BRIEFING - July 2024

Cleaning up steel in cars: why and how?

Summary

An ambitious uptake of green steel in cars by 2030 is feasible and can deliver significant climate benefits with limited costs for both industry and consumers.

As carmakers continue their transition to selling only electric cars and thereby reducing tailpipe emissions to zero, the climate impact of the materials used to make a car will fall increasingly under the spotlight and will need to be addressed as the sector strives to become net zero by 2050 at the latest. Indeed, a vehicle's embedded, or production, emissions are expected to account for around 60% of an electric car's total lifecycle emissions by 2030, with steel making up an important part, with estimates ranging from 16% to 27%.

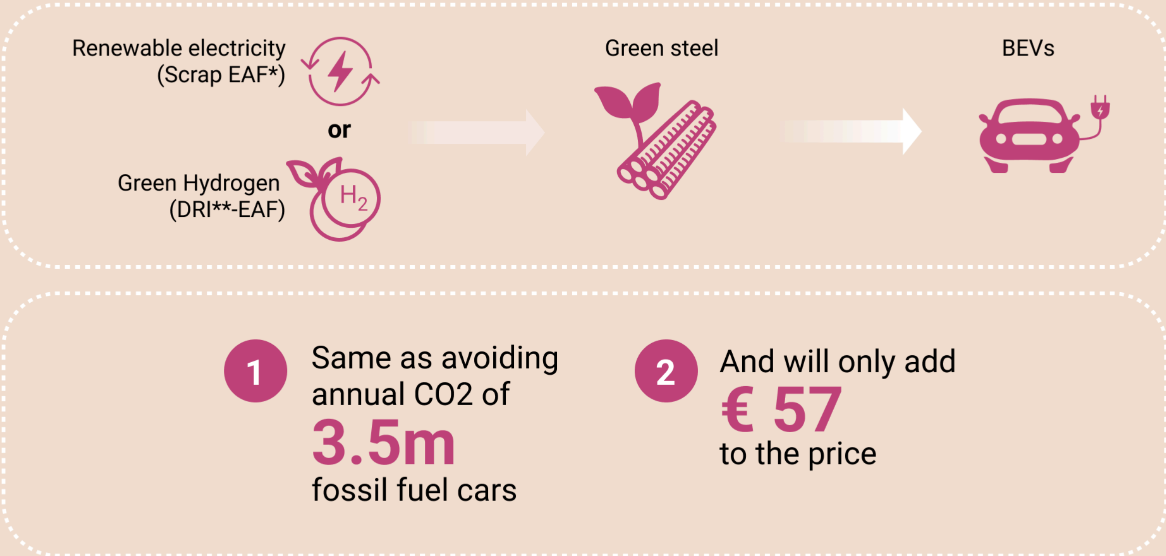
With global steel demand projected to grow by more than a third by 2050, there is a pressing need to develop green steelmaking processes for all steel using sectors. Government subsidies are coming thick and fast to support the transition from the current coal-based steelmaking to one powered by renewable electricity and hydrogen. Securing the billions of investment needed to green steel production will be highly dependent on having a clear market demand and offtake, however. Green steel is defined as either produced via green hydrogen, direct electrification processes, or as recycled steel.

The automotive sector is well positioned to create this demand and be a lead market for green steel in Europe. Steel is a vital component of the automotive sector, accounting for approximately 17% of EU steel consumption, which makes the automotive industry the number two consumer of steel in Europe, behind only the construction sector. The relatively high value of cars, especially of premium brands, also means they can absorb the short-term green premium of greener steel. However, despite the promising potential and growing excitement around green steel and its use in cars, many questions remain unanswered about its feasibility, climate benefits, and cost. This paper, published alongside a new report by Ricardo, *The use of Green Steel in the Automotive Industry*, seeks to answer some of these questions.

First, there is projected to be enough green steel available for an ambitious uptake in new cars already by 2030. Based on tracking and assessments of new green steel production announcements, including existing scrap steel production, total green steel production capacity is projected to reach 172 Mt in Europe by 2030. This is more than enough to cover total projected demand from the automotive sector, which reaches just 21 Mt by then (assuming a shift to lightweighting and less steel use in the sector), and still enough to

cover higher expected demand if we take the sector's 2022 annual consumption of 35.7 Mt (and assume no lightweighting takes place at all).

Green steel in cars cuts embedded CO2 emissions at negligible cost



*Electric Arc Furnace. **Direct Reduced Iron. Source: Ricardo (2024) The use of green steel in the automotive industry. Note: Based on 40% green steel target for new cars in 2030 and Ricardo's assumption of future lightweighting trends in cars.

Second, shifting away from conventional steel to using just 40% green steel can reduce the CO2 emissions of producing cars in Europe by 6.9 Mt in 2030. That's equivalent to the annual emissions of 3.5 million fossil fuel cars. Switching to 100% green steel in new cars by 2040 will reduce emissions equivalent to taking 8.1 million ICEs off the road, demonstrating the significant climate potential that green steel offers carmakers as they look to reduce their scope 3 emissions on the way to net zero.

Finally, switching to green steel in cars, in line with T&E's recommendations (40% in 2030, 75% in 2035 and 100% in 2040), will have a negligible impact on the price of a new car, adding only €57 to the sticker price of a BEV in 2030, an additional €49 in 2035, before almost reaching cost parity by 2040 (just €8 more). The cost increase is slightly higher if we assume the steel content of the BEV remains constant based on current levels - i.e. no lightweighting - coming in at just over €69 in 2030 - less than the cost of fitting a new car floor mat.

Although a higher CO2 price and a lower price for renewable electricity (also as an input for green hydrogen production) is expected to make green steel more competitive in future years, policy makers have an opportunity to put in place regulations and incentives that can help kick start a shift to green steel in the automotive industry and the steel sector as a whole in Europe. T&E proposes policymakers adopt the following:

1. **A clear and European-wide definition of green steel that is in line with the IEA definition of near-zero emission steel and using the sliding scale approach** - between 400 kg and 50 kg CO2 per ton of steel produced (depending on the amount of scrap used as an input). The proposed definition is technology neutral and sets a uniform and clear end-point that ensures comparability for the production of crude steel. The recently introduced green steel label "LESS" by the German Steel Association which is building on this IEA definition is a first step in this direction.
2. **Creating a green lead market with targets for carmakers to use an increasing amount of green steel in new cars.** From 2030, carmakers should be required to use a minimum of 40% green steel in new cars that are sold in the EU (including scrap), increasing to 75% by 2035 when green steel supply is expected to ramp up significantly. From 2040, all steel used in cars should be required to be green. Carmakers should be given an average target to be met across their entire offer of new cars, giving them flexibility to meet them via premium models first, before commercialising across the vehicle range. This target can be done via the end-of-life vehicles (ELV) regulation currently being revised and discussed by lawmakers.
3. **Improve the quality of recycled steel scrap via measures under the End of Life Vehicle regulation.** Despite almost half of all EU steel production coming from the secondary scrap steel, use of scrap steel in new cars is limited by insufficient quality grades being produced by current recycling processes. For high performance steel grades used in the automotive industry to contain post-consumer scrap, the scrap needs to have very low copper content after recycling. Measures that can help increase the supply of automotive quality steel scrap include:
    a. Setting material quality standards in the recycling industry to mandate the maximum copper content of recycled steel fractions coming from ELVs;
    b. Better dismantling of parts and components of end of life vehicles (ELVs) prior to shredding, as is included in the Commission's proposal for a revised ELV regulation.

1. Introduction - why do we need green steel in cars?

1.1 Steel - a growing climate problem in cars

As the automotive industry shifts towards selling only zero emission cars in Europe by 2035, the climate footprint of vehicle production becomes increasingly important as carmakers look to become climate neutral, like all other economic sectors, by 2050 or earlier.

With tailpipe emissions reducing and on a path to zero, emissions from the production phase - also known as a vehicle's embedded emissions - are expected to account for around 60% of an electric car's total lifecycle emissions by 2030. Steel makes up an important part of the non-use phase chunk of emissions in an EV[1], with estimates ranging from 16%[2] to 27%[3]. Just under 30% of the embedded emissions come from the battery, but with advances decarbonised battery materials and battery production and regulation in place to reduce these emissions[4], relative emissions from automotive steel are set to grow.

1.2 The steel sector is a big emitter

The steel sector itself is a big emitter and is one of the most emission intensive sectors of the economy. Globally it is responsible for 7% of CO2 emissions, a little lower at 5% of the EU's total emissions, whereas in Germany, the sector makes up almost 30% of total industrial emissions[5]. Furthermore, the sector is not currently on track to meet net zero by mid-century, with total emissions still rising and less than 1 Mt of near-zero emission steel currently being produced[6].

Steelmaking is a very energy intensive process and the current dominant technology used to make it is mostly based on coal. Currently, around 75% of steel worldwide is manufactured in coal-fired blast furnaces, releasing substantial carbon dioxide emissions into the atmosphere. For the EU, this figure reaches 57% of crude steel production. As countries and industries alike strive to achieve ambitious net-zero targets, addressing this significant industrial source of CO2 pollution must take centre stage.

The good news is that it can be produced much greener through deployment of low-carbon technologies and resource efficiency. Greening steel is a major industrial opportunity and one that Europe must seize if it wants to maintain a competitive steel industry and the jobs that come with it.

1.3 The automotive sector should be a lead market for green steel

As global steel demand is projected to surge by more than a third by 2050, mostly in emerging market economies, there is an increasingly pressing need to develop green steel. Developing clean steelmaking processes takes time, effort and a lot of capital however, which has prompted governments to open up their cheque books to subsidise local companies. Examples include the €2 billion in state aid given to German steel giant ThyssenKrupp for construction and installation of a direct reduction plant and two melting units to replace part of their existing blast furnace capacity in Duisburg, whereas ArcelorMittal has so far collected over €2 billion in subsidies from the French and German governments for its own green steel plans.

[1] For an ICE, steel represents a bigger share of embedded emissions, estimated at 34% (source, ETC), although much less looking from a life-cycle (LCA) perspective as tailpipe emissions from fuel use dominate
[2] See source, Kearney
[3] See source, ETC
[4] The new EU Battery Regulation requires battery makers to first report (from 2025) their battery lifecycle carbon footprint emissions before maximum emission thresholds will be set (from 2028).
[5] https://www.germanwatch.org/sites/default/files/germanwatch_climate-neutral_steel_2023.pdf
[6] https://www.iea.org/reports/breakthrough-agenda-report-2023/steel

However, subsidies alone are not enough, and **financial investment decisions in green steel production are highly dependent on having a clear market demand and offtake**. **The automotive sector is uniquely positioned to create this demand, as it is heavily dependent on steel**. In 2022, automotive steel consumption within the EU reached 35.7 Mt, representing 17% of total finished steel demand in the EU[7][8], while in Germany steel demand in the automotive industry reaches almost a third of total annual production[9]. For some steelmakers in Europe, the automotive sector makes up close to half of all orders[10]. Importantly, cars use mostly flat steel, which is made primarily by the conventional and most polluting blast furnace production route. Ensuring demand from carmakers for green steel can therefore help de-risk investments targeted towards the most carbon-intensive steel production processes[11] and give the necessary signal to producers to invest in and scale up production more quickly than would otherwise have been the case.

The relatively high value of cars, and carmakers' latest sky-high profits, also means they can absorb the short-term green premium of cleaner steel, which will be higher than conventional steel until sufficient commercial scale is reached. Unlike for other steel using sectors, the cost of sourcing steel is marginal compared to the value added to the vehicle during the manufacturing stages and its final price when sold to end-users. This is particularly the case for premium car brands, as the costs associated with the green premium become proportionally less significant as the price of a vehicle increases. Several studies have estimated that the cost of requiring carmakers to produce cars with green steel will be less than 1% of the retail price of a new vehicle[12] - *see also Section 6 of this report for a detailed analysis of the cost impact of green steel in cars*.

To contrast with another steel intensive sector, demand from the construction sector, which uses more steel than the automotive sector (37% of total demand), relies mostly on long products (rebar, wire rod, merchant bars and sections), where high amounts of scrap - and therefore low-carbon - steel are already used in the production process[13].

Carmakers themselves have been making lots of noise about commitments to use green steel in new cars too. European brands including BMW, Mercedes and Volvo have entered into binding agreements with suppliers like H2 Green Steel to source substantial quantities of

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[7] EUROPEAN STEEL IN FIGURES 2023 https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2023/FINAL_EUROFER_Steel-in-Figures_2023.pdf
[8] Whereas automotive makes up 12% of global steel demand
[9] The German Steel Association. https://issuu.com/stahlonline/docs/wv-stahl_fakten-2023_web_675f7c6814999b?fr=sY2E0NzY4ODg5Njg
[10] From discussions with steelmakers
[11] https://sandbag.be/wp-content/uploads/Report-on-Demand-side-2.pdf
[12] See both Energy Transitions Commission pg.25 and Greenpeace pg.7; also Bundesministerium für Wirtschaft und Klimaschutz (BMWK) study pg.19, which estimates cost increase of a finished car of between 300-700EUR
[13] https://sandbag.be/wp-content/uploads/Report-on-Demand-side-2.pdf

lower-carbon steel annually. Similarly, Porsche and several direct suppliers of production materials for Porsche will receive nearly zero-emission steel from H2 Green Steel starting in 2026. This marks the second agreement between H2 Green Steel and a Volkswagen Group company, with the first being with Scania, announced earlier in 2023. The First Movers Coalition for steel, which brings together the purchasing power from companies to send a demand signal to the market, also includes Volvo Group, Ford and GM as well as automotive supplier ZF Friedrichshafen. A similar initiative, SteelZero, a global corporate initiative led by Climate Group, has been joined by 40 businesses committed to driving the transition to a net zero global steel industry, including Volvo Cars and Polestar. This shows carmakers and suppliers are ready and willing to use greener and more expensive material in their cars in order to decarbonise their supply chains. **Voluntary commitments such as these, however, can easily be delayed, scrapped or greenwashed** with creative accounting tricks, meaning **much more needs to be done to ensure a reliable lead market for green steel in Europe**.

1.4 New analysis to fill the knowledge gap on green steel in cars

Despite growing interest in the potential of green steel in the automotive sector, substantial knowledge gaps remain regarding its feasibility, as well as the potential climate benefits and cost implications that come with it. In an attempt to fill these gaps, T&E commissioned Ricardo to conduct an analysis of the potential impacts on both greenhouse gas (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 green steel with the focus on the automotive sector, answering the question of whether there will be enough green steel to use in cars.
- Provide an overview and assessment of both the emission savings potential and production costs of the different low-carbon and green steel production pathways, compared to conventional steel.
- Compare the CO2 impact and savings of cars built with conventional steel and green steel.
- Assess the cost implications at both the vehicle fleet and individual vehicle level of using green steel in cars.

Ricardo modelled and compared different scenarios for the uptake of green steel in cars, reflecting a ‘do nothing’ Conventional scenario assuming that the current share of automotive steel produced from primary BF-BOF and secondary ‘scrap’ EAF production technologies remain constant; a Baseline scenario based on publicly available automotive OEM targets for lower-carbon steel supply and wider decarbonisation of production supply chains; and an Ambitious scenario, in line with the highest announced proposed uptake of green steel in the automotive sector by OEMs.

This paper summarises the findings of the Ricardo study and includes conclusions and recommendations for policymakers.

2. What is green steel?

As policymakers and companies grapple with implementing commitments to deliver significant emission reductions on the way to reaching climate neutrality by 2050, the concept of "green steel" is gaining prominence. Europe, in particular, is 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 commercialisation. Government funding is on the rise to support these efforts. For instance, the EU has allocated substantial funding for hydrogen technologies, aiming to accelerate the transition to sustainable steel production. One notable example of progress is the Swedish steelmaker H2 Green Steel, which will start in 2025 producing "green steel" using renewable hydrogen instead of coal.

Currently though, there is no universally agreed definition of green steel. The most common steel production route today requires reducing iron ore with a type of coal (coke) in blast furnaces at very high temperatures. If you take this as a baseline, then many production pathways could be considered as green or low-carbon, as they still reduce emissions in relative terms. For example, coke can be replaced in the manufacturing process with unabated natural gas, gas with CCS, or with grey, blue, or green hydrogen - all offering varying emission reduction potential. Producing steel from secondary scrap sources in so-called Electric Arc Furnaces (EAF), representing around 40% of current EU production, delivers significant environmental and climate benefits compared to the conventional blast furnace route. In addition to preventing recycled materials from being wasted, scrap EAF steel offers a reduction of around 80-85% of GHG emissions, and 90-95% if only powered by renewables, compared to the conventional route[14].

2.1 A definition of 'green steel'

The International Energy Agency (IEA) defines near zero emission steel as having a CO2 emission intensity of between 400-50 kg of CO2 equivalent per tonne of steel produced (kgCO2e/t)[15]. According to the so-called sliding scale approach, the precise CO2 threshold value depends on the amount of scrap used (as a share of total metallic inputs) in the production process. The more scrap that is used, the lower the threshold, as the use of scrap in steelmaking inherently reduces emissions intensity (as inputs are rated as zero). For crude steel production with zero scrap use (iron ore provides all the metallic inputs) the threshold for near

[14] Ricardo (2024) The use of green steel in the automotive industry.

[15] https://iea.blob.core.windows.net/assets/c4d96342-f626-4aea-8dac-df1d1e567135/AchievingNetZeroHeavyIndustrySectorsinG7Members.pdf

zero emission steel is 400 kg of CO2 equivalent per tonne (kgCO2e/t) of crude steel[16] (and 50 kgCO2e/t for 100% scrap). The reason for this is that iron ore based production, as described above, requires far more energy than scrap based production (five to seven times more[17]), since stripping oxygen from iron ore is extremely energy intensive.

Although the threshold does not address degrees of incremental progress, which will also be needed as the steel sector decarbonises (and which can be driven by other complementary tools like carbon pricing), the emissions reduction potential of conventional process routes, as well as alternative lower-carbon process routes including natural gas and CCS, are limited. It is therefore incumbent on policymakers to put in place the right signals to accelerate the roll out and commercialisation of new green, or near zero-emission steel production processes as fast as possible. According to the IEA, their proposed threshold is compatible with the end goal of the Net Zero Emissions by 2050 Scenario, and, importantly, sends a clear signal of what technologies need to be scaled in the long term, in a sector where returns on investments take place over decades[18].

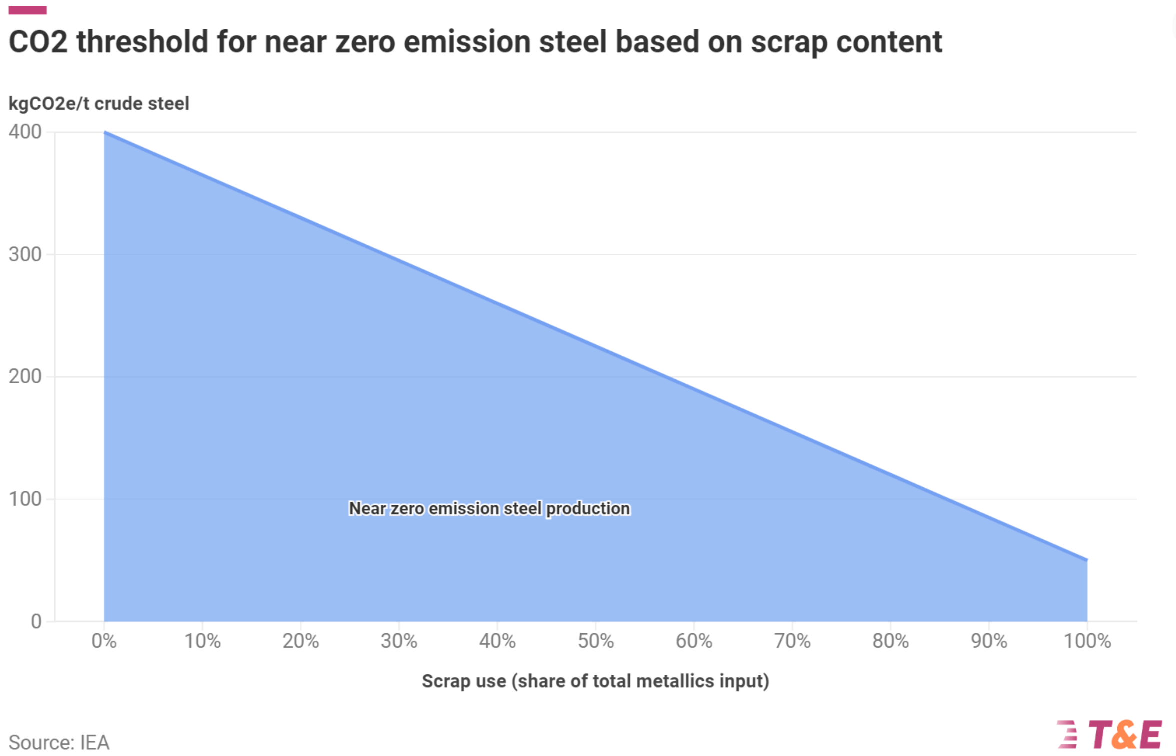

Figure 1: CO2 threshold for defining near zero emission steel

[16] This compares to IEA reference values of 2,945 kgCO2e/t for a pulverised coal injection blast furnace-basic oxygen furnace (PCI BF-BOF) plant and 1,485 kgCO2e/t for a natural gas direct reduced iron electric arc furnace (NG DRI-EAF) plant, assuming best available technology energy performance levels.

[17] https://www.agora-industry.org/fileadmin/Projekte/2021/2021-06_IND_INT_GlobalSteel/A-EW_298_GlobalSteel_Insights_WEB.pdf

[18] The IEA threshold for near zero emission steel was also designed in coordination with the Climate Group and the Mission Possible Partnership. Other initiatives such as the First Movers Coalition, the ResponsibleSteel Standard and the German Green Steel Label "LESS" also use the same sliding scale definition of near zero emission steel in their work.

The definition and thresholds proposed are, furthermore, technology neutral and do not imply a specific production pathway or exclude a specific strategy and the focus is on the production processes of the materials. The threshold sets a uniform and clear end-point in these processes that ensures comparability for the production of crude steel. There are several technologies and technology pathways that should be viable to meet the proposed threshold, depending, of course, on the amount of renewable energy used and associated upstream emissions produced[19]. These include, but are not limited to: **scrap steel produced in an EAF; steel made from green hydrogen based direct reduced iron fed into an EAF (the integrated DRI-EAF route); and ironmaking through electrolysis**.

2.1 Overview and assessment of steel production pathways

For an overview of the different steel production pathways and assessment based on their cost, climate potential and technological viability, please refer to the Annex[20]. A summary of this assessment is provided in the table below.

Overview and assessment of steel production pathways today

Low ○○○ ●○○ ●●○ ●●● High

Expected to increase ↑

Expected to decrease ↓

Possible pathways	CO2 reduction potential [1]	Affordability [2]	Technology maturity
Conventional: Blast Furnace-Basic Oxygen Furnace	○○○	●●● ↓	●●●
Secondary (scrap) Electric Arc Furnace	●●●	●●●	●●●
'Blue' Blast Furnace-Basic Oxygen Furnace	●○○ [3]	●●○	●○○
Natural gas based Direct Reduced Iron (DRI)	●○○	●●○	●●○
'Blue' hydrogen based Direct Reduced Iron (DRI)	●●○ [3]	●○○	●○○
'Green' hydrogen based Direct Reduced Iron (DRI)	●●●	●○○ ↑	●○○
Iron Ore Electrolysis [4]	●●●	●○○	○○○

[1] Our benchmark for CO2 reduction is the threshold established under the IEA definition of near zero emission steel of 0.4 t CO2e/ton steel produced. [2] Some uncertainty around variable cost of feedstocks including natural gas, hydrogen and renewable electricity depending on region. [3] Significant uncertainty about CO2 reduction potential of CCS. [4] Assuming renewable electricity used.
Source: Ricardo (2024) The use of green steel in the automotive industry.

[19] The upstream end of the supply chain boundary encompasses the supply and processing of the main raw material input to steelmaking: iron ore. Mining (including extraction, transportation and beneficiation) and agglomeration processes are both included within the scope.
[20] For a more detailed overview of the technology pathways for steel production, please refer to section 3 of Ricardo (2024) The use of green steel in the automotive industry. Please note that pathways using CCUS (carbon capture utilisation and storage) were not assessed by the consultants.

When talking about green steel, the technology mix from a longer-term decarbonisation perspective and that is compatible with the EU's climate goals, is still open, with secondary (or scrap) EAF steel (powered by clean electricity), green H2-DRI-EAF steel and direct electrolysis (though less developed today), powered by green energy all possibilities. None of these options are likely to be a silver bullet in their own right, with uncertainties over the cost and availability of green H2 or the sufficiency of scrap in order to close the decarbonisation gap fully. It is therefore crucial that policy allows all of these to develop and improve, focusing on the scale and quality of scrap, and scaling of the other two green production methods.

The low-carbon status of blue hydrogen depends on optimistic assumptions about emissions throughout the full supply chain: upstream emissions, the capture rate of CCS, leakage of CO2 during CO2 transport and storage. These issues are unlikely to be resolved by 2030. Therefore, blue hydrogen, and any associated steel making pathways, is not a realistic long-term solution to achieving full decarbonisation.

As carmakers and policymakers alike consider how best to reduce emissions related to steel use in vehicles, a guiding principle to follow should be: **as much scrap steel as possible and, then, as much green primary steel as necessary**.

Europe needs to put in place policy instruments which allow all climate compatible technology routes to scale, while leaving enough flexibility for the market and businesses to decide on the relative role of each pathway.

3. There will be enough green steel to cover all automotive demand

Having looked at the different green and low-carbon technology options for greening steel in cars, it is important to understand whether there will actually be enough of it to meet demand from carmakers. In 2022, total automotive steel consumption in the EU reached 35.7 Mt, whereas total automotive finished steel demand in the EU reached 23.7 Mt[21], representing 17% of total EU steel demand. This makes the automotive industry the second largest consumer of steel in Europe, behind only the construction sector. Total annual steel consumption was almost 148 Mt in 2022, whilst European steel demand (or apparent consumption) for 2022 was nearly 140 Mt[22].

[21] 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.

[22] https://www.eurofer.eu/assets/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2023/FINAL_EUROFER_Steel-in-Figures_2023.pdf

In 2022, actual steel production in Europe reached 136 Mt. 56.3% of this came from the conventional Blast Furnace – Basic Oxygen furnace (BF-BOF) primary route, whilst 43.3% was fully electrified using an Electric Arc Furnace (EAF) following the secondary scrap route[23].

3.1 Current scrap steel use in cars

Although the supply of available scrap steel in Europe consistently exceeds recycled steel demand in the EU, the use of recycled steel in the automotive sector from the scrap EAF production route is currently very low. According to Ricardo, this is 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%[24], which means it goes to sectors like construction which can use such steel grades without any issue. To facilitate greater scrap steel uptake, upgrading production sites may be necessary to facilitate the manufacturing of high-volume, high-quality recycled steel. Requirements on recyclers to improve the quality by setting EU-wide standards would also help.

Although the use of recycled steel from scrap EAF production is currently limited in the automotive sector, around 15% of the steel used comes from the scrap EAF route. 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[25]. Based on these numbers, we can calculate that just 6% of current total scrap steel production in the EU goes into new cars (see below), despite there being no technical limitation for using scrap steel in new car manufacturing.

[23] *Ibid*
[24] https://www3.weforum.org/docs/WEF_Closing_Loop_Automotive_Steel_2023.pdf
[25] *Ibid*

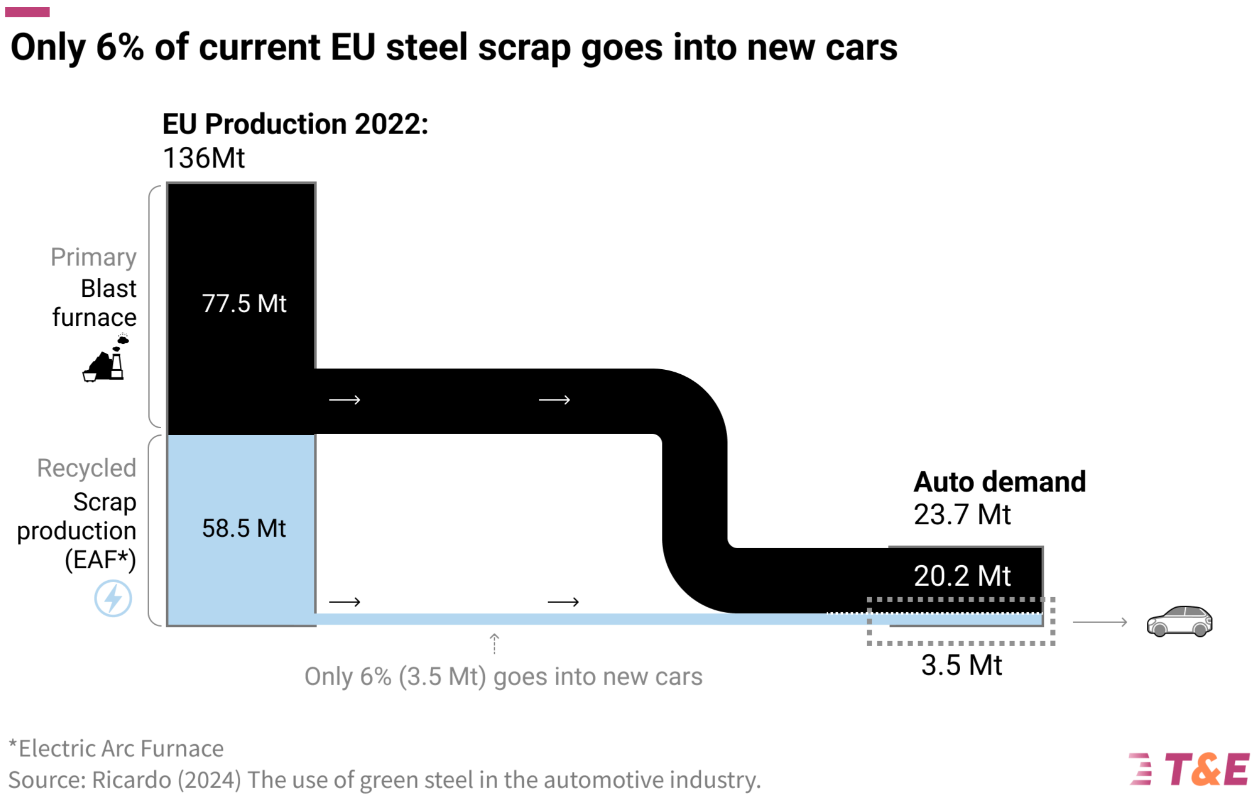

Figure 2: current steel scrap flows into new car production

Improved scrap sorting of grades - proposed under the new End of Life Vehicles regulation proposal[26] - and voluntary OEM targets and mandatory recycled content targets hold potential for recycled steel from EAFs to play a much bigger role in the decarbonisation of automotive steel, however. Volvo has committed to use 25% recycled steel by 2025 and 35% by 2030. BMW plans to use 50% scrap steel by 2030.

3.2 Outlook for automotive demand for green steel in Europe

Based on Ricardo's own tracking and assessments of green steel announcements, to date, there have been new green and lower-carbon steel production announcements totalling 85 Mt[27] of production capacity by 2030 in Europe. The majority (82%, or 70 Mt) of newly announced capacity are from the integrated "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[28]. Combining newly announced lower-carbon steel production capacity with

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

[27] Please see Section 2.3. Ricardo (2024) The use of green steel in the automotive industry for more details. Note that announcements covering grey (using natural gas) and blue (using CCS on fossil fuels) technology pathways have been removed from this paper as they are not compatible with the EU's long term climate goals.

[28] Although classed as green by Ricardo, whether or not steel made from DRI using electricity from the grid can be classed as green and meet the IEA's near zero emission steel threshold will depend on the carbon intensity of the grid electricity in the country or bidding zone in question.

the existing scrap EAF production capacity of 87 Mt, total lower-carbon steel production capacity is projected to reach 172 Mt by 2030, not only well exceeding total automotive sector steel consumption in 2022 of 35.7 Mt, but also almost matching the total 2021 steel production capacity in the EU (190 Mt), see Figure 3.

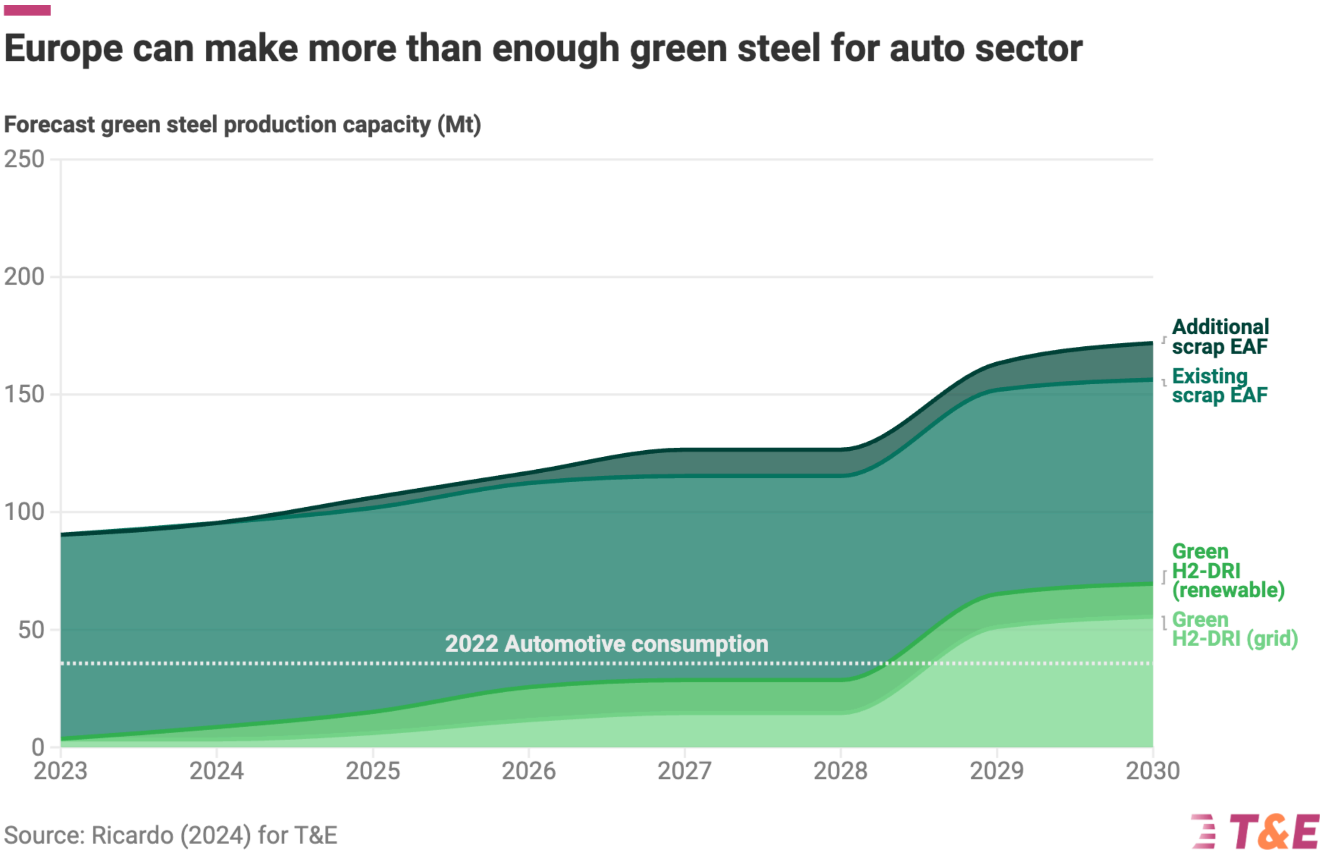

Figure 3: Forecast green steel production capacity by 2030

Despite this optimistic outlook on the future supply of green steel, a word of caution should nevertheless be added. Several steelmakers who have committed, and received billions in state aid, to produce steel using green hydrogen are already publicly rolling back on and delaying these commitments due to concerns regarding the availability and cost of green hydrogen, promising instead to use natural gas as a transition feedstock (see also below: Case Study Germany: Green steel production and demand in the automotive industry).

3.3 Outlook for automotive demand for green steel in Europe

So far, demand for green steel in the automotive sector is outstripping other steel-using sectors. According to Ricardo, of the 48 global supply agreements for green steel in place in 2021, the automotive sector accounted for 22 (46%). There are now 26 European OEM supply agreements with lower-carbon steel producers, with carmakers securing a total 1.8 Mt of lower-carbon steel by 2030. The majority of demand for lower-carbon steel from automotive sector supply agreements is currently from the H2-DRI route using green hydrogen from renewable electricity. The combined steel supply from the green H2-DRI route using either grid or renewable electricity is anticipated to reach 1.3 Mt (72% of the current supply agreements in place) by 2030.

This 1.8 Mt represents only 9% of total automotive steel demand in 2030, however. Despite this, the potential introduction of lifecycle emissions reporting for automotive OEMs and their use of LCA emissions to support corporate reporting of scope 3 carbon emissions will increase the pressure on carmakers to source an increasing supply of green steel going forward. Indeed, several automotive companies, including Mercedes-Benz, ZF, Scania, Volvo and BMW, have penned voluntary actions and commitments on greening the steel they use[29]. However, as with all voluntary industry pledges, commitments by automakers to use green steel in new cars mean very little in reality unless backed by enforceable regulation (see Section 7 on policy recommendations).

Other factors influencing future demand for automotive steel include consumer willingness to pay the so-called "green premium" for vehicles using lower-carbon steel. However, several studies have estimated that the cost of requiring carmakers to produce cars with green steel will be less than 1% of the retail price of a new vehicle (see Section 6 for more detailed analysis on this point).

According to Ricardo, another key trend that is expected to influence future demand for automotive steel is lightweighting, which involves reducing the weight of vehicle components through design and material innovations. Light alloys and composites, such as aluminium and carbon fibre, are potential lightweight alternatives to steel in passenger vehicles. Under their modelling, it is projected that the steel content of an average battery electric passenger car will reduce from 35% of total weight in 2020 to 17% in 2050. This corresponds to a reduction in steel volume from over 700 kg in 2020 to under 240 kg by 2050.

In any case, there is projected to be more than enough overall lower-carbon and green steel supply from EU27 production to meet demand from the automotive sector, with the estimated automotive steel demand in 2030 of around 21 Mt representing only 11% of total lower-carbon steel production capacity[30]. Even when assuming steel use in the automotive industry remains stable (i.e. with no lightweighting) based on 2022 levels (35.7 Mt) and all automotive steel demand is for green steel, there will still be more than enough green steel to go round.

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[29] See Appendix 1 – Announcements made by automotive OEMs in Ricardo (2024) The use of green steel in the automotive industry.

[30] 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 Sections 2 and 4 of Ricardo (2024) The use of green steel in the automotive industry for further details.

Case Study Germany: Green steel production and demand in the automotive industry

With a production of 35 Mt (2023) Germany is Europe's largest steel producer[31]. Compared to other European markets, it is still dominated by the conventional BOF-BF route which currently represents about 70% of German steel production, while the remaining 30% is produced by the EAF-route[32]. This heavy reliance on the coal-fired conventional route is the reason why in Germany, the steel sector is responsible for a third of total industrial emissions with the transformation of the industry posing a significant challenge for the country. Looking to tackle this task, the Federal Government, the steel producing German federal states and the European Commission are supporting the transformation to green steel in Germany with almost seven billion euros[33].

According to Agora Industry (2023) the green steel announcements (for primary steel, not including scrap) by German steel companies for 2030 add up to approximately 17 Mt. The overall steel demand by the German automotive industry has been between 26%-28% in recent years, which roughly adds up to the planned production capacity of green primary steel in 2030.

However, as these numbers move in a positive direction, a degree of caution is to be advised for the following reasons:

1. The first hydrogen DRI plants in Germany will only be operational in 2026.
2. There is still a lot of uncertainty on the availability & the price of hydrogen in Germany, which means most of the new DRI plants will run on natural gas for a longer transition period. For example ArcelorMittal's planned DRI plant in Bremen is only obliged to use 100% green hydrogen by 2040.
3. While ArcelorMittal, the owner of the steel plants in Bremen & Eisenhüttenstadt (production capacity of ca. 5 Mt.) has received over 1 billion Euros in state aid from the EU and Germany to invest in new H2-DRI and EAF facilities; the company has, unlike their competitors ThyssenKrupp and Salzgitter, not taken a final investment decision yet.

4. Overview of green steel uptake scenarios

As part of the study done by Ricardo[34], the impacts of varying lower-carbon steel uptake scenarios within the automotive sector were modelled. The "Baseline" scenario is informed by

[31] Wirtschaftsvereinigung Stahl Annual Report 2023
[32] http://www.stahl-online.de/startseite/stahl-in-deutschland/zahlen-und-fakten/
[33] http://www.handelsblatt.com/politik/deutschland/dekarbonisierung-sieben-milliarden-euro-fuer-gruenen-stahl-und-das-ist-erst-der-anfang/100009407.html
[34] Ricardo (2024) The use of green steel in the automotive industry.

publicly available automotive OEM targets, both for use of lower-carbon steel 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 in 2020[35] to 100% by 2050 (when it is assumed all steel will need to be decarbonised in line with EU long-term climate targets), reaching 25% and 57% lower-carbon steel shares by 2030 and 2035 respectively. An "Ambitious" scenario was developed in line with the highest 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, a "Conventional", or 'do-nothing' 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.

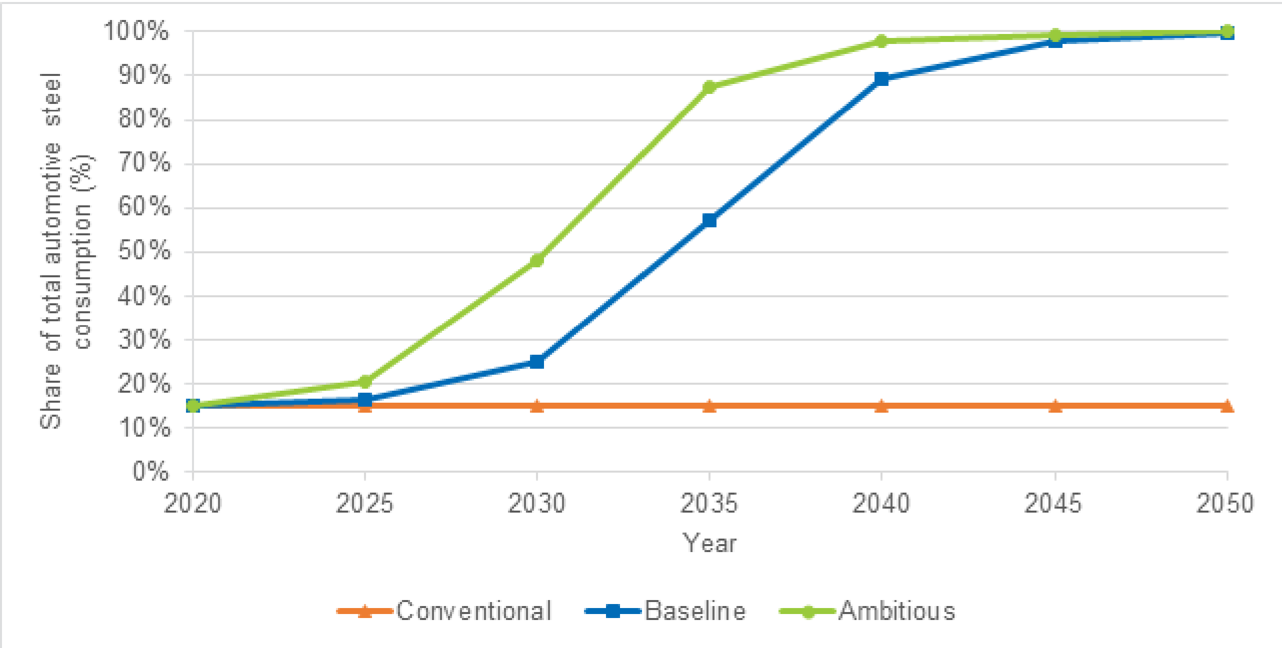

Figure 4: Green steel uptake scenarios for domestic automotive steel consumption as modelled by Ricardo

The lower-carbon steel shares assumed in the different scenarios are split between different technological pathways, as discussed in Section 2 and the Annex and are explained below.

Scrap EAF steel is assumed to make up 15% of domestic automotive steel demand in 2020, after which 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[36]. Under both the Baseline and Ambitious scenarios, secondary EAF steel is

[35] The share of scrap EAF steel currently already used in the automotive sector
[36] This assumption is based on the amount of steel available from end of life (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

projected to make up 19% of demand in 2030 and just over 30% in 2035. Ricardo also developed a high secondary EAF uptake scenario, which assumes that automotive demand reaches 27% in 2030, 44% in 2035 and 48% by 2050, representative of the current scrap EAF share of European steel production capacity.

Primary green steel 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 (see Appendix 1 – Announcements made by automotive OEMs in Ricardo study). Green H2-DRI is expected to be the dominant lower-carbon steel production pathway, making up around 80% of currently announced automotive steel demand by 2030[37]. Under the Ambitious scenario, Green H2-DRI steel is assumed to make up 25% of total steel in cars by 2030, 50% by 2035 and close to 60% by 2040, remaining stable until 2050.

None of the grey H2 or natural gas (NG)-DRI production pathways are assumed to contribute to lower-carbon automotive steel as these pathways have limited automotive demand (8% of announced volume by 2030); are broadly viewed as a transition technology between current production and Green H-DR; and have variable and very limited emission reduction potential (see Section 2 and Annex). Similarly, 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 H2-DRI) pathway, in addition to their highly questionable climate benefits, these technologies also do not feature in the automotive steel demand scenarios between 2020-2050.

The rest of the steel uptake under the Ambitious scenario that is not either secondary EAF or Green H2-DRI is assumed to come from imports. 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, however. As such, it is assumed that the automotive sector reduces its share of imported steel by half to 4.5% in 2050.

5. Ambitious uptake of green steel in cars can deliver significant climate benefits

To assess the potential climate benefits of using green steel in cars, Ricardo looked at both emissions associated with steel used in cars at the fleet level and the individual vehicle level.

as a whole decarbonises, limiting the amount of recycled steel from other scrap sources that is available for the automotive sector.

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

First, when looking at the total cumulative CO2 emissions from the production of steel used in the production of new passenger cars (fleet level), Ricardo shows that, with an accelerated uptake of green steel as per the Ambitious scenario (i.e. close to 50% green steel by 2030 and 88% by 2035) compared to the less ambitious uptake in the Baseline scenario (25% green steel by 2030 and 57% by 2035), 70 MtCO2e can be eliminated between 2020 and 2050. **Compared to the Conventional, or 'do nothing', scenario, the Ambitious scenario results in significant cumulative emissions savings of 277 MtCO2e by 2050, equivalent to the yearly emissions of Spain**[38].

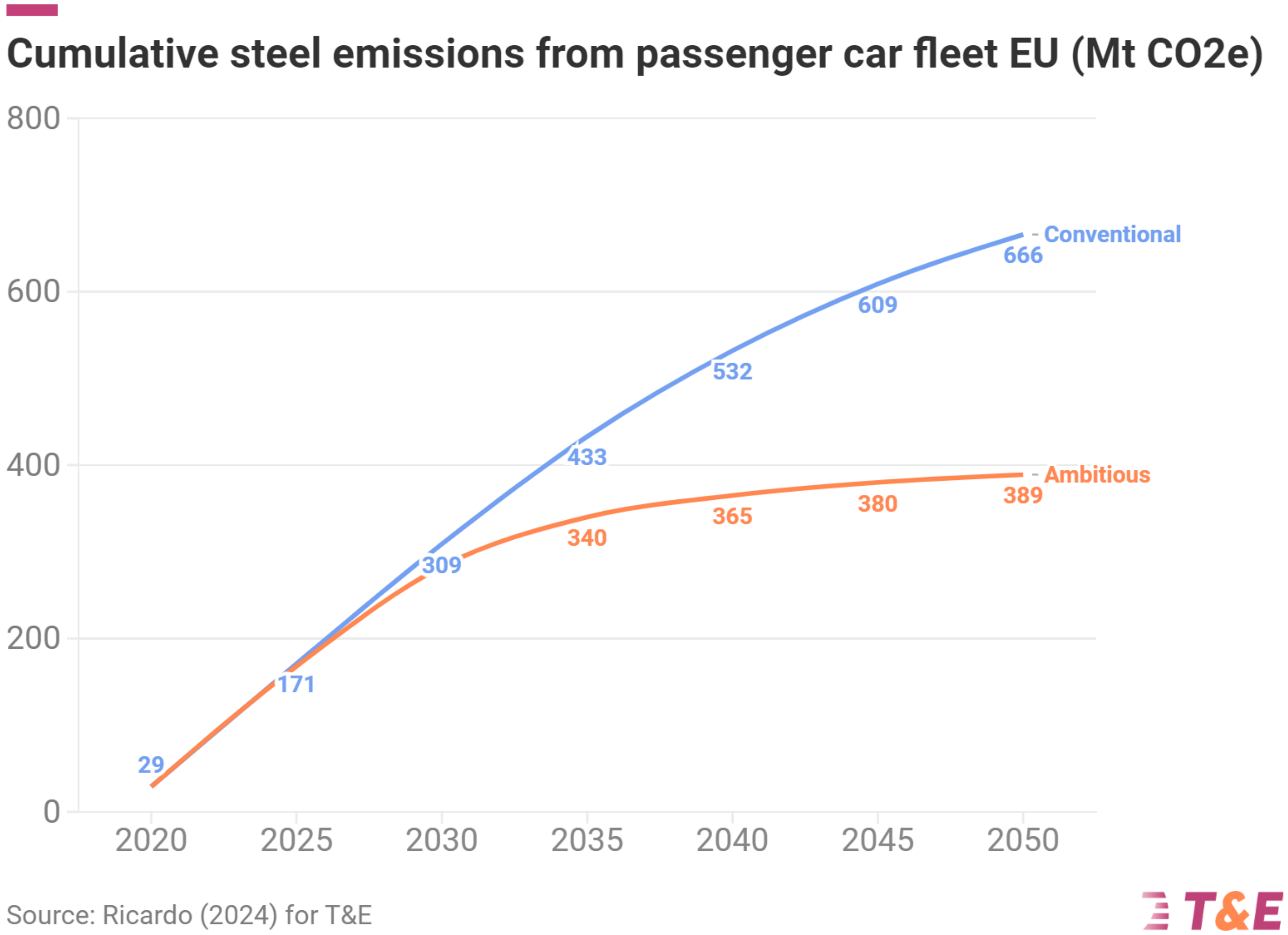

Figure 5: Cumulative CO2e emissions of steel used in new passenger cars across EU27 under the Conventional and Ambitious Scenarios, 2020-2050

Switching to green steel in new cars in line with T&E's recommendation of 40% in 2030 can reduce the CO2 emissions of producing cars in Europe by 6.9 Mt. This is equivalent to avoiding the annual emissions of 3.5m fossil fuel cars (see Figure 6). Ramping up to 75% green steel use in new cars, this will remove the emissions equivalent to 7.2 million fossil fuels cars in 2035 and 8.1 million in 2040 following a shift to 100% green steel.

[38] Spain's 2021 emissions were 289 MtCO2

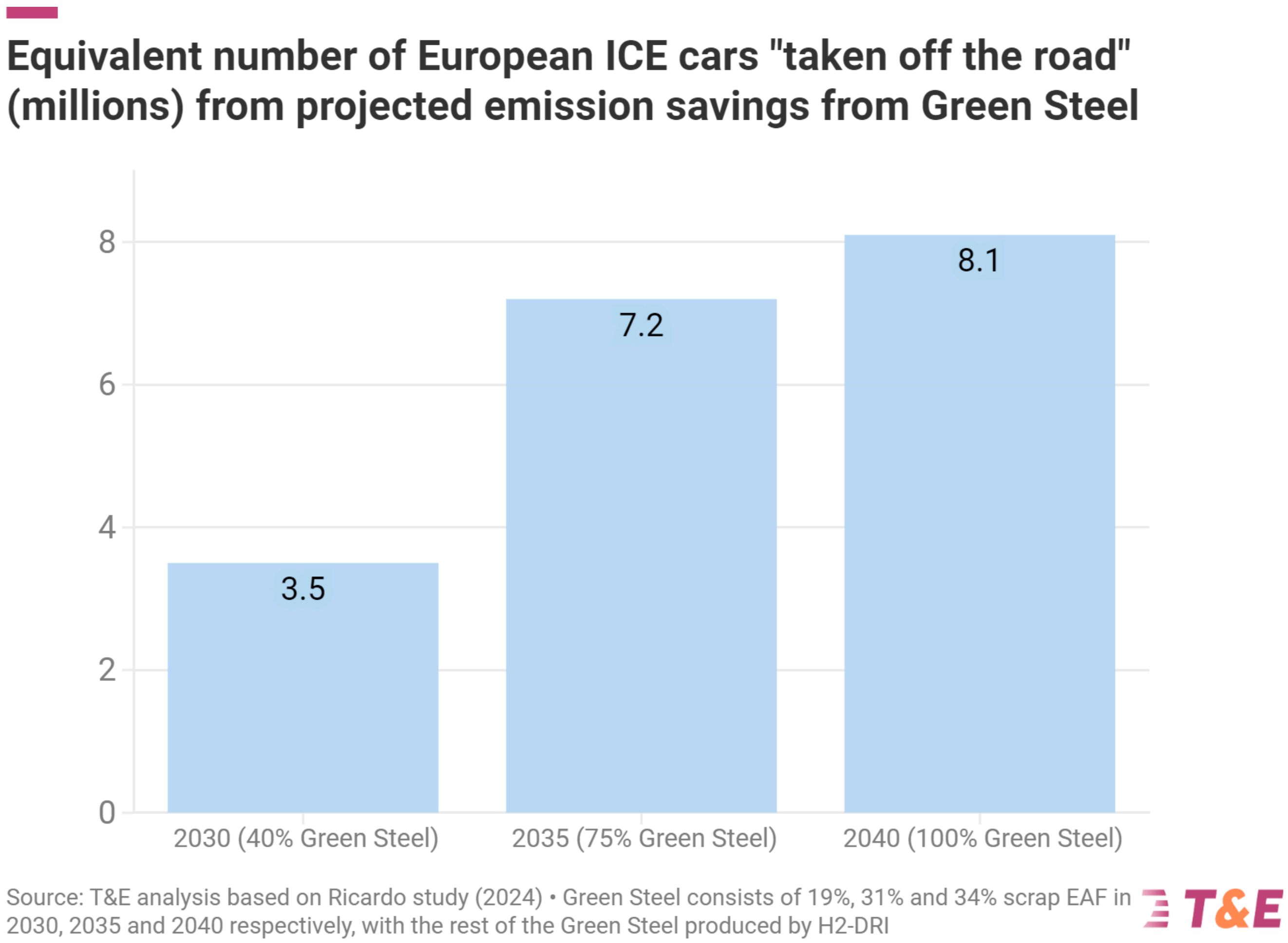

Figure 6: equivalent number of ICE cars 'taken off the road' in Europe (millions) from projected emission savings from green steel in new cars

Moving to the individual vehicle level, 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[39]. With tailpipe emissions from new cars reducing and on a path to zero[40], emissions from the production phase of a vehicle are expected to account for around 60% of an electric car's total lifecycle emissions by 2030.

For a mid-sized battery electric car (e.g. Tesla Model 3) using only conventional steel from the BF-BOF route, the total vehicle production emissions in 2030 equals 36.5 gCO2e/km. **By switching to using 100% green steel (a mix of both scrap EAF and green H2-DRI), carmakers can reduce their vehicle production emissions by 10%** to 32.7 gCO2e/km. A similar reduction can be achieved in 2040 where replacing conventional steel with green steel can reduce the car's embedded emissions from 27.5 gCO2e/km to 25.2 gCO2e/km (see Figure 7).

[39] https://www.kearney.com/industry/automotive/article/-/insights/polestar-and-rivian-pathway-report-

[40] The EU adopted a 100% CO2 reduction target for new cars and vans from 2035, effectively meaning all new cars must be battery electric from this date on

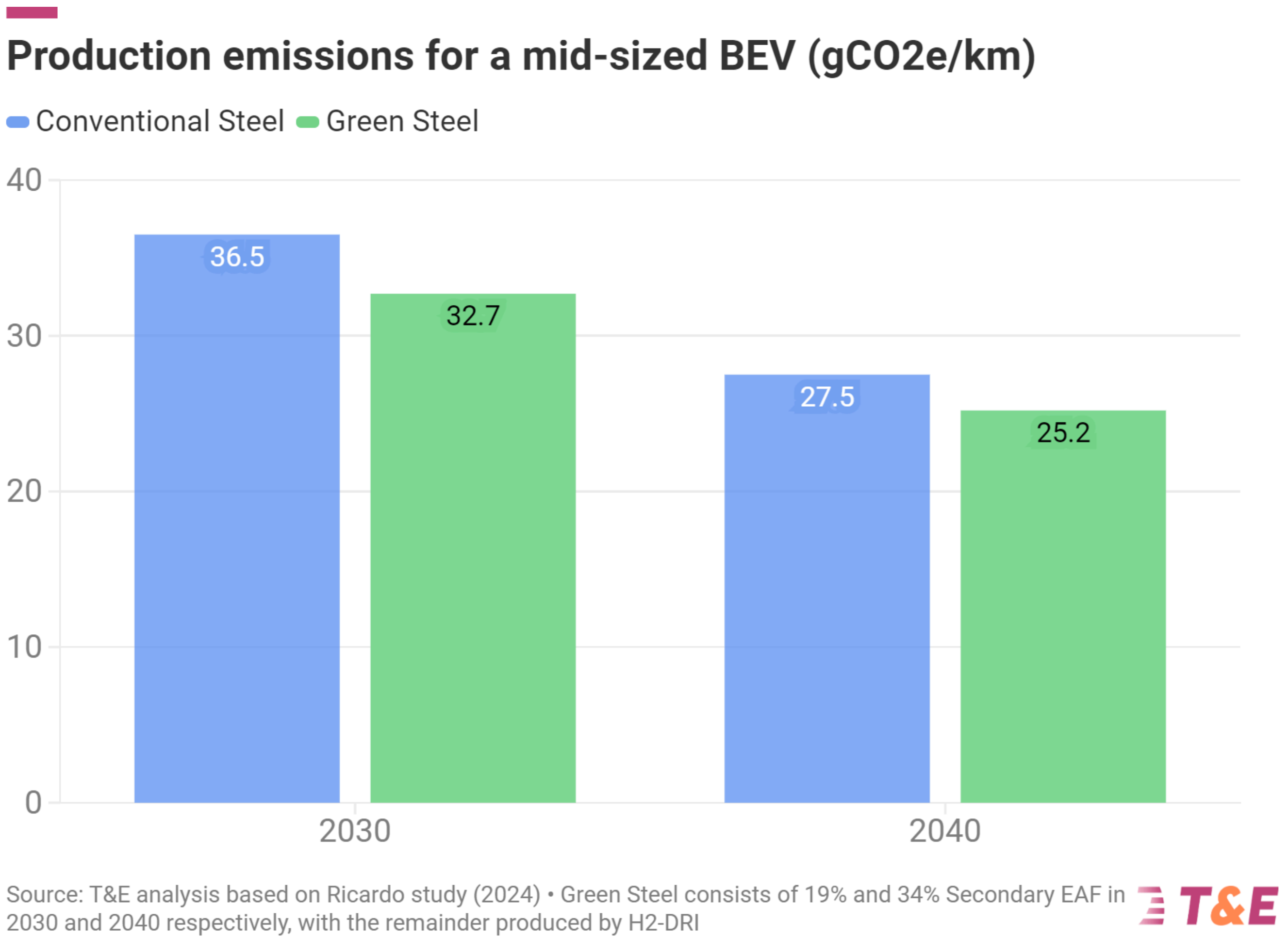

Figure 7: Production emissions of a mid-sized battery electric passenger car in 2030 and 2040

With most carmakers embracing a target-setting process that aligns with the goals of the Paris Agreement and look for solutions to reduce their scope 3 emissions, replacing conventional climate-harming steel with green steel in their cars can be an important contributor to reducing overall emissions on a path to reaching net zero by 2050.

6. Switching to green steel in cars has negligible cost impact, especially for consumers

In general, increased automotive demand for green steel is projected to increase the cost of steel content in vehicles in the short term compared to steel content under the Conventional scenario (where today's share of just 15% scrap and 85% conventional steel is assumed), albeit by a relatively small amount. However, from 2040, it is projected to become more affordable as lower-carbon steel infrastructure becomes widely available and costs for key feedstocks for lower-carbon steel (such as renewable electricity and hydrogen) reduce.

6.1 Using green steel will cost carmakers more initially, before becoming cheaper in 2040

According to analysis done by Ricardo[41], the cost difference of the steel content between the Ambitious and Conventional 'do nothing' scenarios peaks in 2030 at just €43 per passenger car and then reduces between 2030-2050 to deliver a cost savings of €9 per vehicle by 2040 and €53 per vehicle by 2050. The total cost of the steel content for both scenarios in 2030 is €462 and €419 respectively. This means that a car using close to 50% green steel in 2030 (in line with the assumptions of the Ambitious scenario) will cost carmakers just €43 more per vehicle produced compared to what it costs them today.

For a car using 100% green H2-DRI steel in 2030 (the highest cost option), the steel content cost is higher than under the Ambitious scenario and reaches a total cost of steel content of €524 per vehicle (25% higher, or €105 more, than using conventional steel) in 2030.

It is projected that all green steel scenarios deliver a cost saving for carmakers from 2040 onwards as the cost assumptions and inputs for lower-carbon steel reduce, for example the price of key feedstocks such as renewable electricity and hydrogen, and as infrastructure becomes more widely available.

A high cost sensitivity analysis was also modelled, to account for the fact that key feedstocks for the production of green steel and CAPEX costs have been revised upwards in recent years[42]. Even under the high cost assumption, the steel cost difference for passenger cars between the Conventional scenario and the Ambitious scenario peaks at €59 per vehicle in 2030 (instead of €43) before reducing slightly to €55 in 2035[43].

[41] Based on Ricardo's assessment of the latest literature. Please see Ricardo (2024) The use of green steel in the automotive industry Section 6 for a full bibliography
[42] For more details of the cost assumptions and sensitivities, please see Ricardo (2024) The use of green steel in the automotive industry Sections 4.1.1.1 and 4.3
[43] See graph in Annex (A2) for projections of the total cost of steel content in an average passenger car under all green steel uptake scenarios (Conventional, Baseline, Ambitious and 100% green H2-DRI steel) with Default and High cost sensitivities, 2020-2050

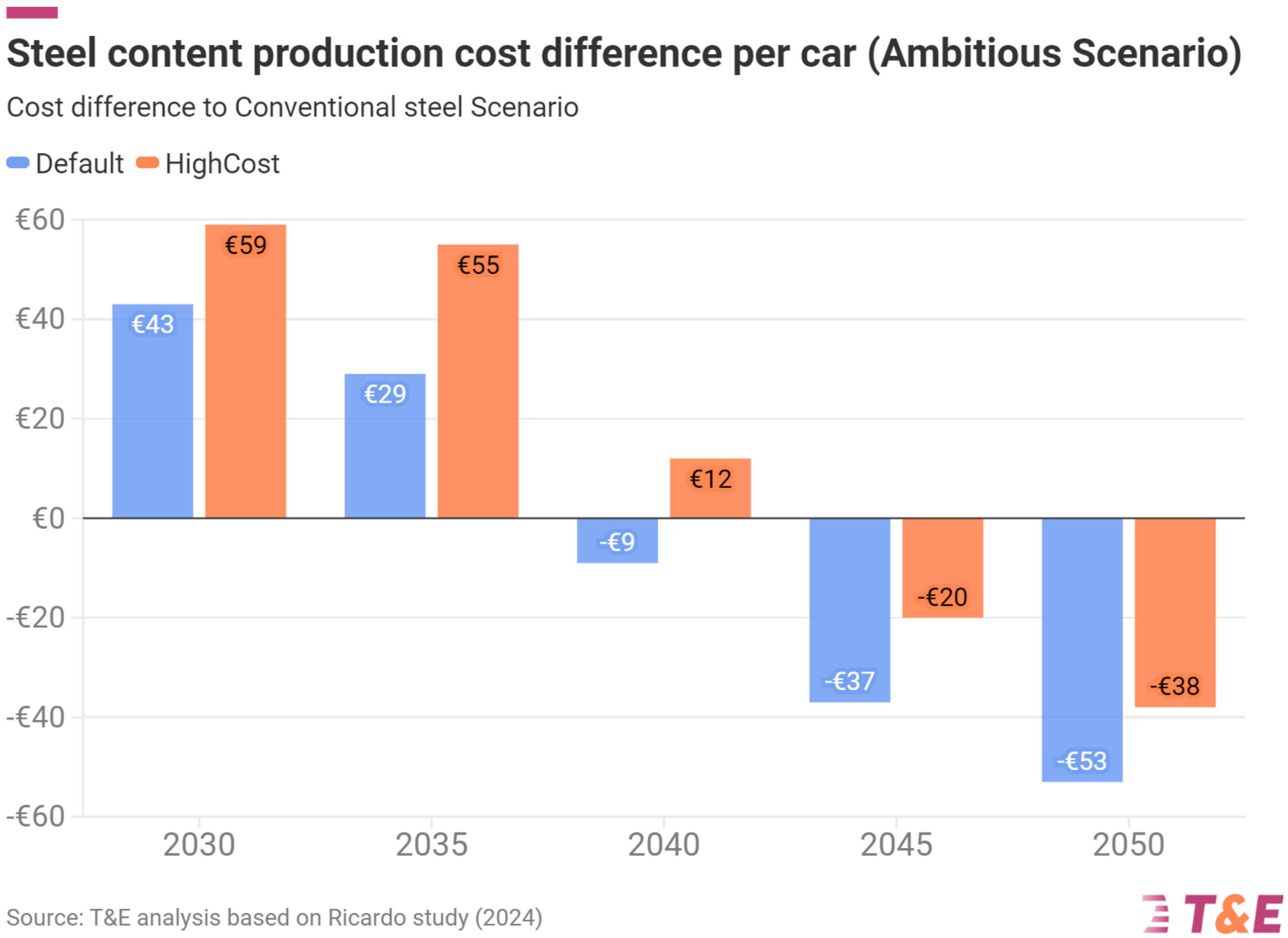

Figure 8: Difference in production cost of steel content per passenger car (mid-sized BEV) between the Ambitious and Conventional steel scenarios, 2020-2050

6.2 Switching to green steel will have negligible impact on price of a car

Any increases, however limited, in the production costs of green steel are expected to be passed on by carmakers to consumers through changes in the retail or sticker price of the car. In their analysis of this question, it was assumed by Ricardo that a change in the cost of steel will be passed on through an increase in the retail price with the addition of a 40% margin for passenger cars and 20% margin for commercial vehicles[44].

For passenger cars, the price increase for a mid-sized BEV using 40% green steel (a mix of scrap EAF and green H2-DRI) is just €57 in 2030, reducing to just €49 in 2035, before almost reaching cost parity by 2040 (just €8 more). The cost increase is slightly higher if we assume the steel content of the BEV remains constant based on current levels - i.e. no lightweighting - coming in at just over €69 in 2030 - less than the cost of fitting a new car floor mat.

[44] 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.

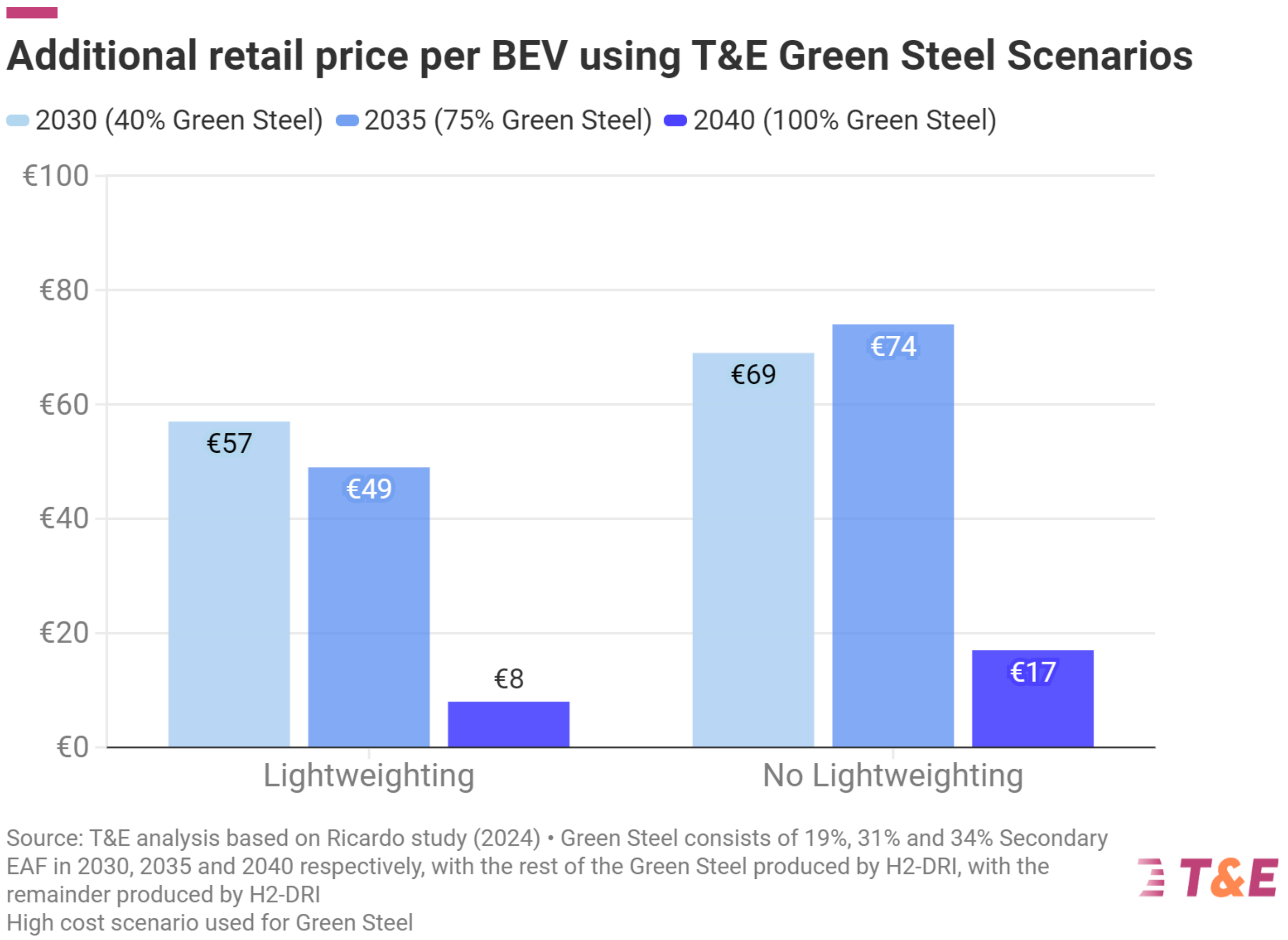

Figure 9: Additional cost (retail price) of a mid-sized BEV using only green steel

Therefore, on an individual vehicle level, the impact of an ambitious uptake of green steel in cars on the retail price paid by consumers is negligible and reaching cost parity in later years due to a reduction in lower-carbon steel prices relative to conventional steel.

The same also applies for trucks, where the use of 100% green steel from the green H2-DRI pathway leads to a slightly higher retail price increase of between 1-2% increase in 2025 compared to steel from the Conventional scenario. However, this initial premium for 100% green H-DR steel decreases to 0.5% for articulated lorries in 2030, 0.2% in 2040, before introducing price savings of less than 1% between 2040-2050. The greater steel content in non-BEV trucks 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[45].

[45] See Ricardo (2024) The use of green steel in the automotive industry, Section 4.3.3 for more details

7. Recommendations

Considering the urgency for action and timeframes for innovation and steel plant investment cycles, it is important to establish reliable policies and support systems that can support the investments and long-term planning needed to transition to green steel.

Policy and regulatory support, coupled with an increase in CO2 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.

T&E recommends policymakers to consider putting in place the following:

A clear and European definition of green steel

- **that is in line with the IEA definition of near-zero emission steel and using the sliding scale approach, i.e. between 400 and 50 kg (or 0.4 to 0.05 t) CO2 per ton of steel produced**, in order to incentivise the uptake of both secondary EAF and green H2-DRI produced steel. The proposed definition is technology neutral and sets a uniform and clear end-point that ensures comparability for the production of crude steel. The recently introduced green steel label "LESS" by the German Steel Association which is building on the IEA definition is a first step in this direction. The LESS system contains a classification scale in the label system, whether the steel is "Near-Zero" - or "low-emission (A-D)" steel.
    - There are several technologies and technology pathways that should be viable to meet the proposed threshold, depending on the amount of renewable energy used and associated upstream emissions produced. These include, but are not limited to: **green hydrogen direct reduced iron (DRI)-EAF steel, secondary scrap EAF steel, and ironmaking through electrolysis (both with renewable electricity)**.

Mandates or targets for carmakers to use an increasing amount of green steel in new cars, applicable from 2030

- Despite carmakers talking the talk on using more green steel, voluntary commitments mean very little in reality unless backed by enforceable regulation that will ensure they also walk the walk[46]. In line with the Ambitious scenario of green steel uptake modelled by Ricardo (see Section 4), **carmakers should be required to use a minimum of 40% green steel in new cars from 2030**, increasing to 75% in 2035, until all steel used in cars is required to be green by 2040.

[46] European car manufacturers promised to voluntarily reduce average CO2 emissions of new cars to 140 g/km by 2008, starting in 1995, when average CO2 emissions were 186 g/km, however by 2005 it was clear that the manufacturers would miss that voluntary commitment. Policymakers subsequently adopted a mandatory regulation that set CO2 targets backed by fines if companies are non-compliant.

- This can be done either **via the end-of-life vehicles (ELV) regulation** currently being revised and discussed by lawmakers, or via separate CO2 standards for automotive steel (extending to trucks, trains and buses in the future. Carmakers would be given an average target to be met across their entire offer of new cars, giving them flexibility to meet them via premium models first, before commercialising across the vehicle range.
- The target should be based on the technologies and pathways for green steel production as identified by the IEA definition of near zero steel (see above and section 2). Carmakers would then be able to source either scrap or primary green steel, or a mix, to meet their targets.

Improve the quality of recycled steel scrap via measures under the End of Life Vehicle regulation

- Despite 43% of EU steel production coming from the secondary scrap EAF route, only 6% of this total is used in new car production (see Figure 2, Section 3.1). The main reason for this is that scrap steel is often not of the quality required for automotive use due to copper contamination from the recycling process. 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%[47].
- There is however no technical limit to using recycled steel in vehicles and improvements in the sorting and recycling process can be made. Several measures have been proposed under the new End-of-Life Vehicles regulation proposal to this end. For instance, in Article 30 it is proposed that **specific parts and components of an ELV are removed prior to shredding**, which can help improve the quality of the grades coming out the other end for use in new cars.
- In addition, T&E proposes to set **mandatory quality requirements on steel recycled from ELVs** so that it meets the quality standard required for reuse in automotive applications, i.e. with a maximum copper content of 0.06%. This option could potentially afford more flexibility to recyclers, some of which claim that best available post-shredding technologies can deliver the sufficient grades required without the manual dismantling of parts beforehand.

A new vehicle ecoscore to reduce the carbon impact of vehicles beyond the tailpipe

- Under the existing EU car CO2 policy framework, all electric cars are rated the same: as zero emission. This fails to take account of the differences in resource, climate and energy efficiency between EV models.
- A new methodology and framework for an environmental score for EVs should combine energy efficiency and material carbon footprint, including steel. Such a score would incentivise manufacturers to reduce the environmental impact of EVs by encouraging improvements in not only vehicle efficiency and the use of low carbon and smaller batteries, but also through procurement of green steel or aluminium.

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47 https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/steel-industry-net-zero-tracker/#:~:text=EAF%2Dbased%20secondary%20steel%20production,premium%20of%208%2D13%25

8. Conclusions

As carmakers make the transition to selling only electric cars and thereby reducing tailpipe emissions to zero, the climate impact of the materials used to make a car will become increasingly important and will need to be addressed as the sector strives to become net zero by 2050 or earlier. Indeed, a vehicle's embedded, or production, emissions are expected to account for around 60% of an electric car's total lifecycle emissions by 2030, with steel making up an important part.

Many carmakers are already preparing for this and have set voluntary targets to increase the amount of green and recycled steel in their new cars. However, despite the promising potential and growing excitement around green steel and its use in cars, many questions remain unanswered about its feasibility, climate benefits, and cost. This paper, alongside a new Ricardo study, *The use of green steel in the automotive industry*, has aimed to answer some of these questions.

First, cars can and should make an ideal lead market for greening steel. Despite the billions of euros of subsidies doled out already, financial investment decisions in green steel production are highly dependent on having a clear market demand and offtake for their product. The automotive sector is uniquely and well positioned to create this demand, as it is heavily dependent on steel, with carmakers making close to half of some steelmakers orders in Europe. The relatively high value of cars, especially premium brands, also means they can absorb the short-term green premium of greener steel.

Second, there is projected to be enough green steel for an ambitious uptake in new cars already by 2030. Based on Ricardo's tracking and assessments of green steel announcements there have been new green steel production announcements totalling 85 Mt of production capacity by 2030, which, when combined with existing scrap EAF production capacity of 87 Mt, total green steel production capacity is projected to reach 172 Mt by 2030. This is more than enough to cover total projected demand from the automotive sector, which reaches just 21 Mt, assuming a broad shift to lightweighting and less steel use in the sector, and even plenty to cover the 2022 annual consumption of 35.7 Mt if we assume no lightweighting takes place.

Third, shifting from conventional to using only green steel (a mix of secondary EAF and green H2-DRI steel) would reduce the total embedded carbon emissions of a battery electric car by one-sixth (or 17%) by 2030, demonstrating the huge climate potential that green steel offers carmakers as they look to reduce their scope 3 emissions on the way to net zero.

Fourth, switching to green steel in cars will have a negligible impact on the price of a new car, adding only €57 to the sticker price of a BEV compared to one made with conventional steel in 2030, an additional €49 in 2035, and just €8 by 2040. The cost increase is slightly higher if we assume the steel content of the BEV remains constant based on current levels - i.e. no lightweighting - coming in at just over €69 in 2030 - less than the cost of fitting a new car floor mat. For the cost of less than €100 euros per car, we can build a green steel sector in Europe.

Whilst an increase in CO_2 emission prices and a reduction in the cost of renewable electricity are both expected to help to make green steel pathways economically and strategically attractive for investment by the steel industry and automotive sector, policy and regulatory support will be crucial to establish a lead market for automotive green steel that will be important to provide a demand signal and de-risk the necessary investments. First and foremost Europe needs to establish an ambitious and harmonised definition of green steel, in line with the IEA definition of near-zero emission steel and using the sliding scale approach (between 400 and 50 kg CO_2 per ton of steel produced). Second, a priority for the coming legislative term should be to set mandates from carmakers to use a minimum and growing share of green steel in new cars that are sold in the EU from 2030. Finally, measures to improve the quantity and quality of recycled steel should be included in the revised End of Life Vehicles regulation.

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ANNEXES

A1. Overview and assessment of steel production pathways

A.1.1 Conventional: Blast Furnace-Basic Oxygen Furnace

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 and 56% of European crude steel in 2020.

The main feedstock for the BF-BOF pathway is mined iron ore, which is first pre-processed into pellets at dedicated plants at temperatures between 1,200-1,500 °C. Coke (coal), 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 iron ore is then reduced in the blast furnace (BF) at around 1,500 °C, using injected coke to remove the oxygen and produce pure (pig) iron. The molten pig iron is then poured into the basic oxygen furnace (BOF), where oxygen is blown into the liquid iron to reduce the impurities so it is steel grade. The crude steel from the BOF is then cast into different intermediary steel products through various hot-and cold-rolling downstream processes.

A1.1.1 Decarbonisation potential of BF-BOF steel

Producing one tonne of crude steel via the BF-BOF production pathway creates approximately 1.2 tonnes of CO2 from direct emission sources, namely through the consumption of coke in the chemical reduction of the ore. Indirect emissions from the production of reagents, electricity and heat in each stage of production results in roughly 1.0 additional tonnes of CO2 per tonne of steel. As such, **the BF-BOF production pathway produces between 1.8 and 2.2 tCO2e/t steel**, compared to the current global average of 1.7 tCO2e/t steel produced by all methods combined.

A1.1.2. Production cost of BF-BOF steel

Between 2015 and 2020, the average cost of crude steel from integrated BF-BOF production was €436/tonne of steel. 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. However, with renewable electricity costs anticipated to fall and CO2 emissions prices expected to increase, the BF-BOF pathway is projected to no longer be cost-competitive compared to innovative production processes by 2040.

A1.1.3. 'Green steel' assessment of BF-BOF steel

Compared to the alternative pathways explored below, the BF-BOF pathway is the most carbon intensive by far (e.g., the green H2-DRI-EAF pathway offers up to 98% CO2 emission reduction, see Section 9.6.1). The current integrated BF-BOF plants already maximises energy efficiency at close to the optimum limit, with retrofitting technologies to further lower the CO2 emissions of this pathway (e.g., CCS, hydrogen injection into the BF) remaining so far unaffordable and limited outside of small-scale projects.

As automotive manufacturers begin to decarbonise their supply chains in order to reach net zero production emissions by 2050, longer-term reliance on BF-BOF steel is simply not a feasible option.

A1.2. Secondary (scrap) Electric Arc Furnace steel

Electric Arc Furnace (EAF) refers to a furnace that uses electric arcs to generate heat[48]. 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 scrap EAF steel is a highly utilised 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%.

A1.2.1. Decarbonisation potential of secondary EAF steel

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 CO2 emission (exact figure depending on the carbon intensity of the electricity used to power the EAF), see below.

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 chemical form. CO2 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 0.2-0.3tCO2e/t steel (depending on grid

[48] 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.

mix). At present, secondary EAF steel can reduce around 80-85% of carbon emissions, which is around 1.5 tonnes of CO2 per tonne of steel. These figures are then expected to improve further as electricity grid mixes in Europe and globally continue to be decarbonised. Additionally, scrap steel avoids the consumption of 1.4 tonnes of iron ore, 740kg of coal and 120kg of limestones.

If powered by 100% renewable electricity, this method offers a promising pathway towards near-zero-emission steel and can reduce emissions by 90-95% compared to BF-BOF[49].

A1.2.2. Production cost of secondary EAF steel

Crucially, the secondary EAF route offers significant emissions reductions with no significant cost difference with the BF-BOF route in future years, and a very low premium in the near-term. In 2019, the average cost of producing scrap-based EAF steel was between €320-460/t , which is comparable to or slightly lower than the cost for primary BF-BOF steel. The scrap steel itself costs €190-280/t. 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.

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. There are 148 EAFs in Europe, with a capacity of 90 MT of crude steel.

A1.2.3. 'Green steel' assessment of EAF steel

Although there is no technical limit to using recycled steel in vehicles, typical scrap steel sorting and processing methods often leads to "downcycling", where high-quality steel is mixed with lower grades with greater impurities. For this reason, it is often stated that secondary EAF steel is currently not directly applicable for some automotive applications which require high-quality grades. 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%[50]. Improvements in the sorting and recycling process can however be made - some of which have been proposed under the new End-of-Life Vehicles regulation proposal - to ensure high-quality grades are captured and maintained through the Secondary EAF process to increase its use in cars.

An additional consideration is that there is simply not enough scrap, especially high-quality scrap, to meet the global steel demand out of secondary steel. Estimates suggest 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. Secondary EAF steel scores well on both sustainability and viability (both

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[49] https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/steel-industry-net-zero-tracker/#:~:text=EAF%2Dbased%20secondary%20steel%20production,premium%20of%208%2D13%25.

[50] *Ibid*

in terms of cost and scalability and maturity of the technology) and should be an important part of carmakers' efforts to decarbonise their production emissions going forward. However, it is unlikely to entirely meet the green steel demand of the automotive sector, and will need to be complemented with primary steel supply.

A1.3. 'Blue' BF-BOF steel

Conventional blast furnace made steel can theoretically rely on carbon capture and storage (CCS) technology to reduce emissions. CCS refers to the method of capturing CO2 emission at the production site and then permanently storing it in a location, such as an underground reservoir, that prevents it from being re-emitted. Although major steelmakers like ArcelorMittal, Thyssenkrupp and Tata Steel have been attempting to develop large-scale projects, CCS is far from being adopted at scale in the iron and steel industry, and a lot of uncertainty remains on its ultimate viability.

A1.3.1. Decarbonisation potential of 'blue' BF-BOF steel

Estimates on the emission reduction potential of steelmaking with CCS are also highly uncertain, with ranges from just a 20% to an 80% reduction compared to conventional steelmaking. The amount of reduction depends, unsurprisingly, on the amount of CO2 that can be captured from the BF-BOF process. As the process has numerous emission sources, CCS equipment has to be fitted to all of these, which makes achieving a high level of overall CO2 reduction using CCS extremely difficult. Consequently most projects to date have focussed on fitting CCS technology to the blast furnace only where just over 50% of the CO2 originates from, as large quantities of carbon in the form of coke and coal are processed as a reductant and a fuel.

A1.3.2. Production cost of 'blue' BF-BOF steel

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 CO2 emission. However, similar to its decarbonisation potential, CCS cost estimates vary a lot, with BNEF estimating 20% and Agora around 60-120% higher costs compared to the conventional integrated route. The gap between the two methods is reflected primarily by the CAPEX required to retrofit existing BF plants and apply CCS technology. However, assuming a CO2 price of €85/ton, CCS is cheaper than the conventional route without CCS.

A1.3.3. 'Green steel' assessment of 'blue' BF-BOF steel

There are significant uncertainties and limitations that come with relying on CCS to decarbonise conventional BF-BOF steelmaking and as such, should not be considered as a viable green, nor even low-emission alternative by industry or policymakers. According to Ricardo, it "does not appear to be realistic to decarbonise automotive steel to a significant extent". On top of its uncertain and limited decarbonisation potential, 'blue' BF-BOF steelmaking is still an unproven technology with low TRL, and would require investment to retrofit the current integrated route. This is estimated to result in higher costs by 2050 compared to other decarbonisation routes.

A1.4. Natural gas based Direct Reduced Iron steel

Natural gas based Direct Reduced Iron steel (NG-DRI) or 'grey' steel, refers to an already commercialised method of steelmaking that uses natural gas to power a so-called direct reduced iron or DRI plant. While the conventional steelmaking route reduces primary iron ore using blast furnaces, Direct Reduced Iron, also known as sponge iron, is produced in fluidized bed reduction (FBR) furnaces where the iron ore is mixed with a reducing agent to separate the oxygen from the iron ore. This reducing agent can be either a gas or a solid. When natural gas is used, the iron ore is converted into DRI as oxygen combines with natural gas, generating water and carbon dioxide as by-products. The DRI is then fed into EAFs for steel production, in a similar fashion as described in Section 9.2 when talking about secondary EAF steel production from scrap.

A1.4.1. Decarbonisation potential of NG-DRI steel

The decarbonisation potential of the NG-DRI route will vary depending on the electricity sources used to power the EAF, but assuming the EAF is running on an EU average grid mix, **NG-DRI steel has a decarbonisation potential of around 50% compared to conventional BF-BOF steel** (slightly lower on a global average mix and higher if the EAF runs on renewables). This equates to around 1 tonne of GHG emission per tonne of NG-DRI steel production.

The main source of emission is the direct CO2 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, as already mentioned, is able to deliver further reduction as the grid mixes decarbonise.

A1.4.2. Production cost of NG-DRI steel

NG-DRI steel costs around €671/t, which is higher than the average cost for the conventional integrated BF-BOF route. 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 and hence the cost of NG-DRI steel production is subject to volatility in natural gas prices. Considering the major natural gas production countries are not located in the EU, the construction and operation of the plants would likely not be efficient (Ricardo study).

A1.4.3. 'Green steel' assessment of NG-DRI steel

NG-DRI steel has a very limited decarbonisation potential, however, especially compared to secondary EAF and other hydrogen-based (see below) routes. Direct carbon emission from the chemical reaction are inevitable, meaning its CO2 reduction will not be sufficient to meet the EU's longer term net zero climate goals. An additional climate concern is that, during the production of natural gas, there is a risk of fugitive methane gas emissions (a significant concern, since each tonne of methane has 25 times the global warming potential of one tonne of CO2). These emissions could hypothetically be reduced by CCS technology however (see Section 9.3).

A1.5. 'Blue' hydrogen based Direct Reduced Iron steel

Hydrogen based DRI, or H2-DRI, refers to steelmaking that uses hydrogen as the reducing agent in a DRI process. Blue H2-DRI uses 'blue' hydrogen that is produced via conventional reforming of fossil fuels (usually, natural gas), but where the carbon emitted from its production is captured via CCS. The steelmaking method follows the same production route as other DRI-EAF steel routes (as described in Section 9.4). The primary ore is reduced in a fluidized bed reduction (FBR) furnace into DRI and is then used as a feedstock in EAFs for steel production. In the blue H2-DRI route, the reductant is blue H2 instead of natural gas, meaning the chemical reaction which separates the oxygen from the iron ore only generates water as a by-product.

A1.5.1. Decarbonisation potential of blue H2-DRI steel

Although blue hydrogen is categorised as lower-carbon hydrogen, it is not, and cannot be, zero-carbon hydrogen. According to Ricardo, studies suggest that around 10-20% of the carbon emitted to produce hydrogen via natural gas reforming cannot be captured. A more recent study study compared "blue" H2 to "grey" H2 and natural gas, and found that **"blue" H2 could, at best, only achieve a 40% reduction in life-cycle GHG emission intensity** per MJ, when compared to the straight use of natural gas. Therefore, blue H2-DRI steel can only be expected to achieve partial and limited decarbonisation compared to the conventional BF-BOF route.

The best that can be said for the blue H2-DRI route is that it is compatible with a transition away from conventional blast furnace steelmaking towards the DRI-EAF route with green hydrogen. As it is part of the same DRI family and uses the same infrastructure, it could be used as a stepping stone to using green H2 in the same process.

A1.5.2. Production cost of blue H2-DRI steel

According to Ricardo, the cost of producing blue H2-based DRI steel is expected to be higher than other routes. Assuming a price of €85 per tonne of CO2 emitted, H2-DRI "blue" steel is expected to cost €870 per tonne of steel produced. This is 70% higher than the integrated route and would be due to the high cost of blue hydrogen and the investment required to construct DRI-EAF facilities. There is, however, a high degree of uncertainty around the cost as multiple economic factors will influence the relative cost of the blue H2-DRI route, compared to using green H2: the cost of natural gas and cost of CCS (for "blue" H2 production), the electrolyser and the cost of renewable electricity (for "green" H2 production. According to Ricardo, the most important factor determining the competitiveness of the blue-H2 route is the cost of natural gas. If the sky high gas prices seen in 2022 would be in anyway indicative of future gas prices in Europe, then blue hydrogen will not be feasible from an economic point of view and make little sense from a European steelmaker perspective.

A1.5.3. 'Green steel' assessment of blue H2-DRI steel

Blue H2-DRI steel making shares many of the same limitations as the other non-conventional routes relying on CCS technology. With both a limited decarbonisation potential and uncertainties over the cost, it does not appear to be a viable pathway for greening automotive steel. Not only this, but blue H2-DRI is far from being a commercially available alternative. According to Ricardo, there is today no blue hydrogen plant tested at a commercial scale yet and if the steel industry wanted to switch to hydrogen-based steel today, it would require 130% of the total current supply. Furthermore, the long-distance transportation of hydrogen would require significant infrastructure.

A1.6. 'Green' hydrogen based Direct Reduced Iron steel

H2-DRI "green" steel refers to the steel that is produced based on the same DRI process described in Sections A1.4 and A1.5 above; the only difference between H2-DRI "Blue" steel and H2-DRI "Green" steel being how the hydrogen is produced. In the green route, green H2 is used as the reducing agent for the iron ore. In this way, hydrogen is produced by splitting water in an electrolyser, with the electricity used to power the electrolyser being sourced by renewable energy.

A1.6.1. Decarbonisation potential of green H2-DRI steel

Green H2-DRI steel, along with secondary EAF powered by renewables, offers by far the greatest decarbonisation potential of the alternative steelmaking routes, as green H2 can be almost fully decarbonised along with the electricity grid (used for the EAF following the DRI step).

According to Ricardo, the grid emission intensity that would be needed to break-even or equalise the GHG emissions from conventional BF-BOF steel and electrolyser-H2-DRI steel is 532CO2e/kWh. Given that, in Europe, the average grid mix carbon intensity is 300gCO2e/kWh, electrolyser-H2-DRI steel is already a clear winner. However, certain countries, such as Sweden and France, already boast highly decarbonised grids (Sweden has grid mix carbon intensity of 7gCO2e/kWh, while it reaches 68 gCO2e/kWh for France), while the EU27 grid continues to get greener each day and is expected to reach around 110gCO2e/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 CO2 emissions of around 53kg per tonne of steel embedded in the extraction of iron ore and other feedstocks, which require additional actions such as electrification of mining equipment. Nevertheless, **the green-H2-DRI route, assuming renewable energy used for both the H2 and EAF, offers between a 97% and 99% emission saving compared to the BF-BOF route**.

A1.6.2. Production cost of green H2-DRI steel

According to Ricardo, the current cost estimates of producing H2-DRI "green" steel are all over €560 per tonne of steel. These are relatively higher than the conventional BF-BOF route, therefore 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.

The price difference is highly dependent on both the price of green hydrogen and renewable electricity. 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. Should these projections be realised, then eventually H2-DRI "green" steel would become cheaper than conventional BF-BOF steel in the future. However, as with all other alternative pathways, uncertainties remain, and cost estimates for green H2 in 2050 range between 1 €/kg to over 5 €/kg[51], leading to H2-DRI "green" steel in Europe potentially being cheaper or 60% more expensive than today's steelmaking costs.

A1.6.3. 'Green steel' assessment of green H2-DRI steel

Green H2-DRI 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 flat steel products used by the automotive industry, utilising primary ore. The green H2-DRI steel route not only has sufficient decarbonisation potential that satisfies the EU's net zero goal, but its production scale is also not limited by the shortage of input, unlike secondary scrap steel. Although both increased scrap steel, which is better from an energy and resource efficiency point of view, and green H2-DRI steel will be needed to decarbonise automotive 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.

Similarly to other hydrogen based routes, the green H2 route shares the same concerns about supply of green hydrogen, with most of the hydrogen produced today (95%) being grey hydrogen produced from coal or natural gas, emitting GHG. Therefore, expanding electrolyser capacity and renewable energy to power the electrolyser is crucial and some areas may not have low-cost renewable energy or hydrogen transportation infrastructure. Furthermore, due to capacity and price issues, sourcing green hydrogen leaves high uncertainty in terms of production cost as discussed above.

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

Although not yet commercialised on a large scale, there are several announced production facilities in Europe, with the first full-scale green H2-DRI-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 also plans 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.

A1.7. Emerging Technologies: Iron Ore Electrolysis

In addition to the pathways explored above, iron ore electrolysis technology is an emerging and promising route for decarbonising automotive steel, and is already widely used for metals such as zinc and aluminium. Replacing the iron ore reduction stage, its fundamental concept is that an electric current passes through iron ore in an electrolyte, producing liquid iron to be fed into the electric arc furnaces. Electricity is the only energy requirement for reduction and does not produce any direct CO2 emissions. This means, when 100% renewable electricity is used, it is possible to achieve 100% carbon reduction compared to the conventional BF-BOF route. It can also avoid the upstream stages like H2 production.

Demonstration projects such as the Siderwin project led by ArcelorMittal successfully validated the technology (electrowinning) at Technology Readiness Level (TRL) 6. However, it is not expected to be commercially available until 2050 and therefore its usefulness and scalability for decarbonising automotive steel is unclear.

A2. Additional graphs

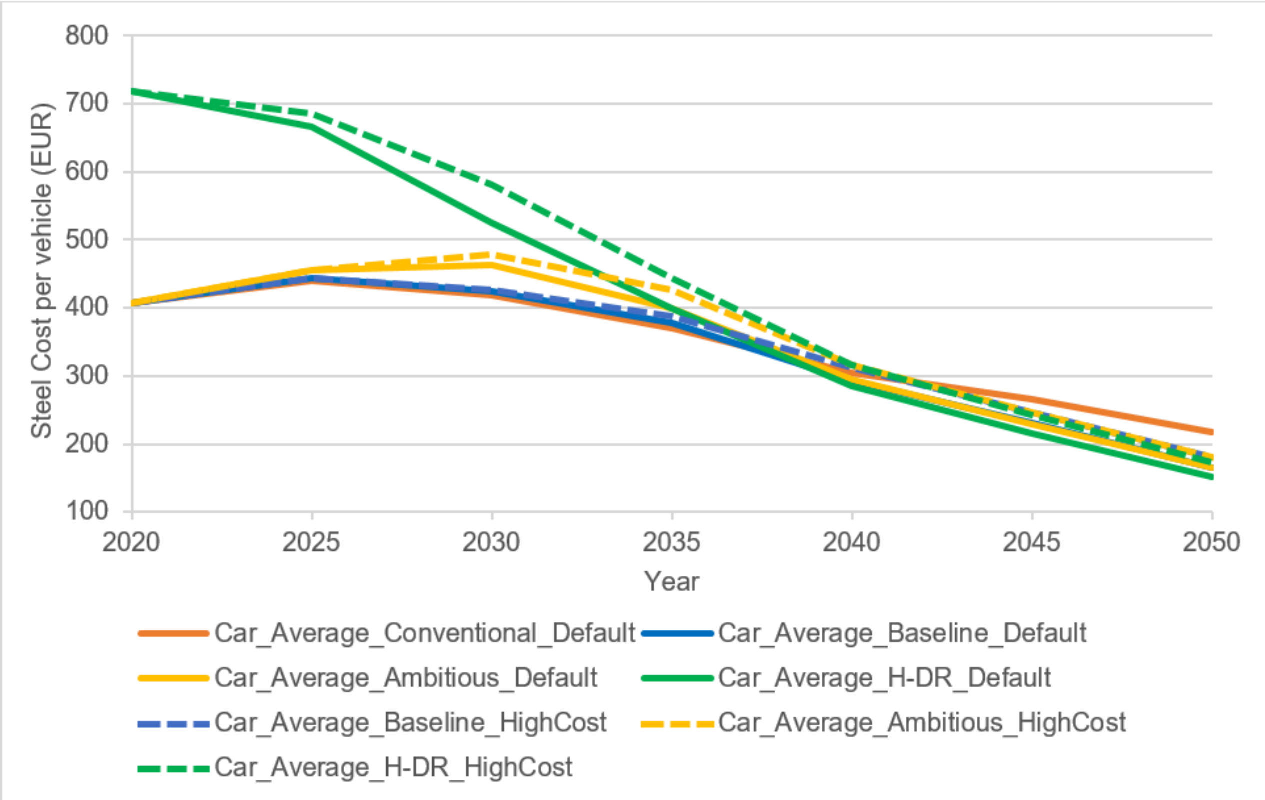

Figure A.1: Cost of steel content in an average passenger car under a Conventional, Baseline, Ambitious and 100% H2-DRI steel content mix with Default and High cost sensitivities, 2020-2050

Source: Ricardo modelling analysis for this project