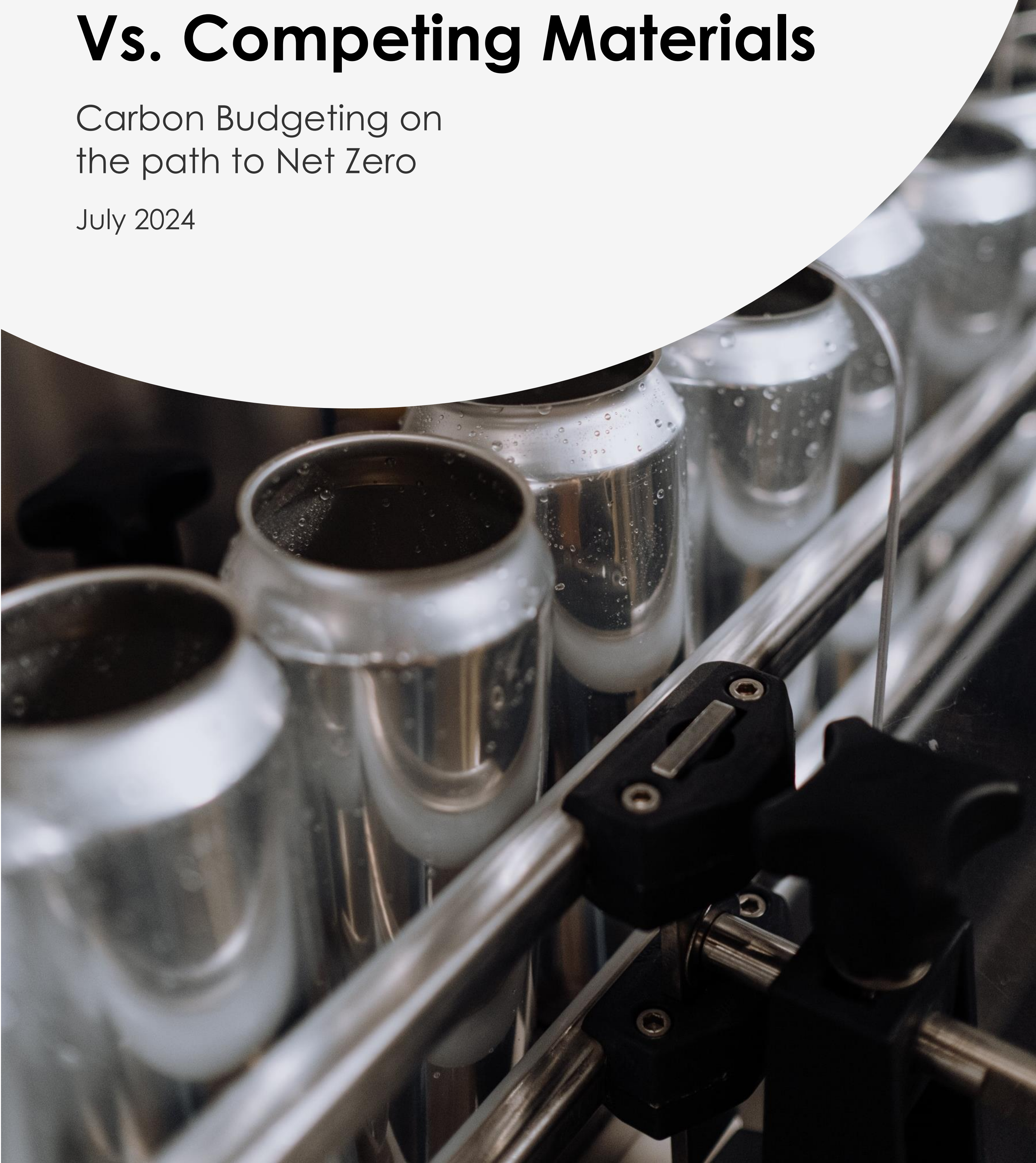
Decarbonisation Pathways in Aluminium Vs. Competing Materials

Carbon Budgeting on the path to Net Zero

July 2024



Report for

International Aluminium

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Executive Summary

This study builds upon Eunomia's previous studies into materials decarbonisation pathways which found that our key material industries are likely to have great difficulty in reducing GHG emissions in line with a 1.5°C future, particularly if current consumption levels continue or increase. The scope of this report is focused on aluminium in comparison to four competing materials— steel, copper, container glass, PVC —taken from the perspective of their global value chains. The analysis looks at the Net Zero pathways that are being proposed by the industries and how these compare with 1.5°C aligned carbon budgets.

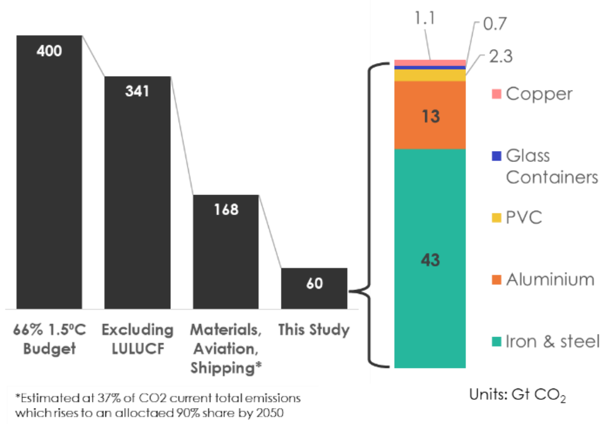
Although proposed industry pathways exist for some materials, their methodologies differ, making comparisons challenging. By applying a consistent methodology, this study aims to assess which materials are better positioned to stay within their respective budgets and identify their strengths and weaknesses on the path to Net Zero.

Methodology and Scope

Given the considerable uncertainty around climate change projections it is important to recognise there is no correct answer, however it is still crucial to be ambitious and reach a target sooner rather than realise that irreversible change has already taken place. We have therefore adapted our previous method to account for the 'hard to abate' sectors— namely materials, aviation and shipping. Today the share of global GHGs for 'hard to abate' sectors is estimated to be 37%. The cumulated carbon budget in this report are set based on a scenario where this share increases steadily to 90% by 2050. This recognises that *all* sectors need time to decarbonise regardless of whether their path is clearer (in energy for example). The result of this is that these industries are assigned 49% (168Gt) of the non-LULUCF cumulative GHG emissions budget.

Of that 168Gt, this study focuses on materials that account for 60Gt of the budget which is set based on their current emission levels – see Figure 1.

Figure 1 – Determining Cumulative Carbon Budgets for 'Hard to Abate' Sectors.



The analysis looks at the Net Zero pathways that are being proposed by the industries and how these compare with 1.5°C aligned carbon budgets.

The sectors are also defined by their Scope 1 and 2 CO_2 emissions (their direct emissions and those of the energy they use up to the factory gate) from cradle to gate (mining to semis product). This is to account for the potential overlap or double counting between sectors and the focus on the direct operations of the material value chain. This is important when assigning a carbon budget in a meaningful way — energy use in downstream transport for example, is out of scope.

There are exceptions to this whereby Scope 3 emissions are included. Specifically in the steel sector whereby the mining and production of coking coal is categorised as Scope 3. However, it accounts for a significant portion of the CO_2 emissions from steel and the coking coal is typically primarily used for steel making. This process is therefore included due to its importance on the path to Net Zero. Similarly, and for consistency, the mining and processing of raw materials is included for the other materials, but these are typically less important from a CO_2 perspective.

Conclusions: Comparing the Key Challenges

There are critical actions and time milestones that all industries need to observe.

- All material industries will be required to take significant action within the next five years to manifest a downward trend in global CO2 emissions, otherwise it is unlikely that their carbon budgets will be met.
- Commercialisation and mass deployment of new technologies will need to be in full swing from 2030 onwards.
- In all cases, closed-loop recycling can aid towards Net Zero by reducing primary demand. However, the importance of this varies between materials and decarbonising primary production should not be sacrificed.
- From a global perspective, the trajectory of China's decarbonisation—particularly from an energy generation perspective—will be a critical determinator of whether the global budget can be met.
- The difference in impact between geographic areas for all materials provides and opportunity for data driven purchasing decisions to influence the speed of decarbonisation.
- The current industry plans – where they exist – are likely to fall short of carbon budgets that align with 1.5°C. More emphasis should therefore be made on reducing overall demand for materials alongside decarbonisation strategies.

Some materials will rely more on green energy than others.

For Steel, glass and PVC there will need to be a transition away from fossil fuels as a heat source or reactant. These industries are dominated by natural gas and coal which will need to be phased out.

Aluminium and copper already rely heavily on electricity and therefore the challenge is to make sure there is enough green energy available where it is needed in order to deal with expanding demand.

Some materials will need to transition to entirely new technologies.

Copper and aluminium production is likely to stay mostly the same, with the latter requiring further development of anode replacements and low-carbon refining processes. The fundamental processes are not intrinsically linked to fossil fuels and therefore most infrastructure can remain intact.

Steel requires a mix of technologies to mitigate or remove the need for coking coal as a fuel and reductant in the iron making process. Entirely new plants focusing on DRI for primary and EAF for secondary will be required.

Glass furnaces will need to be retrofitted or newly installed with the capability of running primarily on electricity, whilst PVC faces the potential for a fundamentally disruptive shift from fossil to bio-based feedstocks—one which is not fully embraced by the current value chain. This is alongside the need to electrify steam crackers and move away from coke-based production in China.

Recycling cannot be relied upon alone.

Recycling plays a significant role for most materials although for copper, steel and PVC and to a lesser extent, aluminium, much of the material is ‘locked-up’ in construction and not available for recycling. This means that recycling can only contribute so much at a global level but will vary in importance when honing in on the product level. Furthermore, the benefits of recycling differ between materials due to the energy intensity of the processes.

Table 1 shows a summary of the key challenges that these industries are facing and where in the value chain these are. Regarding energy transition, infrastructure and technology development and recycling; each material varies in the where investment is most needed.

Table 1 – Net Zero Challenges Vary Between Materials

Material	The **Reliance** on Electrical green grid transition and expansion of capacity	The **need** for new technology and manufacturing infrastructure replacement	**Technical maturity** of replacement technologies	The **maturity** and availability of Recycling processes
Aluminium	●●●● Smelting is electricity-driven and dominates the impact.	●● Anode replacement will be required to fully decarbonise	●●● Inert anode and refinery calciner not yet fully commercialised	●●●● Recycling is common due to the high value and expanded capacity is all that is needed
Steel	●●● Relatively low electricity use currently, but will need to grow with new technologies	●●●● Most current blast furnaces will need to be replaced	●● A broad technology mix with varying readiness levels will be required	●●●● Scrap steel is very commonly recycled and expanded capacity is all that is needed
Copper	●●●● The process is heavily dependent on electricity	● The core process will remain unchanged	●●● It is unclear which alternative fuels will be used in machinery	●●● High value and easy to integrate, but centred on few geographic locations
Container Glass	●●●● The shift to electric furnaces will increase electricity demand	●●● All furnaces will need to be replaced with hybrid or fully electric	●● Furnaces are only just beginning to be tested at the scales required	●●● Glass recycling rates vary significantly by region and not all collected goes to remelt
PVC	●● The move to electric steam crackers will require more capacity	●●●● A switch to electricity driven steam crackers for ethylene and bio-based feedstocks will be required	●● Ethylene production is common, but electric steam crackers and bio-based are not	● Recycling is not well established and challenging to integrate. Legacy chemicals are problematic

Key: ● = Low; ●●●● = High

E.g ● PVC has a **LOW** maturity of reycling

●●●● Aluminium has a **HIGH** maturity of recycling

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Introduction

This study builds upon Eunomia's previous studies into materials decarbonisation pathways in the reports "Is Net Zero Enough for the Material Production Sector?"[a]. and "Decarbonisation of Single Use Beverage Packaging."[b] The former Focussed on the four materials with the greatest emissions globally and found that each is likely to have great difficulty in reducing GHG emissions in line with a 1.5°C future by 2050, particularly if mass consumption continues and increases.

Conducted on behalf of the International Aluminium Institute (IAI), this study builds on our approach to evaluating decarbonisation pathways against a carbon budget. It explores global aluminium and four materials that compete with it in certain sectors. Although proposed industry pathways exist for some materials, their methodologies differ, making comparisons challenging. By applying a consistent methodology, this study aims to assess which materials are better positioned to stay within their respective budgets and identify their strengths and weaknesses on the path to Net Zero.

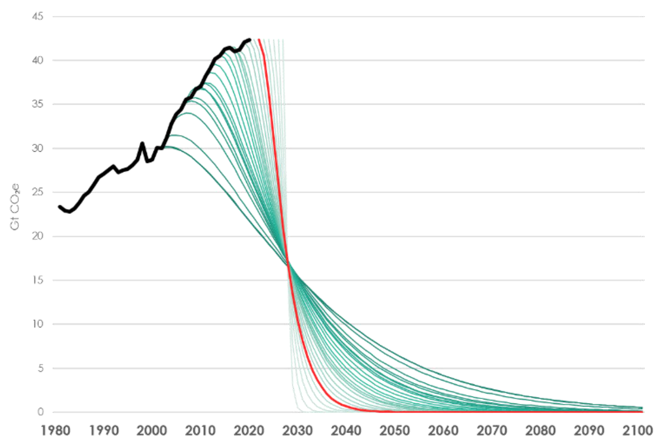
Whilst this study has been funded by the IAI to help understand aluminium's strengths and weaknesses relative to other materials, Eunomia has retained an independent approach to offer a transparent assessment of the materials under focus.

Methodology

Net Zero and Carbon Budgeting

Eunomia's previous reports on carbon budgeting have taken the approach that each sector takes a budget according to its current share of CO_2 emissions. This differs from other approaches, including that of the Mission Possible Partnership (MPP)[3] that have defined certain industries as 'hard to abate' and therefore worthy of being allowed additional budget under the assumption that other sectors can and will decarbonise faster. The specific budget calculations for these sectors are not disclosed by MPP. Furthermore, the MPP also take the IPCC's 50% probability of staying within 1.5°C compared with Eunomia's choice of 66% which leads to a 500 and 400Gt budget respectively. The choice between these is largely a value judgement rather than one lead by scientific consensus. Furthermore, the uncertainty around the carbon budget is compounded by the emissions of non-CO_2 GHG emissions which are assumed by the IPCC to be largely mitigated but could change the budget by ±220Gt depending on how these emissions are tackled in future.[4]

Figure 2 – Global Carbon Budget Pathways



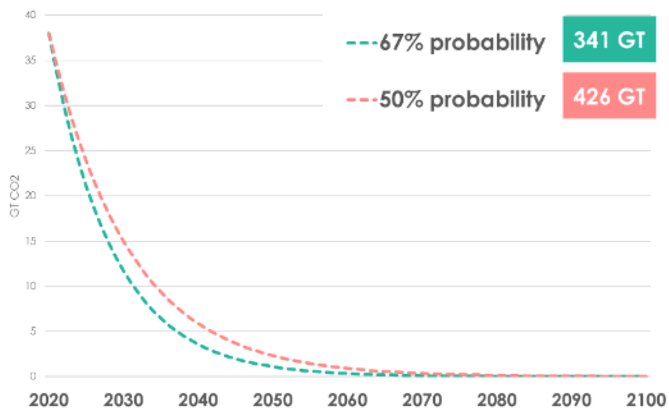
Source: Adapted from Robbie Andrews (2019); based on Global Carbon Project & IPPC SR15

The final complication is that Net CO_2 from land use, land-use change, forestry (LULUCF) is also included in the budget, but there is no consensus around which emissions contribute and the exact scale of these at present. The MPP assigned 50Gt of the budget to this under the assumption that all deforestation stops by 2030. The IPCC estimates that 2019 LULUCF emissions were 6.6Gt and therefore it has been decided that for this study a more conservative approach would be to keep the LULUCF budget proportional to other sectors which leads to 59Gt.

The IPCC's estimate for 2019 CO_2 emissions is 38Gt with an additional 6.6Gt for LULUCF. Splitting the 400Gt budget proportionally leaves a total budget for non- LULUCF of 341Gt compared with MPP's of 450Gt. If the baseline 50% 500Gt is used, the budget would be 426Gt.

With all of this said, it is also important to recognise that the IPCC estimates were based on a 2020 baseline, and we are now four years past that date. Other than the notable dip in 2020 itself due to the Covid pandemic, none of the industries in this report are known to have seen a notable decline in GHG emissions from that point.

Figure 3 – 1.5°C Trajectories



Given the considerable uncertainty around climate change projections it is therefore important to recognise there is no correct answer, however it is still important to be ambitious and reach a target sooner rather than realise that irreversible change has already taken place. We have therefore adapted our method to account for the 'hard to abate' sectors. We have extended these beyond MPP's (aluminium, cement and concrete, chemicals (ammonia) and steel; aviation, shipping, and trucking) in recognition that the majority of materials still have their challenges and that there are notable exclusions from MPP's list such as the plastics industry. To that end, whereby the current share of global GHGs for 'hard to abate' sectors is estimated to be 37%, the carbon budgets in this report are set based on a scenario where this share increasing steadily to 90% by 2050. This recognises that *all* sectors need time to decarbonise regardless of whether their path is clearer (in energy for example). The result of this is that these industries are assigned 49% (168Gt) of the cumulative GHG emissions budget through to 2100.

Of that 168Gt, this materials in this study have a combined budget of 60Gt which is set based on their current emission levels – see Figure 4.

As seen in Table 2 The budgets for this study have increased from previous Eunomia work to take account of 'hard to abate' sectors. The differences between this study and the MPP budgets are also show for the applicable materials – the key driving difference being the 400 vs 500Gt starting point. This study estimates the budget for aluminium to be 13% and 23% smaller than in the MPP study for aluminium and steel respectively.

Figure 4 – Carbon Budget Setting

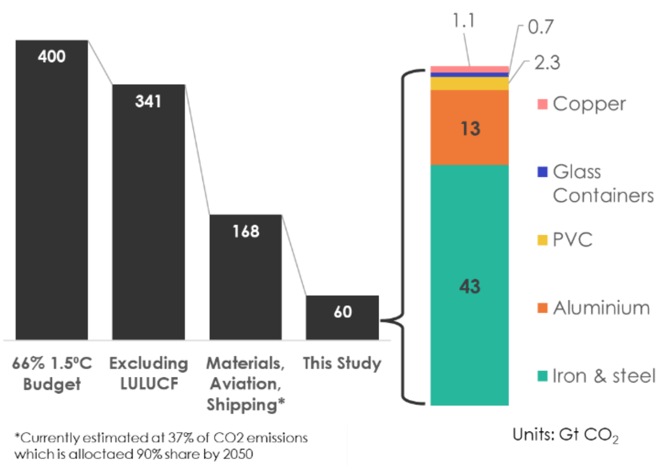


Table 2 – Material Carbon Budgets Gt CO_2e

Material	Eunomia (2022)	Eunomia (2024)	MPP
Aluminium	9	13	15
Steel	30	43	56
Copper	n/a	1.1	n/a
Glass	n/a	0.7	n/a
PVC	n/a	2.3	n/a

Scope

The scope of this report is the focus on aluminium in comparison to four competing materials— ***steel, copper, container glass, PVC*** —taken from the perspective of their global value chains.

The analysis looks at the Net Zero pathways that are being proposed by the industries and how these compare with 1.5°C aligned carbon budgets. As previously mentioned, the carbon budget is a CO_2 specific budget that does not include other GHGs.

For each sector this includes their direct CO_2 emissions, the CO_2 from direct and indirect energy use, and upstream emissions from raw materials use up to the factory gate. To avoid the potential overlap or double counting between sectors and to keep the focus on the operations of the material value chain energy use in downstream transport, is out of scope.

It is important to account for upstream emissions (also known as Scope 3) as they can be a significant part of the overall impact. Often, industries are almost entirely responsible for driving these emissions, even if they are not emitted directly. For example, in the steel sector, the mining and production of coking coal contribute significantly to CO_2 emissions. Coking coal is primarily used in steelmaking, making its inclusion critical on the path to Net Zero. Similarly, for consistency, the mining and processing of raw materials are included for other materials. However, these typically have a lesser impact from a CO_2 perspective.

Some non-CO_2 emissions are included for some materials due to their importance and lack of inclusion in other inventories. These include:

- Aluminium – PFCs from anode consumption
- Steel – methane emissions from coking coal extraction
- Glass – methane emissions from coal extraction (furnace heating)
- PVC – methane from fossil fuel and coking coal extraction

Further details specific to each material pathway can be found in the Appendix.

The Road to Decarbonisation: Results

Aluminium Global Decarbonisation: Challenges and Solutions

The Baseline

The modelling for aluminium takes the MPP strategy from April 2023 as its starting point.[5] The baseline assumes that current demand is 98 million tonnes (Mt), projected to increase to 179 Mt by 2050, reflecting a 2.2% Compound Annual Growth Rate (CAGR). Notably, the baseline scenario of this study—representing a business as usual approach from the industry—does not account for potential changes over this period, including electricity decarbonisation that may already be underway. This deliberate omission facilitates more meaningful sector-to-sector comparisons, particularly for industries with varying dependencies on electricity decarbonisation. This approach contrasts with the MPP baseline scenario, which assumes a consistent and ongoing level of electricity decarbonisation, irrespective of the actions taken by the aluminium industry.

The calculated CO_2 emissions from one tonne of primary aluminium in the 2020 baseline are 15.8 tonnes, encompassing all major processes but excluding transport and a minor amount of ancillary materials. The International Aluminium Institute (IAI) calculates the comprehensive impact to be 16.4 tonnes when considering these additional aspects for 2020 which decreased to 15.1 in 2022.[6] It is crucial to focus on industry-specific impacts and exclude those from transport and other smaller scope 3 emissions. This exclusion is necessary because such emissions are already accounted for in inventories for their respective sectors.

The following provides a summary of key interventions modelled in this study, chosen based on the MPP's 1.5°C scenario, where the aluminium industry is deemed most likely to meet a carbon budget.

Recycling

The MPP projects that 33% of the current demand is fulfilled by recycled aluminium, and this proportion is anticipated to rise to 54% by 2050. These percentages are relatively low due to the diverse applications of aluminium, especially in construction and transport, where the material has a prolonged lifespan spanning many years or even decades. Consequently, primary production contributes to the accumulation of aluminium in ongoing use, essentially adding to the existing "stocks."

In contrast, single-use, rapidly cycled applications, such as beverage cans, exhibit significantly higher recycling rates and, consequently, a greater recycled content.

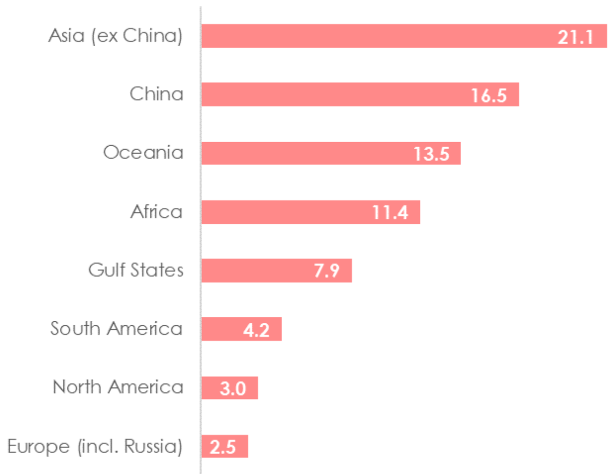
Material Efficiency

The MPP study suggests that implementing material efficiency improvements in design of final products plus longer lifetimes of building especially in China and extended car sharing could potentially reduce the overall demand for aluminium to 150 million tonnes (Mt) from the anticipated 179 Mt in 2050. This emphasises the significance of ongoing enhancements in design and manufacturing practices alongside decarbonisation efforts. This study adopts the same assumption, highlighting the critical role of continuous improvement in design for sustainable resource use and reduced demand.

Smelter Electricity Decarbonisation/CCUS

The electricity for the smelter accounts for between 20-80% of the primary aluminium carbon footprint depending on where the aluminium is produced (see Figure 5). On a global scale, this averages around 65%, primarily due to the prevalence of Chinese aluminium production relying on coal, constituting approximately 60% of global output. Therefore, mitigating CO_2 emissions from this process stands as the primary focus for the worldwide primary aluminium sector.

Figure 5 Carbon Footprint of Alumina Smelting by Country (tCo2e/tonne)[i]



The MPP has developed various electricity decarbonisation scenarios, including their 1.5°C scenario, which is replicated in this study. This particular scenario heavily relies on Carbon Capture, Utilisation, and Storage (CCUS) to mitigate the production of 48% of the world's aluminium between 2030 - 2035. In this model, the rest is achieved via renewable electricity, 33% is expected to be directly generated from self-generated renewable sources, with the remaining 19% sourced from Power Purchase Agreement (PPA)[ii] arrangements with the local grid. Consequently, a significant portion of global aluminium production still involves the use of fossil fuels—particularly coal— under this scenario.

Direct Emissions

The development of low or carbon-free anodes (including inert anodes and chloride-based technologies) holds the potential to address the issue of two types of greenhouse gases (GHGs) released during the smelting process and is anticipated to be available by 2030.

In the conventional smelting process, oxygen is released from the alumina, and it reacts with the carbon anode, resulting in the formation of CO_2. In contrast, with an inert anode, only oxygen is released, eliminating other undesired reactions.

While this study primarily focuses on CO_2 emissions, it is crucial to note that perfluorocarbons (PFCs) are also released by the carbon anode during smelting. These emissions are included in the CO_2 budget within this study, as their allocation elsewhere remains unclear. Moreover, PFCs are expected to become a proportionally more significant source of GHG emissions for the aluminium industry as electricity decarbonisation advances unless mitigated through the use of inert anodes.

Alternatively, capturing direct CO_2 emissions through CCUS is potentially a viable option. However, it is important to note that PFCs would not be captured using this technology, limiting the overall effectiveness of its implementation.

Refinery Energy

This tackles the shift from fossil fuels in the refinery digestion process to electricity and, to a lesser extent, hydrogen- based calcination. Additionally, Mechanical Vapour Recompression (MVR) is employed, utilising waste heat to significantly enhance efficiency. Currently, all of this technology except for calcination is available, and the transition is assumed to commence from 2025.

[i] Calculated from IAI energy mix data for 2021, using Ecoinvent GHG factors – Eunomia did not have access to the full IAI environmental models and utilised only the public data sources. Figures may therefore differ slightly from IAI published GHG figures.

[ii] PPA – power purchase agreement. Long-term contracts to purchase electricity from the grid which is assumed to be decarbonised.

Possible Pathway Towards Net Zero

The journey to Net Zero is not solely shaped by intervention choices, but also hinges on the timing and speed of their implementation. Most interventions in the model are set to commence between 2025 and 2030, requiring 15 to 20 years to fully realise their impact.

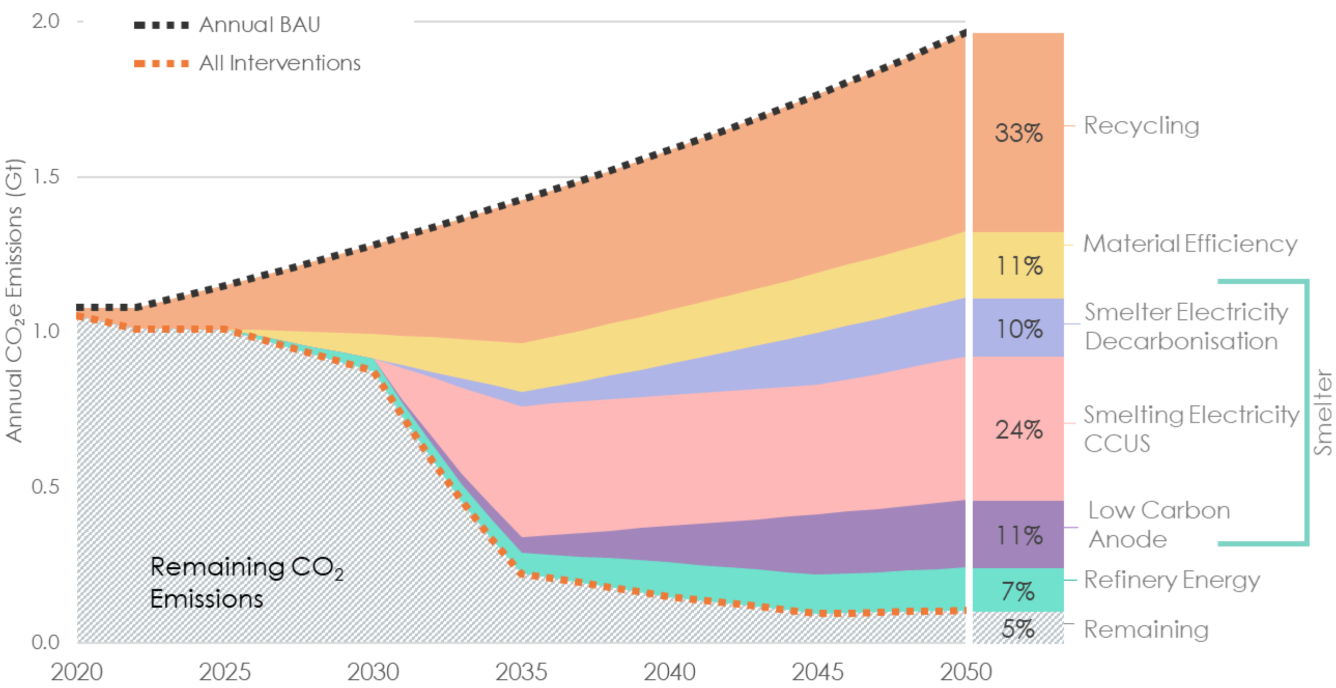
As shown in Figure 6, while the increase in recycling and potential material efficiency improvements can cut annual CO_2 emissions by approximately 44%, this reduction is offset by the anticipated rise in demand over the next 25 years (demonstrated by the doubling of emissions in the BAU scenario).

As discussed, the electricity use or CCUS implementation in a smelter is key to decarbonisation—accounting for 33% of the reduction potential. The total energy demand for this process is estimated to be 930TWh in 2020, increasing to 1,700TWh under the BAU scenario or 1,160TWh by 2050 if all recycling and material efficiency goals are achieved. In 2020, 33% (286 TWh) was generated from low-carbon sources, primarily hydro. In the CCUS scenario, an additional 300TWh would be required. In the absence of CCUS, a further 800TWh would be needed, either locally generated or through grid connections and power purchase agreements (PPA). This heavily relies on grid connection availability, the grid's capacity to handle increased load, and a substantial shift towards low-carbon electricity.

The remaining emissions primarily consist of the residual smelting emissions that are not captured by CCUS which is assumed to be 90% efficient. There are also upstream emissions associated with the coal extraction and processing that cannot be avoided by implementing downstream technologies such as CCUS. Furthermore, there are other minor emissions associated with heat utilisation in the value chain, necessitating replacement with electricity, zero-carbon fuels, or mitigation through CCUS.

The MPP suggests that any non-mitigated emissions can be eliminated with offsets. The nature of these offsets, their credibility and implementation is likely to change significantly by 2050 and therefore are excluded from this study.

Figure 6 – Aluminium GHG Emissions Pathways, Gt CO_2e/year



Comparing to the Carbon Budget

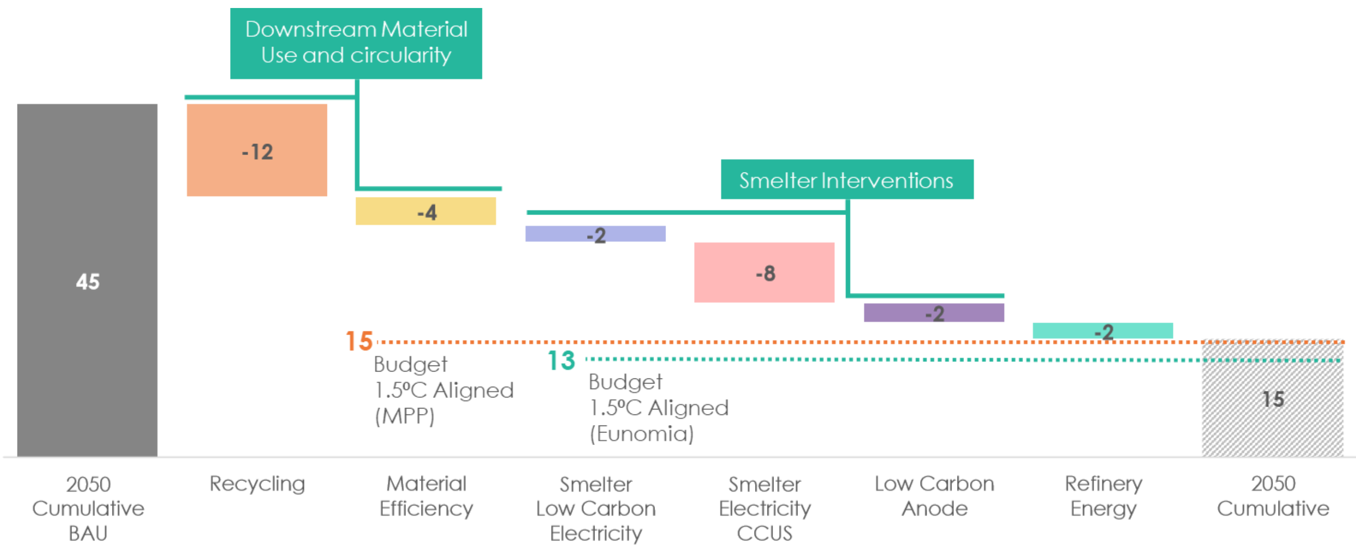
The carbon budget set by the MPP was 15Mt and the revised Eunomia budget is 13Mt. Figure 7 shows that the cumulative emissions modelled for this study meet the 15Mt target but fall slightly short of 13Mt.

Recycling emerges as the most impactful contributor to cumulative reductions, benefiting from both the significant advantages of reducing primary aluminium and an earlier initiation compared to other interventions. It stands as a proven and reliable intervention that should be consistently pursued. Any slowdown or delay in achieving the projected 54% recycling target would exert additional pressure on other intervention areas. However, it is essential to acknowledge the inherent limits of focusing solely on circularity and other material efficiencies.

The focus for primary aluminium is on the smelting process. In this scenario, the MPP assumption is that CCUS will be the main technological approach due to China's reliance on coal. While a substantial portion of the aluminium industry in the Americas and Europe already relies on hydroelectric power, China, producing 60% of the world's primary aluminium with 82% of it derived from coal power, holds a significant influence over the required changes. The trajectory of change in China will heavily impact whether the budget is exceeded. Alternatively, if China places a greater emphasis on low-carbon electricity this could yield similar, if not better results as CCUS is typically only 90% efficient currently.

The modelled pathway follows the MPP assumption that CCUS will be fully deployed to mitigate emissions from coal-fired electricity by 2035, with the most significant ramp-up expected from 2030. Extending this deployment to 2040 at a slower pace would result in cumulative emissions increasing to 16Mt, with an additional 1Mt for every five-year delay. This impact intensifies if CCUS deployment does not commence by 2035, leading to fruition by 2050, resulting in 19Mt of emissions.

Figure 7 – Aluminium Cumulative emissions, Gt CO_2e, 2020 to 2050



The Challenges Ahead

The previously outlined pathway and cumulative emissions scenario represent one potential approach toward achieving Net Zero. Aluminium, as a material, possesses both inherent strengths and weaknesses, some of which are intertwined with the chosen pathway direction.

The key strengths and weaknesses are highlighted below:

Weaknesses	Strengths
There is a potentially high reliance on CCUS for mitigating coal-fired electricity generation which will still require ~1Mt of coal annually (around half that of current use). Full deployment by between 2030 and 2035 is likely to be very optimistic when the current financial incentives to do so are minimal.	The aluminium smelting process is principally driven by electricity, therefore the transition away from fossil fuels does not require a technological shift in the smelter as well as the transition to green electricity.
	The considerable value and well-established practices of recycling aluminium indicate a substantial potential for increasing the availability of secondary materials, consequently reducing overall primary demand. Primary demand reduction is likely to be the most important downstream intervention.
Depending on the extent of CCUS deployment in smelters, an additional 300 to 800 terawatt-hours (TWh) of low carbon electricity generation is required by 2050 to meet projected demand. The lower end of this range is equivalent to the current consumption of either Italy or the UK. It is anticipated that a considerable portion of this required electricity will come from the utilisation of nuclear small modular reactors (SMRs). However, it is important to note that such technologies possess a low Technical Readiness Level (TRL), and the acceptance of nuclear power varies significantly by region.	Critical transition technologies such as inert anodes and electric boilers for the refining process generally possess a high Technical Readiness Level (TRL). Their significance is expected to grow, particularly as the decarbonisation of smelting electricity progresses. Outside of the use of inert anodes, the fundamental process of smelting itself does not need to change or result in a technology shift.
The dominance of a single country—China, with 60% of global primary capacity—on the global stage is a significant factor. Without substantial action in China, achieving global Net Zero for aluminium appears unattainable.	Low-carbon primary aluminium is already present and commercially accessible in various regions globally, including the Americas and Europe. This serves as a blueprint for improvement. Decisions made in procurement now can significantly drive the development of a market for low-carbon aluminium, creating financial incentives for further developments.

Steel Global Decarbonisation: Challenges and Solutions

The Baseline

The modelling for steel adopts the MPP strategy from September 2022 as its starting point, aligning with the same baseline year used in this study.[7] Considering the current technology mix, CO_2 emissions from one tonne of primary steel for the 2020 baseline are calculated to be 2.7t. This figure reduces to 2.12t when recycled steel is included. The MPP estimates this to be 2.0t.

The most significant contributor to CO_2 emissions in steel production is the use of coking coal. While the CO_2 released in a blast furnace is notable, the mining and production of coking coal itself also make substantial contributions. Some inventories, including the MPP, exclude the latter from the steel's impact, categorising it as a scope 3 (upstream indirect) emission. However, given the critical role of coking coal almost exclusively for steel production, it is included in the present study. This inclusion also encompasses the methane emitted from coal mining, constituting around 40% of the greenhouse gas (GHG) emissions for each tonne of coking coal produced.[8] Similar to the approach taken with non-CO_2 emissions for aluminium, it was determined that these should be included here. This results in a 16% increase to the average global steel emissions and 20% to primary steelmaking itself.

The following provides a summary of key interventions modelled in this study.

Material Efficiency

The baseline assumes current demand at 1,875 million tonnes (Mt), projected to increase to 2,547 Mt by 2050, reflecting a 1.1% Compound Annual Growth Rate (CAGR). The MPP, in its 'high circularity' scenario, proposes various material efficiency activities to reduce this demand by 41% to 1,509 Mt—a net reduction compared to the present day.

The pathways for achieving such ambitious demand reduction are predominantly downstream of the steel industry. They involve implementing more shared services, and building spaces, along with using less steel or alternative materials in vehicles and buildings.

The degree to which these measures are implemented will significantly impact the industry and future capacity requirements. High levels of material efficiencies would necessitate the closure of over 80% of blast furnaces. Currently, 1,300 million tonnes are produced through this process, projected to be reduced to 200 Mt by 2030 with substantial demand reduction. Without demand reduction, this reduction would be less pronounced, reaching only 400 Mt.

Recycling

The Electric Arc Furnace (EAF) is the primary technology employed for recycling in steel production. This method utilises electricity to melt scrap steel, representing a well-established process that is currently witnessing increased investment. EAF production contributes approximately 10-15% of the CO2e emissions of primary steel, and being electricity-driven, it can be decarbonised through improvements in low-carbon grid electricity.

According to MPP estimates, EAF accounts for 25% of current demand, with projections indicating an increase to 40% by 2050. Assuming material efficiency improvements are implemented to reduce overall demand, this would necessitate a 30% increase in the current EAF capacity. Without such improvements, the capacity would need to double to meet the demand.

New Technology

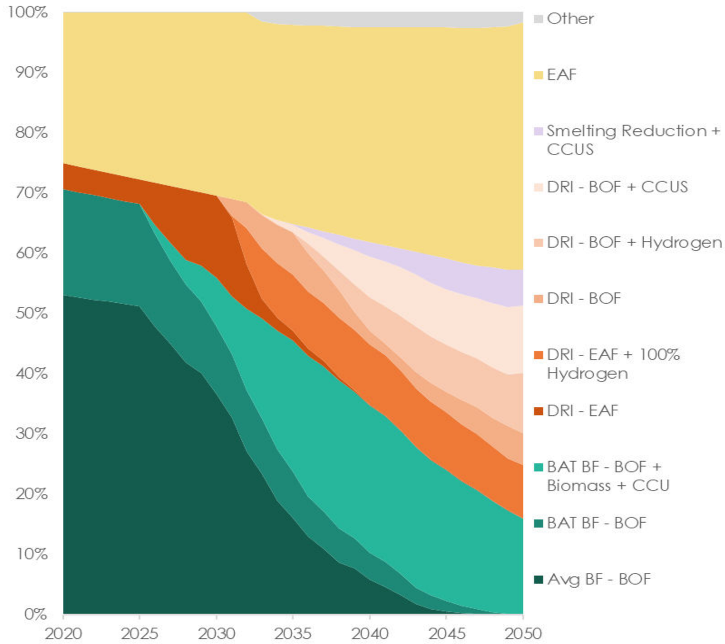
To decarbonise steel production, a fundamentally new approach is required, as the largest emissions arise from the use of coking coal in a blast furnace (BF). Various technological approaches are being considered, with the MPP report outlining 18 different variations in their 'carbon cost' pathway. These range from modifying the existing blast furnace/basic oxygen furnace (BF-BOF) route with hydrogen or biomass and CCUS, to introducing novel methods such as direct reduced iron (DRI) or smelting reduction, all aimed at eliminating coking coal from the process.

The MPP also envisions an immediate and decisive technology shift for steel decarbonisation, predicting a reduction in the Blast Furnace route from 71% to 49% by 2025. However, as of 2024, this trajectory is not universally evident, as new BF facilities are still being constructed in some locations[9] while others are being shut down in favour of Electric Arc Furnace (EAF) furnaces.[10] In this study, we therefore assume that the technology shift for primary steel decarbonisation will commence from 2025 at the earliest.

Figure 8 illustrates the technology mix and pathway employed in this study, adapted from the MPP 'carbon cost' scenario by consolidating options into 9 core technologies within broader technology groups. This scenario was chosen as it is the only scenario projected to meet the MPP's carbon budget. Notably, the current conventional Blast Furnace-Basic Oxygen Furnace (BF-BOF) route is projected to be entirely phased out by 2045, with the BF only being retained where coke is replaced with biomass. However, the technical challenges associated with this replacement still need to be overcome. Additionally, the MPP assumes carbon capture credits resulting from off-gases from biomass use in methanol production and subsequent plastics manufacturing. Given the speculative nature of this scenario, such credits have been excluded in the present study.

Variations of Direct Reduction Iron (DRI) are modelled to substitute Blast Furnaces for the majority of primary demand. This technology eliminates the reliance on coking coal and is fired by natural gas, which has the potential to be substituted with hydrogen or mitigated with CCUS. This projection is grounded in the further commercialisation and expansion of this existing technology, making it less speculative. Detailed technology descriptions can be found in Appendix A.2.0.

Figure 8 – New Technologies Pathway



Source: Adapted from data accessed from https://dash-mpp.plotly.host/mpp-steel-net-zero-explorer/

Low Carbon Electricity

The final intervention is the increase of green grid electricity. Whilst the steel making process is not currently driven by large amounts of electricity due to the reliance on heat energy from coking coal, it is important to highlight what is needed in the transition as steel will become more reliant on electricity in the future. Current electricity use is estimated at 459 TWh rising to 1,300 TWh if the modelled technology transitions take place and to 772 TWh if the proposed material reductions manifest. As previously noted, the baseline does not include a green grid transition so that the effects of such a transition—which is still not certain—can be compared between industries.

Possible Pathway Towards Net Zero

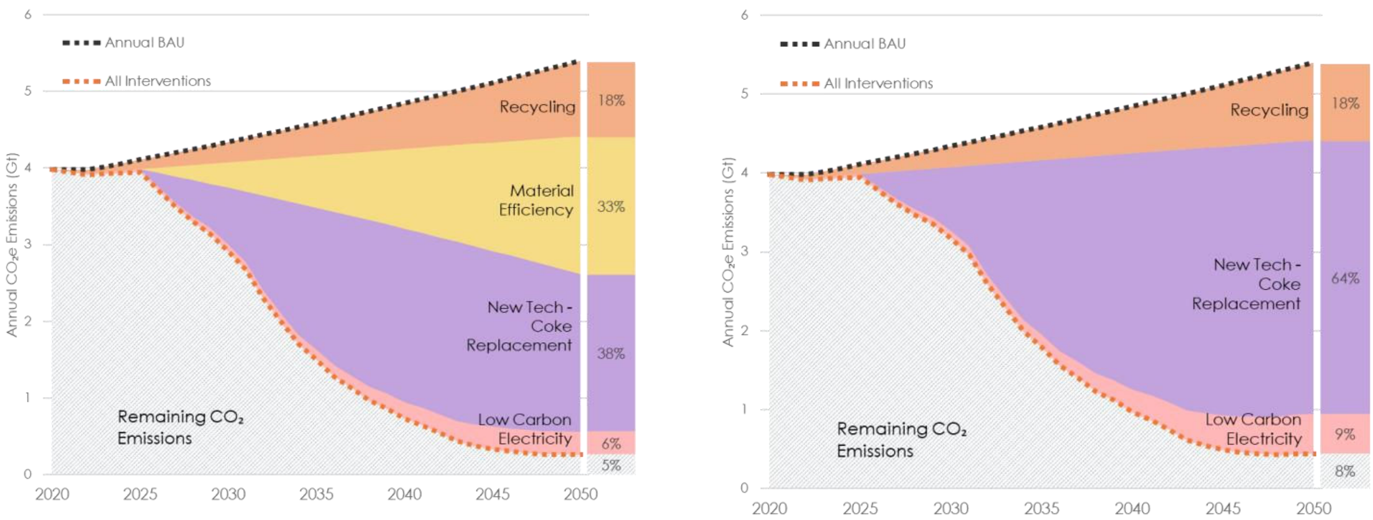
The most impactful single intervention is the introduction of material efficiencies, leading to demand reduction. Using less material undoubtedly represents the most potent lever for achieving Net Zero. However, the MPP sets ambitious targets without providing detailed discussions on how these reductions will be achieved. Consequently, the pathway is also depicted in Figure 9 without this intervention. The notable consequence is that remaining CO_2 emissions are higher due to the new technologies not yet achieving full Net Zero status. While this could be rectified over time, considerable uncertainty exists around the contributions of new technologies, given that no single technology has emerged prominently as of yet.

In terms of the required new technologies for coke replacement or mitigation, the transition appears pivotal and more globally significant than recycling. Although the modelled pathway begins five years later than suggested by the MPP, it still necessitates 14% of all steel to be produced from DRI by 2030, up from the current low of 4%. The full commercialisation and adoption of the DRI process is likely to be the primary driver in decarbonising primary steel, especially when combined with an EAF, offering the potential for Net Zero production. Currently, this field is largely dominated by a single player, Midrex, which accounts for 60% of the current DRI market, with India and Iran being the top producers. North America and Europe contribute minimally to DRI steel production. .[11]

Slightly more ambitious is the target for 10% of steel to be produced using hydrogen as a reductant in current steelmaking by 2030. However, the MPP views this as a transitional technology peaking within 10 years, to be eventually replaced by biomass. The utilisation of existing furnaces with retrofitted mitigation or alternative reductants is primarily anticipated in China.

Figure 9 – Steel GHG Emissions Pathways, Gt CO_2e/year

Including Material Efficiency | Excluding Material Efficiency



Comparing to the Carbon Budget

Without the proposed material efficiency improvements, the demand for steel is projected to surge by over 30%. This surge impacts cumulative emissions, causing them to increase to 64 gigatons (Gt) by 2050, surpassing the established budget. This situation places additional pressure on primary steel to accelerate its shift away from coking coal, building upon the ambitious projected pathway outlined here.

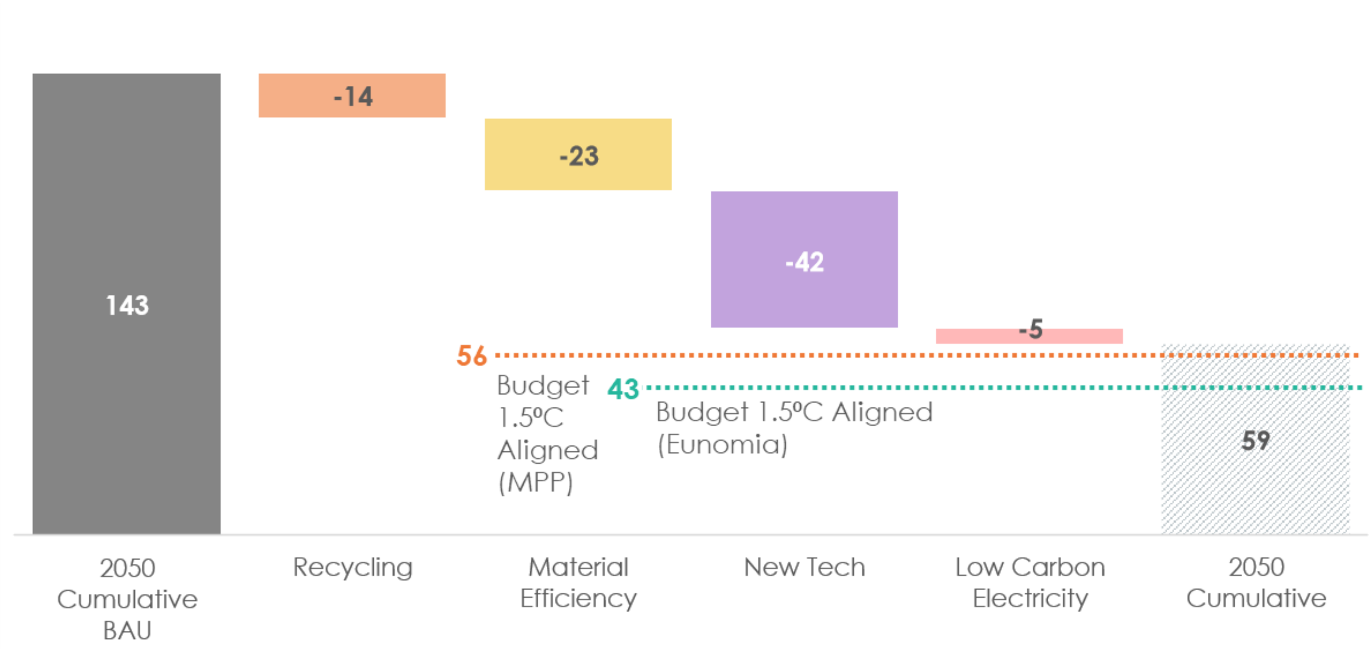
The significant rise in primary demand, especially in the early stages of the pathway, significantly contributes to the escalating cumulative emissions. Moreover, uncertainties surrounding the application of key technologies result in residual emissions that are not entirely mitigated.

The transformative shift in steelmaking technology stands out as the single most crucial intervention in budget considerations. Even with a proactive departure from current practices, it will be challenging for the steel industry to remain within the established budget.

Recycling plays a vital role, but with an anticipated recycling rate increase of only 15 percentage points, this intervention alone cannot be relied upon. However, if recycling fails to meet the projected increase and stays the same as current levels, it could lead to a 3Gt rise in overall cumulative emissions.

As mentioned, electricity currently has a minimal role in steelmaking compared to other metals, but its importance will grow as other segments of the sector decarbonise. For instance, to fully realise the benefits of recycling, an Electric Arc Furnace (EAF) would need to be powered by low-carbon electricity.

Figure 10 – Steel Cumulative emissions, Gt CO_2e, 2020 to 2050



The Challenges Ahead

The previously outlined pathway and cumulative emissions scenario represent one potential approach toward achieving Net Zero using the MPP's 'Carbon Cost' scenario as a basis for the necessary technological changes. Steel, as a material, possesses both inherent strengths and weaknesses, some of which are intertwined with the chosen pathway direction.

The key strengths and weaknesses are highlighted below:

<table>
<tr><th>Weaknesses</th><th>Strengths</th></tr>
<tr><td>The move towards electricity for primary and an increase in secondary production will require an additional 300 to 800 terawatt-hours (TWh) of low carbon electricity generation by 2050 depending upon whether demand can be reduced. The lower end of this range is equivalent to the current consumption of either Italy or the UK. (Note that this is the same range as estimated for aluminium, but for 20 times more material)</td><td rowspan="2">The Net Zero pathway relies on recycling which using an electric arc furnace (EAF) is a well established and growing industry that integrates easily into the steel making process. The use of electricity as the power source also means that it can use decarbonised grid to produce the lowest impact steel.

Many countries have a surplus of secondary steel, which can be utilised more locally by deploying electric arc furnaces (EAF). This approach reduces the need to export the material across the world and then import primary steel from other locations.</td></tr>
<tr><td>The current route of reacting coking coal and iron ore in a blast furnace is not likely to be a viable route in future and therefore a full technological revolution is required and this must take place at a pace considerably faster than is being demonstrated by the steel industry currently.

There is not one single technological route to producing low-carbon steel. This means that research and innovation is divided between several competing technologies that ultimately seek to remove the reliance on coking coal.</td></tr>
<tr><td>A large proportion of production and projected future infrastructure is expected to remain tied to the blast furnace route – notably the production based in China which is currently responsible for twice as much primary steel production than the rest of the world combined.

There is currently no commercially available low carbon steel via this route and there are significant challenges to overcome before replacing coking coal with hydrogen or biomass becomes a credible route. China's technological progress in this area is therefore pivotal in determining whether the global steel industry can meet the carbon budget.</td><td>The MPP pathway suggests a significant reduction in demand is possible due to improvements in material efficiencies and design optimisation which will be important in the transition. If these opportunities are realised it will take significant pressure off the primary production industry giving another 5+ years of development time to commercialise. Conversely, if these are not realised, 'peak emissions' will need to have already taken place and therefore the carbon budget will likely be unattainable, and Net Zero harder to achieve.</td></tr>
</table>

Copper Global Decarbonisation: Challenges and Solutions

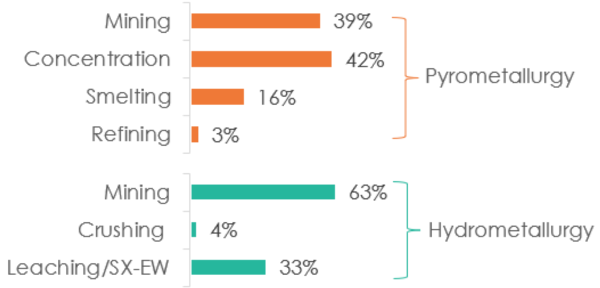
Baseline

The modelling for copper takes the International Copper Association's (ICA) 'Pathway to Net Zero' as its starting point.[12] The baseline assumes that current demand is 25 million tonnes (Mt), projected to double to 50 Mt by 2050. Ensuring consistency across the modelled sectors, the baseline scenario does not account for projected electricity decarbonisation but includes an expected decline in copper ore grade, leading to increased emissions from the mining process.

The calculated CO_2 emissions from one tonne of refined copper amount to 3.8 tonnes for primary production and 0.8 tonnes for secondary production. Primary copper production utilises two methods: pyrometallurgy, representing 81% of primary production, and hydrometallurgy, constituting the remaining 19%.[13]

While overall emissions and electricity dependency are comparable for both production methods, there exists a distinction in carbon footprint distribution, as depicted in Figure 11 (further information available in appendix). For both processes; however, in contrast to other metals, the mining stage stands out as the most impactful. This is primarily attributed to the substantial amounts of ore that must be processed for each tonne of copper, with concentrations ranging from 0.4% to 0.6%.

Figure 11 - Carbon Footprint of Copper Production by Process
(% of total CO_2e emissions)[iii]



Geographical variations in production have also been considered. Notably, 47.4% of copper mining and concentration occurs in Latin America, primarily in Chile and Peru. Subsequently, a significant portion of copper concentrates is exported to Asia for additional processing, notably to China, where 48.5% of the world's copper is eventually smelted and refined.

The following provides a summary of key interventions modelled in this study, chosen based on the International Copper Alliance's 'Pathway to Net Zero'.

Recycling

The ICA projects that 16% of the current copper demand is met by recycled post-consumer scrap, with expectations for this proportion to increase to 23% by 2050. These percentages remain relatively low due to the long average lifetime of copper-containing products, especially in applications such as electricity transmission. Additionally, the growth in demand necessitates additional production from primary sources, thereby diluting the absolute impact of any rise in recycling efforts.

[iii] SX-EW refers to Solvent Extraction and Electrowinning.

Energy Efficiency

Energy efficiency measures have started to be implemented in the copper industry, particularly concerning the concentration process in the pyro route, which heavily relies on electricity and contributes a significant proportion of CO_2 emissions from production. This study assumes that implementation began in 2020 and will complete by 2050, resulting in a 30% reduction in electricity required for concentration. Incorporated in this estimate are potential efficiency gains from technological innovations in the mining, smelting, refining, and hydrometallurgy processes, which are not yet operational.

Electricity Decarbonisation

Electricity comprises over 60% of the primary copper carbon footprint, as it is required at every stage of production, for both pyro- and hydrometallurgy. This underlines the potential for electricity decarbonisation to be a high-impact intervention, especially considering it can begin implementation immediately.

The intervention's timeframes span from 2025 to 2040. Although electricity grids globally are transitioning towards renewable energy sources, the pace of adoption varies among regions. The selected start date takes into consideration these variations, especially considering that significant production occurs in Latin America and China, where the carbon intensity of electricity currently exceeds that of regions like the EU.

The potential for this intervention to make a significant contribution to decarbonisation hinges on the availability of ample amounts of green electricity to meet the requirements of copper producers and other energy-intensive industries. Considering the projected increase in demand for copper, the industry is expected to require ~54 TWh of green grid capacity by 2030, rising to ~369 TWh by 2050.[4] Hence, the potential for copper producers to decarbonise electricity depends on the pace of transition to renewable sources in electricity grids.

Alternative Fuels & Equipment Electrification

This study assumes that between 2032 and 2050, processes currently reliant on direct burning of fossil fuels, such as mining and smelting, will decarbonise through electrification or the adoption of alternative fuels.[5]

Processes will be electrified where technically feasible, utilising decarbonised electricity for operations. In cases where electrification is not viable, alternative fuels such as green hydrogen and biodiesel will be employed. It is unclear exactly how and in what proportion these alternative fuels will be deployed therefore it is assumed that half of smelting processes will transition to electrification, employing electric furnaces instead of natural gas furnaces, while the other half will utilise alternative fuels such as hydrogen. In mining, a similar 50/50 split is applied to the energy mix, with alternative fuels also including biodiesel.

Presently, the deployment of large-scale equipment electrification and alternative fuels is restricted. These technologies are modelled to become available from 2032; however, this is contingent on factors such as market readiness and financial viability. Considering the significant impact of the mining process on copper production, the fuel usage in heavy mobile equipment becomes particularly crucial. "Green" hydrogen is recognised as a promising technology, especially where battery-based electric vehicles face limitations. However, the commercial viability of both hydrogen generation and the development of vehicles and fuelling infrastructure is still in its early stages at present.[14]

[4] Figures reflect the requirement for green grid electricity across all interventions where electricity is utilised.

[5] The selection of the starting year 2032 was made to accommodate regional differences in access to and adoption of emerging technologies.

Possible Pathway Towards Net Zero

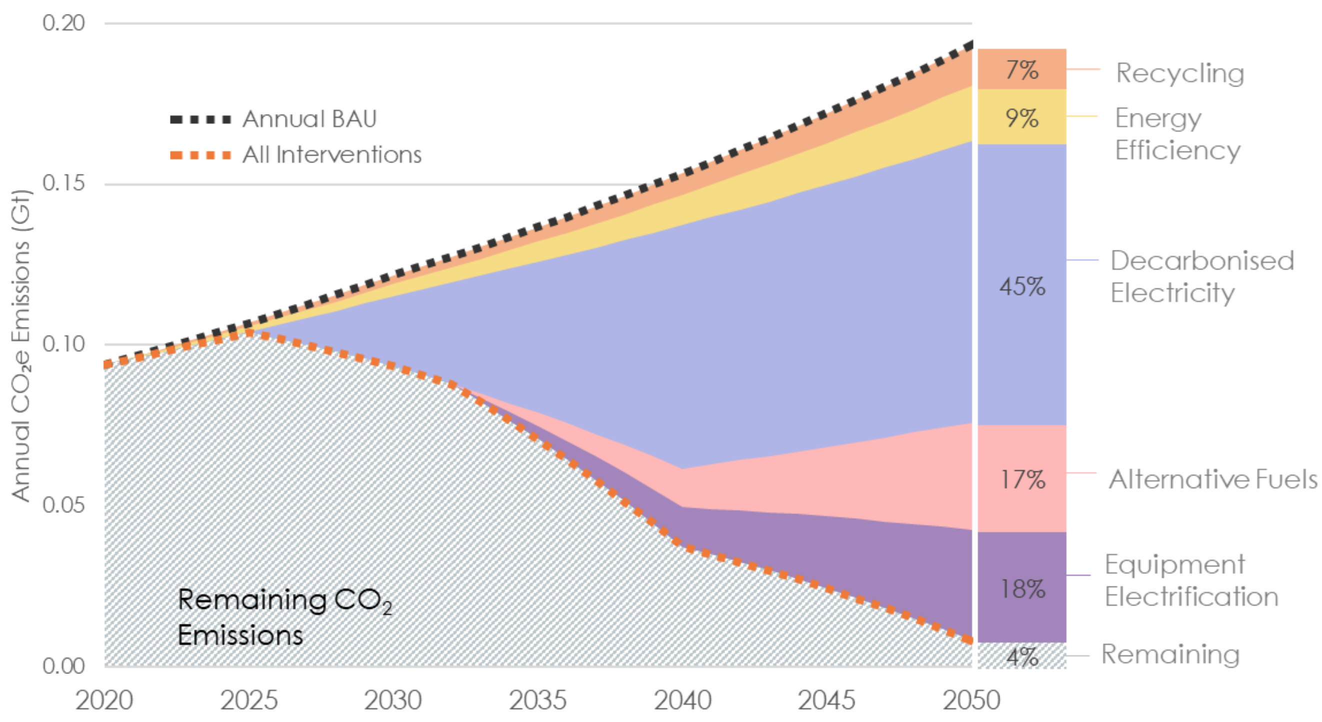
The transition to decarbonised electricity holds the potential to contribute to nearly half of copper's abatement efforts, making it a pivotal aspect of the industry's decarbonisation plans. As previously discussed, the pace at which this intervention can be adopted is contingent on grid connection availability, the grid's capacity to handle increased load, and a substantial shift towards low-carbon electricity.

Although not insignificant, recycling offers the smallest abatement potential. While emissions from recycled copper are approximately 80% lower compared to those from virgin copper, the contribution of recycling to decarbonisation is limited by persistently low recycling rates, both presently and in the future.

Emission reductions from energy efficiency measures remain consistent throughout the modelling period. However, the modelling underlines the importance of prompt action, as improvements in energy efficiency only influence emissions if implemented before the decarbonisation of electricity grids, given their significance for electricity-intensive processes.[6]

The industry's ability to meet the modelled timeframes largely depends on the technology available to individual producers in their respective countries, which can vary significantly. While the pathway has been designed with geographical variations in mind, accurately predicting the pace of technology implementation in certain countries remains challenging. This challenge is particularly relevant to smelting and refining operations in China, where the country has committed to achieving carbon neutrality by 2060, a decade after the copper industry aims to reach net zero emissions. According to the ICA, Chinese copper production is expected to follow a similar decarbonisation trajectory as the global pathway, although the implementation of interventions may take longer to initiate.

Figure 12 – Copper GHG Emissions Pathways, Gt CO_2e/year



[6] Modelling the interaction between two interventions was not possible due to the static nature of the model in this study.

Comparing to the Carbon Budget

In the absence of a carbon budget set by the MPP or by the Copper industry itself, Eunomia calculated the budget for copper to be 1.3Gt. Figure 13 shows that the cumulative emissions modelled for this study fall short of this target, at 2 Gt by 2050.

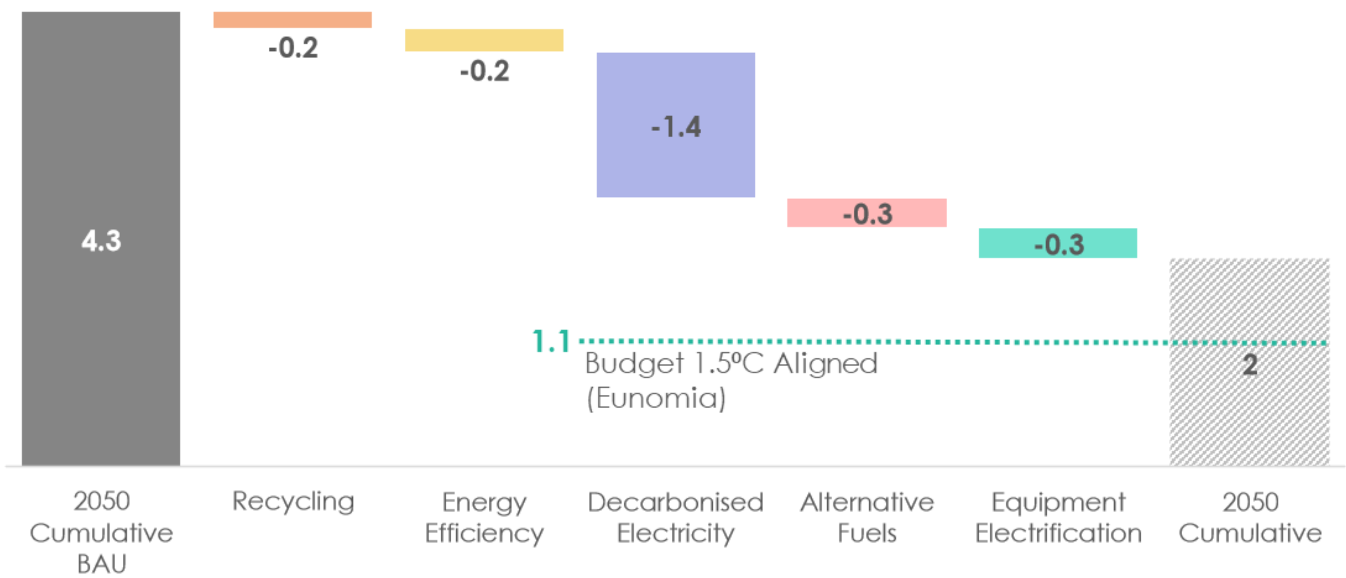
Decarbonising electricity contributes the most to cumulative reductions due to its early initiation and maturity, as well as the heavy reliance on electricity in copper production. While it serves as a significant lever for decarbonisation, its viability hinges on rapid growth in renewables and substantial expansion of green grid capacity.

The significance of rapid implementation cannot be emphasised enough, especially when it comes to impactful interventions like the adoption of alternative fuels and electrification of equipment. Despite accounting for 35% of total abatement potential, the delayed adoption predicted by ICA results in a minimal impact on reducing cumulative emissions. For comparison, if these interventions commence immediately and finish sooner than anticipated, for example in 2040, the copper industry would be significantly closer to reaching the budget, with cumulative emissions totalling 1.5Gt by 2050.

Despite being initiated earlier than other interventions, recycling and energy efficiency initiatives exhibit limited impact on cumulative emissions. Increasing their effectiveness poses challenges. For recycling, hurdles persist in acquiring post-consumer recycled materials given the limited waste generation and the predicted 7 percentage point increase in recycled post-consumer scrap.

As for electrical efficiency improvements, these take place concurrently with the decarbonised electricity and therefore the benefit—in carbon terms—is somewhat lost. Nevertheless, given the increasing demand for low carbon electricity, energy efficiency will still be an important and likely cost-effective intervention.

Figure 13 – Copper Cumulative emissions, Gt CO_2e, 2020 to 2050



The Challenges Ahead

The previously outlined pathway and cumulative emissions scenario represent one potential approach toward achieving Net Zero based on the work from the International Copper Association's (ICA).

Copper, as a material, possesses both inherent strengths and weaknesses, some of which are intertwined with the chosen pathway direction.

The key strengths and weaknesses are highlighted below:

Weaknesses	**Strengths**
There's little commitment or expectation from the industry to cut copper demand or improve material efficiency, despite projections of a doubling of demand by 2050.	Most of the Interventions depend on existing technologies rather than speculative or experimental ones. The core production processes themselves do not need to change, only the energy systems used to power them.
In certain countries, notably China, decarbonisation efforts may commence slower than modelled, potentially resulting in higher cumulative emissions. This is important given the overall impact of China's production on the global value chain.	Mining and concentration, the main sources of GHG emissions, are concentrated in a few countries. This concentration could be advantageous if leaders, particularly in countries like Chile and Peru, prioritise decarbonisation. Such efforts could lead to a significant reduction in emissions associated with copper production.
The low Technical Readiness Level (TRL) for electrification and alternative fuels in mining and smelting delays implementation, significantly affecting cumulative emissions. The importance of the mining process in the production of copper compared with other metals underlines the importance of transitioning mining machinery to more sustainable fuels.	Electricity decarbonisation, a key transition technology, is already underway in many regions with a global trend toward reducing grid carbon intensity. While this transition is expected, the speed of the transition will have a notable impact on the carbon budget. Reliance on electricity decarbonisation demands substantial green electricity, necessitating increased grid capacity projected to be ~369 TWh by 2050.
Despite secondary production emitting significantly fewer emissions than primary production, the potential for recycling to contribute to decarbonisation is constrained by limited access to recycled materials.	

Glass Packaging Global Decarbonisation: Challenges and Solutions

Baseline

In comparison to the other materials examined in the study, glass packaging (container glass) stands out as uniquely product-specific. Unlike metals and plastics, which can be shipped in their raw material state for various purposes, glass is directly formed into its final product without intermediate stages.

In the absence of global or large scale regional Net Zero strategies for packaging container glass, the modelling draws on Eunomia's previous European work that used the Net Zero strategy from British Glass. The baseline begins with the current state, estimating that 74 million tonnes (Mt) of packaging glass is produced annually, although precise figures vary across market reports. Forward-looking growth rates also vary, with some reports suggesting a potential increase to around 100 Mt by 2030. Beyond that, projections become speculative, but a consistent ~5% CAGR, based on historic growth could see the market reaching 270 Mt by 2050. From 2030 onwards, a more conservative 2% CAGR is therefore assumed, leading to an estimated production of 164 Mt by 2050.

The furnace technology and melting fuel are crucial aspects of the glass packaging industry. Global data capturing every country's practices is unavailable, given the localised nature of glassmaking. Typically, packaging glass, in its empty state, is not transported over long distances due to cost considerations and the ready availability of raw materials in all continents. The predominant fuel used is believed to be natural gas, offering consistent and controllable heat. However, coal-rich countries, such as China, have a significant portion of their furnaces fired with coal and its derivatives. Reflecting the regional nature of glass making, China is much less dominate in the global glass industry compared with other materials with the Asia Pacific region (which also includes India) accounting for around 37% of global revenues.[15]

In this study, the modelling of the glassmaking process is based on European production, but with a global electricity grid mix and with an estimation of the ratio of natural gas to coal-fired furnaces. However, real-world variations in technology will exist based on the age of furnaces, primarily impacting process efficiencies. Given these caveats, the baseline shows that the CO_2 emissions per tonne of primary container glass is 0.97t as a global average, reducing to 0.91t with 20% recycled content.

The assumptions around market and technology used for the modelling are provided in Appendix A.4.0.

Recycling

Determining the content in container glass on a global scale is challenging. Even in Europe, obtaining an accurate and reliable figure proves difficult. Recycling cannot serve as a proxy for recycled content, as glass may end up in other products such as glass fibre insulation or be used as aggregate. Thus, recycling or collection rates represent a theoretical maximum for recycled content, but in reality, this is much lower as typically only the best cullet is utilised in container glass. Figures quoted for recycled content often (though not consistently) include 'internal cullet,' rejected glass recycled within the production facility—essentially a process inefficiency accounting for 10-20% of the furnace output. It is crucial not to misrepresent this as post-consumer recycled content.

The European Container Glass Federation (FEVE) claims that the average recycled content in Europe is 52%. Official figures for the USA are unavailable, but the Glass Packaging Institute (GPI) reported a 33.1% recycling rate in 2018.[16] Therefore, the average recycled content is likely considerably lower than this. O-I, a major global glass container manufacturer, states that their current *external cullet* rate is 38%, with plans to reach 50% by 2030, although much of this is from its operations in Europe.[17]

Considering the rest of the world, *collection rates* for Latin America range between 12-24%, and recycling rates in China[18] and India[19] are estimated to be around 20% and 35%, respectively.

The baseline average external cullet is therefore estimated to be 20%, with internal cullet at 15%. Under the recycled content intervention for this study, external cullet is modelled to move to 70% and internal cullet to decrease to10%, as recycling and process efficiencies improve, representing an ambitious but potentially achievable maximum circularity scenario.

Lightweighting

Lightweighting is potentially one of the key methods to reduce demand by reducing the amount of material needed per unit. According to FEVE figures, material use per unit of container class in Europe has increased by around 2% between 2012 and 2022 (see Appendix for figures).[20] Whilst this trend is in the wrong direction—and it is not clear what is driving this—10% reduction is estimated as a global average in this scenario to demonstrate the importance of this intervention along the decarbonisation pathway.

Furnace Electrification and Alternative Fuels

The most important change on the path to Net Zero for the glass industry is to move from fossil fuel fired furnaces to fully electric or 'hybrid' furnaces – 80% electric, 20% natural gas with a further transition to biomass and hydrogen.

It this assumed in the modelling that this would begin in 2025 and the whole industry will be converted by 2045 and that all electricity comes from low carbon sources. In absence of an industry plan, we look to individual company commitments here, but there are very few firm commitments towards updating furnaces. Ardagh is due to bring online their first large scale hybrid furnace in Germany in 2024.[21] Whilst O-I is concentrating on its 'Magma' modular furnace that focuses on improving efficiency, but currently still relying on natural gas – the potential to use biofuels or hydrogen in the future is claimed, but not yet commercialised.[22]

Other commitments around the existing electricity use (typically around 20% of the glass making energy requirement) have also been made. For example, Verallia have committed to 90% 'low carbon' electricity by 2040 and OI, 40% by 2030.[23,24] However, these commitments will only be fully effective if combined with electrification of the furnaces themselves. Given the lifespan of a furnace, or 15-20 years (and sometimes 30 years plus) it is therefore important that all new and replacement furnaces are hybrid to ensure Net Zero by 2050 is possible.

CCUS

Whilst the furnace technology can change, and the recycled content increased, the production of primary glass necessarily involves a reaction that releases CO_2. Typically, for every tonne of glass that is produced, around 0.2 tonnes of CO_2 is released from carbonates such as the soda ash.[25] This represents, region depending, 20-30% of the GHG emissions per tonne, but this ratio will increase as other interventions improve energy related emissions. This can be reduced with changes to raw material compositions, but ultimately capturing the released CO2 may be the only pathway to Net Zero.

Raw Materials

The final area to address is the raw materials used in production of primary glass. Both limestone and silica are mined which uses relatively small amounts of heat and electricity generated from fossil fuels. Soda ash is either mined from trona ore – 33% of the time[26]- or produced synthetically. The latter is much more energy intensive and contributes to around 10% of the overall glass making emissions. Replacing fuels and electricity with low carbon alternatives will become increasingly important to reach Net Zero for glass, but the earlier the soda ash industry itself acts, the more impact this can have on reducing cumulative emissions also.

Possible Pathway Towards Net Zero

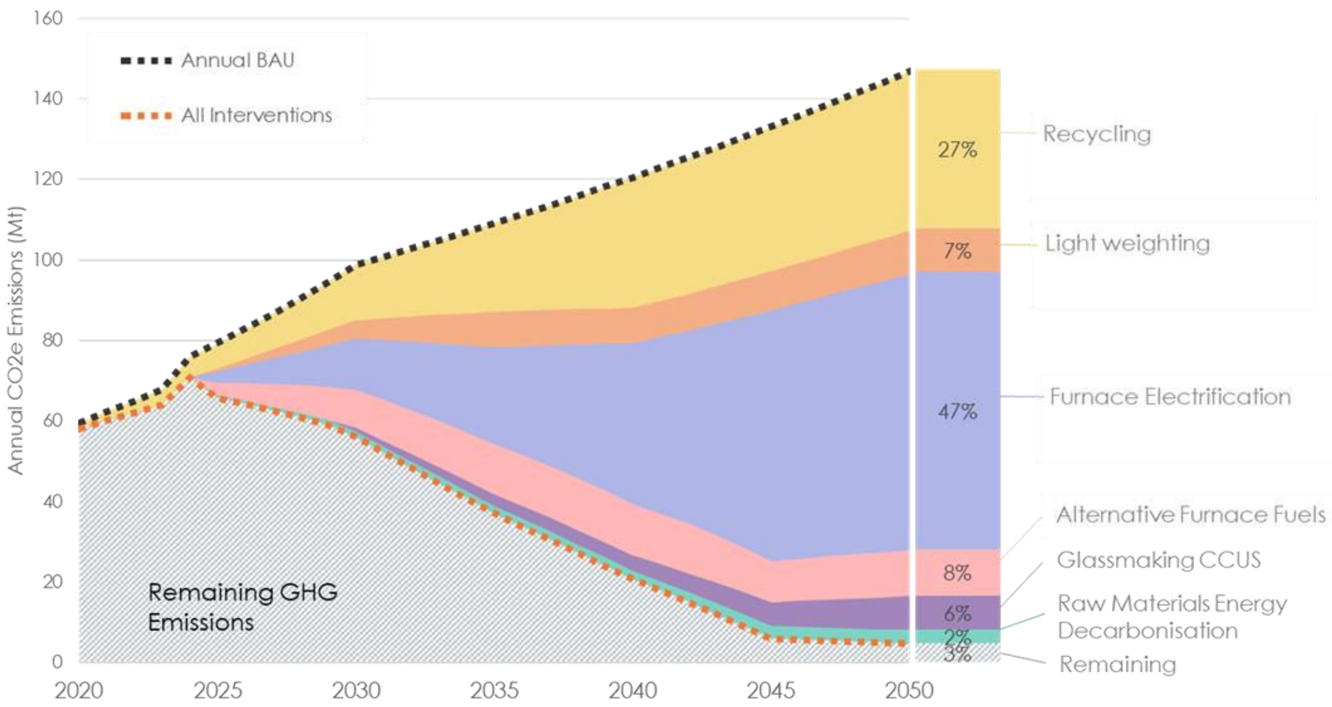
The modelled increase in recycling demonstrates a substantial contribution to the Net Zero pathway, yet it likely represents a best-case scenario, assuming a global average of 70% recycled content for glass containers. This marks a significant improvement from the current 20% estimate and relies on increasing global collection rates. However, the glass industry benefits from an integrated recycling process that eliminates the need for separate furnaces, making it more adaptable to scaling up recycled content in tandem with primary production compared to other materials.

Moreover, although the decarbonisation of raw materials energy accounts for only 6%, this is due to the markedly reduced demand for raw materials. Typically, raw materials, particularly soda ash, constitute around 8% of the current glass carbon footprint. This figure reduces to 4% with 70% recycled content.

The key technological leap required for swift progress toward Net Zero is furnace electrification, likely to be in the form of the hybrid furnace. This transformation must be coupled with the generation or acquisition of low-carbon electricity to be most effective, and this is therefore assumed to occur concurrently. This necessitates an additional 68TWh of low-carbon electricity generation to be established before 2045, aligning with the modelled completion of the transition to hybrid furnaces.

The transition to alternative fuels for the remaining 20% of furnace energy requirements is anticipated in the future but has yet to be implemented. The access to green hydrogen is expected to face high competition, and the feasibility of producing the required amounts remains unclear. Trials are underway for sheet glass in the UK, [27] and announcements have been made about potential construction of container glass facilities by the end of the decade therefore certain parts of the industry are actively working towards implementing this intervention. [28]

Figure 14 – Glass GHG Emissions Pathways, Gt CO_2e/year



Comparing to the Carbon Budget

Despite a substantial assumed increase in recycling and recycled content, the combined contribution to the budget falls short of meeting the overall target of 0.7 Gt. This is partly due to furnace energy use only reducing by 2.5% for every 10% recycled cullet resulting is a less significant benefit compared to some other materials.[29] This underscores the importance of not solely focusing on ambitious collection and recycling efforts for glass.

In fact, dedicating efforts to lightweighting existing products by 10% can yield a third of the cumulative benefits achieved through a such a massive push for increased recycling. Therefore, emphasising upstream design considerations may also deliver substantial long-term results and are potentially easier to implement than downstream collection systems.[7]

The shift to furnace electrification is projected to commence in 2025, aligning with other interventions (excluding CCUS) which are already in the construction phase. However, for meaningful impact, there must be a consistent and ideally exponential growth in furnace electrification rather than a few isolated plants. Presently, few glass manufacturers are committing to such wholesale changes. To meet the proposed budget, this transition should be completed by 2035—10 years ahead of the pathway modelled here—, along with the adoption of alternative fuels.

While CCUS has a relatively modest impact, implementing it in all furnaces by 2035 instead of 2045 could result in a 10% reduction in cumulative emissions.

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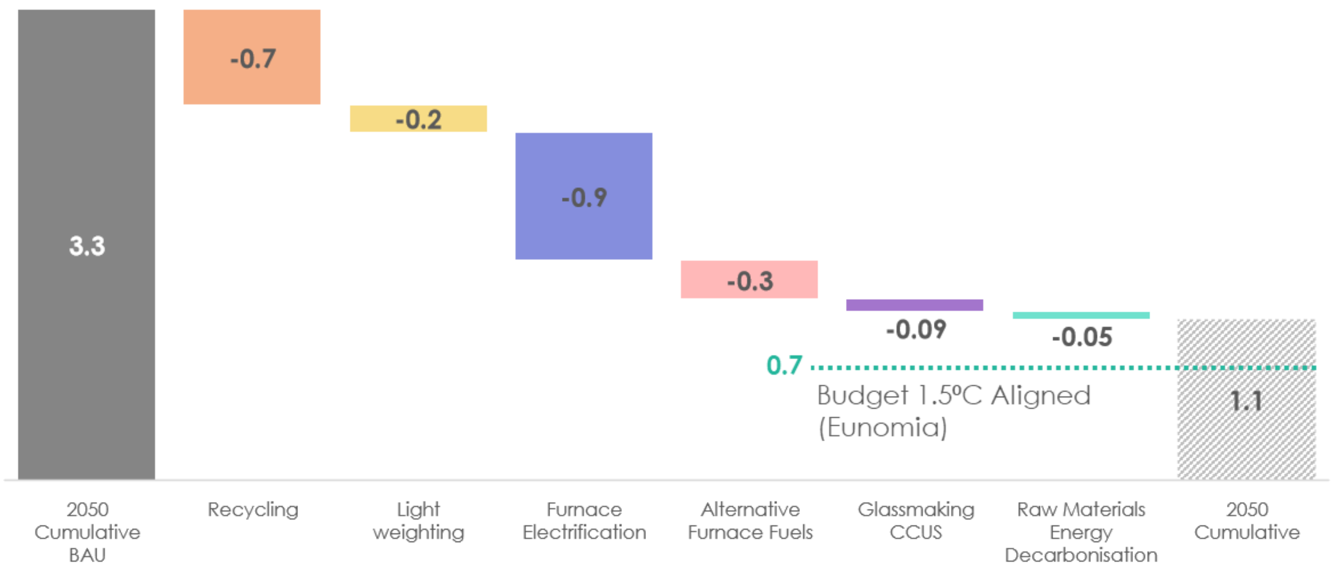
Figure 15 – Glass Cumulative emissions, Gt CO_2e, 2020 to 2050



[7] Note that lightweighting at the product level could also be implemented for the other materials in the study, but was not investigated as the raw materials can be used for many applications; glass production is always product/application specific.

The Challenges Ahead

The previously outlined pathway and cumulative emissions scenario represent one potential approach toward achieving Net Zero in absence of an industry strategy to reach Net Zero.

Glass, as a material, possesses both inherent strengths and weaknesses, some of which are intertwined with the chosen pathway direction.

The key strengths and weaknesses are highlighted below:

Weaknesses	Strengths
The ambitious recycled content target of 70% set for this study cannot be achieved by the glass industry alone. There needs to be accompanying collection and sorting infrastructure to support this.	The glass industry is set up to include high levels of recycled content as part of an integration with primary material manufacture without significant changes to processing.
There is a lack of firm commitment to transition to electrified glass making in a timeframe that is likely to stay within the suggested carbon budget. Furthermore, the transition will also require an additional 68TWh of electricity generation annually that must come from low carbon sources.	The pathway to Net Zero is generally not complex as electrification of the furnace is the key development. This means that Manufacturers can therefore concentrate on realising this transition without the concern of investing in a technology with limited prospects.
Full decarbonisation is likely to require hydrogen as a substitute for natural gas. There will be significant challenges in producing green hydrogen in the quantities required for the many industrials that may be looking to rely on this in future.	The global market for glass is far less dominated by China compared with other materials. This means that decarbonisation is not reliant on one single country's actions and the costs for transition can be distributed regionally.

PVC Global Decarbonisation: Challenges and Solutions

Baseline

In the absence of global or large scale regional Net Zero strategies for Polyvinylchloride (PVC), the modelling for this study is entirely bespoke.

The current global capacity is 60.7million tonnes (Mt) with a utilisation of 82% giving a total production of 50Mt. China accounts for 41% of this with North America and Europe accounting for the majority of the remainder.[30] Industry growth is modelled to be 2% CAGR through to 2050 based on US projections that suggest a 73% growth resulting in global production of 87Mt by 2050.[31]

PVC production is primarily divided into two routes based on the chemicals used for vinyl chloride monomer (VCM) production. Approximately 67% of global production utilises the ethylene route, where ethylene and chlorine combine to produce VCM. Ethylene is commonly derived from steam cracking of petroleum or natural gas. The alternative method involves coking coal and lime to produce calcium carbide, further synthesised into acetylene. Chlorine is then introduced via hydrochloric acid, along with acetylene, to produce VCM.

The calcium carbide (CC) route is comparatively more energy intensive and is only known to be used in China due to the low cost of coal in the region. Due to this, it is considerably more carbon intensive. For the baseline, the CC route is calculated to emit 7.32 kg/CO_2e per kg produced. This compares with 2.15 kg/CO_2e for the ethylene route. A combined global figure is estimated at 3.77kg/CO_2e taking into account the relative market shares.

This study also incorporates recent improvements in understanding methane emissions from the fossil fuel extraction process[32] For example, naphtha, a common fuel used in steam cracking, is now recognised to be responsible for around ten times the methane emissions previously thought, resulting in a doubling of its CO_2e emissions and a subsequent increase in downstream PVC polymer by around 10%. The latest methane emissions from coal extraction in the CC route are also included, as identified for steel.

As for other materials in this study, the end of life (EoL) is taken into account with the reduction in demand associated with recycling. PVC, when it enters residual waste (landfill or incineration), it is considered inert and has zero climate change impact. However, when incinerated, CO_2 is released, making it important to estimate how much PVC will enter this route. OECD projections estimate that while plastic use will increase, the incineration rate will remain largely static at 19% for the baseline. [33]

Notably, PVC is used extensively in long-lifespan applications in buildings and construction, and it is estimated that only 49% of the material's mass placed on the market is available as waste in any given year in Europe. [34] If this trend holds globally, the incineration rate is estimated to be around 9%.

Recycling

Recycling of PVC is typically challenging, particularly for flexible variants in building applications that suffer from legacy chemicals—phased-out or banned chemicals such as plasticisers and fire retardants— that make the end products impossible to sell in some markets unless those chemicals are removed.

There have been several attempts to used dissolution or chemical recycling to overcome this issue, but with variable success and low proven commercial viability.

In contrast rigid PVC used in, for example, window frames is more straight forward to process using basic mechanical means for remelt into new frames – it is largely a homogeneous and clean material.

Figures for current recycling rates are sparce. Some estimates are available for Europe and the US. Europe appear to be leading the way, globally, but with the equivalent of 4.5% of European production from post-consumer recycling. This increases to 8% for post-industrial, totalling 0.81Mt. The US reports 1.1 billion pounds (0.57Mt) of recycling, most coming from post-industrial sources, equivalent to 7% of available waste.[35]

It is estimated that 1.7Mt are recycled globally every year which under the baseline equates to a total global recycling rate of 7.6% of the available waste generated.[36] There is considerable uncertainty around the limits and possibilities to recycling PVC. However, for this analysis it is estimated that 60% of available post-consumer waste (27% of material placed on the market) is recycled into new products by 2050. Given the lack of data on recycling processes, a basic mechanical recycling process is assumed as a minimum requirement which is estimated to have an impact of 0.2kg CO_2e/kg.[37] Data sources and method are described further in Appendix A.5.0.

Steam Cracker Electrification

As part of the effort to reduce reliance on fossil fuels, electrifying steam crackers instead of using fossil fuel becomes a critical step for the entire polymers industry. This benefit extends beyond the PVC sector, as ethylene is a key component in various other polymers, including polyethylene and PET. However, to maximise the positive impact, this electrification must be accompanied by a transition to low-carbon electricity, as failure to do so could potentially increase the overall environmental impact.

Additionally, this electrification is a prerequisite for the anticipated technology shift in China, moving away from the calcium carbide route and toward the ethylene route. The full benefits of this transition are realized when both electrification and the technology shift occur concurrently.

Low Carbon Electricity and Alternative Fuels

Many of the processes involved in the value chain use electricity and fossil fuel derived heat to run the process. Where there is not expected to be a shift in technology, these processes can be decarbonised by removing reliance of fossil fuels. For heat generation this can be a move towards biomass and hydrogen.

Technology Shift

The shift in China from the calcium carbide to the ethylene route reduces electricity-intensive production, cutting around 90% of the 9.3 kWh per kg required. Shifting to the ethylene process would only require about 10% of the electricity, contributing to an overall demand reduction. This transition eliminates reliance on coking coal, eliminating direct process emissions from coal, lime, and calcium carbide production, constituting about 40% of overall emissions. These emissions are notably reduced in an electrified ethylene cracker.

Biobased Feedstocks

The final intervention is to remove the need for fossil feedstocks that are fed into the steam cracker. There are already trials being undertaken of bio-based naphtha used as a direct replacement.[38]

This transition provides a two-fold benefit: firstly, the elimination of methane emissions from oil and gas, and secondly, when the bio-based feedstock is combusted, whether as part of the process or during end-of-life, the resulting CO_2 emissions are of biogenic origin, thereby considered neutral upon release. Due to uncertainties surrounding bio-based feedstocks and variations in their synthesis methods, it is assumed that the CO_2 impact per tonne is equivalent to naphtha, but without these emissions.

It's essential to note that the introduction of bio-based feedstocks impacts only a portion of the polymer, approximately 50%, as the remaining portion is derived from chlorine. Although the production of chlorine is energy-intensive, it utilises saltwater as its feedstock.

Possible Pathway Towards Net Zero

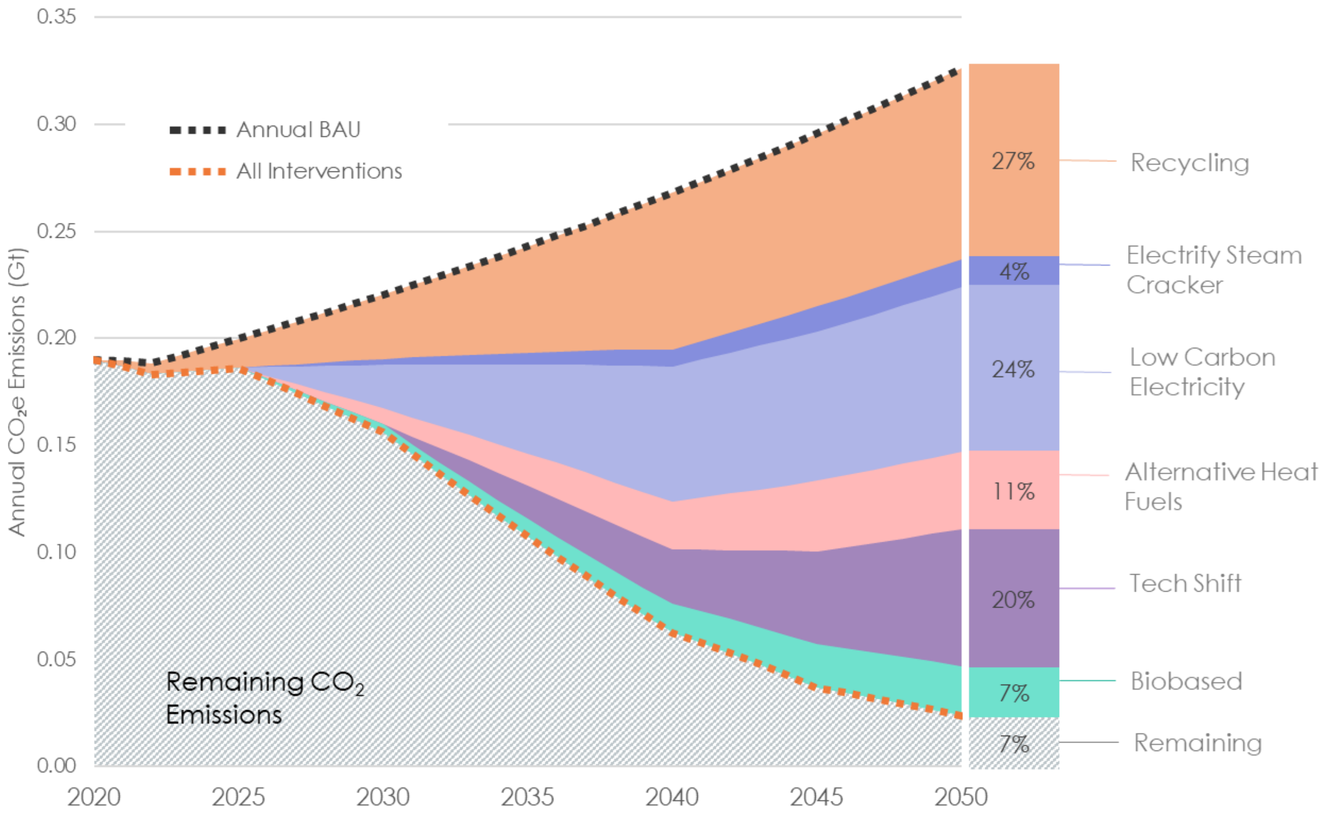
The modelled pathway highlights the significant impact of recycling on achieving Net Zero if the ambitious target of reaching 70% recycling of available waste is realised. This approach comes close to offsetting the modelled demand increase. However, this is based upon a relatively mechanical recycling that uses clean, rigid PVC in a relatively low energy intensive process. To expand this out further, there may be more energy intensive process such as chemical recycling that would need to be implemented. This is a significant source of uncertainty around the future of recycling for PVC.

To achieve Net Zero, decarbonising the 50TWh of electricity required for a complete transition to ethylene-based production is crucial. Additionally, there would be an additional 60TWh capacity needed for steam cracker electrification, as electricity demand more than doubles. Furthermore, if production increases align with the modelled trend, a further 80TWh would be required.

The shift from calcium carbide-based production to ethylene in China is imperative due to the high carbon footprint associated with the former. If these plants persist, other interventions become necessary, as the carbon footprint per tonne of material would only be reduced by approximately half with additional measures. These interventions may involve deploying CCUS at various points to eliminate direct emissions in calcium carbide, lime, and coking coal production. Mitigation strategies for upstream methane emissions from coking coal would also be essential, resulting in a continued heavy reliance on fossil fuels and CCUS.

The impact of biobased interventions is relatively low given the conservative assumptions used. However, there is potential for increased efficiency and the use of carbon sequestration credits to further reduce the remaining 7% of emissions from the production of biobased feedstocks.

Figure 16 – PVC GHG Emissions Pathways, Gt CO_2e/year



Comparing to the Carbon Budget

The carbon budget assigned to the global PVC industry is 3Gt, and based on the modelled interventions and their implementation pathway, the industry is projected to exceed this, reaching 3.4Gt. If Chinese manufacturing does not shift to ethylene-based production, the difference will more than double. However, if the shift begins as early as 2025, the PVC industry could reduce the overshoot by half, contingent on the simultaneous shift to low carbon electricity.

Improvements in recycling are also crucial. If recycling rates remain at today's levels (~7% of available waste), manufacturing changes alone cannot bridge the necessary gap, leading to an additional overshoot of 0.4Gt.

The required recycling capacity for this change is an increase from 1.7Mt to 27.5Mt—a 16-fold increase. Achieving only half of this would result in cumulative emissions rising to 3.6Mt.

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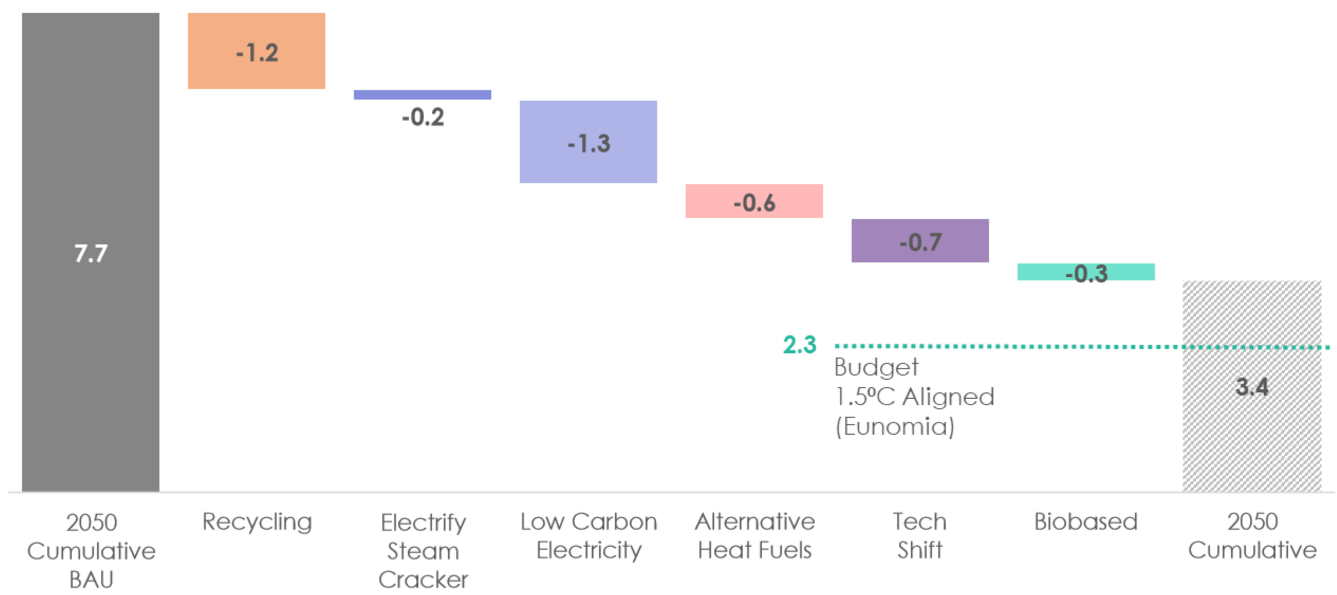
Figure 17 – PVC Cumulative emissions, Gt CO_2e, 2020 to 2050



The Challenges Ahead

The previously outlined pathway and cumulative emissions scenario represent one potential approach toward achieving Net Zero and it should be noted that there is no industry strategy to achieve this at present. PVC, as a material, possesses both inherent strengths and weaknesses, some of which are intertwined with the chosen pathway direction.

The key strengths and weaknesses are highlighted below:

Weaknesses	Strengths
There is a high reliance on the value chain for ethylene production and unless the chemicals and polymer industries are united in achieving a fast transition to Net Zero, the PVC industry alone cannot enact the necessary changes.	The need for ethylene to decarbonise means that the burden for the change is shared across the chemicals industry and not on one single polymer.
The current use of calcium carbide-based PVC manufacturing in China has a strong influence over the global carbon footprint of PVC. The transition to ethylene-based manufacturing would need to take place, but it is uncertain whether this will and the speed it will take place.	The majority of the key technologies that will be needed for decarbonisation already exist and there now needs to be the commercial drivers in place to enact the necessary changes.
Increasing recycling rates faces challenges due to legacy chemicals present in recycling streams, making it difficult to achieve high circularity. The absence of a clear technological pathway for achieving high circularity through recycling rates (as modelled at 70% of available waste) poses a challenge. Overcoming these challenges is essential to realize a 16-fold increase in recycling capacity by 2050. Additionally, a better understanding of PVC stocks and flows in different regions is necessary to optimise recycling infrastructure.	
With the interventions modelled, there is still around 7% remaining before reaching Net Zero. This reflects the uncertainty around how biobased feedstocks will perform and how the whole ethylene industry can access such a feedstock in a sustainable way.	

Conclusions: Comparing the Key Challenges

There are critical actions and time milestones that all industries need to observe.

- All material industries will be required to take significant action within the next five years to manifest a downward trend in global CO2 emissions, otherwise it is unlikely that their carbon budgets will be met.
- Commercialisation and mass deployment of new technologies will need to be in full swing from 2030 onwards.
- In all cases, closed-loop recycling can aid towards Net Zero by reducing primary demand. However, the importance of this varies between materials and decarbonising primary production should not be sacrificed.
- From a global perspective, the trajectory of China's decarbonisation—particularly from an energy generation perspective—will be a critical determinator of whether the global budget can be met.
- The difference in impact between geographic areas for all materials provides and opportunity for data driven purchasing decisions to influence the speed of decarbonisation.
- The current industry plans – where they exist – are likely to fall short of carbon budgets that align with 1.5°C. More emphasis should therefore be made on reducing overall demand for materials alongside decarbonisation strategies.

Some materials will rely more on green energy than others.

For Steel, glass and PVC there will need to be a transition away from fossil fuels as a heat source or reactant. These industries are dominated by natural gas and coal which will need to be phased out.

Aluminium and copper already rely heavily on electricity and therefore the challenge is to make sure there is enough green energy available where it is needed in order to deal with expanding demand.

Some materials will need to transition to entirely new technologies.

Copper and aluminium production is likely to stay mostly the same, with the latter requiring further development of anode replacements and low-carbon calcination. The fundamental processes are not intrinsically linked to fossil fuels and therefore most infrastructure can remain intact.

Steel requires a mix of technologies to mitigate or remove the need for coking coal as a fuel and reductant in the iron making process. Entirely new plants focusing on DRI for primary and EAF for secondary will be required.

Glass furnaces will need to be retrofitted or newly installed with the capability of running primarily on electricity, whilst PVC faces the potential for a fundamentally disruptive shift from fossil to bio-based feedstocks—one which is not fully embraced by the current value chain. This is alongside the need to electrify steam crackers and move away from coke-based production in China.

Recycling cannot be relied upon alone.

Recycling plays a significant role for most materials although for copper, steel and PVC and to a lesser extent, aluminium, much of the material is 'locked-up' in construction and not available for recycling. This means that recycling can only contribute so much at a global level, but will vary in importance when honing in on the product level. Furthermore, the benefits of recycling differ between materials due to the energy intensity of the processes.

Table 3 shows a summary of the key challenges that these industries are facing and where in the value chain these are. Regarding energy transition, infrastructure and technology development and recycling; each material varies in the where investment is most needed.

Table 3 – Net Zero Challenges Vary Between Materials

Material	The **Reliance** on Electrical green grid transition and expansion of capacity	The **need** for new technology and manufacturing infrastructure replacement	**Technical maturity** of replacement technologies	The **maturity** and availability of Recycling processes
Aluminium	●●●● Smelting is electricity-driven and dominates the impact.	●● Anode replacement will be required to fully decarbonise	●●● Inert anode and refinery calciner not yet fully commercialised	●●●● Recycling is common due to the high value and expanded capacity is all that is needed
Steel	●●● Relatively low electricity use currently, but will need to grow with new technologies	●●●● Most current blast furnaces will need to be replaced	●● A broad technology mix with varying readiness levels will be required	●●●● Scrap steel is very commonly recycled and expanded capacity is all that is needed
Copper	●●●● The process is heavily dependent on electricity	● The core process will remain unchanged	●●● It is unclear which alternative fuels will be used in machinery	●●● High value and easy to integrate, but centred on few geographic locations
Container Glass	●●●● The shift to electric furnaces will increase electricity demand	●●● All furnaces will need to be replaced with hybrid or fully electric	●● Furnaces are only just beginning to be tested at the scales required	●●● Glass recycling rates vary significantly by region and not all collected goes to remelt
PVC	●● The move to electric steam crackers will require more capacity	●●●● A switch to electricity driven steam crackers for ethylene and bio-based feedstocks will be required	●● Ethylene production is common, but electric steam crackers and bio-based are not	● Recycling is not well established and challenging to integrate. Legacy chemicals are problematic

Key: ● = Low

●●●● = High

E.g ● PVC has a **LOW** maturity of reycling

●●●● Aluminium has a **HIGH** maturity of recycling

Appendix

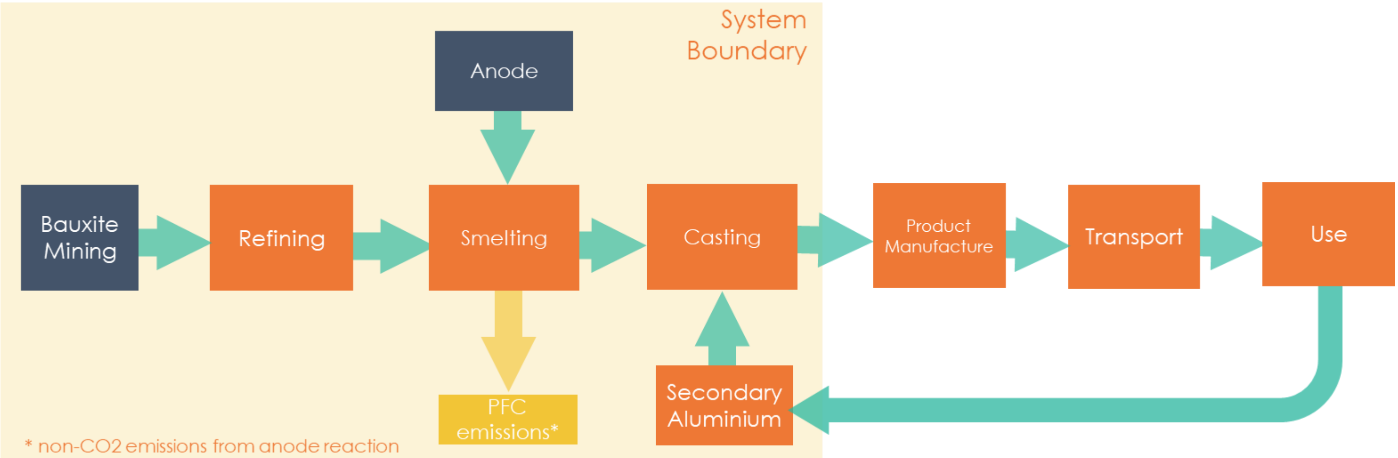
Additional Key Data and Assumptions

A.1.0 Aluminium

System Boundaries

Figure A 1 shows the basic system boundary used for aluminium production in the study. The value chain remains broadly consistent during the decarbonisation pathway with most changes taking place within energy systems. Included are the CO_2 emissions resulting directly from these processes through chemical reactions or burning of fossil fuels and the indirect production of the electricity used. The materiality principal is adhered to whereby the cut-off is to include at least 95% of the cradle-to-gate emissions with the focus on the most important with regard to decarbonisation. PFC emissions from the anode reaction during smelting are the only non-CO_2 emissions to be included. As the focus is on cradle to gate, downstream transport and any manufacturing into products is excluded and end of life is considered with regard to recycling. Other end of life processes (incineration, landfill) are considered for the purposes of this study to be zero impact due to aluminium being inert from a CO_2 perspective, but the material is considered lost from the system.

Figure A 1- Aluminium System Boundary



Intervention timeline

Table A 1 shows the timing of the interventions used in the pathway.

Table A 1– Timeline of Aluminium Interventions

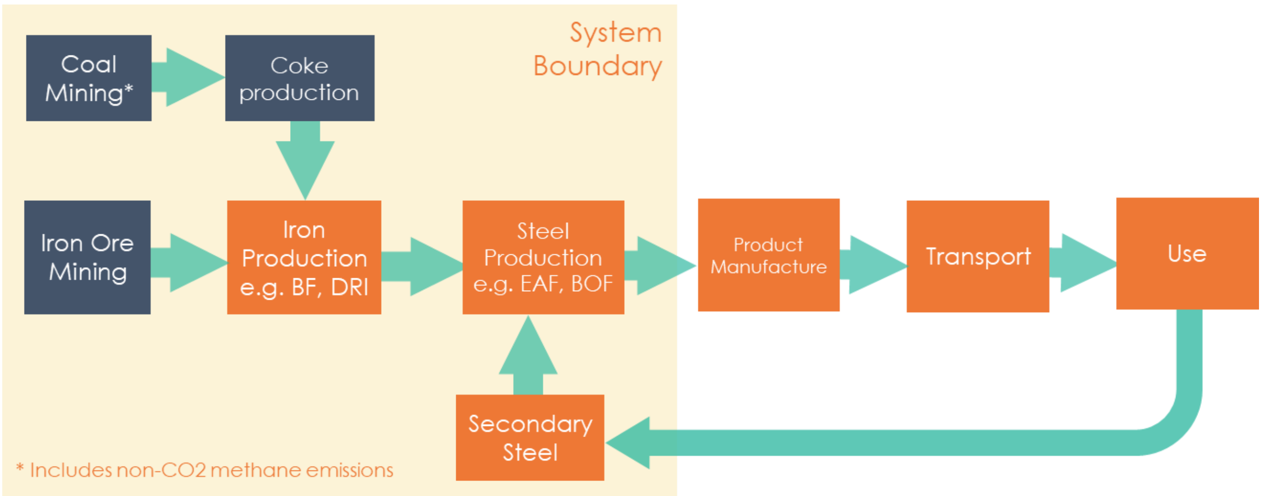
Intervention	Start Year	End Year
Recycling	2020	2035
Smelter Decarbonisation	2030	2045
Smelter CCUS	2030	2035
Material Efficiency	2025	2035
Anode Replacement	2030	2045
Alumina Energy	2025	2040

A.2.0 Steel

System Boundaries

Table A 2 shows the system boundary used for steel making in the study. The exact pathway the materials take varies depending upon the specific process, but the broad steps are represented here for the current system. For latter scenarios, parts of the process are reduced or eliminated (e.g. coking coal) and other fuels are brough it (e.g. hydrogen). The CO_2 emissions resulting directly from these processes through chemical reactions or burning of fossil fuels and the indirect production of the electricity used are all included. The materiality principal is adhered to whereby the cut-off is to include at least 95% of the cradle-to-gate emissions with the focus on the most important with regard to decarbonisation. Methane emissions from the extraction of coal for coking are also included due to importance in the overall result (see Table A 2). As the focus is on cradle to gate, downstream transport and any manufacturing into products is excluded and end of life is considered with regard to recycling. Other end of life processes (incineration, landfill) are considered for the purposes of this study to be zero impact due to steel being inert from a CO_2 perspective, but the material is considered lost from the system.

Figure A 2- Steel System Boundary



Non-CO2 Emissions

This study focus on CO2 as that is the basis for the IPCC carbon budget. However, important non-CO2 emission sources are included in the study for each material where that industry is entirely responsible for these emissions.

Table A 2- Methane Emissions from Coking Coal Mining

	Coking Coal Production (Mt)[39]	kg methane/ tonne coal[40]	kg/CO2e per kg coking coal
China	554	10.4	0.196
Australia	184	5.4	0.034
Russia	91	22.1	0.068
USA	50	15.2	0.026
Total	**878**	-	**0.323**

Note: Methane GWP is 29.8 as per IPCC (2021)

Steel Making Technologies

The following table summarises the key technologies. This is based on the technology definitions detailed by the MPP with some aggregated into groups to simplify the list where appropriate.

Technology	Description
Average blast furnace-basic oxygen furnace (Avg BF – BOF)	A typical steel mill where iron ore and coking coal are fed into a blast furnace. Pulverized Coal Injection (PCI) is also used to increase efficiency and reduce coking coal requirement. PCI is 195kg/t and 5% scrap is used.
Best available technology blast furnace-basic oxygen furnace (BAT BF – BOF)	The same as above, but utilising best practice This includes increasing PCI to 270kg/t and scrap to 25% and improved efficiency by 10%
BAT BF - BOF + Biomass + Biomass +CCU	As above, but replacing PCI and coking coal with biomass. The emitted gases could be synthesised into methanol and subsequent polymer manufacture. The MPP suggests this could provide a carbon sequestration credit although given the technology and value chain is highly speculative, this is not included here.
Direct Iron Reduction and Electric Arc Furnace (DRI – EAF)	Coal is replaced with natural gas in a Direct Reduction Iron process. The resulting sponge iron is sent to an EAF where it is melted to form the steel output.
DRI - EAF + 100% Hydrogen	As above, but natural gas is replaced with hydrogen
DRI - BOF	As above, but a natural gas fired basic oxygen furnace is used instead of an EAF.
DRI - BOF + Hydrogen	As above, but hydrogen is used instead of natural gas.
DRI - BOF + CCUS	As DRI -BOF, but carbon capture is used to capture the CO_2 emissions from fuel burning.
Smelting Reduction + CCUS	Liquid steel is produced from iron ore without coking coal in a cyclone converter furnace. Pulverised coal is still required, which it mitigated with CCUS.
Electric Arc Furnace (EAF)	Scrap steel is melted in an arc furnace using electricity supplemented with natural gas for all other heat requirements. Power consumption in EAF is assumed to be ~1.9 GJ electricity/t liquid steel with 100% scrap feed.

Intervention timeline

Table A 5 shows the timing of the interventions used in the pathway.

Table A 3– Timeline of Steel Interventions

Intervention	Start Year	End Year
Recycled Content	2020	2050
Material Efficiency	2025	2050
Electricity Decarbonisation	2020	2045

Table A 4 details the technology shifts used to map the pathway in this study which are based on data from the MPP "Carbon Cost" pathway.

Table A 4 – Tech Shift Timelines

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Avg BF - BOF	53%	53%	52%	52%	52%	51%	48%	45%	42%	40%	37%	33%	27%	23%	19%
BAT BF - BOF	18%	17%	17%	17%	17%	17%	16%	14%	13%	12%	11%	11%	10%	9%	8%
BAT BF - BOF + Biomass + CCU	0%	0%	0%	0%	0%	0%	1%	3%	4%	6%	8%	10%	14%	17%	20%
DRI - EAF	4%	4%	4%	4%	4%	4%	7%	9%	12%	12%	14%	13%	7%	3%	2%
DRI - EAF + 100% Hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	6%	8%	9%
DRI - BOF	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	4%	6%	6%
DRI - BOF + Hydrogen	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
DRI - BOF + CCUS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
Smelting Reduction + CCUS	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
EAF	25%	26%	26%	27%	27%	28%	28%	29%	29%	30%	30%	31%	31%	32%	33%
Other	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

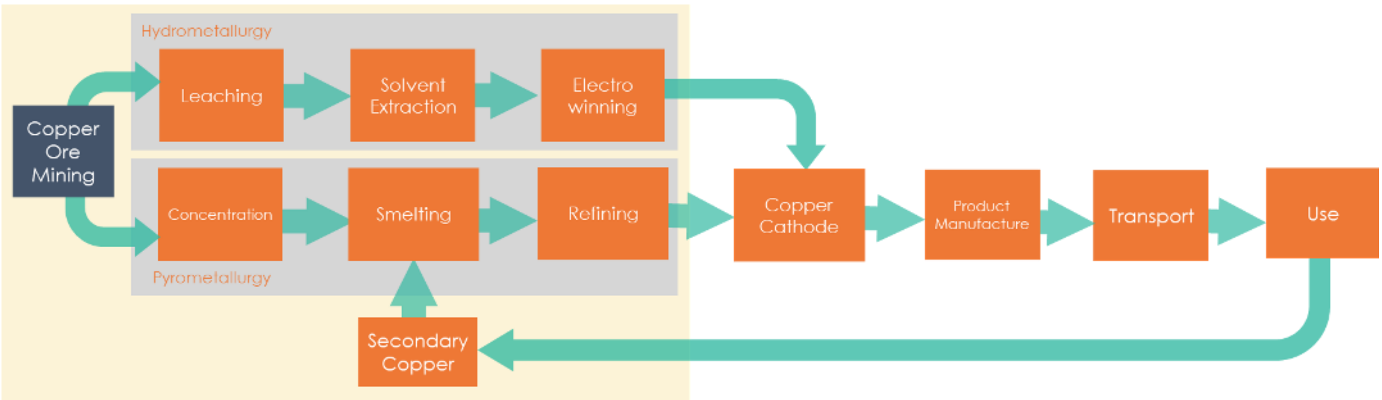
	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Avg BF - BOF	16%	13%	11%	9%	8%	6%	5%	3%	2%	1%	1%	0%	0%	0%	0%	0%
BAT BF - BOF	8%	7%	6%	6%	5%	4%	4%	3%	3%	2%	2%	1%	1%	0%	0%	0%
BAT BF - BOF + Biomass + CCU	22%	23%	24%	25%	24%	24%	24%	24%	23%	23%	22%	21%	20%	19%	17%	16%
DRI - EAF	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
DRI - EAF + 100% Hydrogen	9%	10%	10%	10%	10%	10%	10%	10%	10%	10%	9%	9%	9%	9%	9%	9%
DRI - BOF	7%	6%	5%	5%	3%	2%	2%	2%	3%	3%	3%	4%	4%	5%	5%	5%
DRI - BOF + Hydrogen	0%	2%	2%	3%	5%	6%	6%	7%	8%	8%	8%	8%	8%	8%	9%	10%
DRI - BOF + CCUS	1%	2%	3%	4%	6%	7%	7%	8%	9%	9%	9%	10%	10%	11%	11%	11%
Smelting Reduction + CCUS	0%	1%	1%	2%	2%	2%	3%	3%	4%	5%	5%	5%	5%	6%	6%	6%
EAF	33%	34%	34%	35%	35%	36%	36%	37%	37%	38%	38%	39%	39%	40%	41%	41%
Other	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	3%	3%	2%	2%	2%
	100%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

A.3.0 Copper

System Boundaries

Figure A 3 shows the basic system boundary used for copper production in the study. The two primary manufacturing process—hydrometallurgy and pyrometallurgy— are included in their relative proportions. The value chain remains broadly consistent during the decarbonisation pathway with most changes taking place within energy systems. Included are the CO_2 emissions resulting directly from these processes through chemical reactions or burning of fossil fuels and the indirect production of the electricity used. The materiality principal is adhered to whereby the cut-off is to include at least 95% of the cradle-to-gate emissions with the focus on the most important with regard to decarbonisation. As the focus is on cradle to gate, downstream transport and any manufacturing into products is excluded and end of life is considered with regard to recycling. Other end of life processes (incineration, landfill) are considered for the purposes of this study to be zero impact due to aluminium being inert from a CO_2 perspective, but the material is considered lost from the system.

Figure A 3- Copper System Boundary



Baseline changes

The baseline accounts for a decline in the grade of copper ore, affecting primarily pyrometallurgical production, as hydrometallurgy already utilises a lower grade of copper ore. Assumptions regarding the ore grade have been derived from the International Copper Association's 'Pathway to Net Zero', which projects the current copper content of mined copper ore to be 0.58%. This figure is anticipated to decrease to 0.53% by 2030 and persist at that level until 2050. [8] A declining grade of copper ore increases the energy required for the mining process, as a larger quantity of copper must be extracted to yield the same final product.

Copper production

While overall emissions and electricity dependency are comparable for both production methods, there exists a distinction in carbon footprint distribution, as depicted Figure A 4and Figure A 5. This discrepancy arises from variations in production methods and their respective applications. Following mining, pyrometallurgy necessitates an energy-intensive concentration step to produce copper concentrate, typically containing around 30% copper. This prepares the copper ore for smelting and refining into the final product, refined copper. Conversely, hydrometallurgy bypasses the concentration step but is

[8] International Copper Association. "Copper - The Pathway to Net Zero," (2023).

primarily employed for extracting copper from low-grade ores, rendering the mining process inherently more energy intensive.

Figure A 4- Carbon Footprint of pyrometallurgical copper production by process

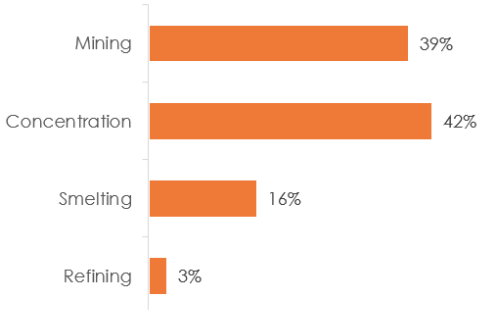
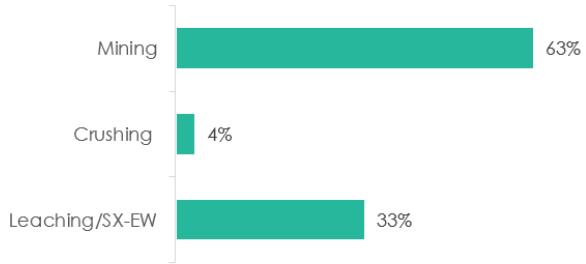


Figure A 5 - Carbon Footprint of hydrometallurgical copper production by process



Recycling

The recycling rate modelled in this study pertains solely to post-consumer scrap. Industrial scrap, classified as a process inefficiency, is excluded from the recycling rate as it does not contribute to reducing the demand for primary copper. This study assumes that copper recycling is undertaken through pyrometallurgical production methods. In this process, copper scrap is combined with concentrate at the start of the smelting process. From this point onward, it undergoes identical processes as primary production and utilises the same technological methods. Considering that secondary production bypasses the mining phase, which is the most emission-intensive production stage for copper, CO_2 emissions from recycled copper can be as much as 80% lower than those from primary production.

Intervention timeline

Table A 5 shows the timing of the interventions used in the pathway.

Table A 5– Timeline of Copper Interventions

Intervention	Start Year	End Year
Recycling	2020	2050
Energy Efficiency	2020	2050
Decarbonised Electricity	2025	2040
Alternative Fuels	2032	2050
Equipment Electrification	2032	2050

Treatment of by-products

The production of copper facilitates the extraction of several valuable by-products, such as molybdenum, gold, rhenium, selenium, silver, and tellurium. The economic allocation of environmental impacts associated with these by-products is determined using 10-year average prices.

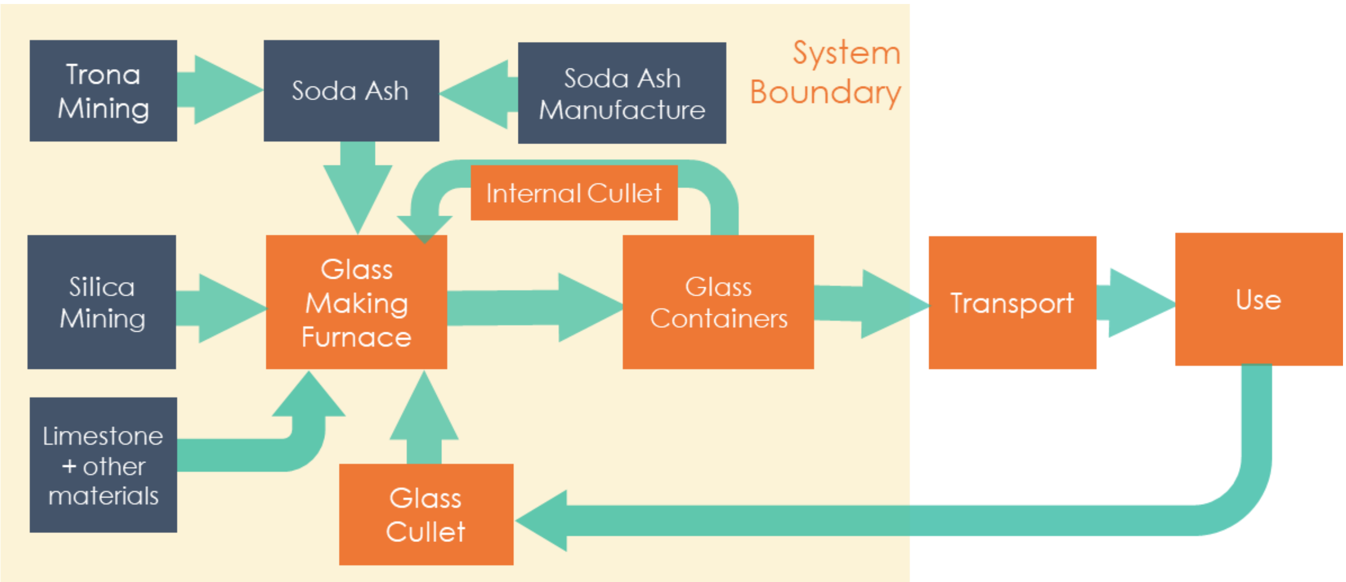
A.4.0 Glass Packaging

System Boundaries

Table A 6 shows the basic system boundary used for glass container production in the study. The value chain remains broadly consistent during the decarbonisation pathway with most changes taking place within energy systems and the way in which the furnace is fuelled. Soda ash is produced from a mix of mining and manufacture, with the former contributing the most in North America and Europe due to the proximity of the two large trona mining areas (Wyoming, USA and Turkey). The process diagram differs from the other materials in this study as the manufacture of the end product is included. This is because glass not produced as an intermediate product for containers. As result of this, the wastage from the forming process is also included as internal cullet which is recirculated into the furnace.

Included are the CO_2 emissions resulting directly from these processes through chemical reactions or burning of fossil fuels and the indirect production of the electricity used. The materiality principal is adhered to whereby the cut-off is to include at least 95% of the cradle-to-gate emissions with the focus on the most important with regard to decarbonisation. As the focus is on cradle to gate, downstream transport excluded and end of life is considered with regard to recycling. Other end of life processes (incineration, landfill) are considered for the purposes of this study to be zero impact due to glass being inert from a CO_2 perspective, but the material is considered lost from the system.

Figure A 6- Glass System Boundary



Furnace Fuelling

It is assumed that for the majority of the world glass is produced using natural gas as the main furnace fuel. The main exception to this is China which also uses other fuels. The split detailed in Table A 6 is based on a 2022 article.[41] These figures are similar to a 2019 study by Hu, P. et al.[42], which claimed that 70% of furnaces were coal-powered (based on 2014 data) – however, there was already a trend of converting such furnaces to natural gas, which may be accelerated by the 14th Five-Year Plan for Energy Saving and Emission Reduction. With China responsible for 37%[43] of the global market the global furnace fuel estimates are derived in Table A 8

Table A 6 – Chinese Furnace Fuels

Natural Gas	Fuel Oil	Coal
40%	2%	58%

Table A 7 – Global Furnace Fuels

Fuel	Proportion
Natural Gas	78%
Fuel Oil	1%
Coal	22%

Intervention timeline

Table A 8 shows the timing of the interventions used in the pathway.

Table A 8– Timeline of Glass Interventions

Intervention	Start Year	End Year
Recycled Content	2020	2040
Furnace Electrification	2025	2045
Alternative Fuels	2025	2045
Lightweighting	2025	2035
Raw Materials Decarbonisation	2025	2045
CCUS	2030	2050

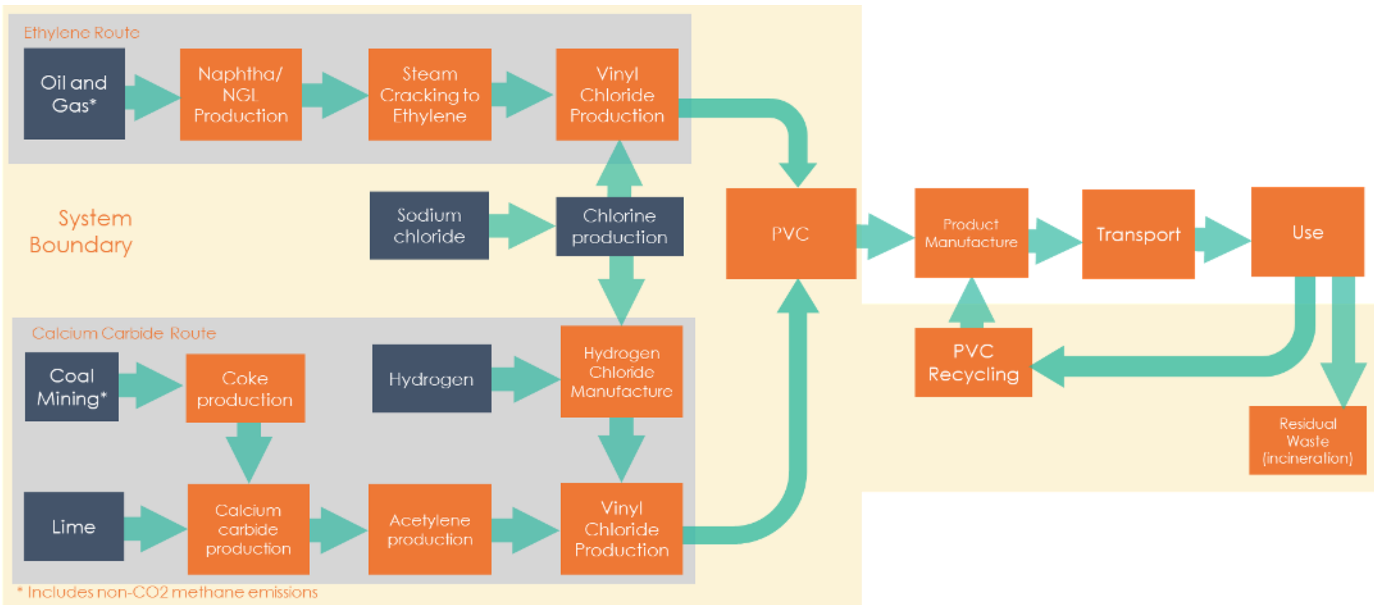
A.5.0 PVC

System Boundaries

Table A 7 shows the basic system boundary used for PVC production in the study. The two primary routes are covered; ethylene based, tied to the petrochemical industry and practiced in most of the world, and calcium carbide based, tied to the coal industry mainly confined to China. The value chain is expected to change somewhat, with move towards ethylene-based production in China.

Included are the CO_2 emissions resulting directly from these processes through chemical reactions or burning of fossil fuels and the indirect production of the electricity used. The materiality principal is adhered to whereby the cut-off is to include at least 95% of the cradle-to-gate emissions with the focus on the most important with regard to decarbonisation. As the focus is on cradle to gate, downstream transport and any manufacturing into products is excluded. End of life is considered with regard to recycling and, in addition, where the residual waste route is incineration, this is also included. Unlike the other materials in this study, when incinerated, PVC does release CO_2 emissions which need to be accounted for. However, as much of the material is 'locked-up' in construction products, only a small amount is available as waste (45%) and for the proportion not recycled, much of this will go to landfill where no impact is assumed due to PVC being inert from a CO_2 perspective, but the material is considered lost from the system.

Figure A 7- PVC System Boundary



Global PVC Market

Table A 9 shows the market data that is used in this study to derive the production quantities that come from the different routes. With these production capacities and data showing that 81% of Chinese production comes through the calcium carbide route, the global split between calcium carbide and ethylene is estimated to be 33% and 67% respectively.

Table A 9 – PVC Global Production and Capacities

	Share	Capacity [a] (Mt)	Production (Mt)[a]
Middle East and Africa	3%	2	2
Russia and Baltic	2%	1	1
Europe	13%	8	6.5
South America	3%	2	2
North America	16%	10	8
South East Asia	4%	2.44	2
North East Asia (Ex China)	15%	9.0	7.4
China	41%	25.2[b]	20.6
India	3%	2	2
	100%	**61**	**50**

a) 2022 capacities for all except China with production 82% of capacity[44]

b) 2019 production China capacities[45]

Intervention timeline

Table A 10 shows the timing of the interventions used in the pathway.

Table A 10– Timeline of PVC Interventions

Intervention	Start Year	End Year
Recycling	2020	2050
Steam Cracker	2030	2045
Electricity	2025	2040
Heat	2025	2045
Tech Shift	2030	2050
Biobased	2030	2045

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