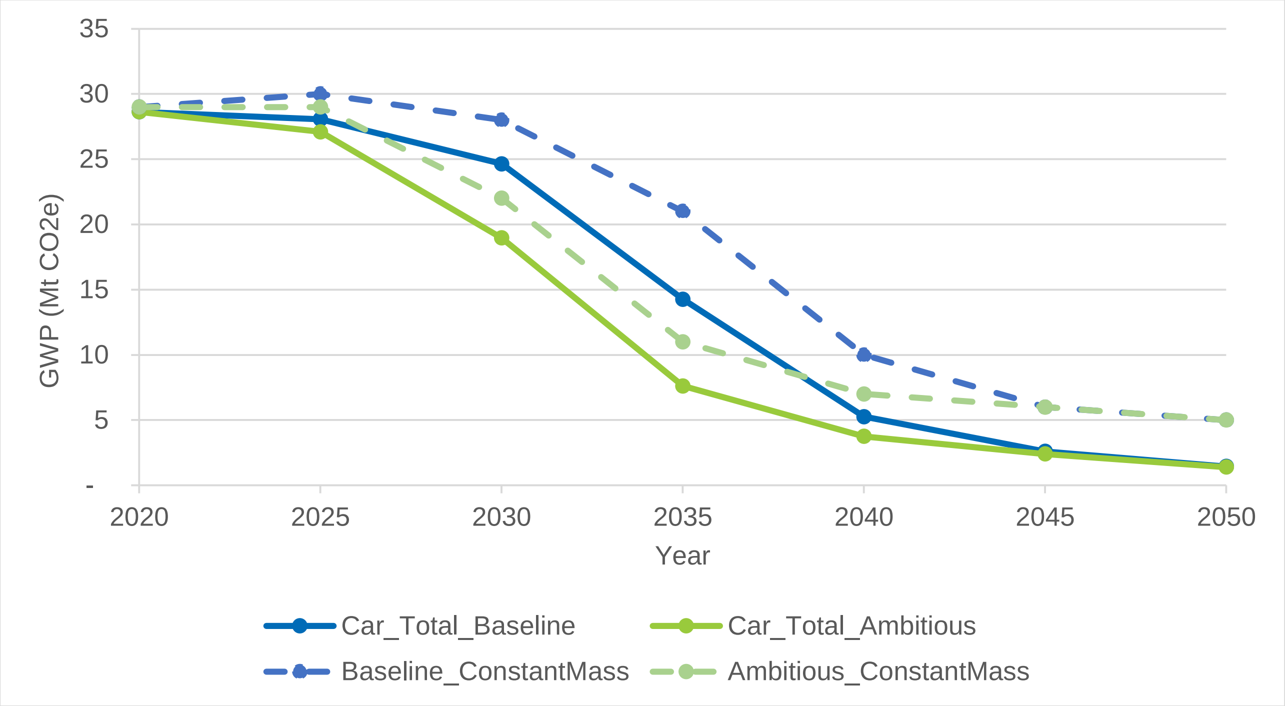
Figure 4-6: Annual GWP from steel for all new vehicles across EU27 under the Baseline and Ambitious scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

Production of passenger cars has the largest contribution to total automotive steel GWP of all vehicle types, with nearly 70% of total emissions in 2020 from this vehicle segment. The total GWP for passenger car production under the two scenarios follows a similar trend to the GWP of all vehicles, see Figure 4-7.

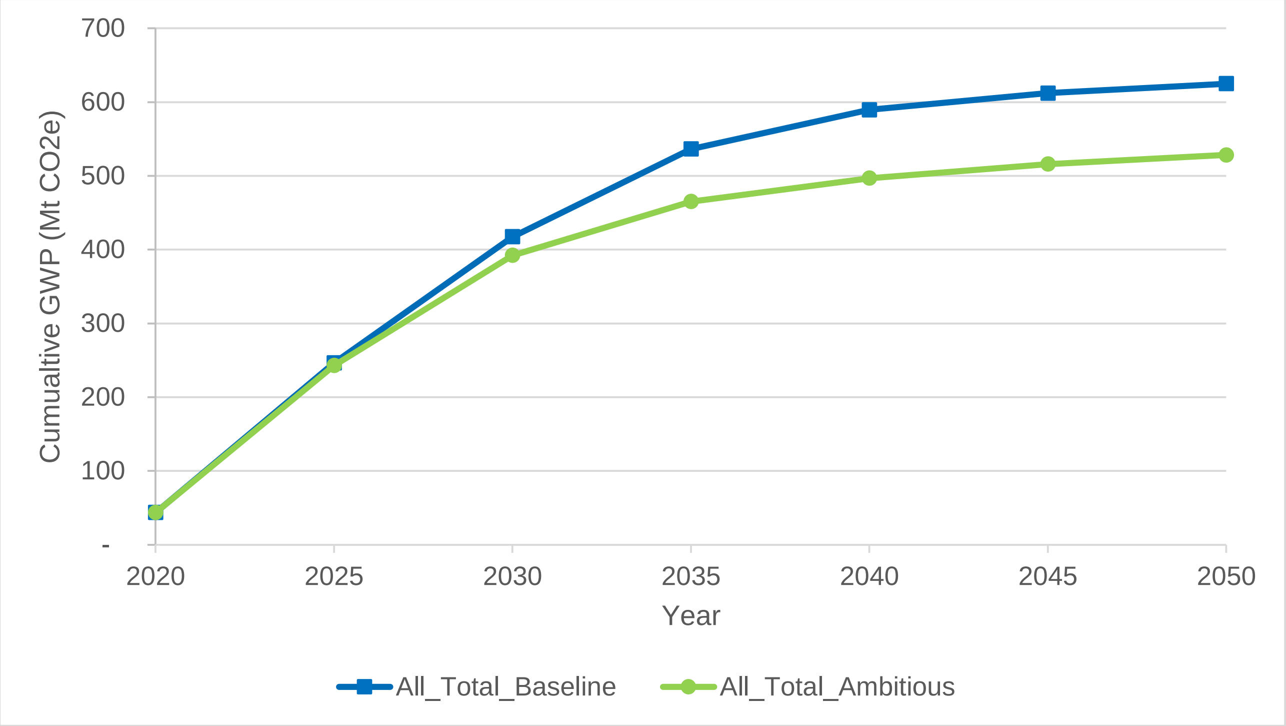
Figure 4-7: Annual GWP of steel of new passenger cars across EU27 under the Baseline and Ambitious scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

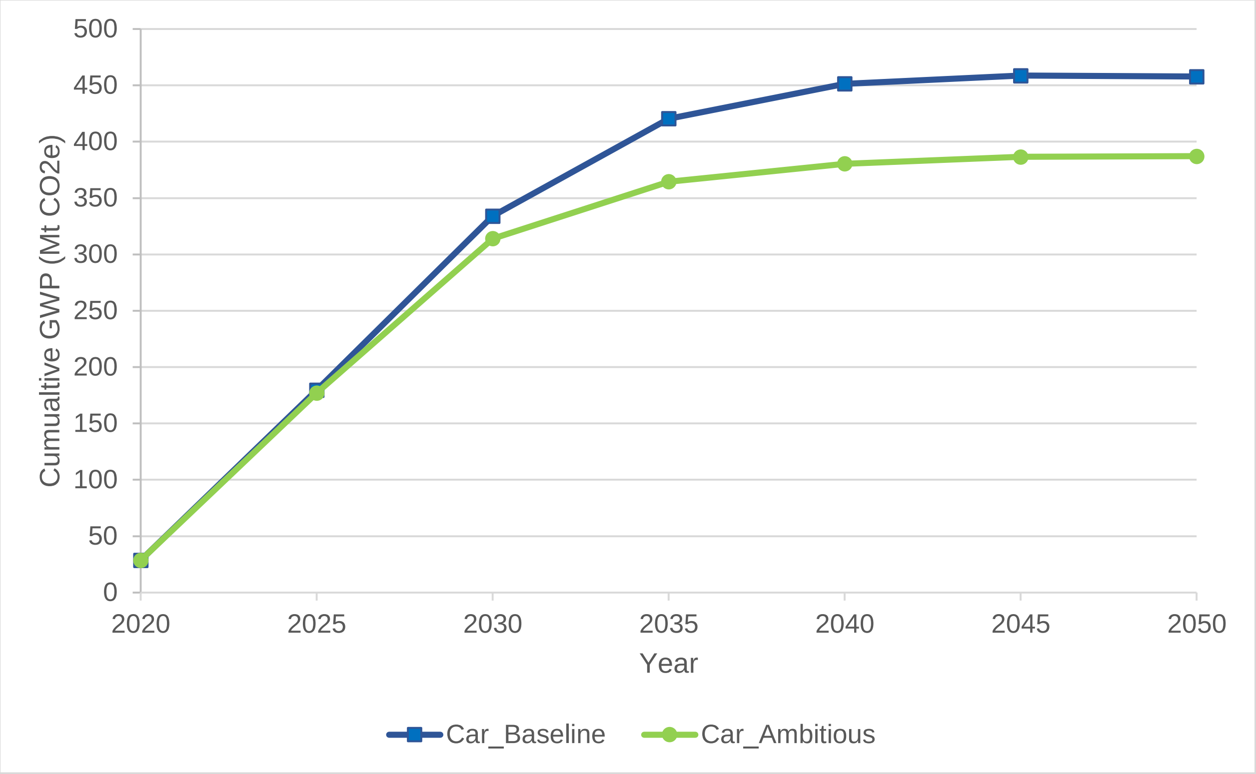
Figure 4-8 and Figure 4-9 shows the cumulative total amount of CO_2e from the production of steel for the automotive industry, at fleet level for all vehicles and for only passenger cars respectively. Between 2020 and 2050, the Ambitious scenario for all vehicles produces cumulative emissions of nearly 530 $MtCO_2e$, creating cumulative GWP savings of nearly 100 $MtCO_2e$ compared to the Baseline scenario over the same period. Hence, 100 $MtCO_2e$ is the total amount of CO2e emissions saved by 2050 from pursuing a faster adoption of lower-carbon, and particularly “green” H-DR, steel in the automotive sector for all vehicles. For the segment of passenger cars, nearly 70 $MtCO_2e$ is the total amount of CO2e emissions saved by 2050 from pursuing a faster adoption of lower-carbon steel.

Figure 4-8: Cumulative GWP of the steel used in new vehicles across EU27 under the Baseline and Ambitious scenarios (all vehicles), 2020-2050



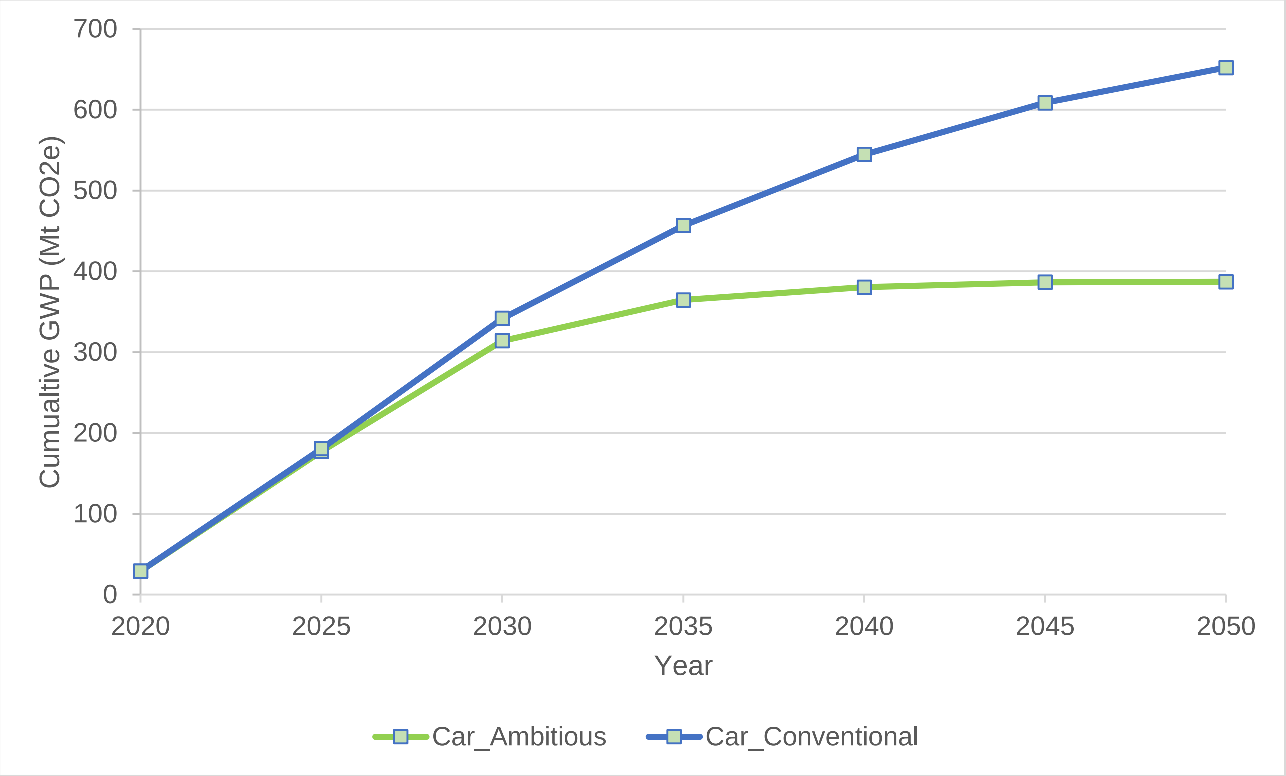
Source: Ricardo modelling analysis for this project

Figure 4-9 Cumulative GWP of the steel used in new passenger cars across EU27 under the Baseline and Ambitious Scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

Figure 4-10 Cumulative GWP of the steel used in new passenger cars across EU27 under the Conventional and Ambitious Scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

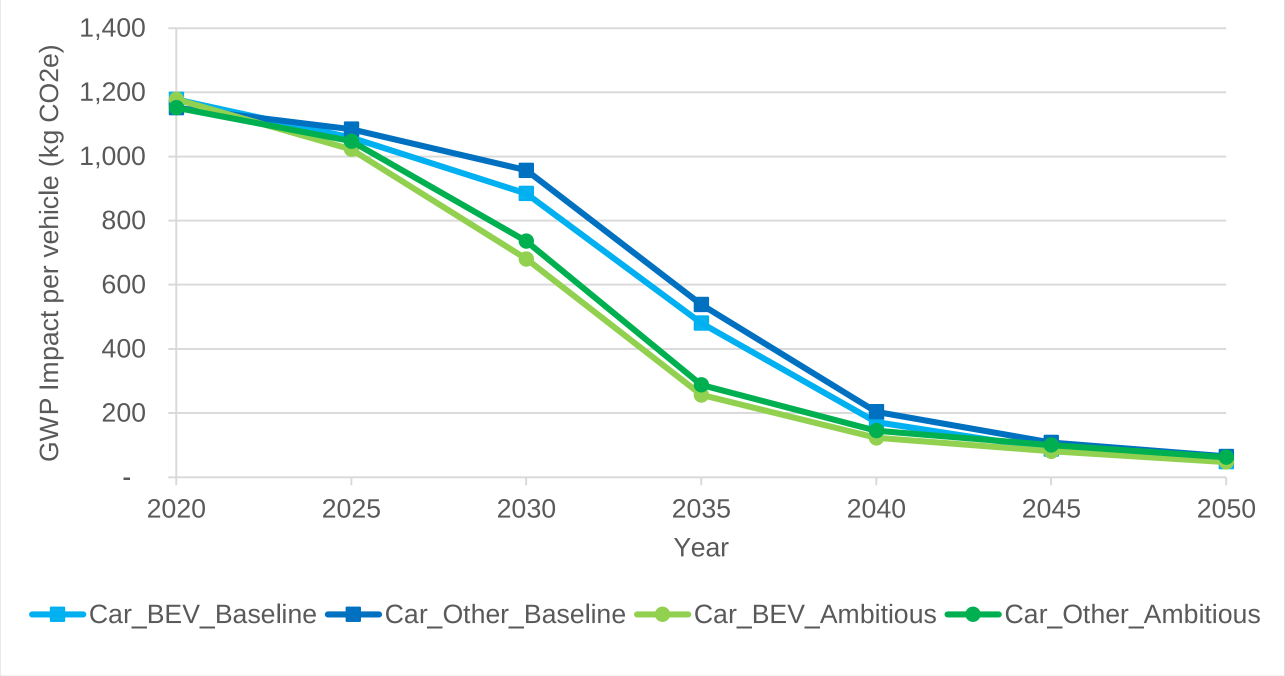
4.2.2 Vehicle steel content emissions

At the vehicle level, the impact on emissions of the lower-carbon steel scenarios vary slightly between powertrains due to the differences in steel content for BEV and non-BEV powertrain types. For passenger cars, vehicles with identical powertrains initially exhibit a similar decrease in GWP between 2020 and 2025. This is primarily attributed to the variance in steel content reductions among different vehicle powertrain types, which outweighs the disparity between the initial GWP reductions under the Baseline and Ambitious scenarios. The GWP associated with steel in BEVs experiences a more pronounced decrease between 2020 and 2030 compared to other vehicle powertrain types, such as ICEVs. This trend is primarily attributable to the underlying Default mass sensitivity assumption of greater application lightweighting in BEVs (to partially offset increased mass due to the battery) relative to ICEVs, resulting in a greater reduction in the overall steel usage per BEV.

However, from 2030 onwards, vehicles with the same powertrains diverge as the difference in GWP reductions between the lower-carbon scenarios increases, with the Ambitious scenario delivering faster decarbonisation of steel content than the Baseline scenario. In 2040, under the Ambitious scenario, passenger car steel content for BEV and non-BEV powertrains has a GWP of 123 $kgCO_2e$ and 145 $kgCO_2e$ respectively, representing a reduction of 79% from the Conventional scenario and 29% reduction from the Baseline scenario, see Figure 4-11.

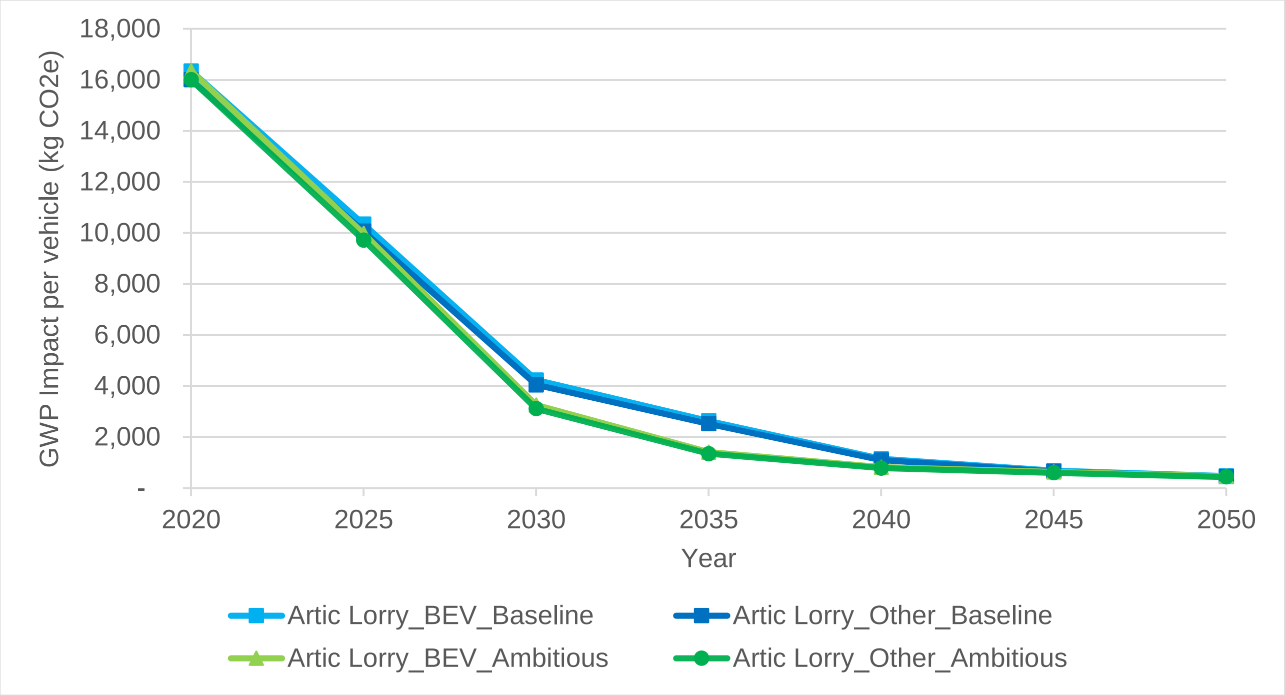
Articulated lorries follow a similar trend to passenger cars, with initial GWP reductions for both scenarios driven by a steep decline in steel content in articulated lorries between 2020 and 2030, see Figure 4-12. Compared to the Conventional scenario, the Ambitious scenario results in a reduction of steel content GWP of 30% by 2030 and 79% by 2040, and the Baseline scenario results in a reduction of 9% by 2030 and 70% by 2040, see Figure 4-12.

Figure 4-11: GWP of steel content in passenger cars, split by BEV and other powertrains, 2020-2050



Source: Ricardo modelling analysis for this project

Figure 4-12: GWP of steel content in articulated lorries, split by BEV and other powertrains, 2020-2050



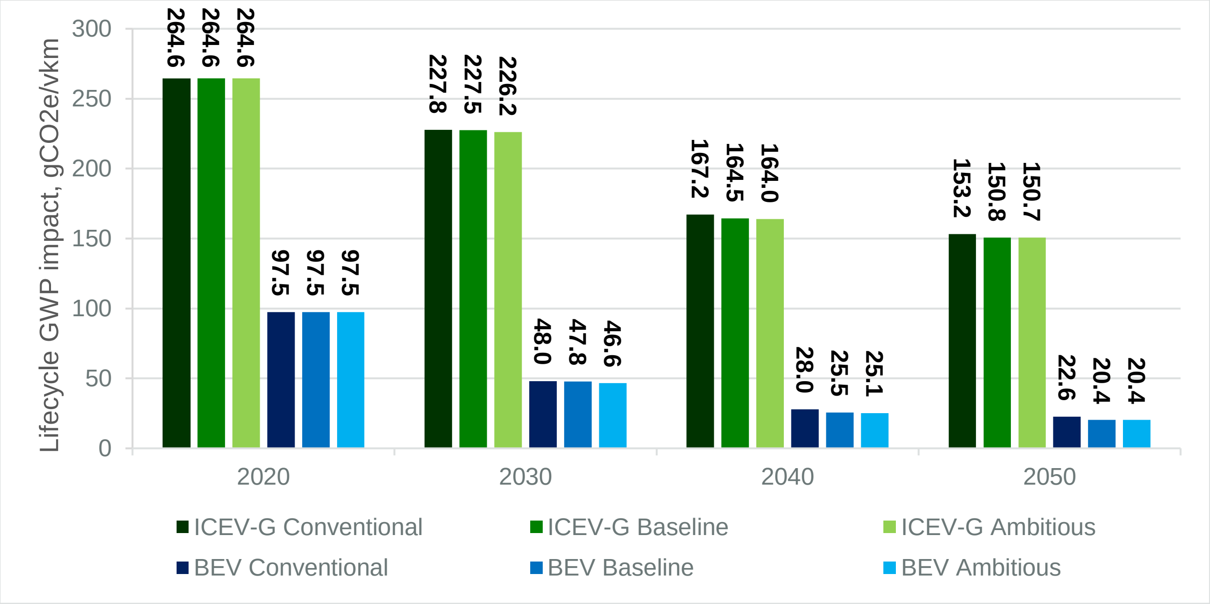
Source: Ricardo modelling analysis for this project

Figure 4-13 and Figure 4-14 below provide an illustration of the whole lifecycle impacts of the different lower-carbon steel scenarios for passenger cars and articulated lorries. Whilst overall GWP savings are significant from the fleet and vehicle steel production perspective, it can be seen that from a vehicle lifecycle perspective the improvements are relatively small in proportion to the entire footprint over a vehicle's operational lifetime. This is due to a combination of steel production being a smaller share compared to other lifecycle impacts (but a larger share for BEVs due to no tailpipe emissions – just over 10% in 2020), as well as anticipated shifts to lighter vehicle designs in the future using less steel (see Section 2.1). For further information on the contribution of steel manufacturing to overall vehicle lifecycle emissions, see Appendix 3.

In particular, for a BEV passenger car, lifecycle emissions are projected to decrease by around 77% between 2020-2050 under the Conventional scenario, due to steel content reduction. However, the adoption of lower-carbon steel under the Baseline and Ambitious scenarios is responsible for around 0.4% and 2.2% (respectively) in the overall lifecycle emissions by 2030 and by around 7% reduction in the overall lifecycle emissions by 2050 (for both lower-carbon scenarios).

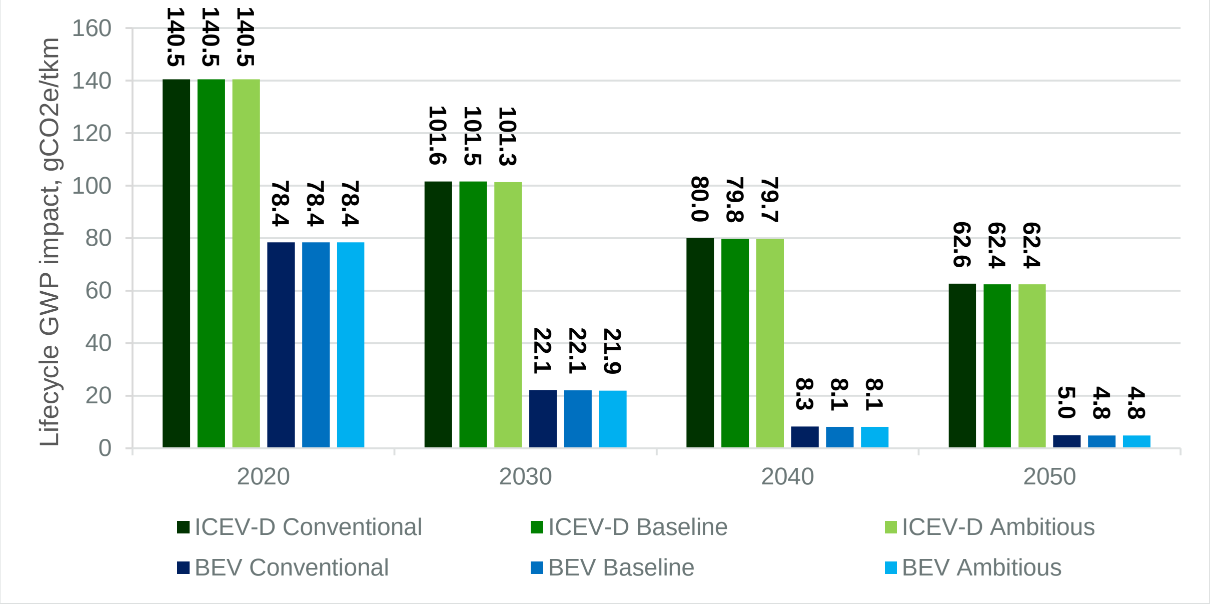
Note that it is expected that the sale of new ICEVs in the EU27 will be phased-out by 2035, meaning that the GWP impact of this vehicle powertrain can be disregarded for 2040 and later years.

Figure 4-13: Lifecycle GWP impacts for Lower Medium Cars for different Green Steel scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

Figure 4-14: Lifecycle GWP impacts for Articulated Lorries for different Green Steel scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

4.3 IMPACTS ON COST

Greater automotive demand for lower-carbon steel is projected to increase the cost of steel content in vehicles in the short term relative to steel content under the Conventional scenario, before becoming more affordable by 2040 as lower-carbon steel infrastructure becomes widely available and costs for key feedstocks for lower-carbon steel (such as renewable electricity and hydrogen) reduce. In the analysis that follows, unless otherwise stated, sensitivities for the cost of lower-carbon steel production pathways are set to Default projections, as detailed in Section 4.1.1.

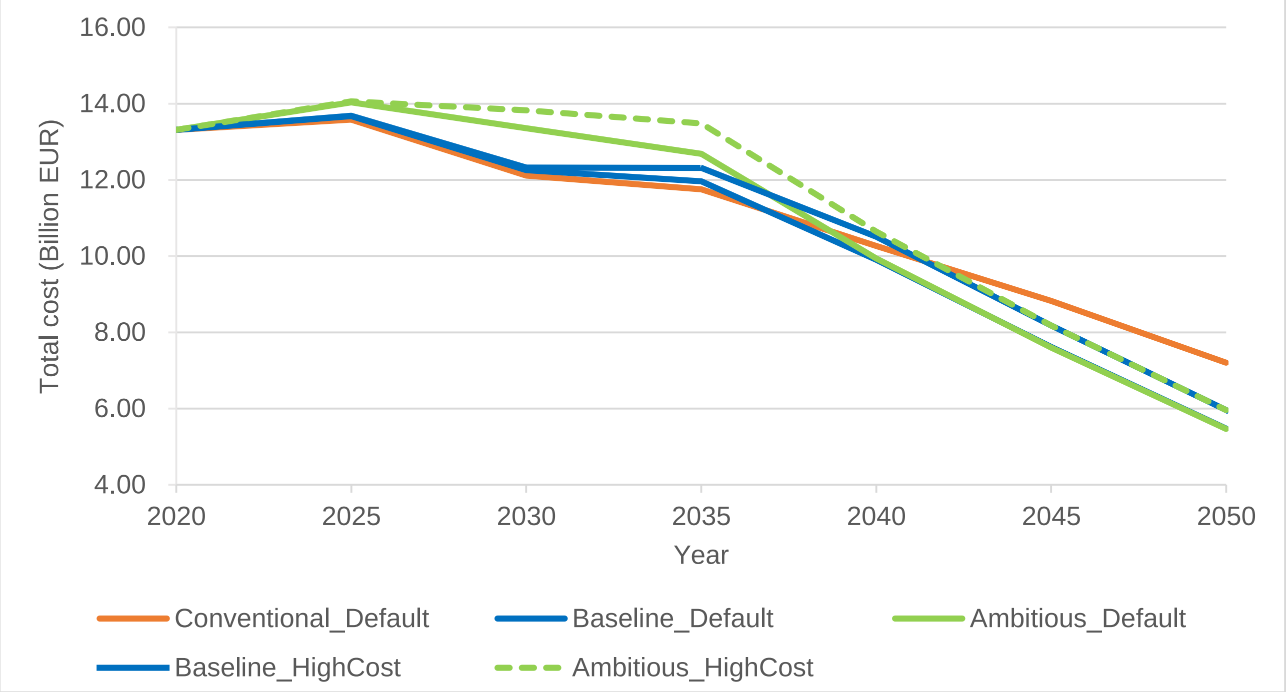
4.3.1 Total automotive steel costs

Figure 4-15 shows the total annual cost for automotive steel under the Baseline and Ambitious scenarios, which reach peaks of €13.7 billion and €14.0 billion respectively in 2025, with the Ambitious peak 2.5% higher than the Baseline scenario. Between 2025 and 2050, the total steel cost for both scenarios' plateaus and declines, with total cost for automotive steel under both scenarios reaching around €5.5 billion by 2050. The rapid reduction in automotive steel costs under both lower-carbon steel scenarios between 2025 and 2050 is driven by a combination of falling lower-carbon steel unit production costs and a decline in the overall steel content in vehicles between 2020 and 2050 (see Section 2.1). Although steel cost under both scenarios is initially higher than the Conventional scenario, the Baseline and Ambitious costs fall below the Conventional cost by 2040 for both, see Figure 4-16. By 2040, the Baseline and Ambitious scenarios create €364 million and €330 million of annual cost savings respectively compared to the Conventional scenario, increasing to annual savings of around €1.2 billion by 2045 and €1.7 billion by 2050 for both lower-carbon steel scenarios.

Considering the High cost sensitivity[21] for the primary lower-carbon steel production technologies (see Section 4.1.1.1), the Ambitious scenario reaches a peak of €14.1 billion in 2025, with an increase over the default cost Ambitious scenario of 3% in 2030 and 7% increase in 2040, see Figure 4-15. This increase is due to the higher cost and early uptake of steel from Green H-DR which occurs under the high cost Ambitious scenario. The High cost Baseline scenario remains largely unchanged from the Default Baseline in early years, with an increase in costs between 2035 and 2050 as the share of steel from Green H-DR increases.

Compared to the Conventional scenario with Default costs, the High cost Ambitious scenario reaches a peak cost difference of €1.7 billion between 2030-2035, or around 3 times higher than the Baseline scenario, with a gradual decline to achieve a cost reduction versus Conventional by 2045. Similarly, the cost difference for the High cost Baseline scenario remains above the Conventional until 2045, with a peak of €560 million in 2035. Both scenarios reach cost reductions of €1.2 billion by 2050 for the High cost sensitivity, 28% lower than the reduction under Default costs.

Figure 4-15: Fleet-level cost of Green Steel scenarios for EU27 (all vehicles), 2020-2050



Source: Ricardo modelling analysis for this project

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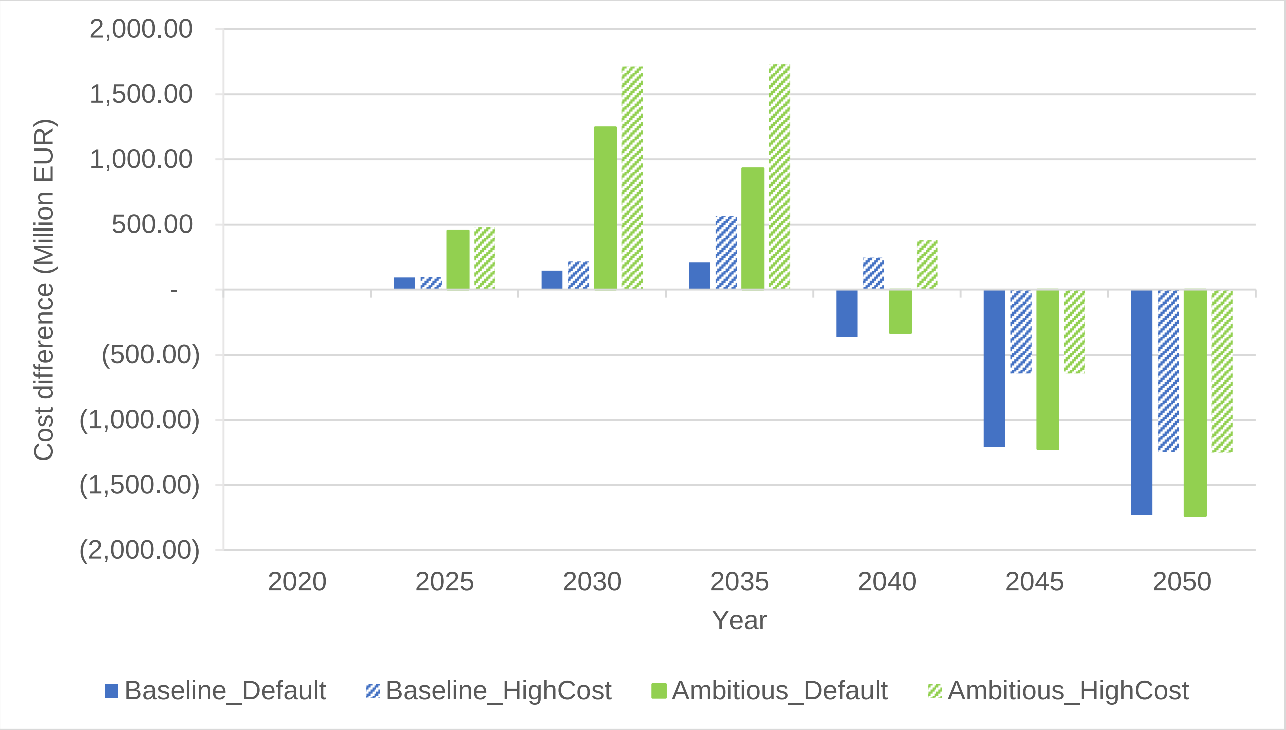
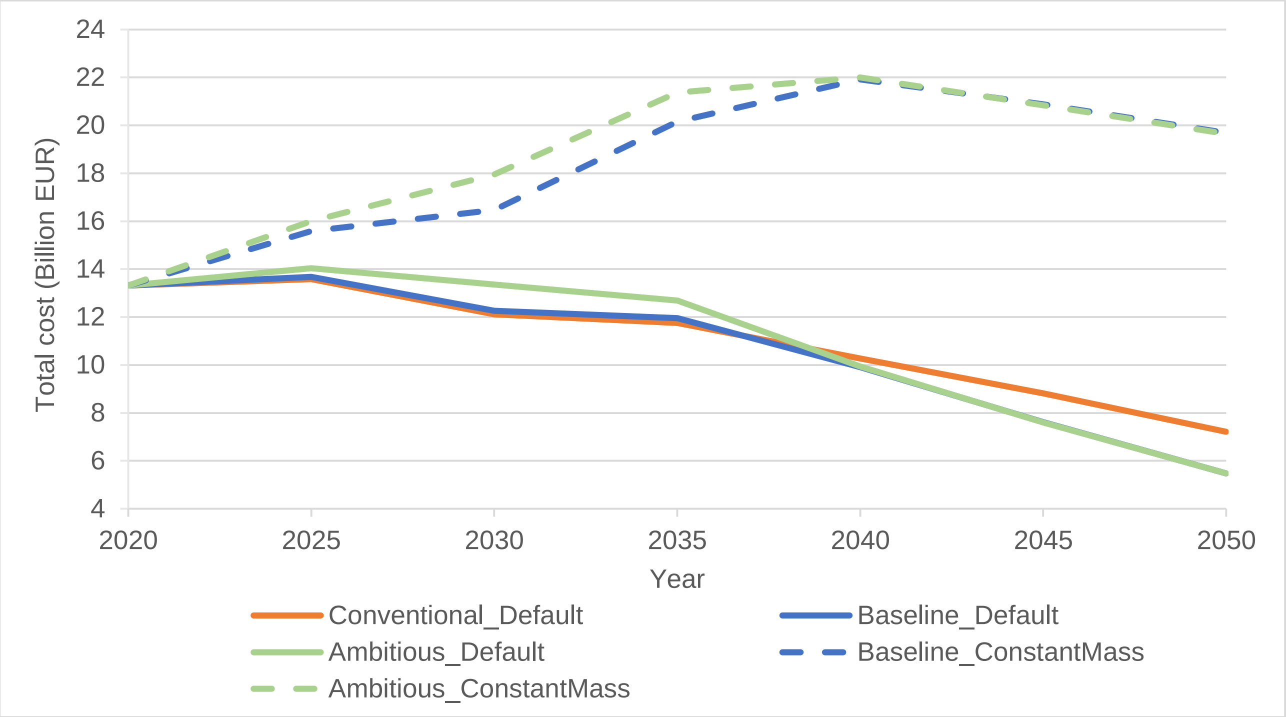
[21] Sensitivities in a forecasting model refer to the variations or changes in the model's output resulting from adjustments made to certain input variables or assumptions. In this project, sensitivities are included for Cost (Default, Low and High), GWP (Default, Low and High), Recycled steel share (Default, Low and High) and Imported steel share (Default, Low and High). See a 4.1.1 for further details.

Figure 4-16: Fleet-level cost difference between Green Steel and Conventional scenarios for EU27, 2020-2050



Source: Ricardo modelling analysis for this project

Figure 4-17 Sensitivity on steel content on the fleet-level cost of Green Steel scenarios for EU27 (all vehicles), 2020-2050



Source: Ricardo modelling analysis for this project

We also observe the impact of the vehicle lightweighting trend on the cost of their steel content. Assuming a constant steel content, the cost of total fleet steel content increases until 2040 (due to increasing size of the European fleet/production), after which it begins to decrease due to advancements in manufacturing technology. In the Default scenario, where lightweighting is expected, the total cost of steel content for vehicles begins to decrease fleet-wide starting from 2025.

4.3.2 Vehicle steel content costs

At the vehicle-level, the cost for steel content in an average[22] passenger car and articulated lorry under the Conventional, Baseline and Ambitious scenarios are shown in Figure 4-18 and Figure 4-19Figure 4-19, respectively. An additional trend is included assuming 100% green hydrogen DRI steel. Both Default and High-cost sensitivities are included for all lower-carbon scenarios.

4.3.2.1 Passenger car

For passenger cars, total cost of vehicle steel content under both the Baseline and Ambitious scenarios reaches a peak in 2030 and declines thereafter, see Figure 4-18.

The Baseline scenario shows a small increase from 2020 costs between 2025 and 2030, reaching a peak total cost of vehicle steel content of €443 in 2025 before declining in line with the Ambitious scenario to around €165 total cost of vehicle steel content by 2050. However, there is no cost difference for passenger car steel content between the Baseline and Conventional scenarios between 2020-2030, with the Baseline scenario delivering a cost saving of €10 per vehicle by 2040 and €52 per vehicle by 2050.

The Ambitious scenario has a peak in total cost of vehicle steel content of €462 per vehicle in 2030, representing a 13% increase on 2020 steel costs, before falling to around €165 per vehicle by 2050, same as for the Baseline scenario. The cost difference between the steel content under the Ambitious and Conventional scenarios peaks in 2030 at €43 per passenger car (due to faster uptake of lower-carbon steel than the Baseline) and reduces between 2030-2050 to deliver a cost saving of €10 per vehicle by 2040 and €52 per vehicle by 2050.

For an average passenger car using 100% steel from the green H-DR-EAF pathway, the steel content cost is higher than both the Baseline and Ambitious scenarios between 2020-2050, with a total cost of steel content of €524 per vehicle (25% higher than conventional steel and 23% increase compared to the Baseline) in 2030 and total cost of steel content of €284 per vehicle (7% lower than conventional steel and 3% decrease compared to the Baseline) in 2040.

Considering the High range of lower-carbon steel costs, the steel cost difference for passenger cars to the Conventional scenario for the Baseline scenario reaches €7 in 2030 and peaks at €17 per vehicle in 2035, and peaks for the Ambitious scenario at €59 per vehicle in 2030 before reducing slightly to €55 in 2035. The cost differences for both lower-carbon steel scenarios reduce to cost savings by 2050 of €37 per vehicle.

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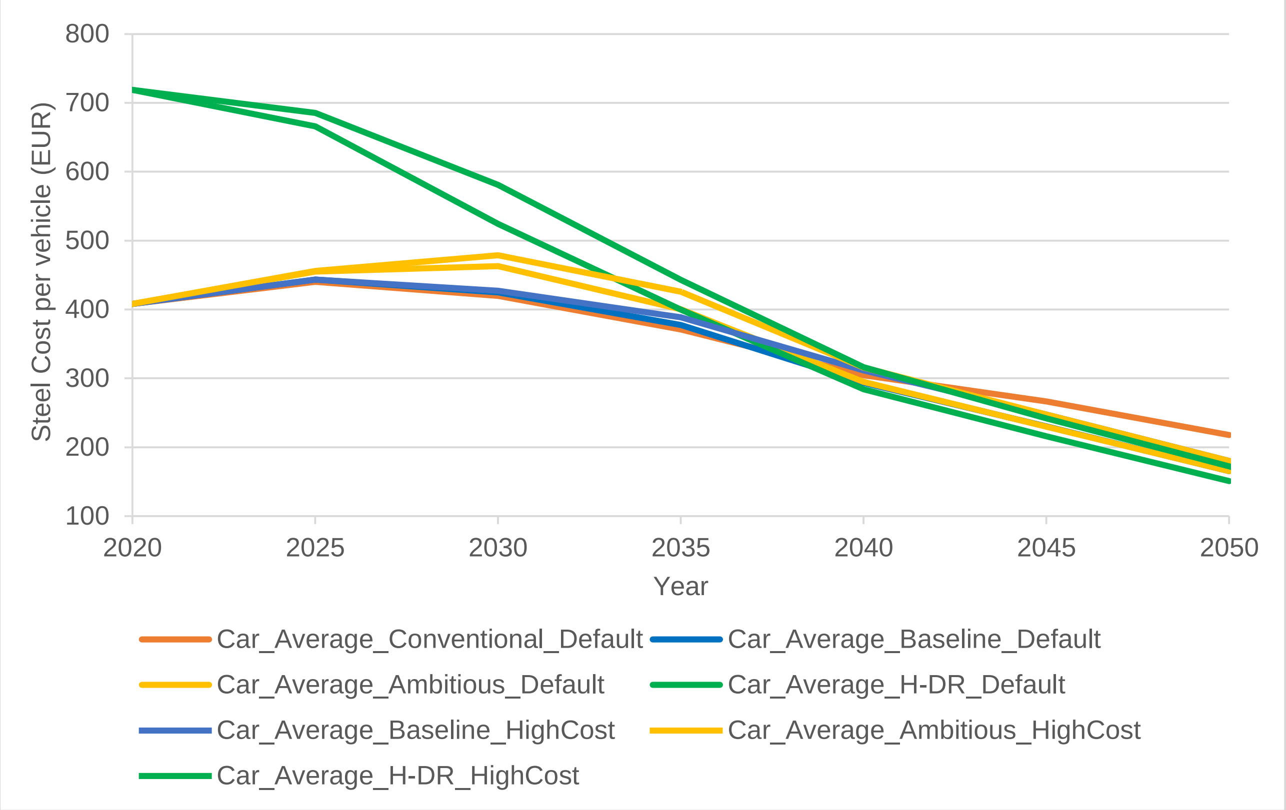
[22] The average powertrain's steel content for a given year was found by using a weighted average of the steel content for BEV and non-BEV powertrains alongside projections for the share of vehicle sales by powertrain between 2020 and 2050.

Figure 4-18: Cost of steel content in an average passenger car under a Conventional, Baseline, Ambitious and 100% H-DR steel content mix with Default and High cost sensitivities, 2020-2050



Source: Ricardo modelling analysis for this project

4.3.2.2 Articulated lorry

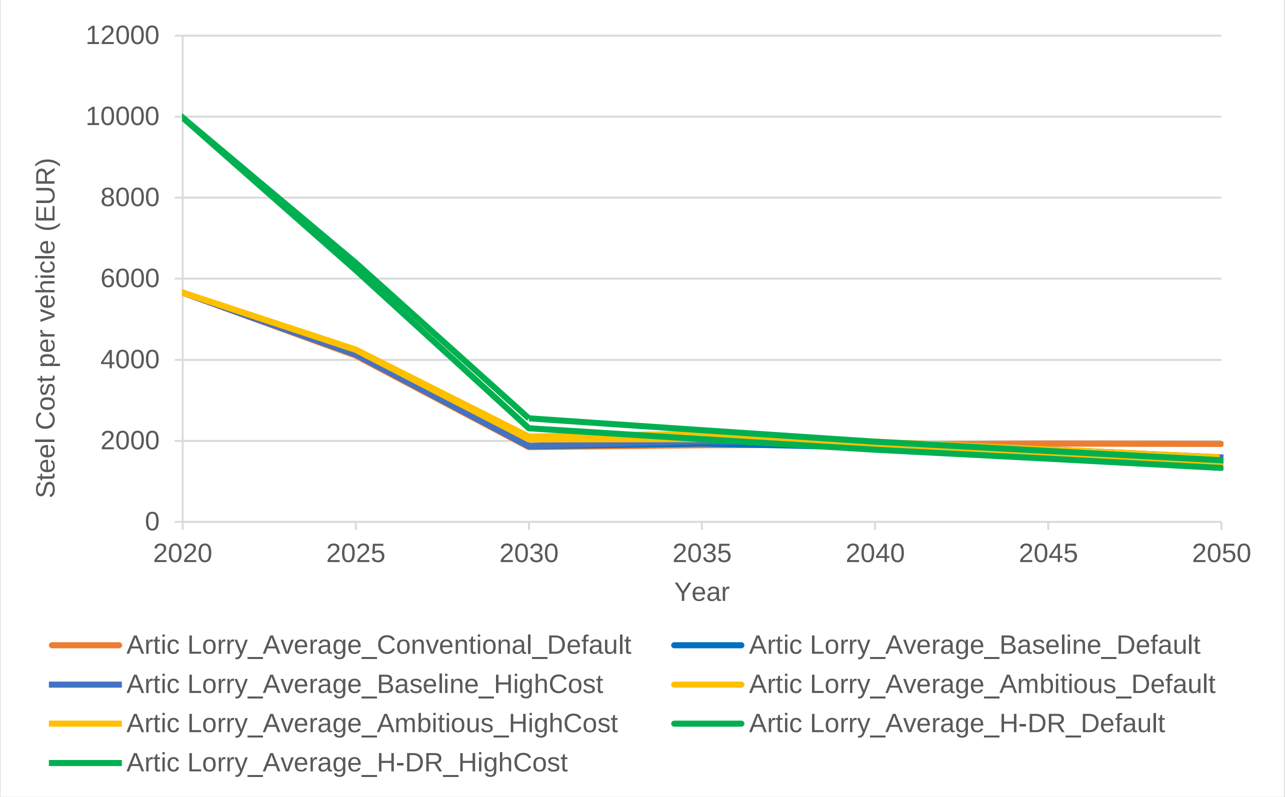
Figure 4-19 shows the projections for the cost of steel content in an average articulated lorry (tractor-trailer) for the Conventional, Baseline, Ambitious and 100% H-DR scenarios, with both Default and High cost sensitivities considered.

Due to the significant reduction in the steel content of articulated lorries projected between 2020-2030, the cost for vehicle steel content reduces despite an initial increase in steel production unit costs under each of the lower-carbon steel scenarios. Steel cost is projected to be €1,860 and €2,000 per vehicle under the Baseline and Ambitious scenarios respectively by 2030, reducing from around €5,600 in 2020. After 2030, the steel content costs continue to decline gradually, reaching €1,460 by 2050 for both lower-carbon scenarios. The cost difference of vehicle steel content under the Baseline scenario compared to the Conventional scenario remains near-zero between 2020-2030, with the Baseline scenario delivering cost savings of €70 by 2040 and €460 by 2050. Under the Ambitious scenario, the cost difference of vehicle steel content to the Conventional scenario reaches a peak of €190 per vehicle in 2030, before reducing to a cost saving of €270 by 2040 and €460 by 2050.

Similar to the Baseline and Ambitious scenarios, the cost of 100% green H-DR steel in articulated lorries is higher prior to 2030, reaching €2,300 in 2025, but reduces to below the Ambitious scenario by 2035 and below the Baseline scenario by 2040.

Considering the High range values for lower-carbon steel costs, the cost difference for articulated lorry steel content compared to the Conventional scenario peaks at €90 difference per vehicle under the Baseline scenario and at €280 difference per vehicle under the Ambitious scenario in 2035, before reducing to cost savings for both lower-carbon steel scenarios of €330 per vehicle by 2050. Hence, pursuing the Ambitious scenario with the High cost sensitivity results in a peak increase in the total cost of an ICE articulated lorry of less than 1% in 2030 compared to the a vehicle with Conventional steel content (ICCT, 2022).

Figure 4-19: Cost of steel content in an average articulated lorry under a Conventional, Baseline, Ambitious and 100% H-DR steel content mix with Default and High cost sensitivities, 2020-2050



Source: Ricardo modelling analysis for this project

In addition to the above comparison to the Conventional scenario, a comparison of the additional cost for the Ambitious scenario and 100% green H-DR steel content compared to the Baseline scenario can be considered to determine the vehicle-level cost of pursuing faster levels lower-carbon steel deployment in the automotive sector than current industry ambitions.

Figure 4-20 below shows the cost difference of vehicle steel content between the Baseline and Ambitious scenarios for passenger cars (top) and articulated lorries (bottom). The difference in production costs of steel content between the two lower-carbon scenarios peaks in 2030 for both indicative vehicle types, with the steel content under the Ambitious scenario being €38 higher per passenger car and €168 per articulated lorries than the Baseline scenario. However, the cost difference between Baseline and Ambitious scenarios quickly declines to near-zero by 2040. Considering the Ambitious scenario with High steel costs, the cost difference to the Baseline scenario peaks at €51 per passenger car and €227 per articulated lorry in 2030, and declines slightly to near-zero cost difference by 2045.

Figure 4-20: Difference in production costs of steel content between the Baseline and Ambitious scenarios for passenger cars (top) and articulated lorries (bottom), 2020-2050

Source: Ricardo modelling analysis for this project

Figure 4-21Figure 4-21 below shows the cost difference of vehicle steel content between the Baseline scenario and 100% green H-DR steel for passenger cars (top) and articulated lorries (bottom). The cost difference to the Baseline for steel produced from 100% H-DR is more significant in early years, with a €220 premium per vehicle for passenger cars and around €2,100 premium for articulated lorries in 2025. However, the cost difference between the Baseline and 100% green H-DR steel quickly declines, reaching near- cost parity with the Baseline by 2040 and small cost savings by 2050.

Figure 4-21: Difference in production costs of steel content under the Baseline scenario and “green” steel from green H-DR for passenger cars (top) and articulated lorries (bottom), 2020-2050

Source: Ricardo modelling analysis for this project

4.3.3 End-consumer retail price impact

The changes in production costs for lower-carbon steel in the period 2020-2050 is expected to be passed on by automotive OEMs to end consumers through changes to the retail price of vehicles. It is assumed that a change in steel cost under the lower-carbon steel scenarios versus the Conventional scenario will be passed on to consumers through an increase in the retail price with the addition of a 40% margin for passenger cars and 20% margin for commercial vehicles[23]. This additional cost margin is based on additional contributions to the retail price, including OEM profit, overhead costs, and taxes. Retail prices for each vehicle category in 2020 are used to determine the percentage change due to steel cost.

For both passenger vehicles (see Figure 4-22, top) and articulated lorries (see Figure 4-22, bottom), the steel cost increases between the Conventional and Baseline or Ambitious scenarios will lead to negligible retail price increases of less than 0.2% for BEV powertrains and near-zero for non-BEV powertrains between 2025-2035, with nearly 0% price difference in 2040 and small price savings between 2040-2050, reaching around 0.3% price reduction for BEVs and 0.1% for non-BEVs in 2050 for both vehicle types. The larger retail price increases in the non-BEV powertrains are influenced by the larger steel content found in ICE and other non-battery electric powertrain vehicles.

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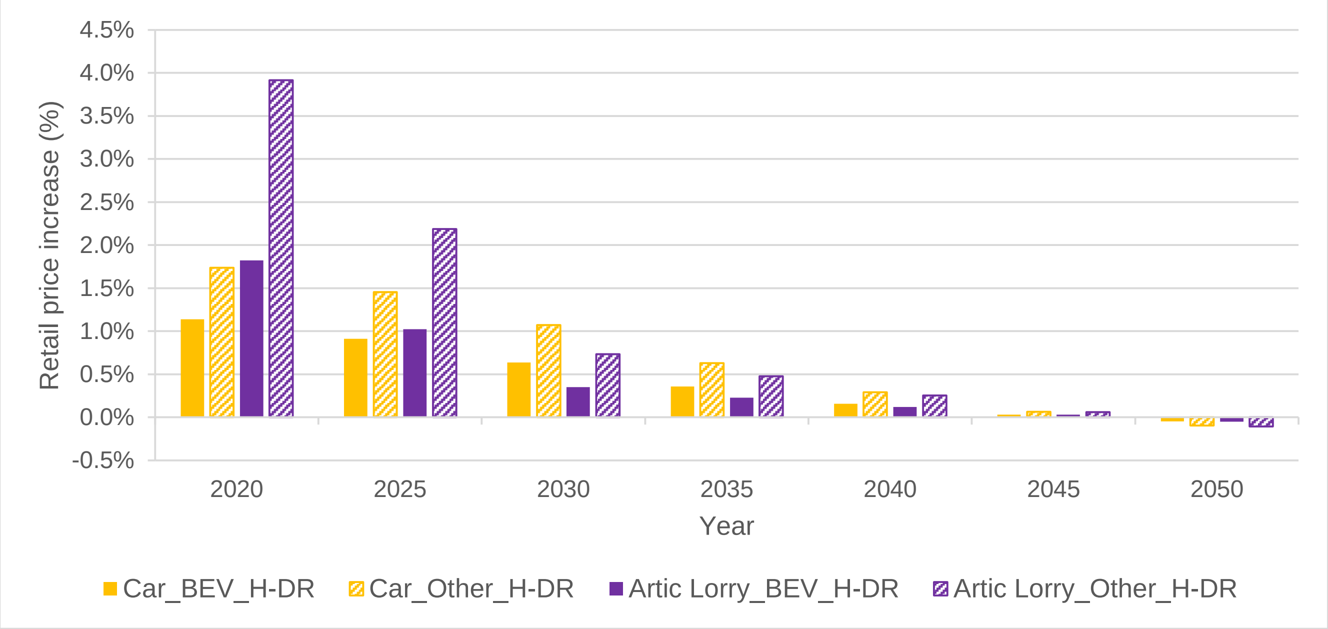
[23] From Ricardo analysis and consultation with industry stakeholders.

Figure 4-22: Retail price increase (%) for passenger cars (top) and articulated lorries (bottom) under the Baseline and Ambitious scenarios compared to Conventional steel content, 2020-2050

Source: Ricardo modelling analysis for this project

Adopting 100% of steel from the green H-DR pathway leads to slightly higher retail price increases of between 1-1.5% for passenger cars, and between 1-2% increase for articulated lorries, in 2025 compared to steel from the Conventional scenario, see Figure 4-23. However, this initial premium for 100% green H-DR steel decreases to 0.5% for articulated lorries and 0.1% for passenger cars in 2030, 0.2% for both vehicle types in 2040, before introducing price savings of less than 1% between 2040-2050 for both passenger cars and articulated lorries. As for the lower-carbon steel scenarios, the greater steel content in non-BEVs means that the retail price increase is greater for these vehicle powertrains, particularly in earlier years where steel content reductions from lightweighting is still limited and the cost of lower-carbon steel remains higher than conventional steel.

Figure 4-23: Retail price increase (%) for passenger cars and articulated lorries using 100% H-DR steel compared to Conventional steel content, 2020-2050



Source: Ricardo modelling analysis for this project

Therefore, **on an individual vehicle level, the impact of all lower-carbon steel scenarios on the retail price paid by consumers for vehicles is limited to less than a 1% rise in early years and a slight price reduction in later years due to a reduction in lower-carbon steel prices** relative to the Conventional scenario.

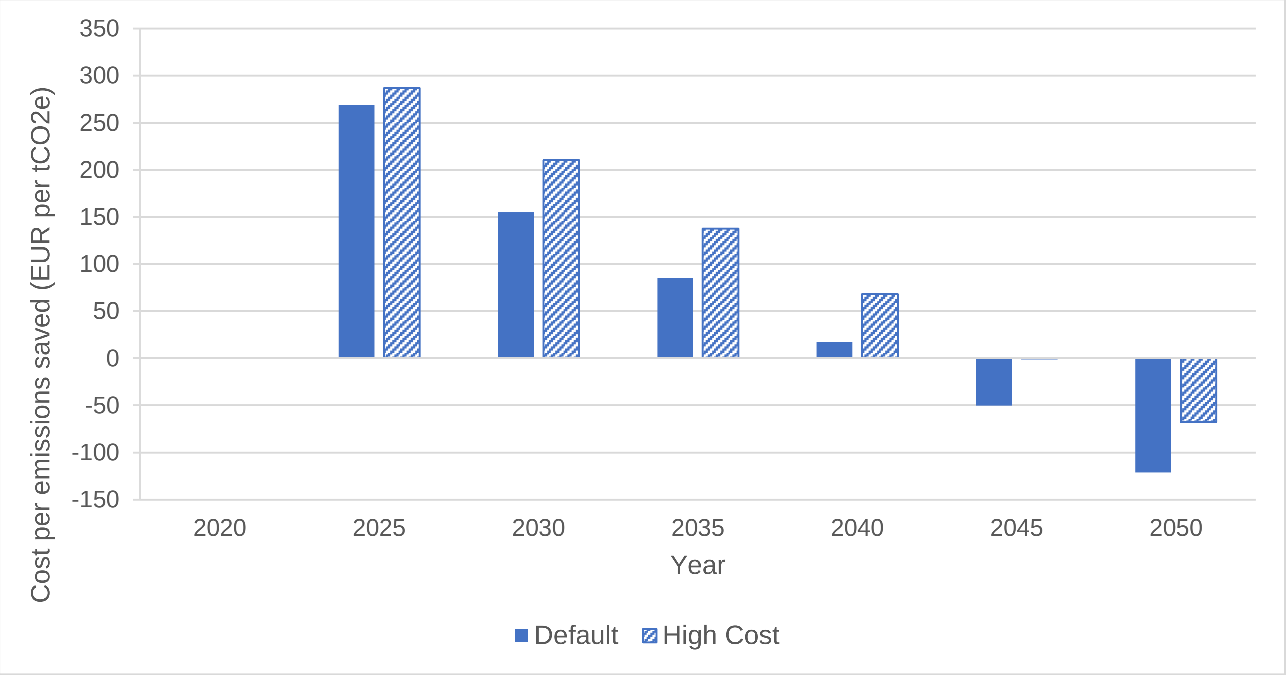
4.3.4 Abatement cost for the Ambitious scenario

Figure 4-24 compares the additional cost of steel under the Ambitious scenario relative to the Baseline with the subsequent emission reductions between the two scenarios. In 2025, the abatement cost to pursue the Ambitious scenario is €270 per tCO_2e. Moreover, as the Ambitious scenario becomes increasingly cost competitive with the Baseline scenario between 2025-2050, the abatement cost falls to €155 in 2030, €85 in 2035 and near-zero by 2050. With steel produced from the Ambitious scenario becoming more affordable by 2040 as lower-carbon steel production costs fall. After 2040, the Ambitious scenario reaches negative abatement costs, meaning that the more ambitious steel decarbonisation delivers a net economic gain between 2040-2050.

For the lower-carbon scenarios with High steel costs, the initial abatement cost is €287 per tCO_2e in 2025, before falling to €137 per tCO_2e by 2035 and negative costs by 2050.

In February 2023, the price of emissions allowances in the EU27 reached €100 per tCO_2e for the first time since the EU Emission Trading System was introduced (EMBER, 2023). As of October 2023, the carbon price has fallen slightly to around €80 per tCO_2e. Hence, **ensuring a carbon price above €150 per tCO_2e** (or around €200 per tCO_2e under High costs) **would allow the Ambitious scenario to be cost-competitive with the Baseline**, further incentivising European steel producers and automotive OEM consumers to pursue the faster steel decarbonisation pathway.

Figure 4-24: Cost per emissions saved under the Ambitious versus Baseline scenarios, 2020-2050



Source: Ricardo modelling analysis for this project

5. DISCUSSION AND CONCLUSION

During this project, the current and future market for green steel within the automotive sector has been characterised and the potential impacts on projected supply and demand of green steel on the automotive sector's decarbonisation targets quantified.

Two scenarios for the deployment of the identified lower-carbon steel pathways were developed: a Baseline scenario matching current automotive demand, informed by automotive OEM supply announcements; and an Ambitious scenario aligned with the highest decarbonisation targets in the automotive sector, achieving 50% lower-carbon steel by 2030. These two lower-carbon steel scenarios were compared to each other and a Conventional scenario assuming no change from production technologies for automotive steel in 2020.

Using projected costs and emissions of each steel production pathway from Section 3 and Ricardo expert analysis, the impact of the two lower-carbon steel scenarios were evaluated, both at the automotive industry level and at the vehicle level for indicative vehicle categories.

Steel costs under the Ambitious scenario were found to be higher than the Baseline between 2025 and 2035, with the cost difference for total automotive steel under the Ambitious scenario peaking at 2.5% (€300 million) above the Baseline scenario in 2030. This is due to a greater uptake of lower-carbon steel between 2025 and 2035 under the Ambitious scenario, with the cost of lower-carbon steel alternatives projected to remain higher than primary BF-BOF cost during this period. However, from 2040 onwards, the Ambitious scenario achieves cost parity and reductions relative to the Baseline scenario, due to the affordability of lower-carbon alternatives compared to primary BF-BOF after 2040. Under the High cost assumptions, the Ambitious scenario has a greater cost increase compared to the Baseline between 2025 and 2035 at both the vehicle and total EU27 fleet level, however, declines to near-zero cost difference by 2040.

At the vehicle-level, and for the average projected green steel costs, the cost difference between the Baseline and Ambitious scenarios was found to be small, reaching a peak increase of €14 per passenger car and €63 per articulated lorries in 2030 (€40 and €170 for the high-cost sensitivity, respectively). However, the initial cost increase under the Ambitious scenario rapidly declines to zero by 2040 and delivers cost savings by 2045, matching the trend of total automotive steel cost. Subsequently, the impact on end-consumer retail prices was found to be small, with smaller than 1% rise in total price projected for indicative vehicle types between 2025 and 2040 and around 1% decline in total retail price from after 2040 for both the Baseline and Ambitious scenarios compared to the price of steel under the Conventional steel pathway. In particular, the deployment of 100% "green" steel from the Green H-DR steel pathway in a passenger car results in a cost premium of 1.5% in 2025, 1% in 2030, and 0% of total retail price by 2040 compared to conventional steel content. Therefore, although "green" H-DR steel technology is more expensive in earlier years, its impact on overall vehicle cost is short-term, limited and quickly reduces to deliver cost savings in the medium term.

The potential GWP reduction by following the Ambitious scenario was found to be significant, with a difference in cumulative automotive steel GWP reduction by 2050 of 100 $MtCO_2e$ compared to the Baseline scenario, representing a 16% reduction in cumulative emissions from the Baseline. The Ambitious scenario achieves a GWP reduction of nearly 50% by 2030 and 90% by 2040 compared to 2020 levels. The automotive industry would need to follow the Ambitious scenario to play their part in the EU's climate ambition.

Similarly, the emission reductions at the vehicle level by 2040 are significant under the Ambitious scenario relative to conventional steel content, with passenger car steel GWP reducing by 89% compared to 2020 GWP and 79% compared to the Conventional steel scenario in 2040. The Baseline scenario provides a more gradual reduction in GWP, with an 80% reduction compared to 2020 GWP and 70% compared to the Conventional pathway by 2040. Hence, the Ambitious scenario achieves a reduction in the carbon intensity of the steel content of passenger cars of 28% GWP compared to the Baseline scenario by 2040. In particular, the deployment of 100% "green" steel from the Green H-DR steel pathway in a passenger car delivers a GWP saving of 93% in 2025, 94% in 2030, and 96% by 2040 compared to conventional steel content. Therefore, "green" H-DR steel technology is key to achieving rapid decarbonisation within the automotive steel sector.

Comparing the difference in average cost and GWP of both lower-carbon steel scenarios, the cost for emissions saved under the Ambitious scenario is €102 per tCO_2e (€200 per tCO_2e for high cost) in 2025, declining to below zero by 2040 as steel costs under the Ambitious scenario fall below the Baseline. Therefore, maintaining a carbon price for allowances in the EU ETS above €100 up to 2030 would make the production and consumption of automotive steel under the Ambitious scenario cost competitive with the Baseline.

An additional sensitivity on the future projected steel content in the vehicle was also conducted, as45umming that this remains constant in the future (instead of decreasing due to actions taken to reduce new vehicle mass to improve operational efficiency). This analysis showed, first, that the expected trend of vehicle lightweighting has a significant impact both on emissions and costs. In the case of GHG emissions, in the year 2035 where the highest gap is found, keeping the steel content constant, emissions are almost 50% higher than in the default scenario that considers the trend of lightweighting. In the assumption of the constant steel content, the potential for GHG reduction resulting from green steel in the ambitious scenario is significantly greater than for the default assumptions – more than double by 2035 (reducing in later periods). We also notice how the trend of vehicle lightweighting affects the cost of their steel components. If we assume a constant steel content, the overall cost of steel content for the entire fleet rises until 2040 (and hence the impacts of more ambitious green steel is amplified). However, after this point, it starts to decline. Anticipating vehicle lightweighting, the cost of the steel content used for the entire fleet starts decreasing in 2025.

In conclusion, this report has found that pursuing a high-uptake lower-carbon steel scenario compared to the current automotive demand would require minimal initial cost in the short-term whilst achieving a significant reduction in the GWP from automotive steel consumption. As such, the Ambitious scenario for lower-carbon automotive steel supply developed in this project would help to ensure that the automotive sector decarbonises in line with the EU's Fit for 55 and net zero targets for 2030 and 2050, whilst securing a strong green steel industry in Europe to support the automotive sector and wider economy in the future. Whilst announced European lower-carbon steel production capacity is expected to meet the demand from the automotive sector, some policy interventions, such as increased carbon pricing for steel and mandated minimum targets for lower-carbon steel in the automotive sector, may be required to ensure an ambitious demand and supply of lower-carbon steel to the automotive sector.

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Appendices

A1 Appendix 1 – Announcements made by automotive OEMs

Action/ Goals	**Date**	More details on the action/ announcement	Link
H2 Green Steel (H2GS) has signed a seven-year binding agreement with ZF, a Germany-based supplier to the global automotive industry	July, 2023	Between 2025 and 2032, H2GS will provide ZF with 250,000 tonnes of GS from its factory in northern Sweden, equivalent to 10% of ZF's annual steel requirements. This will reduce CO2 emissions by 475,000 tonnes. H2GS uses electricity from renewable sources and green hydrogen (along with "end-to-end digitalisation") to produce its GS.	ZF reli–s on green steel - ZF
Mercedes-Benz and H2 Green Steel have signed a binding agreement for the delivery of about 50.000 tonnes of green steel annually	June, 2023	Following Mercedes-Benz's early investment in the start-up in 2021, H2GS will supply the automotive manufacturer with 50,000 tonnes of GS from its steel plant in Boden, northern Sweden (commencement date not provided). H2GS and Mercedes-Benz will also establish a recycling facility for scrap steel at the Borden plant. The two companies have also agreed to develop local GS supply to Mercedes-Benz's North and South American manufacturing plants.	Mercedes-Benz and H2 Green Steel announce agreements in both Europe and North America — H2 Green Steel
Mercedes-Benz announced a new goal to source over 200,000 tonnes of CO2-reduced steel from European suppliers annually by 2030	June, 2023	M-B is aiming to use more than 200,000 tonnes of CO2-reduced steel in its European production facilities from local suppliers by 2030, as part of its wider "Ambition 2039" decarbonisation strategy for a carbon-neutral supply chain and vehicle. Announced plans with suppliers include: • CO2-reduced steel from ThyssenKrupp Steel using direct reduction plants from 2026; • CO2-reduced steel from Salzgitter Flachstahl GmbH – the current production process uses scrap steel in an EAF (60% CO2 reduction), but will be upgraded to use direct reduction combined with EAFs by 2026, as part of the "SALCOS® - Salzgitter Low CO_2 Steelmaking Program" initiative; • SSAB will provide green steel from its Oxelösund facility in Sweden from 2026, following conversion of the blast furnaces to EAFs and green energy (renewable electricity and hydrogen); • H2GS will provide 50,000 tonnes of GS from its Boden, Sweden plant from 2025, and work with Mercedes-Benz to decarbonise the autom'tive manufacturer's steel supply chain in North and South America (see above).	Mercedes-Benz purchases CO_2-reduced steel from Europe | Mercedes-Benz Group > Sustainability > Climate
Scania places first green steel order in further step towards decarbonized supply chain	June, 2023	H2GS will provide GS for Scania trucks, with production at the Boden plant in northern Sweden beginning in 2025 and first deliveries in 2027. This supports Scania's target to use 100% GS by 2030.	Scania places first green steel order in further step towards decarbonised supply chain

Volvo delivers electric trucks with fossil-free steel	November, 2022	From 2022, Volvo has been using CO2-reduced (90% lower carbon emissions compared to conventional production) steel in its heavy-duty (44-tonne) electric trucks, produced by Swedish steel producer SSAB using green electricity and hydrogen. Together with Volvo Group's participation in the WWF Climate Savers program to tackle emissions from its supply chain	Volvo delivers electric trucks with fossil-free steel to customers (volvotrucks.com)
H2 Green Steel and Salzgitter AG will supply BMW Group's European plants with steel produced exclusively using hydrogen and green power from renewable energies from 2025 onwards. The BMW Group plans to [also] increase its percentage of secondary steel in stages, reaching up to 50% by 2030.	October, 2021 AND February, 2022	In 2021, BMW Group signed an agreement with H2GS to supply steel to its European manufacturing plants from 2025. In 2022, BMW Group signed an agreement with Salzgitter AG to supply lower-carbon steel to BMW Group's European plants from 2026 onwards. Together, the two agreements will supply over 40% of the steel required by the company's European plants and save around 400,000 tonnes of CO2 emissions per year. In total, BMW Group press plants in Europe process more than half a million tonnes of steel per year. These agreements are a key step towards meeting BMW Group's goal of sourcing steel with 95% reduced CO2 emissions from 2025, and reducing CO2 emissions in their steel supply chain by about two million tonnes by 2030. Also, both agreements with H2GS and Salzgitter AG commit to increasing recycling of steel scrap and the use of secondary steel by BMW Group. In particular, BMW Group and H2GS have agreed to return 40% of the post-consumer steel scrap from BMW plants to H2GS's EAFs for recycling. BMW Group currently use between 20% and 100% secondary steel in their vehicles, and have a target of reaching 50% by 2030. BMW also invested in electricity-based green steel production by US steelmaking start-up Boston Metals (Automotive World, 2021).	BMW Group significantly increases use of lower-carbon steel in series production at European plants AND BMW Group significantly increases use of lower-carbon steel in series production at European plants
Porsche partners with H2 Green Steel to decarbonise vehicle production processes	November, 2023	Production at H2 Green Steel's steel plant in Boden, Sweden, is planned to begin in 2025, with up to 35,000 tonnes of the low-emission steel produced expected to be used per year for the series production of Porsche vehicles. In comparison, 220,000 tonnes of steel were used in Porsche cars in 2022.	Porsche partners with H2 Green Steel to decarbonise vehicle production processes | Mobility | H2 View (h2-view.com)
VW reaches agreement with Salzgitter to source lower-carbon steel from 2025.	March, 2022	Volkswagen (VW) Group signed an agreement with Salzgitter to source lower-carbon steel from 2025. VW will use the steel for future automotive projects, including its new all-electric Trinity model that will go into vehicle production at the Wolfsburg plant from 2026. Salzgitter is planning to cut carbon emissions gradually by more than 95% by 2033.	VW inks green steel deal as it focuses on sustainable supply chains (autovistagroup.com)

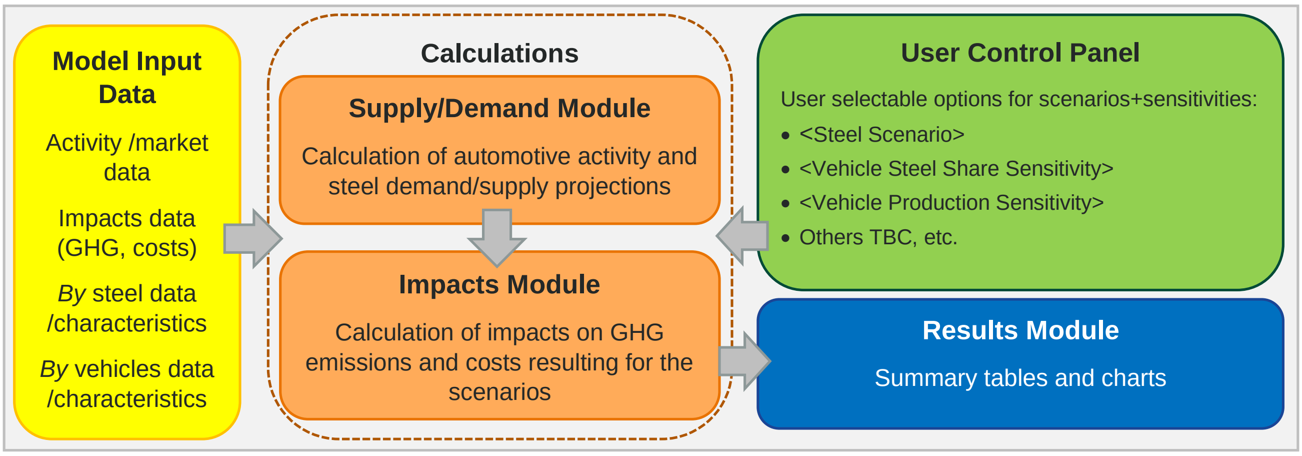
		The agreement also includes establishing a closed-loop recycling system for steel at VW Group's main plant in Wolfsburg. Steel residues will be transferred to Salzgitter, which will recycle them into new steel products.	
General Motor's goal of using 50% sustainable material in their fleet from 2030			
Toyota's 2050 Environmental Challenge		Toyota's strategy involves six 'challenges', the second of which aims to eliminate CO2 emissions from the entire vehicle lifecycle (Toyota, 2015) (Toyota Motor Corporation, n.d). These commitments are further reflected in increased discussions with material suppliers – steelmakers in particular – over introducing greener material into the sector's value chain	Environmental Challenge 2050 | Discover Toyota | Toyota UK
Ford has pledged to use 10% green steel by 2030 as part of the World Economic Forum's First Mover coalition	May, 2022	Ford in Europe is entered into agreements with Tata Steel Nederland, Salzgitter Flachstahl and ThyssenKrupp to secure supply of 10% low carbon steel for its future vehicles by 2030 whilst achieving carbon neutrality for its European supply chain by 2035.	Ford joins First Movers Coalition, announces commitment to help commercialize zero-carbon technologies | Automotive World AND Ford Takes Next Steps Towards Carbon Neutrality in Europe by 2035 – Signs MoUs with Key Suppliers to Secure Delivery of Low Carbon Steel | Ford of Europe | Ford Media Center

A2 Appendix 2 – Modelling methodology

Ricardo conducted the main quantitative modelling analysis to develop the green steel uptake scenarios and provide the main results for the study in terms of volumes of green steel, GHG emissions impacts (savings) and costs.

To provide the results/outputs requested in the ToR, Ricardo employed a combination of analysis using our existing in-house models (e.g. our vehicle LCA modelling framework) and bespoke (most likely MS Excel-based) modelling for this project – see conceptual outline in Figure A1. As indicated in earlier Task 1, Ricardo used information from pre-existing European scenarios from E3 Modelling's PRIMES and GEM-E3 models – i.e. no new modelling was conducted using these models for this project.

Figure A1: Initial conceptual outline of the proposed bespoke scenario modelling



Model Input Data

Activity /market data

Impacts data (GHG, costs)

By steel data /characteristics

By vehicles data /characteristics

Calculations

Supply/Demand Module

Calculation of automotive activity and steel demand/supply projections

Impacts Module

Calculation of impacts on GHG emissions and costs resulting for the scenarios

User Control Panel

User selectable options for scenarios+sensitivities:

- <Steel Scenario>
- <Vehicle Steel Share Sensitivity>
- <Vehicle Production Sensitivity>
- Others TBC, etc.

Results Module

Summary tables and charts

A1.1 MODEL SCENARIOS FOR DEMAND AND SUPPLY OF 'GREEN STEEL' IN THE EU AUTOMOTIVE INDUSTRY

Two scenarios were assessed in this project (1) Business-As-Usual (BAU), (2) Accelerated-Green-Steel (AGS). In order to calculate the impacts of the different scenarios, Ricardo developed the bespoke modelling framework used to characterise the steel scenarios, demand and supply, and to calculate the resulting impacts, and investigate key sensitivities/uncertainties in these (i.e. as conceptually outlined in Figure A2):

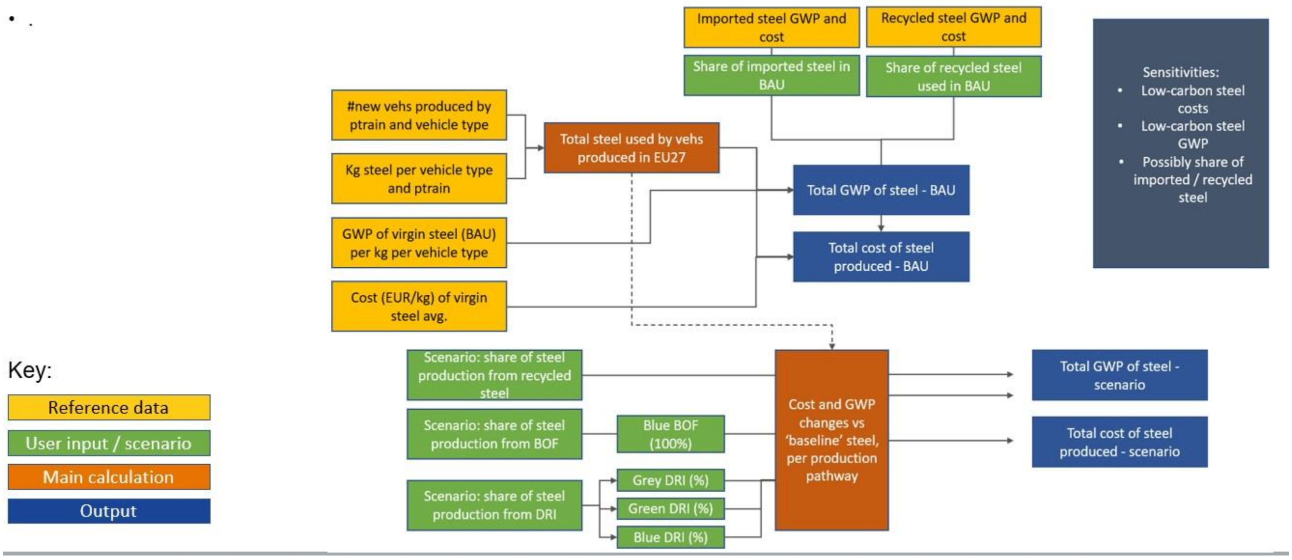
- **Step 1:** Define the overall model specification and conceptual design
- **Step 2:** Implement the modelling framework

Step 1: Define the overall model specification and conceptual design

In this first step, Ricardo developed the high-level concept presented above into a more detailed model specification and outline, prior to development of the model. This is an important step to ensure that the approach is clear and agreed, enabling more efficient and robust model development. This included defining all anticipated input datasets, modelling outputs and intermediate calculation flows across the different modules/work sheets.

The following diagram (Figure A2) shows the used modelling framework, which includes outputs on global warming potential (GWP) and costs of the different scenarios and sensitives.

Figure A2: Schematic of the green steel modelling framework developed for the project



After discussing this specification for the model design with T&E at different project progress meetings, Ricardo refined the model specification and outline design before beginning the full model development. It should be emphasised that this is still a relatively high-level model, as it is clearly not possible to fully model in great detail the automotive and steel sectors. However, the key inputs to the model are informed by scenario data from much more sophisticated models (such as the PRIMES and GEM-E3) and from relevant sources extracted in the literature review phase. All this ensures the results provided are of a high quality.

Step 2: Implement the modelling framework

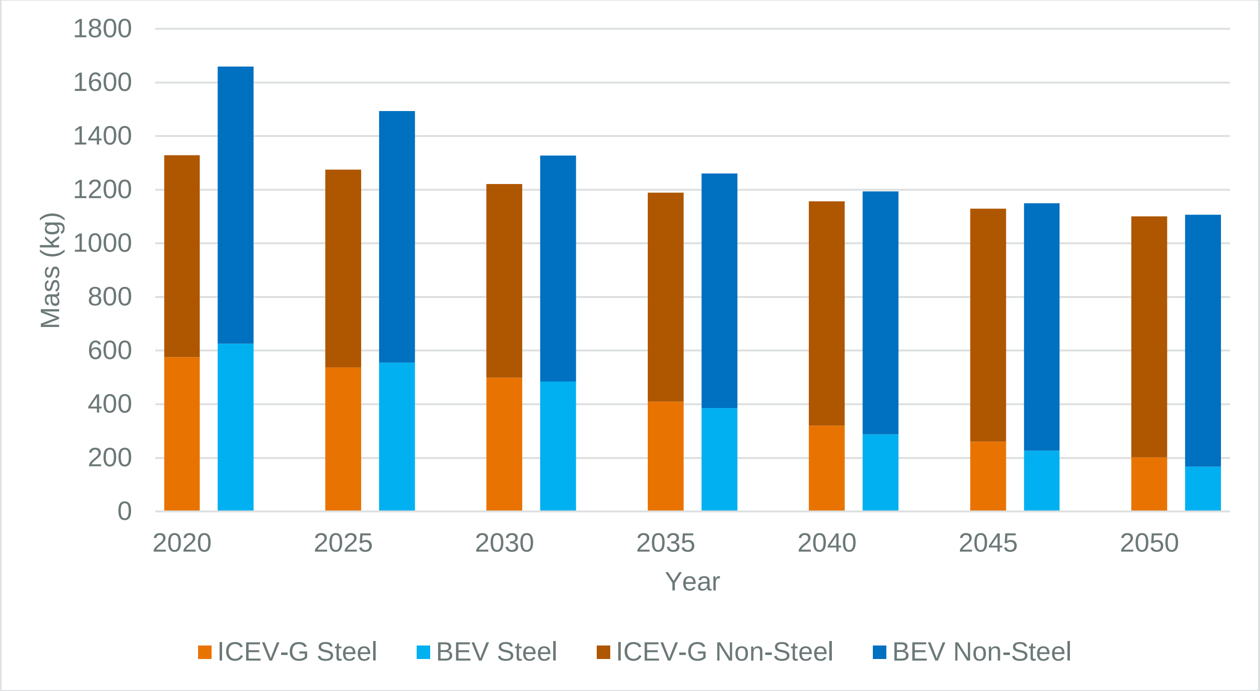
Once the specification and more detailed design of the model was agreed, Ricardo fully develop the bespoke model, using information/data from the evidence collection stage. The scenarios included a Business-as-usual scenario without policy intervention and an Accelerated-Green-Steel in line with most ambitious automakers' commitments to date, assessing quantities or volumes of "green steel" planned for 2030, 2035 and 2040. Flexibility is provided in the modelling for exploring the effects of key parameters/uncertainties affecting this, such as:

- The future change in the EU vehicle fleet – and its impact on demand for new vehicles (i.e. also for different vehicle types – cars, vans, trucks and buses)
- The share of imports for meeting this demand and potential changes in exports of EU produced vehicles
- The % share and total mass of steel in vehicles (i.e. affected by material substitution and overall vehicle mass/design), including batteries for BEVs.
- The share of BEV vs ICEVs (at least) in vehicle production (particularly for HDVs where this may be more uncertain), as this is expected to have a non-trivial impact on total steel content.

The final fully developed model was used to provide results for the final report providing results for 2030, 2035 and 2040, as well as the quantification of impacts on GHG and costs for the scenarios – discussed further in the next section.

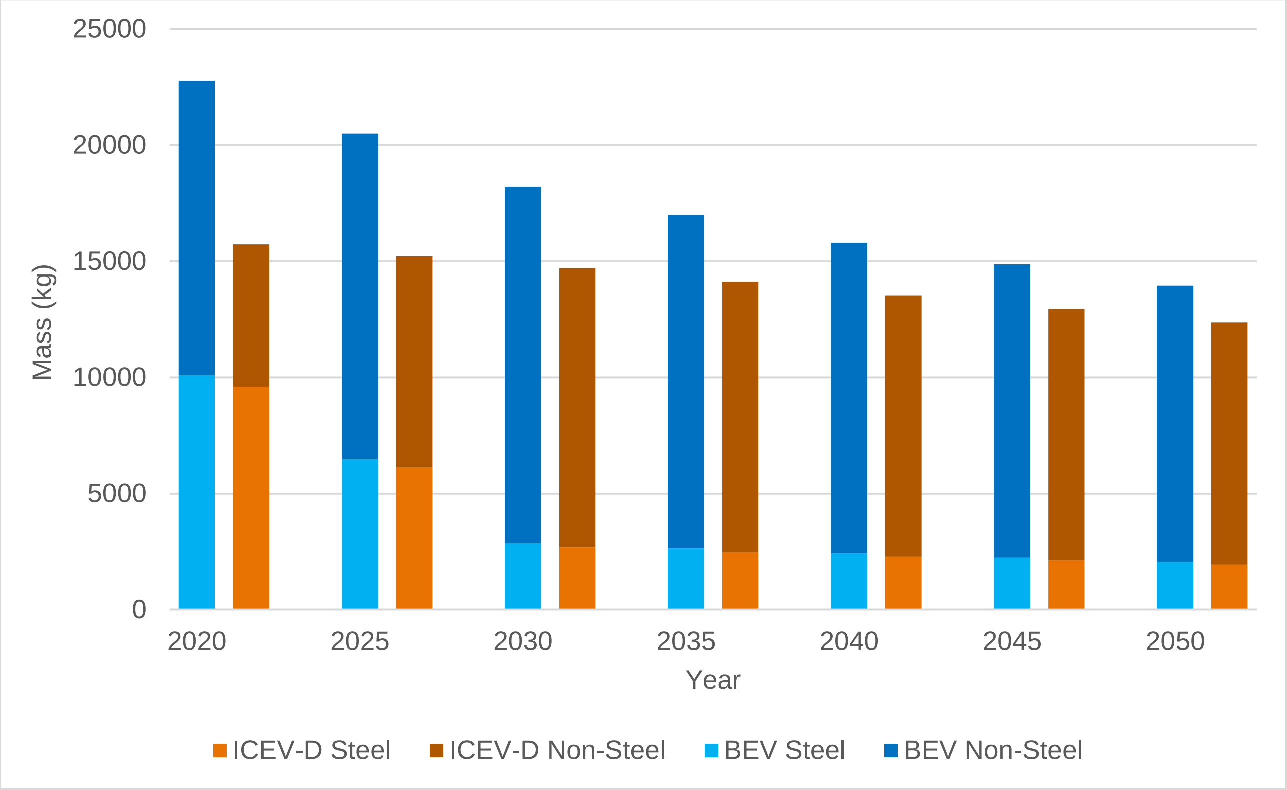
The total steel used in vehicles as a share of total vehicle mass was extracted from internal Ricardo LCA modelling used in previous projects. Figure A3 and Figure A4 show a decline in steel content as a share of vehicle mass between 2020 and 2050 for both passenger cars and articulated lorries.

Figure A3: Mass of steel and non-steel content in Lower Medium passenger car, 2020-2050



Source: Ricardo LCA internal modelling.

Figure A4: Mass of steel and non-steel content in Articulated Lorries, 2020-2050



Source: Ricardo LCA internal modelling.

A1.2 CALCULATE GHG EMISSIONS SAVINGS AND COSTS FOR THE ‘GREEN STEEL’ SCENARIOS

Ricardo approached this methodological activity through two distinct steps:

Step 1: Sector/fleet-level impacts of ‘green steel’ scenarios

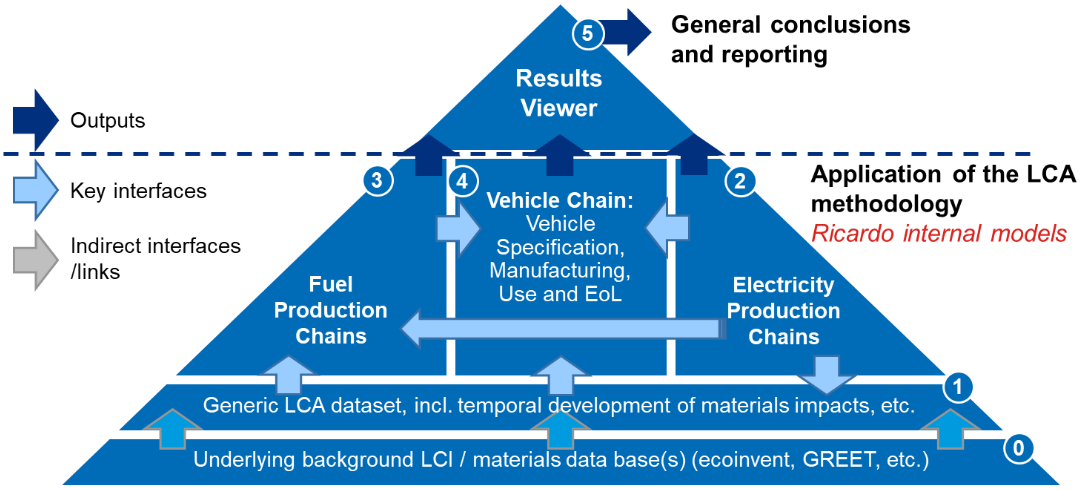
Based on the bespoke model developed, Ricardo calculated the total GHG emissions savings and costs resulting from the two core scenarios, as well as a range of sensitivities on these.

Step 2: Vehicle-level effects of the ‘green steel’ scenarios on the lifecycle impacts of road vehicles

Ricardo also calculated the potential impacts of the two scenarios for ‘green steel’ uptake on the overall lifecycle GWP impact of new vehicles at the vehicle-level. This was carried out using Ricardo’s vehicle LCA modelling framework (overview provided in Figure A5) which Ricardo have used in multiple projects for the European Commission, UK DfT, European Parliament, as well as in work for a number of private automotive sector clients. As part of this model Ricardo implemented the ability to adjust the shares of different types of ‘green steel’ as part of previous analysis – most recently included in our work for the European Parliament TRAN Committee.

Ricardo calculated results for a range of vehicle types (light and heavy-duty) and for at least ICEV and BEV powertrains, so that the significance of the effects can be seen at a production and overall lifecycle level.

Figure A5: Overview of Ricardo’s vehicle LCA modelling framework



A3 Appendix 3 – Contribution of steel production to vehicle lifecycle emissions

The lifecycle emissions (LCEs) of a vehicle are the total emissions produced during a vehicle's production (embodied emissions), operation (use-phase emissions) and disposal. Around 65% of lifecycle emissions of an ICEV are from tailpipe emissions released during vehicle operation (KEARNEY, 2023), with BEVs delivering significant LCE savings through the elimination of tailpipe emissions - around 80% by 2030 and 86% by 2050 for passenger cars using EU27 grid-mix electricity (Ricardo, 2023).

For passenger cars, emissions released during the production of (raw) steel for the automotive sector currently comprise between 15% and 30% of total production emissions for BEVs and ICEVs respectively (KEARNEY, 2023). With production emissions representing around 15% of overall lifecycle emissions, steel manufacturing represents a small share of total lifecycle emissions for passenger car ICEVs (around 4% in 2020) and a larger, but still limited, share for BEVs (around 12% in 2020).[24] For articulated trucks, the share of the lifecycle impacts due to steel manufacturing is even smaller, due to the much higher use-phase distances covered during its operational lifetime.

Moreover, lightweighting is expected to further reduce the contribution of steel manufacturing to production emissions, and subsequently LCEs, between 2020-2050, see Figure 2-1 and Figure 2-2. Also, this project only considers the GWP impact from the manufacturing of steel, with additional energy and material losses from the manufacturing of steel parts for use in vehicles not included in the emission impacts.

Therefore, the combination of an initially low contribution to vehicle LCEs, and projected further steel content reductions, means that the potential impact of lower-carbon steel use on the overall LCE impacts is limited. To illustrate, steel manufacturing emissions, in absolute values and share of LCEs, between 2020-2050 under the Conventional, Baseline and Ambitious steel scenarios, are shown in Figure A6 for passenger cars.

For passenger cars, in the Conventional scenario, steel manufacturing contributes 10.8 gCO2e/vkm (or 4% of total LCEs) for ICEVs and 10.6 gCO2e/vkm (12% of LCEs) for BEVs in 2020, before reducing in absolute terms for ICEVs and BEVs to 4.3 gCO2e/vkm and 3.8 gCO2e/vkm respectively in 2050. Reductions are more significant in the Baseline and particularly Ambitious scenarios for 2030.

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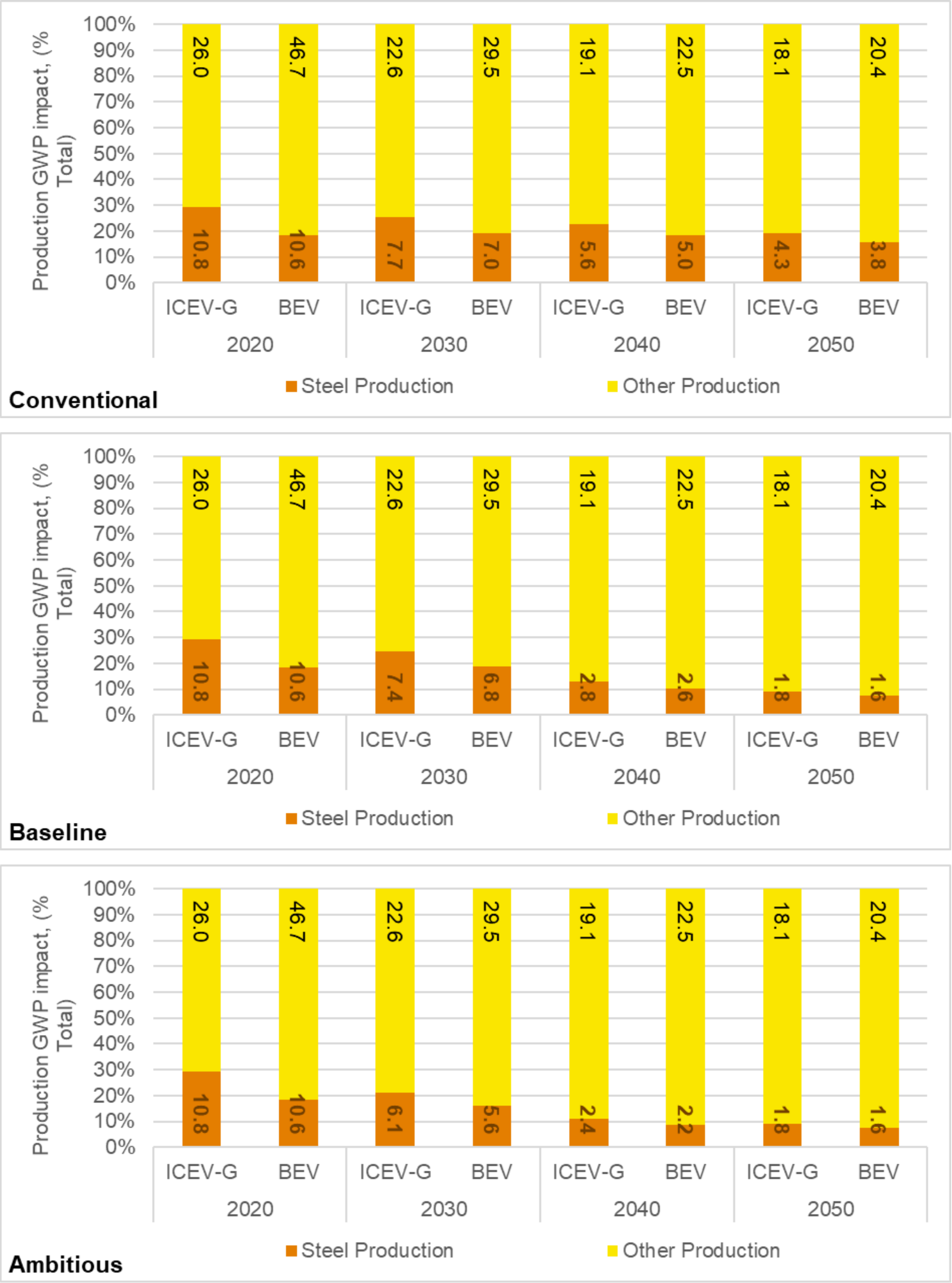
[24] Based on previous Ricardo LCA work.

Figure A6: Share of steel production emissions of total passenger car lifecycle emissions, 2020-2050, for Conventional, Baseline and Ambitious Scenario pathways. In-graph absolute values are in gCO_2e/vkm.

Source: Ricardo LCA internal modelling.

Figure A7: Share of steel production emissions of total passenger car production emissions, 2020-2050, for Conventional, Baseline and Ambitious Scenario pathways. In-graph absolute values are in gCO_2e/vkm.



Source: Ricardo LCA internal modelling.

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